Design and Development of Transfer Chute to Handle Alternate Fuels and Their Mix in Indian Cement Plants

THESIS

Submitted in partial fulfilment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

KAPIL KUKREJA

Under the supervision of

Prof. MANOJ KUMAR SONI

and co-supervision of

Dr. BIBEKANANDA MOHAPATRA

BIRLA INSTITUTE OF TECHNOLOGY & SCIENCE

PILANI – 333031 (RAJASTHAN) INDIA

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समर्पित.....

समर्पित उस परमपिता को, जिसने ये जीवन वरदान दिया
मेरे पिता को, जिन्होंने पीएचडी करने का उत्साह प्रदान किया

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समर्पित मेरी माँ को, जिनका मुझ पर आशीष भरा हाथ रहा
मेरी पत्नी और बेटी को, जिनका हर परिस्थिति में साथ रहा
मेरे भाई-बहिन, दोस्तों को, जिनका मुझसे जुड़ा जज़्बात रहा |

Birla Institute of Technology & Science, Pilani
Pilani Campus

CERTIFICATE

This is to certify that the thesis titled **"Design and Development of Transfer Chute to Handle Alternate Fuels and Their Mix in Indian Cement Plants,"** submitted by **Kapil Kukreja** ID No **2018PHXF0106P for** the award of Ph.D. of the Institute embodies original work done by him under my supervision.

Signature (Supervisor): ____________

Prof. MANOJ KUMAR SONI
Professor, Department of Mechanical Engineering,
BITS Pilani, Pilani campus, India
Date: 18/10/2023

Signature (Co-supervisor): ____________

Dr. BIBEKANANDA MOHAPATRA
Advisor & Consultant-CMO Cell, UltraTech Cement Limited
Former Director General,
National Council for Cement and Building Materials, Ballabgarh, Haryana, India

Date: 18.10.2023

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Kapil Kukreja
October 2023

ABSTRACT

The world's annual energy consumption is about 580 million terajoules, of which 80% still rely on fossil fuels. Industrial processes and energy combustion contribute about 89% of total global anthropogenic CO_2 emission. One such industry is the cement industry which utilizes fossil fuels as its primary source of energy. India is the second largest producer of cement in the world after China. Indian cement industry has an annual manufacturing capacity of 594.14 million metric tonnes with an annual production of 361.00 million metric tonnes (MT) with a specific CO_2 emission of 0.67 tons per ton of cement. The presence of the Indian cement manufacturing group during COP26 and COP27 showed the commitment of the industry to achieve net zero CO_2 emissions by 2070. The last decade has been challenging for the Indian cement industry to secure the availability of coal & petcoke (the main fuel for cement production) and control the production cost & profitability due to an increase in fuel price.

Further, India, the second largest populated country in the world, is facing the severe problem of waste management & handling waste generated by society and industry. India generates about 50 million metric tonnes of Municipal Solid Waste (MSW), 9.24 million MT of Hazardous Waste (HW), 3.46 million MT of plastic waste, and 683 million MT of crop residues annually. Indian cement industry has evolved with the solution to solve both these problems by using waste generated from society & industry as alternative fuels (AFs) for coal & petcoke. Utilization of waste as AFs in cement plants, known as co-processing, comes with many challenges related to the environment, quality, economics, process, health & safety, and operation and system design.

This research focused on one of the major operation and system design issues, i.e., jamming of transfer chutes when handling multiple types of AFs & their mix, for which the majority of solutions offered by the researchers are addressed either to clear the chute jamming or sensing the jammed chute. But the solution for the chute jamming problem was not found from the system design point of view, especially when the chute is handling AFs and their mix. To keep the research more focused and relevant to the Indian cement industry, a survey was carried out to establish the transfer chute jamming issues, its causes, and the solution being adopted by Indian cement plants. The survey established that the industry is still adopting a conventional approach to chute design, and chute jamming is one of the significant bottlenecks which demands substantial maintenance time and cost. Refused Derived Fuel (RDF), mixed waste, and industrial waste were found to be major AFs for contributors in chute jamming due to the wide range of variations in their properties.

Discrete Element Modelling (DEM) is used as a simulation tool to analyze the issues with conventional transfer chute design being adopted by the Indian cement industry for AFs handling and to develop the new transfer chute design parameters. Seven cement plants located in different cement clusters of India were visited to identify major AFs and their properties being used by industry. RDF, Multi layer plastic (MLP), agro waste/biomass, tyre chips, footwear waste, Effluent Treatment Plant (ETP) sludge, and various mixed solid waste have been identified as major AFs in the industry, and simulations were done for these fuels to design and develop the transfer chute which can handle AFs & their mix without chute jamming.

The experimental set-up consisting of belt conveyors and transfer chutes was designed in line with simulation results, fabricated, and installed at National Council for Cement and Building Materials (NCB) to validate the newly designed transfer chute. The experiments were carried out for a total of 19 nos. AFs, including 11 types of AFs collected from industry and eight nos. of mixed solid waste prepared at NCCBM to validate the design parameters and flexible feature (easy de-clamping & motorized tilting) of newly developed transfer chute for fast cleaning in case of jamming. The performance of the transfer chute was evaluated in various dynamic conditions through experiments, including variation in mass flow rate (3 to 15 tonnes per hour), moisture content (0.18 to 45%), and conveying speed (0.5 to 1.5 m/s). The newly designed transfer chute performed well for all 19 nos. AFs have a wide range of variation in bulk density (0.094 to 0.60 t/m3), moisture content (0.18 to 45%), net calorific value (~1200 to 8500 kcal/kg fuel), angle of repose (25 to 39°), angle of inclination/sliding (~25 to 35°), particle size (~1 to 100 mm). Further, it was recorded that the flexibility feature of the transfer chute reduces the cleaning time from an average of 90 minutes to 6 minutes, which resulted in no feed cut of AFs to the rotary kiln/calciner firing points and no negative impact on the operation, quality, environment, and production of cement. , which may save USD 1,22,000 per annum and reduce the CO_2 emission of ~2400 MT per annum for a 3.00 million MT Capacity cement plant significantly impacting the profitability of cement production and the sustainability of the cement plants.

The current research is an attempt to develop the design parameters of the transfer chute, which can be used by the Indian cement industry to handle multiple types of AFs & their mix without any jamming issues. It will ease the path to achieving a high Thermal Substitution Rate (TSR) by consuming more waste as fuel in the cement production. The research outcomes shall contribute to the Indian cement industry in achieving the high TSR and accruing its associated benefits, such as saving in cost ~Rs. 25 to 76 Crores per annum and reduction in CO_2 emission to the tune of 57,000 to 225000 tonnes per annum at an average TSR value of 10to 30% by 2035.

LIST OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

A	Cross-sectional area	m^2
a_1	Distance of center of gravity of discharge stream	m
B	Horizontal length of bulk solid material at location considered	m
b	Contact perimeter	m
B_w	Belt width	mm
C	Length of contact between bulk solid material and inclined side of the belt	cm
c	Standard Edge Distance	cm
D	Diameter	m
F^e	Electrostatic Force	N
F^v	Van der Waals force	N
F^l	Liquid bridge force (static)	N
g	Acceleration due to gravity	ms^{-2}
H	Height	m
Ho	Bed depth	m
K^1	Distance between parallel parabolic curves	m
Kv	Ratio lateral to normal pressure	
L	Actual Horizontal Length of belt conveyor	m
l	Length of the slider plate	cm
P	Power	kW
Q	Mass Flow	th^{-1}
Q_{tv}	Chute Flow (Theoretical)	m^3h^{-1}
Q_v	Volumetric Flow	m^3h^{-1}
R	Radius of curvature	m

S_i	Cross-sectional area of the chute	m^2
S^*	Cross-sectional area of the material stream in the chute	m^2
V	Velocity	ms^{-1}
V_b	Belt Velocity	ms^{-1}
V_{cr}	Critical Velocity	ms^{-1}
V_s	material stream speed or belt speed	ms^{-1}
V_1	Incoming material velocity before impact	ms^{-1}
V_2	Material velocity after impacting the chute surface	ms^{-1}
V_Θ	Initial Velocity at location considered	ms^{-1}
W	Width of the RDF pile	cm

GREEK LETTERS

α	Chute Inclination angle	deg
α_b	Wrap angle around the head pulley	deg
β_{dyn}	the surcharge angle	deg
ε	Inclination of Conveyor Belt Transition	deg
$\varepsilon_1 / \varepsilon_2$	Divergence Coefficients	
λ	Roll idlers troughing angle	deg
μ	Coefficient of friction between bulk solids and chute surface	deg
ν	Bulk solid’s stream velocity	ms^{-1}
ρ	Bulk Density of the material	tm^{-3}
Φ	Wall friction angle corresponding to Ho	deg
Θ	Angle of incoming material with respect to chute surface	deg
θ_b	Back wall angle	deg
θ_c	Critical angle of chute inclination	deg
θ_I	Angle of Internal Friction	deg
θ_i	Angle of Inclination	deg
θ_s	Side wall angle	deg
θ_R	Angle of Repose	deg
θ_v	Valley angle	deg
ω_1	Discharge angle for the top layer of the material from belt	deg
ω_2	Discharge angle for the bottom layer of the material from belt	deg

LIST OF ABBREVIATIONS

AFs	Alternate Fuels
AoI	Angle of inclination
AQI	Air Quality Index
ARMs	Alternate Raw Materials
CCI	Compressibility Index
CFD	Computational Fluid Dynamics
CPP	Captive Power Plant
CoR	Coefficient of Restitution
CoRF	Coefficient of Rolling Friction
CoS	Coefficient of Static Friction
dBA	Decibels
DEM	Discrete Element Modeling
FAHP	Fuzzy Hierarchy Process
GoI	Government of India
GHG	Greenhouse Gases
GMST	Global Mean Surface Temperature
HW	Hazardous Waste
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
MCB	Miniature Circuit Breaker
MCDM	Multi-Criteria Decision Making

MMAW	Manual metal Arc Welding
MS	Mild Steel
MSDS	Material Safety Data Sheet
MSW	Municipal Solid Waste
MTPA	Million tonnes per annum
NCB or NCCBM	National Council for Cement and Building Materials
OXE	Oxygen Enrichment
PLC	Programmable Logic Controllers
RDF	Refused Derived Fuel
SBM	Swachh Bharat Mission
SMPS	Switching Mode Power Supply
SOP	Standard Operating Procedure
SQP	Sequential Quadratic Programming
SPL	Spent Pot Lining
TDF	Tyre Derived Fuel
TPD	Tonnes Per Day
TSR	Thermal Substitution Rate
UHMWPE	Ultra-High Molecular Weight Polyethylene
VFD	Variable Frequency Drive

CHAPTER 1

INTRODUCTION

The chapter covers a brief background of the origin of the problem statement, including the status of cement production in India & its contribution to global warming, waste management issues in India, crises of conventional fuel availability for the Indian Cement Industry, benefits & challenges of waste utilization as alternative fuels in Indian cement plants, problem statement, research objectives, and research methodology.

1.1 Background

1.1.1 Indian cement industry and its impact on global warming

India is the second largest producer of cement in the world after China. Indian cement industry has an annual manufacturing capacity of 594.14 MT with an annual production of 361 MT. India possesses around 333 manufacturing units, among which 150 are integrated, 116 are grinding units, and five are clinkerization units. India's cement consumption is 260 kg per capita which is still less than the global average of 540 kg per capita[1]. In the cement production process, a large amount of greenhouse gases (GHG), especially by calcination of limestone (~60% of CO_2) and burning of fuels (~40% of CO_2), are emitted [2]. The industry has worked hard to reduce its GHG emission from 1.12 tonne of CO_2/ tonne of cement production in 1996 to 0.670 tonne of CO_2/ tonne of cement production in 2017 (including on-site power generation) [3]. The Indian cement industry alone accounts for 8% of total national emissions. These emissions are a product of electricity consumption, the burning of fossil fuels (coal, gas, etc., for energy use), and the process of converting limestone to lime (process emissions), accounting for 13%, 31%, and 56%, respectively. The CO_2 emission intensity of the Indian cement industry in 2018 was 576 kgCO_2/tonne of cement produced, while the global average is 634 kgCO_2/ton of cement produced[4]. The Indian cement industry is putting its best efforts into reducing the impact of global warming by decreasing its carbon footprint. The presence of the Indian cement manufacturing group during COP26 and COP27 showed the commitment of the Indian cement industry to achieving net zero emissions by 2070[5]. The industry has identified five levers for achieving net zero emission with cement production-(a) Improving Thermal and Electrical Energy Efficiency,(b) Installation of Waste Heat Recovery Systems, (c) Alternate Fuels and Raw Material Utilization, (d) Clinker factor reduction, (e) Newer Technologies like renewable energy and carbon capture & utilization[6].

1.1.2 Waste generation and its management issues in India

Waste management is one of the significant challenges in the sustainable development of India, where industrialization and economic development have resulted in increased waste generation per person. Lack of training in the waste management area and the unavailability of qualified waste management professionals, limited infrastructure & capital investment leads to inadequate waste collection, storage, treatment, and disposal systems[7]. The composition of Indian waste is different as compared to other developed countries — so there is a need for a new approach to waste management. The average amount of solid waste generated per capita compared to the world is much lower, but the highly-dense population makes it a severe problem in India. While comparing, it was also found that Indian waste generation also varies in quantity, quality, and typology, further slow adoption of latest technologies for segregation, treatment, and storage, lack of environmental awareness and public attitude towards the consequence of waste disposal, ineffective implementation of the government policies, etc. make the waste management problem even more severe[8]. In-effective waste management impacts in many ways, including fatality to human life, adverse effects on human health and environment as well as wildlife, and creating a disturbance in ecological unbalance. Waste management of Municipal Solid Waste (MSW), Hazardous Waste (HW), plastic waste, and paddy stubble (Parali) have emerged as leading challenges in India. Fatal due to the Gazipur MSW landfill collapse, accident due to HW dumping in Surat, and fatality of wild elephants due to waste dump at Madukarai are some examples of inefficient waste management in India [9–11]. Health risks to proximate communities of MSW landfill in Mumbai, Kolkatta, and Delhi is eye opener[12–14]. Apart from the impact on health, life, environment, waste generation also demands huge land for disposal, which is yet another area of concern for a highly populated country like India. Fig. 1.1 indicates the projection of MSW generation and land requirement in the next 30 years for disposal of the waste if the issue is not addressed at present:

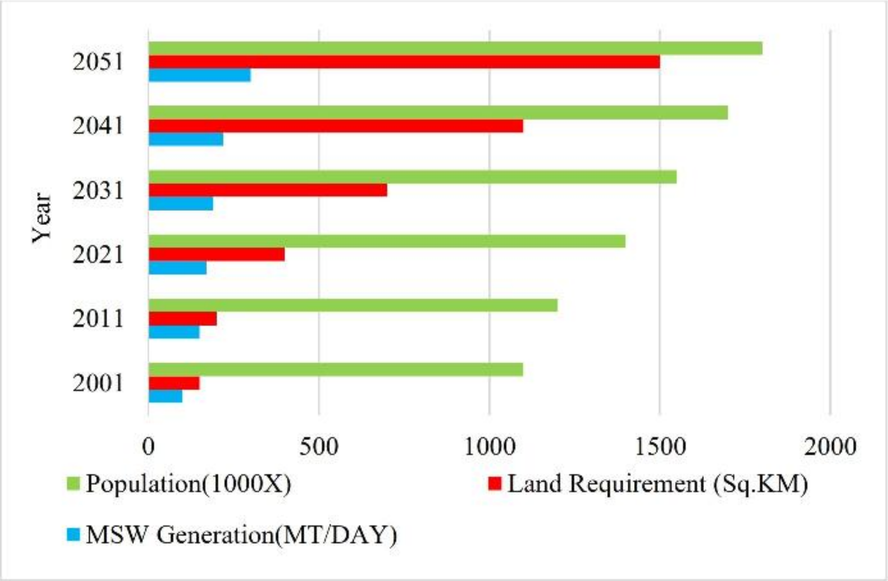


Fig. 1.1 Per-capita waste generation and land requirement [8]

There are 76,235 HW-generating units in the country with an authorized quantity of 42.80 million TPA. An annual increase of about 10% has been observed in the number of HW units compared to the national inventory report for 2019-20. During the year 2020-21, about 9.24 million MT of HW was generated, indicating a 5% increase in the generation of HW compared to the previous year, i.e., 2019-20[15]. Fig. 1.2 shows the status of HW management in India, which indicates that a substantial quantity of HW is being disposed of through landfills.

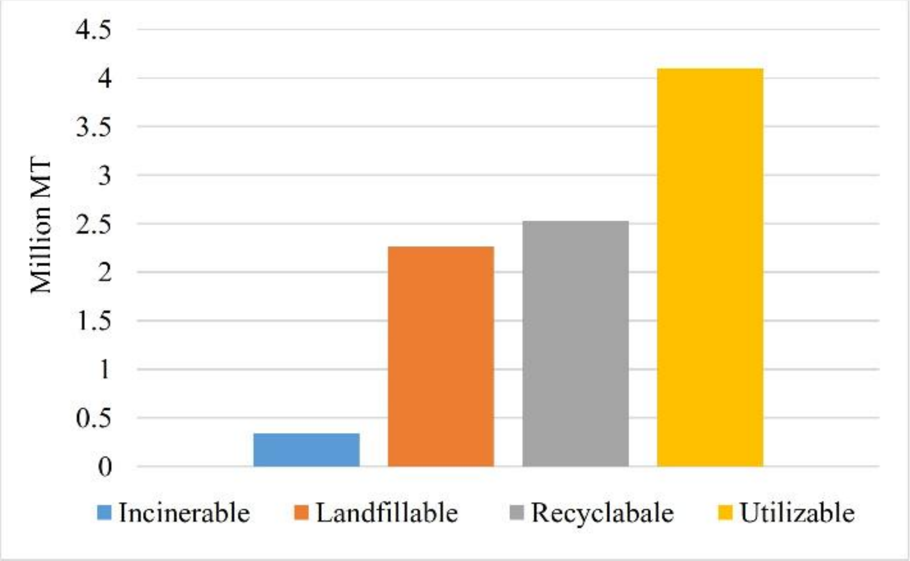


Fig. 1.2 Annual hazardous waste generation in India [15]

As per details provided by 35 States/UTs, the estimated plastic waste generation in

India during the year 2019-20 is 3.47 MTPA, and per capita plastic waste generation has doubled in five years[16]. Mismanagement of waste plastic creates many issues on land as well as marine life. It takes an average of 1000 years to degrade completely; when not managed effectively, plastic waste generated on land, enters into the marine environment through rivers and municipal drainage systems. As a result, it affects the life of aquatic species by impacting their stomach and digestive tract systems and sometimes leading to death [17].

Further, every winter in northern India starts with the news of dangerous levels of AQI resulting from paddy stubble burning (Parali). This is because the volume of the farm waste is humongous, and the window for disposing of it is too small. Limited farm mechanization, scarce human resources, and poor acceptability of paddy straw as fodder are the root causes behind this residue burning[18]. Punjab generated 18 million MT of stubble, of which 70-80 % was burnt. It is detrimental to the environment as it releases toxic substances like CO, SOX, NOX, CH4, VOC, PM, etc. [19].

Hence, the safe disposal of wastes generated in India is the demand of the present era for sustainable development. If necessary steps are taken now, the situation will improve due to the country's growing population.

1.1.3 Fuel Crisis in Indian Cement Industry and Waste as Potential Alternative

Coal and petcoke are primary conventional fuels used to meet the thermal energy requirement for the cement industry. The trend of fuel consumption in India from 2015-17 has indicated that the share of coal has decreased from 41%, with a corresponding increase in petcoke 56% [6]. However, the availability of coal for the Indian cement industry has been uncertain in the last decade. The cement industry faced many incidences of least preference supply of coal over other industries, forcing them to increase the share of petcoke [20–22]. However, the price hike of coal and petcoke in 2021-22, as indicated in Fig. 1.3, has made the situation more complex [23–25].

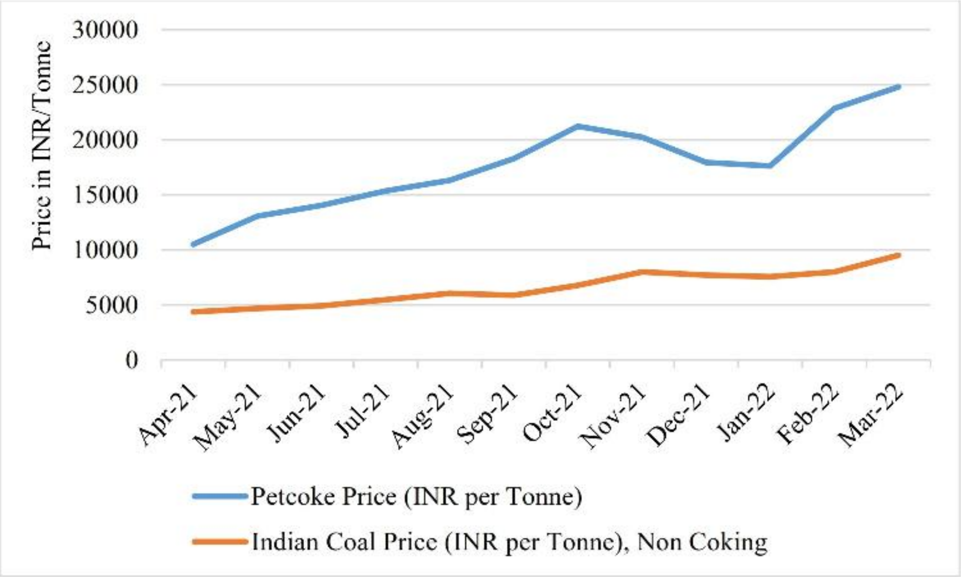


Fig. 1.3 Fuel price trend in India

In view of the above issues related to coal and petcoke, the Indian cement industry has an inclination towards the utilization of waste as an alternative to Coal and Petcoke. Waste utilization as an alternative fuel in the cement manufacturing process is known as co-processing, which does not only address the issues associated with coal & petcoke, i.e., the uncertainty of supply, high price fluctuation, high CO_2 emission, etc. but also provides the sustainable solution for waste management issue in India [26]. Thermal energy by replacing coal through alternative fuels is represented by the term Thermal Substitution Rate (TSR). The trend of TSR by AFs utilization in the Indian cement industry is shown in Fig. 1.4 [1,27].

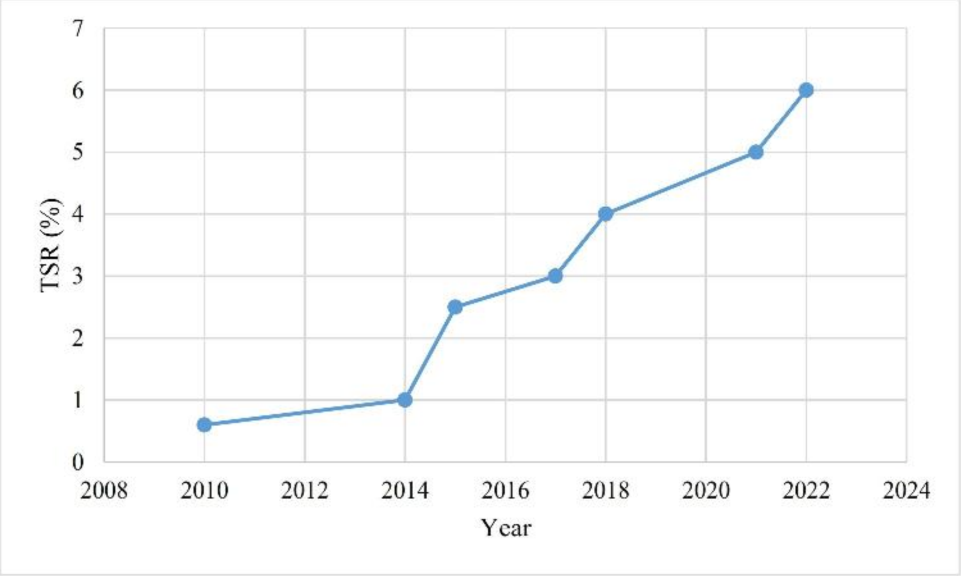


Fig. 1.4 Thermal substitution rate in Indian cement industry

Hence, the utilization of waste as alternative fuel not only resolve the issue of waste management and safe disposal but also it provides a solution to the Indian cement industry for various challenges related to higher price and unavailability of fossil fuel, as indicated in Fig. 1.5. Apart from above advantage, waste co-processing as AFs in cement industry also contribute for the fossil fuel conservation for the future.

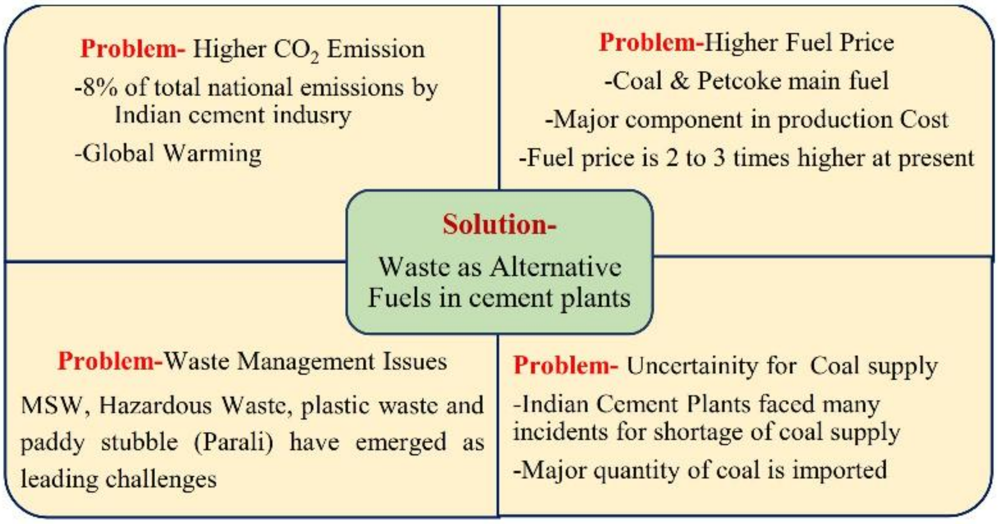


Fig. 1.5 Waste as alternative fuels in Indian cement plant

The cement industry is working towards consuming wastes that provide a sustainable alternative to coal and petcoke as a fuel to the industry. This is like hitting two birds with one stone. One addresses the issue associated with a high quantity of coal/petcoke consumption, its availability & economic viability, which is unpredictable. The other is various problems of processing a massive amount of waste generated in India. However, the utilization of alternative waste fuels comes with many challenges.

1.1.4 Challenges of Utilizing Waste as Alternative Fuels in Indian cement plants

AFs are a mixture of various wastes; hence homogeneity and variation in composition create many challenges related to plant operation, system design, quality, logistics, process, environment, safety, and economic viability. Some of the impacts of AFs utilization are poor heat distribution, unstable pre-calciner operation, blockages in preheater cyclones, build-ups in kiln riser ducts, higher sulfur dioxide (SO_2), nitric oxide (NO_X), and carbon mono oxides (CO) emissions, dusty kiln, and jamming in transfer chutes which should be addressed for achieving high TSR [28,29]. These challenges can be categorized in different areas like environment, operational & system design, product quality, process, economics, logistics, and occupational health and safety. This research focused on the operation and system design issues. Most operational problems result from poor waste pre-processing and can be addressed by close monitoring of pre-processing operations. However, the jamming of transfer chutes emerged as a major operational problem due to a lacuna at the system design stage, for which the majority of solutions offered by the researchers are addressed either to clear the chute jamming or sensing the chute jammed. Nevertheless, the solution for the chute jamming problem was not found from the system design point of view, especially when the chute is handling alternative fuels and their mix.

1.2 Problem Statement

To address the twin problems of processing huge amount of waste generated in India and high quantity of coal consumption, availability of which is unpredictable, the cement industry is working towards consuming wastes that provide a sustainable alternative to coal/petcoke as a fuel to the industry. Due to the nature of cement production, cement kilns are a readymade waste-to-energy solution. While the co-processing of waste in cement industries is a viable option due to numerous advantages like high temperature and residence time in cement kilns and the requirement of vast amounts of energy in the clinker-making process, there are some challenges related to the environment, quality, operation, process, health & safety and logistics. With the challenges, there are several tangible and intangible benefits of co-processing wastes in cement kilns reduction in the overall emission of greenhouse gases, promotion of the concept of circular economy, utilization of waste as a thermal substitute which otherwise is a serious concern, replacing an almost equivalent amount of coal and reduction in pollution, benefiting society as a whole. On the other hand, although the technical problems exist and are known, they need to be addressed. In this research, a solution for one such frequently encountered technical problem during operation, that is, jamming of transfer chutes, authenticated by cement plants pursuing large-scale consumption of waste having heterogeneous physical and chemical characteristics, is studied and arrived at. In order to overcome the existing issues with transfer chutes, this research is an effort to address the problem of transfer chute jamming using alternative fuels & their mix in Indian cement plants at a design level. Fig. 1.6 represents the problem statement of the current research work.

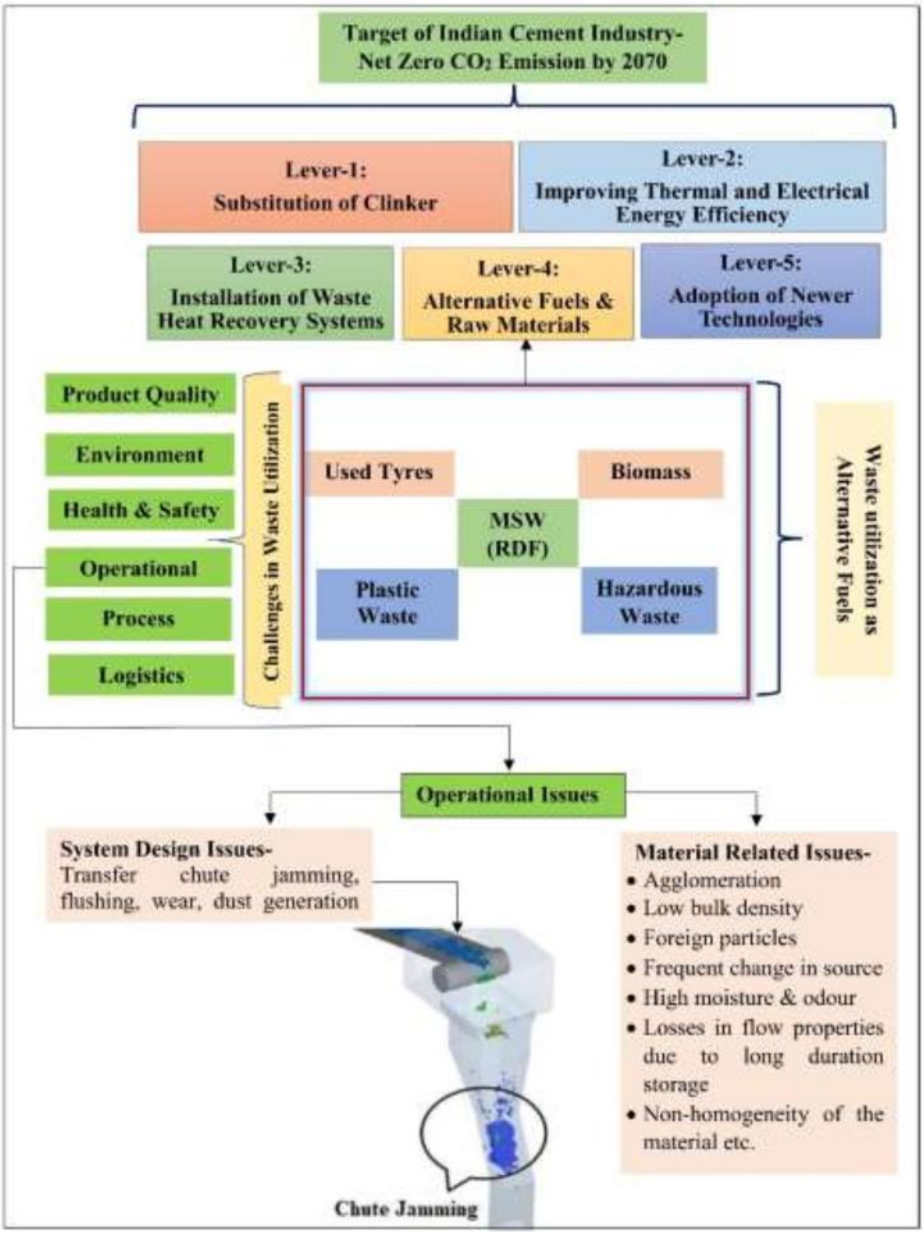


Fig. 1.6 Problem statement

1.3 Objectives of the Research

The present research work aims to design and develop a transfer chute that can handle alternate fuels (RDF, hazardous waste, plastic waste, used tyres, biomass, etc.) and their mix in Indian cement plants without any operational issues. The aim of the present research is to determine the design parameters of the transfer chute, which can be applied at any capacity of the alternative fuel handling system. The intention is to find the minimum possible type(s) chute(s) or a common chute with adjustable mounting accessories to perform in the AF feeding system.

The specific objectives of the research are:

- To study the existing designs of a transfer chute and its associated problems while handling alternative fuels and their mix in Indian cement plants.
- To simulate & develop and find the minimum possible type(s) chute(s) or a common chute system model by using suitable simulation tools
- To develop a flexibility feature in the transfer chute for fast cleaning in case of a jam.
- To carry out the parametric study of the simulated model.
- To develop and fabricate a working model for carrying out the physical experiment to validate the developed design.

1.4 Methodology Adopted

The various phases of the research activity are described below:

Phase I: Literature Review, Site Visits, and Data Collection

An extensive literature survey was carried out in areas of transfer chute design, AFs for cement plants, AFs characterization, selection of relevant simulation models, etc., followed by the survey in the Indian cement industry to establish the transfer chute issues. Site visits were done to interact with the Indian cement plant personnel to understand the operational problems in detail and collection of material samples along with their lab reports.

Phase II: Characterization of Collected Alternate Fuel Samples

Characterization of collected AF samples at the laboratories of NCB Faridabad. AFs properties like particle size, bulk density, particle shapes, moisture content, angle of repose, angle of inclination, etc., were determined for inputs to the simulation tool.

Phase III: Modelling and Simulation

Modelling and simulation were done on Discrete Elements Method (DEM) software, and a case study of an Indian cement plant facing a transfer chute jamming issue was carried out to validate the software. Based on the outcome, a basic transfer chute design was prepared, and simulation work was carried out for various AFs and their mix to optimise the design parameters of the transfer chute.

Phase IV: Design and Fabrication

Based on simulation results, the experimental setup (a set of belt conveyors and transfer chutes) was designed, fabricated, and installed at NCB, Ballabgarh.

Phase V: Experimentation and Data Collection

During this period, the experimentation of the developed design was done on an experimental setup, and data were recorded. The performance of the transfer chute was evaluated and analyzed based on the data collected.

Phase VI: Documentation

In this last phase, suitable conclusions and/or recommendations based on the above analysis were drawn for thesis writing, journal articles, and patent application.

1.5 Organization of the Thesis

Keeping the broad research objectives in mind, the thesis consists of the following eight (8) chapters.

Chapter 1: Introduction;

The chapter covers a brief background of the origin of the problem statement, including the status of cement production in India & its contribution to global warming, waste management issues in India, crises of conventional fuel availability for the Indian cement Industry, benefits & challenges of waste utilization as alternative fuels in Indian cement plants, problem statement, research objectives, and research methodology.

Chapter 2: Literature Review;

This chapter presents a technical review of the prior research work carried out related to the impact of the Indian cement industry on global warming, waste management & disposal issues in India, the fuel crisis for the Indian cement Industry, utilization of waste as alternative fuels & its challenges in Indian cement plants, problems associated at transfer points due to poorly designed chute, transfer chute related issue specifically when handling alternative fuels, reasons of chute problems and available solutions and research gap identified.

Chapter 3 Validation of the Problem Statement;

This chapter validates the problem statement, which has been established through, a survey conducted in the Indian cement industry, AFs technology suppliers, technical consultants, R&D, and Academia working in the field of alternative fuels. The survey has been done to establish how serious the chute jamming is in the Indian cement industry and which types of AFs and their characteristics contribute more to the chute jamming problem.

Chapter 4 Transfer Chute Design- Theoretical & DEM Approach

This chapter discusses the theoretical techniques for the design of transfer chute in material handling system, the limitations of the theoretical approach, various simulation tools available for modeling & simulation, and their features & limitations.

Chapter 5 Modelling & Simulation

This chapter discusses the selection of software for DEM simulation, a case study from a cement plant to validate the accuracy of selected software, design & development of transfer chute design parameters based on simulation results, suitable to handle multiple types of alternative fuels & their mix without any jamming issue.

Chapter 6 Design and Fabrication of Transfer Chute System

In this chapter, the development of the experimental setup of a material discharge through a transfer chute system and the experimental procedure is discussed in detail. The technical specifications of the transfer chute and associated conveying equipment have been finalized based on the simulation results. The complete system was fabricated in a workshop located in Faridabad, Haryana (India), under continuous supervision and erected at National Council for Cement and Building Materials, Ballabgarh, for further experiments.

Chapter 7 Results & Discussion

In this chapter, the performance assessment of the newly designed transfer chute is carried out on the experimental setup (conveyors & chutes) using alternative fuels (AFs) & their mix with different parameters. The results obtained by experimentation are discussed in detail. Transfer chute design is validated on experimental setup for two essential features, i.e., Time required to clean the chute if the chute is jammed. In the end, a comparative analysis of simulation results with experiments outcome was also carried out, and a detailed analysis was done to evaluate the techno-economic advantages of this research work for the Indian cement industry.

Chapter 8 Conclusion and Future Scope of Work

Concludes the thesis by providing a summary of results, recommendations, and future scope of the work.

CHAPTER 2

LITERATURE REVIEW

This chapter presents a technical review of the prior research work carried out related to the impact of the Indian cement industry on global warming, waste management & disposal issues in India, the fuel crisis for the Indian cement Industry, utilization of waste as alternative fuels & its challenges in Indian cement plants, problems associated at transfer points due to poorly designed chute, transfer chute related issue specifically when handling alternative fuels, reasons of chute problems and available solutions and research gap identified.

2 Literature Review

2.1 Indian Cement Industry and Its impact on Global Warming

The world's annual energy consumption is about 580 million terajoules, about 80 % of which still rely on fossil fuels [30,31]. CO_2 emission from industrial processes and energy combustion has a share of 89 % of total global anthropogenic CO_2 emission[32]. Anthropogenic GHG emission is one of the most critical causes of global warming. Anthropogenic activities potentially caused about 1.0°C of global warming after the commencement of the industrial era, with a probable range of 0.8°C to 1.2°C. At the current pace, global warming is likely to reach 1.5°C between 2030 and 2052. The observed global mean surface temperature (GMST) for the decade 2006–2015 was 0.87°C (likely between 0.75°C and 0.99°C), higher than the average over the 1850–1900 era[33]. An increase in global surface temperature impacts the earth and its ecosystem in many undisputable ways, and its effect will persist for millenniums. It will continue to cause further long-term hazards. Economic sectors like forestry and other land use, agriculture, industry, transportation, buildings, electricity, and heat production are the major emitters of GHG[34]. One such industry is the cement industry which utilizes fossil fuels as its primary source of energy[35].

India is the second largest producer of cement in the world after China. Indian cement industry has an annual manufacturing capacity of 594.14 MT with annual production of 361 MT. India possesses around 333 manufacturing units, among which 150 are integrated units, 116 are grinding units, and 5 are clinkerization units. India's cement consumption is 260 kg per capita which is still less than the global average of 540 kg per capita[1]. The initial step of cement manufacture occurs in a preheater and pre-calciner tower where endothermic decomposition of $CaCO_3$ into calcium oxide and carbon dioxide, along with decomposition of other oxides, occur at around 900°C. This reaction requires a humongous amount of energy. This account for up to 60% of emissions from the cement plant. This material, along with fuel, is fed into the rotary kiln where the clinkerization at a temperature as high as 1450°C takes place to form the final product, which is clinker. The emission due to fuel combustion has a share of ~30% of the total CO_2 emission from a cement plant. 1 kg of clinker roughly requires 0.1 kg of coal, which is the dirtiest of all fossil fuels. The pyro-processing unit of the plant it the most energy-intensive unit. These emissions are categorized as direct emissions. The indirect emissions include emissions from Captive Power Plants (CPP), transportation, lighting, crushers, mills, etc. This is 10% of the total carbon emission from the cement plant[1,36–39]. The specific CO_2 emission of cement plants in India is 0.67 tonne per tonne of cement. Indian cement industry in the year 2021 caused the emission of 149 million metric tonnes of CO_2 after experiencing a decline in 2019-2020 due to global lockdown. Fig. 2.1 shows the CO_2 emission from the Indian cement industry in last six decades[40].

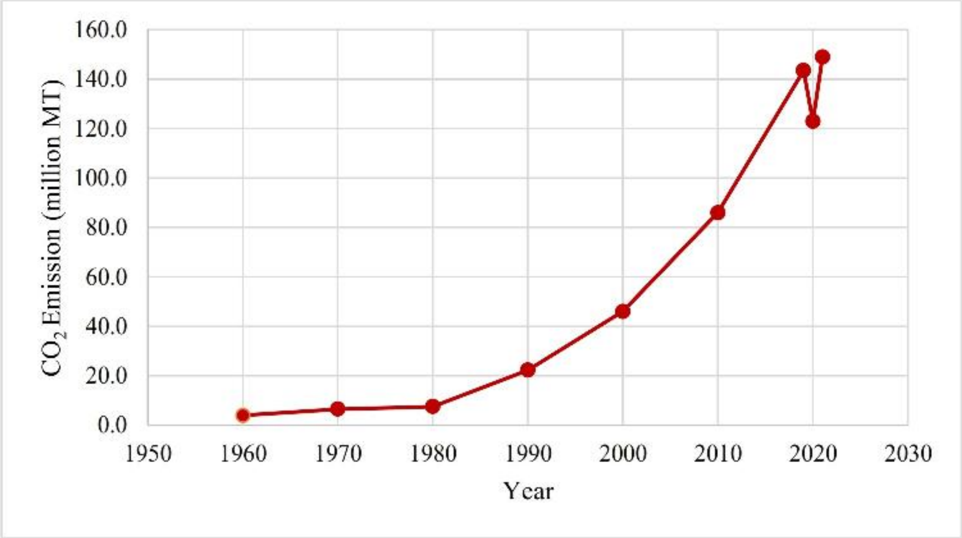


Fig. 2.1 CO_2 emission from Indian cement industry

The Indian cement industry is putting its best efforts into reducing the impact of global warming by decreasing its carbon footprint. The presence of the Indian cement manufacturing group during COP26 and COP27 showed the commitment of the industry to achieve net zero emissions by 2070[5]. The industry has identified five (5) levers for achieving Net Zero Emission with cement production-(a) Improving Thermal and Electrical Energy Efficiency,(b) Installation of Waste Heat Recovery Systems, (c) Alternate Fuels and Raw Material Utilization, (d) Clinker factor reduction, (e) Newer Technologies like renewable energy and carbon capture & utilization[6].

2.2 Waste generation and its management issues in India

Waste is an unavoidable by-product of the development and urbanization of any country. Waste and its afterlife are a massive problem worldwide and especially in Asian countries. The amount of waste generated has a direct relation with the population of the country, and unfortunately, India is undefeated in both categories. Per capita, waste generation also increases as societies become richer and more developed. Waste generation, collection, transport, treatment, and disposal is an uphill battle in India, attributed to the volume in which it is generated. Despite all the challenges, India is working out its way to tackle this crux. India's waste management sector has received tremendous applause due to the widespread awareness generated under the flagship Swachh Bharat Mission. Waste management of MSW, hazardous waste, plastic waste, and paddy stubble (Parali) have emerged as leading challenges in India. India generates about 1, 30,000 to 1, 50,000 MT MSW daily, adding up to 50 million MT annually. This breaks up to 330 to 550 grams per urban inhabitant a day. If the waste generation escalates at the current pace, it will rise to 125 million tonnes by 2031[41]. Delhi NCR has already seen three infamous legacy waste mounds[42]. If this situation is not tackled sincerely, India will have many more such mounds of shame. With rapid urbanization, the nature of waste is also changing from biodegradable to more non-biodegradable. The waste collection facility existing in India used to be outdated, unscientific, and inefficient. Population coverage was also low, and the poor were marginalized[43]. Indians wave always lacked waste segregation habits, and proof of reckless dumping can be seen everywhere. This is one of the most critical shortcomings in utilizing MSW as a fuel because of its low heat value. In major metro cities, the collection efficiency ranges between 70 to 90%, whereas in several smaller cities, it is below 50%. Swachh Bharat Mission (SBM) and MSW have become a silver lining in this case. In 2021, GOI also launched SBM 2.0, aiming to make cities garbage-free and effective sewage and safety management [44,45]. Apart from the impact on health, life, environment, waste generation also demands huge land for disposal, which is yet another area of concern for a highly populated country like India[8].

Hazardous waste still remains one of the major challenges in front of India. It is the most perilous of all its kind as it poses acute threats to the environment and its inhabitants. Hazardous wastes include the form of solids, liquids, sludges, or contained gases that are generated primarily by chemical production, manufacturing, and other industrial activities. Its improper handling can cause environmental issues like land, soil, and air pollution, groundwater table contamination, health hazards to the inhabitants, etc. They might be radioactive, infectious, toxic, carcinogenic, or mutagenic to humans. Reactive waste can cause violent, unstable reactions, and highly corrosive waste can damage surfaces and tissues. India has 76,235 HW-generating units with an authorized quantity of 42.80 million MT per annum. The country has seen an annual increase of about 10% in the number of HW units compared to the national inventory report of 2019-20. 9.24 MT of HW has been generated in the year 2020-2021, indicating a 5% increase in the generation of HW compared to the previous year. 44% was utilizable HW, 27% was recyclable HW, 25% was landfillable HW, and 4% was incinerable HW out of 9.24 MT of generated HW[15]. Burning in landfills is still one of the most common methods of disposal. Waste contractors collecting hazardous waste are mostly untrained, ill-equipped, and poorly paid [7,46]. India has been extensively working in hazardous waste management. CPCB introduced waste management rules in the year 1989 and later carried out multiple amendments, with the latest amendment done on 21st July 2022; rules ensure safe handling, generation, processing, treatment, package, storage, transportation, use reprocessing, collection, conversion, and offering for sale, destruction, and disposal of Hazardous Waste. These Rules lay down roles of various authorities such as CPCB, MoEF, State/UT Govts., SPCBs/PCCs, DGFT, Port Authority, and Customs Authorities, while State Pollution Control Boards/ Pollution Control Committees have been designated with broader responsibilities touching across almost every aspect of hazardous wastes generation, handing and their disposal[47]. However, the absence of required infrastructure, as well as ineffective enforcement for managing hazardous waste, is still an obstacle to getting rid of[7].

Another challenging waste category is plastic waste. Plastic which initially appeared to be a boon to humankind, has now become a bane to the environment and ecosystem. In the last century, the global production of plastics has reached 320 million MT per year, of which 40% is for packaging, and 95% is single-use plastic[48]. This is a significant burden on the waste management system in India. 8% of total waste generated in India is plastic waste[49]. India generated 3.46 million MT of plastic waste in 2019-2020, of which 1.58 million TPA was recycled, and 0.16 million TPA was co-processed in cement kilns[50]. Plastic deteriorates due to abrasion, wear, and tear, creating microplastic that does not decompose. Plastic waste has a very complex structure, comprising various valuable composite materials, harmful emissions, and residual ash. Therefore, managing waste is complicated, as in many cases, the contamination of plastic with other types of waste limits its recyclability[51]. Plastic is highly durable, implying that it can accumulate and get trapped in the environment for centuries and even up to millennia. The severity is such that the world has seen the presence of microplastics in the human placenta[48].

In India, collection and segregation operations are conducted by the multi-tier informal sector, which creates further difficulties in identifying the flow and traceability of the various waste streams. However, plastic waste regulation rules in India evolved from 1989 to the latest in 2022. India started from recycled plastic usage rules to plastic waste management rules, amendment 2022. PW management rules (2016) and the PW management (amendment) rules (2018) forbid to import of scrap plastic of non-halogenated polymers and co-polymers, including but not limited to polymers that are hazardous and specified under schedule. The rules are enforced by the MOEF, taking into consideration Environment (Protection) Act (1986). The Indian Government introduced two amendments to the Hazardous Waste Rules, 2016, which prohibited PW imports into the country altogether.. In March 2021, the draft PW management ruled 2021 was issued by the Union Ministry MoEFCC, re-defining the thickness of the carry bag[52].

Every winter in northern India starts with the news of dangerous levels of AQI resulting from the Paddy stubble burning. This is because the volume of the farm waste is humongous, and the window for disposing of it is too small. Limited farm mechanization, scarce human resources, and poor acceptability of paddy straw as fodder are the root causes behind this residue burning[18]. During different harvesting seasons, crop residues of rice, wheat, sugarcane, maize, cotton, soya bean, and mustard, among others, are burnt in the croplands in various areas of the country. More than 683 million MT of crop residues of different crops are produced, of which about 178 million MT of surplus crop residues are available around the country[53]. An estimated 87 million MT of surplus crop residues is burnt[54]. Punjab generated 18 million MT of stubble, of which 70-80 % was burnt. It is detrimental to the environment as it releases toxic substances like CO, SO_X, NO_X, CH_4, VOC, PM, etc. [19]. There have been many attempts at handling it like bioethanol synthesis, furniture making, mushroom farming, electricity generation, preparation of compost and packaging materials, etc., and in-situ techniques like happy turbo seeder However, they could only utilize a small volume to cause a change[54]. National Green Tribunal (NGT) GoI strictly opposes crop residue burning, particularly in North-Western India. Both central and state governments implemented various policies to help farmers with eco-friendly straw management approaches. Directions have been issued to thermal power plants to co-fire biomass-based Pellets and to industries operating in NCR other than GNCT of Delhi to switch over to PNG or biomass fuels during 2022 MoEF. CPCB also issued guidelines to grant of one-time financial support for promoting the establishment of paddy straw-based palletization and torrefaction plants[55].

Hence, the safe disposal of wastes generated in India is the demand of the present era for sustainable development. If necessary steps are not taken now, the situation will be worse due to the growing population of the country.

2.3 Fuel crisis in the Indian cement industry and waste as a potential alternative

Coal and petcoke are primary conventional fuels used to meet the thermal energy requirement for the cement industry. The availability of coal for the Indian cement industry has been uncertain in the last decade. Indian cement industry faced many incidences of the least preference supply of coal over other industries, which forced them to increase the share of petcoke [20–22]. Hence, the trend of fuel consumption from 2015-17 has indicated that the share of coal has decreased to 41 % with a corresponding increase in petcoke 56 % [6]. However, recent years have been the most challenging for the Indian cement industry. Fig. 2.2 shows the steeply increased in the cost of fuel & power in leading cement manufacturers of India[56]:

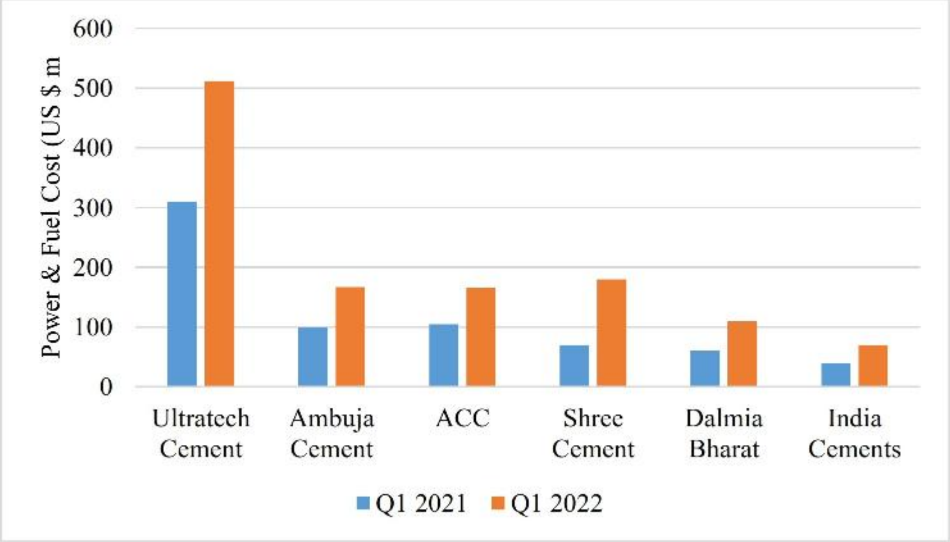


Fig. 2.2 Fuel & power cost trend in a year

Many incidents have been reported in India recently for coal shortage, despite various pro-coal reforms introduced in recent years. In India, imports fulfill the coal shortage, but in 2020 and 2021, the country faced a tough scenario in which the COVID-19 pandemic disrupted coal supplies globally, resulting in higher coal prices globally. The coal power sector, caught between high international coal prices and power plant short stocking/supply of coal, entered a crisis in late September 2021, with many power plants operating with dwindling reserves[57]. While the conflict between Ukraine and Russia in 2022 affected fuel prices, it was worldwide. Indian cement manufacturers need to rethink their energy use and fuel supply techniques. Import changes have already begun as Indian cement companies seek larger volumes of petcoke imports and cheaper thermal coal trade channels. In April 2022, petroleum coke (petcoke) and coal prices in India increased by 21 percent, boosting cement prices by INR 20-50/bag (US$0.25-0.63/bag). However, cement production also increased by 8-10 percent in April as cement companies increased their petcoke consumption and operated at 60-75 percent capacity utilization[58].

In view of the above issues related to coal and petcoke, the Indian cement industry has an inclination towards the utilization of waste as an alternative to coal and petcoke. Waste utilization as an alternative fuel in the cement manufacturing process is known as co-processing, which does not only address the issues associated with coal & petcoke, i.e., the uncertainty of supply, high price fluctuation, high CO2 emission, etc. but also provides the sustainable solution for waste management issue in India and reduces the impact of cement production on global warming [26]. Using waste like MSW, plastic, hazardous waste, agro waste, etc., as alternative fuels in Indian cement plants not only resolves the issue of waste management but also provides the certainty of fuel availability and cost benefits to Indian cement. When comparing the fossil fuel cost with the alternative fuel cost, plants get the benefits of a 60 to 70% reduction in fuel cost[59]. Table 2.1 indicates the available waste which can be used as alternative fuels in the Indian cement industry. Apart from MSW, hazardous waste, plastic waste, and surplus biomass, used tyres are also identified as an alternative fuel for the Indian cement industry:

Table 2.1 Inventories of AFs for Indian cement plants

Waste Available for Alternative Fuel	Total Availability (million TPA)	Availability for Indian Cement Industry (million TPA)	References
Municipal Solid Waste (MSW) based RDF	9.46	4.50	[26]
Hazardous waste	9.24	1.90*	[15]
Plastic Waste	3.47	3.47	[16]
Surplus biomass	145	14.5	[26]

Waste Available for Alternative Fuel	Total Availability (million TPA)	Availability for Indian Cement Industry (million TPA)	References
Used tyres (*estimated*)	1.29	0.65	[26]

** Utilised by Indian Cement Industry in the year 2019-20*

Although AFs provide carbon neutrality to industry, the intergovernmental panel on climate change (IPCC) has not entirely accepted some alternative fuels, such as plastics, oils, or old tyres, as carbon-neutral, despite the fact that their impacts are lower than those of traditional fuels as indicated in Table 2.2. However, because cement kilns are more efficient than other popular incinerators, using any of these alternative fuels, not only carbon-neutral fuels, leads in a considerable net decrease in CO2 emissions[60].

Table 2.2 Fuel net CO_2 emission factor from different fuels

Fuel net CO_2 Emission Factor	(gCO_2/MJ)
Petcoke	101
Coal	96
RDF	8.7
Waste Wood /Agro waste /Biomass	0
Plastic	75
Used Tyres	85

Hence, when comparing the RDF and Biomass, which have been identified as two major AFs for the Indian cement industry, the carbon net emission is almost negligible.

2.4 Challenges of AFs utilization in cement plants

As discussed above, the utilization of AFs in the cement industry has many advantages. However, it comes with many challenges like an issue with energy balance, increased waste gas volumes, a higher amount of primary air & losses due to bypass gas extraction, plant operation, high capacity fuel dosing equipment, high build-ups in kiln & preheater, and cooling down of the sintering zone, etc. Then, there are issues with clinker quality, possible enrichment of harmful elements in clinker, frequent changes in raw mix design, emissions, and carbon monoxide formation in case of inadequate calciner technology [61]. European countries introduced AFs in the early 1950s, and after tremendous learnings and optimization of the cement production process, it is now well established there [62]. It is one of the main reasons that most of literature on challenges of AFs utilization in cement plants is available from

European countries. However, adequate literature sharing the experience of the Indian cement industry is also available. This chapter evaluates the AF's impacts covering the following areas:

- Environment
- Operational & system design
- Product quality
- Process
- Economic
- Logistics
- Occupational health and safety

2.4.1 AFs co-processing impacts on the environment

Joaquim et al. [63][64] assessed the risk of utilizing AFs on the population living in the neighbourhood of a cement plant located in Spain where petcoke was substituted from a special class RDF (35% plastic, 30% paper & carton, 20% wood, and 15% textile). The plant was operated at an average TSR of 15% during this study. They collected a total of 14 nos. samples of soil and herbage and eight air samples within one year at a distance of 500 m to nine km from the cement plant and analyzed them in labs to determine the impacts of AFs on the environment and human health; results were compared for both the scenarios (before and after substitution). They found that there is no change in airborne particulate matters, while a significant reduction was found for several pollutants like polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs), Cobalt (Co), Chromium (Cr), Manganese (Mn), and Nickel (Ni) in vegetation, as well as in soil and Air. The paper concluded that the use of special-class RDF was a good choice for that cement plant. Bahareh et al. [65] evaluated the environmental aspects of RDF utilization as AF in cement production. They found that chlorine content in RDF is a major environmental concern that causes corrosion in the system due to vaporization and condensation of alkali chlorides. However, it was observed that RDF utilization in a cement plant by substituting coal extends the benefits of lowering greenhouse gas (GHG), acidification, summer smog, nitrification, carcinogenic risk potential, and landfill cost. Luciane et al.[66] performed a laboratory investigation to analyze the impact of scrap tyre burning as

AF in cement kiln, and results indicated that burning of scrap tyres in cement kiln may result in a higher level of arsenic trioxide (As2O3). Lafarge Canada [67] shared experiences of using biomass as AF in cement plants. Results recorded with time-analysed indicated that there was no or negligible environmental impact of utilizing biomass in cement plants as AFs. Rahman et al.[68] reviewed the literature to assess the environmental impact of multiple fuel utilization in cement plants that included tyre derived fuel (TDF), SPL, plastic waste, sewage sludge, solvent & spent oil and summarized that CO emission in most cases was higher. However, from the literature, they observed that when TDF was used, SOx and NOx emission increased while the potential of Zn emission also increased. A reduction in NOx emission was observed while using SPL. The use of chlorinated plastic may affect clinker quality and can be a cause of HCl emission. Also, the emission of dioxin and furans can be increased by the presence of chlorine under specific conditions. S. Çankaya and B. Pekey[69] carried out a life cycle impact assessment (LCIA) study of RDF & sewage sludge application in clinker production as AFs for a cement plant located in Turkey. They used the IMPACT 2002+ method as a tool, and results indicated that AFs in clinker production reduce the global warming potential impact and reduce carcinogens, non-carcinogens, ionizing radiation, land occupation, acidification, eutrophication, ecotoxicity, energy, and mineral extraction. Kare Helge[70] conducted an experimental study by using various fuel combinations of hazardous waste along with coal. He characterized the fuels mix chemically, did a leaching test, and concluded that waste fuel (hazardous waste) used as AFs in cement production was enriched with regard to heavy metals. However, these metals are, to a great extent, retained in the clinker. Gautam et al. [71] shared the experience of using RDF, agro-waste, and tyre chips in one of the cement plants in India. They concluded that these AFs are not negatively impacting the environment. They observed that sulfur and heavy metals present in tyre chips are getting entrapped in a stable form and in the crystal lattice of the clinker phases. Nikolay [72] shared his experience of using sewage sludge as AFs in one of the plants located in Russia. During the monitoring of the emission of preheater gases, it was found that there was no increase of sulfur and nitrogen oxides, and in fact, there was a slight reduction of NOx that was noted. Ashley Murray and Lynn Price [73] shared their experience of the Chinese cement sector and stated no significant difference in emissions by using AFs. However, they mentioned that the NOx is reduced in many cases, especially when using biomass, as Nitrogen present in biomass gets converted into ammonia (NH3) which acts as a NOx-reducing agent. RV Vora [74] highlighted the positive impact of utilizing hazardous waste in cement plants on the environment. He shared a case study of Gujarat, India, about how the utilization of hazardous waste has emerged as the most suitable option for destroying hazardous waste without impacting the environment. DS Ghosh and SA Ansari [75] shared the experience of co-processing of plastic waste as AFs in a cement plant. They found substantial CO2 reduction potential, i.e., 17.81 tons per day (tpd) or 6500 tons/annum by utilizing 7t plastic waste per day. Robert Oleniacz [76] presented a case study of an 8500 tpd cement plant, where AFs such as rubber dust, sawdust, and plastics were used along with coal as a source of thermal energy. He established Pearson's linear correlation coefficients between various operating parameters like clinker production, kiln operating time, amount of fuels, Cl and S inputs in fuels, and emission of various pollutants CO2, CO, NOx, SO2, HCl, TOC, and total dust for the AFs along with conventional fuels (coal). He found that AFs do not cause any substantial differences in the volume of emitted basic air pollutants. J. Rivera [77] collected samples of petcoke, RDF, and sludges from a cement plant (located in Europe) and analyzed the same in a laboratory for evaluating the emission of PCDD/F and dl-PCB, and he found that the emission values were well below the limit established by the European Waste Incineration Directive. C.A. Tsiliyannis [78] focused on the environmental gains by utilizing AFs in cement plants along with considerable losses in clinker production. He observed that oxygen enrichment (OXE) of tertiary combination air was beneficial, compensating for losses and improving productivity. He also found that the predicted emission rates under OXE utilization are lower if compliance is maintained, and tertiary air enrichment allows stable flame in the kiln under waste AFs while suppressing NOx formation. Prisciandaro M et al. [79] analysed the process data using statistical tools for establishing the percentage of AFs (tyres & waste oil) along with petcoke in cement plants and they found that if less than 20% of regular fuel is replaced with alternative one, emissions like SOx, NOx, CO in case of tyres are slightly incremented but remaining almost always below the law imposed limits. In the case of waste oils, polluted gas emissions were decreased. Carpio RC and Dos Santos [80] used mathematical approaches such as Sequential Quadratic Programming (SQP), Genetic Algorithm, and Differential Evolution to evaluate the impact of using industrial residue as AFs, and they found no major negative impact on the environment. The values of emissions were well within the limit of restriction values. Schakel W et al. [81] carried out a life cycle assessment (LCA) for applying post-combustion calcium looping when AFs are being used in the cement production process. Results achieved by them show that biomass, instead of coal reduces global warming potential (GWP), and the use of biomass over coal reduces freshwater eutrophication potential and human toxicity potential of the system mainly due to avoid toxic emissions and sulfidic tailings from coal mining, it also helped in reducing fossil fuel depletion substantially. They also shared that when spent sorbent purged from the calcium looping system is used in the clinker production process, CO2 emissions were considerably lower. Ablail Paula [82] emphasized the application of computational fluid dynamics (CFD) for achieving high TSR and reduction of NOx in cement plants while using AFs. He shared that the operating parameters like combustion, calcination, build-ups, hotspots, CO and NOx generation can be determined by doing modeling and simulation on CFD before introducing of AFs in the system. Ghenai C et al. [83] analysed the impact of SPL utilization in cement plants on emission level by implementing the application of CFD approach (DPM). The result showed the final treated SPL as fuel (water-washed SPL followed with sodium hydroxide 'NaOH' and sulfuric acid 'H2SO4' treatments) reduce the temperature, NO, and CO_2 emissions at the exit from the furnace compared to coal. Baidya R and Ghosh SK [84] studied the number of cases of cement plants where AFs (effluent treatment plant sludge, bio sludge, spent carbon, plastic wastes, carbon black, water treatment plant sludge and fast-moving consumer goods rejects) were used, and environment implications were studied by monitoring average stake emission. They shared the results and stated that the uses of AFs solve the waste disposal problem, positively impact to global carbon mitigation efforts, and, finally, enormous monetary gain. Samec N et al. [85] Studied the impact of SPL utilization in the cement industry and found it as a most suitable option as cyanide content in SPL gets destructed completely at high temperatures, and fluoride emission was very low. B.N. Mohapatra et al. [86] indicated various environmental challenges like emission of dioxin & furan, NOx, SOx, HCL, and CO with their possible solutions when utilizing AFs in cement plants.

2.4.2 AFs pre-processing & co-processing issues during operation & system design

The waste conversion process into AFs is known as pre-processing, and further firing of these pre-processed AFs into kiln/calciner is known as co-processing. Pre-processing involves many operations like shredding, screening, drying, impregnation, etc., and co-processing includes material dosing, weighing, conveying, fine shredding, and firing to the calciner/kiln. Both pre-processing and co-processing have their challenges during the system design and operation of the AF system [87][88]. Table 2.3 indicates the various issues and their possible solutions shared by various authors related to pre-processing and co-processing during system design and operation:

Table 2.3 Operational & system design issues of AFs utilization in cement plant

Issue	Impact in Operation	AFs handled	References
Chute Jamming	Downtime of system	MSW (RDF), Biomass, Hazardous waste	[29,89–93]
Oversized three-dimensional materials and Agglomeration of high-quality AF	Impact on material flow and may disturb the operation of the facility and reject useful AFs by screens or classifiers	RDF	[94]
Odor during pre-processing	Difficult working condition	MSW (RDF), Hazardous waste	[95–98]
Low bulk density	Low feed rate	RDF, Biomass	[99]
Change in the source of the material	Disturbance in operation and process	Biomass, Industrial Waste	[100]
Difficult Pre-treatment of TDF	The rigid structure with steel wires and rubber leads the difficulties in the mechanical pre-treatment	TDF	[101]
Foreign particles in AFs including fine ferrous materials	Damage of machine & equipment	MSW (RDF)	[94,102,103]
Long duration storage of AFs	Loss in flow properties due to increased interparticle adhesive force.	TDF, RDF, Biomass	[104]
High Moisture	Difficulty in handling and jamming	MSW (RDF)	[103,105,106]
Non-homogeneity of the material	Difficulty in handling at the plant level	MSW (RDF)	[107,108]

2.4.3 AFs co-processing impacts on the cement production process

Chatterjee A and Tongbo Suib [109] studied various cases and trial data of many authors to understand the impact of AFs utilization, such as MSW (RDF) & biomass, on the cement manufacturing process. A review of the literature by them concludes that the utilization of AFs demands many adjustments in the process the requirement of a high volume of waste gas, primary air requirement for fuel transportation, decrease in recuperation air from the clinker cooler, a shift of the kiln temperature profile towards the kiln inlet which leads to more radiation losses, losses due to bypass gas extraction, highly precise dosing system, blockage and build-ups in kiln inlet, riser duct, and the bottommost cyclones due to volatile components in the AFs, the possibility of forming a reducing environment in the burning zone, conditions leading to higher emissions of SO2, NOx, CO, etc. Ashley Murray et al. [73]shared their experiences in the Chinese cement sector of using AFs (biomass). They stated that the AFs impact the flame temperature due to the high volume of volatile content and, in many cases, decreases while introducing the AFs. R Rajamohan and R.A. Krishnakumar [99] shared their own experiences of a cement plant and stated that the introduction of AFs may lead to the generation of CO at kiln inlet due to more moisture content than conventional fuel. Larsen et al. [101] carried out a research work that concluded that the introduction of AFs (TDF) in cement plants led to unstable calciner operation, poor heat distribution, blocking the preheater cyclones, and additional load in the preheater fan, etc. Moses P.M. Chinyama [110] reviewed the literature and found that the build-ups in the pyro section, i.e., kiln, preheater cyclone is a more common result of AFs (TDF, Sewage Sludge, meat bone meal (MBM), Biomass, and Petcoke) co-processing and High chlorine content in AFs leads to corrosion problem of equipment. Peter Paone [111] shared the systematic approach for enhancing the TSR with AFs (RDF, TDF, Whole Tyre, and Biomass) in the cement plant. He gives various recommendations in the paper, including installing the bypass system and modifying a calciner to increase the retention time from 1 sec to 7 sec, which is required for the complete combustion of AFs. Erich R. Hansen [112] highlighted the process modification while introducing the AFs such as TDF, whole tyre, hazardous waste, RDF, and biomass. He shared that the AFs introduction leads to various issues like lower flame temperature, difficulties in the ignition, difficulties in the metering of the fuel, and varying calorific values, which may impact clinker quality, environment, production losses, and demand; it requires continuous process optimization to avoid negative impacts. He also concluded that the excess air requirement is an important factor to control and ensure the complete combustion of AFs. However, it can be optimized by maintaining the consistency in fuel flow rate. Rathore [113] shared his own experience of one of the cement plants located in the western part of India. He stated that the utilization of AFs (RDF, carbon black, agro waste, ETP sludge, pyrolysis oil, etc.) demands upgrading refractory kiln quality and other phenomena that take place, such as corrosion problems in the baghouse. Azad Rahman et al. [114] analyzed the effects of the flow rate of waste-derived fuels, i.e., TDF, RDF, and MBM, on the energy efficiency and emission from the preheater tower along with the fixed rate of coal with the use of a simulation model developed on Aspen plus software.

They further validated the model for coal and then run for the other waste-derived fuels. They also shared the outcome of the study, which indicates that the TDF, air-dried RDF, and MBM could replace 25%, 15%, and 5% of thermal energy, respectively, to get the advantages in terms of energy efficiency and CO_2 emission over using only coal. W K Hiromi et al. [115] developed a mathematical model for analyzing the process impact of replacing 45% of coal from waste-derived fuels such as RDF, Waste Wood, Hazardous waste, etc., in the main burner. They shared the results which indicates that to maintain the clinker quality and keep the kiln temperature unchanged, production capacity is reduced from 1 to 15%. However, the paper concluded that reducing production capacity can be avoided by introducing a small fraction of pure oxygen in primary air. Zakia Ngadi et al. [116] analyzed the impact on process parameters when utilizing olive pomace as AF by applying a one-dimensional mathematical model. They validated the model against the temperature profile of operation in the rotary kiln and the outcome has been summarized with no major impact on the process, environment by using olive pomace as AF. Christos Aristeides [117] applied the five-step procedure for process balancing for controlling and monitoring the critical process parameter to get the flexibility of adopting AFs in operation without impact on production capacity. He presented a case study where TDF, bio-sludge, and RDF were targeted for replacing petcoke, different combinations of fuels were prepared and results were discussed which indicates that a marginal reduction in clinker production capacity, however, many benefits on an economic and environmental basis. Maria Luiza et al. [118] studied and confirmed that SPL acted like a mineralizer as its properties allow the clinkering temperature reduced by up to 80 deg C. Benoit Pluchon [119] emphasized on the blast- off in AF fired plants as a solution to avoid jamming/ clear build-ups in kiln/calciner/preheater. He suggested an air blaster as a solution to clear the build-ups.

2.4.4 Impact of AFs introduction on the quality of cement

Baidya R and Ghosh SK [84] studied several cases of cement plants where AFs (ETP sludge, bio sludge, spent carbon, plastic wastes, carbon black, water treatment plant sludge, FMCG rejects, etc.) were used. They studied the impact on clinker quality parameters and found marginal changes in clinker quality but well below the production tolerance limit. Samec N et al. [85] studied the impact of SPL utilization in the cement industry on the quality of clinker and concluded that the utilization of SPL in the cement industry is an environmentally sustainable option without impacting the quality of clinker. Azad Rahman et al. [120] analyzed the various ratio which indicated the clinker quality, i.e., Lime Saturation Factor (LSF), Silica

Ratio (SR), and Alumina Ratio (AR). They shared the outcome of a study that shows that the use of MSW also affects AR & SR. Accordingly, raw mix design should be corrected; however, uses of tyre, bagasse, plastic waste, and MBM have little impact on clinker quality. Penny Pipilikaki et al.[121]studied the impact of substituting 6% coal with TDF on the quality of cement produced. The outcome of the study concluded no substantial impact on the cement quality. In fact, iron content in raw material was reduced as the same is present in the form of steel in beads and belts present in tyres. The only difference they found was in the quality, i.e., increased settling time and water demand at the time of cement application due to the high zinc content. Opoczky L and Gavel V [122] studied the effect of trace elements (Cr, Zn, Ti, Ba, Ni, and P) present in waste (used as AFs) on clinker grindability. They experimented, and its outcome established that the trace elements favorably affect the porous structure, shape, sizes, and color of clinker crystal, primarily that of alite and belite, and generally improved the grindability of the clinkers. Strigáč J [123] highlighted the effect of AFs and alternative raw materials (ARMs) on the clinker quality. He evaluated meat-bone meal, sewage sludge, and paper sludge and found these AFs are moderately suitable AFs along with granulated blast furnace slag, air-cooled blast furnace slag, and de-metalized steel slag, fluidized bed combustion fly ash, and waste glass. They concluded the article that the AFs and ARMs increased the belite content, conversely reduced the amount of alite and increased the amount of alkalis promoted reactive orthorhombic C3A. Serrano-González K et al. [124] studied the impact on the reactivity of clinker by using five AFs, i.e., biomass, mass, carbon residue, tyres, and RDF. They prepared a total 8 number of clinker samples using the different combinations of these AFs, a-with all the alternative fuels, b-without Biomass, c-without RDF, d-without Biomass-Tyres-Mass, e-without Biomass-Mass-RDF, f-without Biomass-Tyres, g-without Carbon Residue, and h-without Mass. Their study concluded that the impact of AFs on clinker reactivity may be positive or negative, and it depends on the type of AFs combination used. Hence, the selection of AFs is a key decision and should be established experimentally before introducing it in the main production process. Fayza et al. [125], Hashem FS et al. [126] studied the possibility of using RDF containing waste like rubber waste, tree terminals, rice straw, and mixed trash, plastic waste and its impact on the quality of clinker & cement. Their result shows that the ash residue of these RDF sources in cement clinker reduced the setting times, accelerated the early hydration reaction, and increased the compressive strength of OPC. F.Puertas and Blanco-Varela MT [127], Trezza MA and Scian AN [128] experimentally investigated and compared the clinker and cement properties produced from conventional fuel v/s AFs (animal meals, tyres, or a mixture of the two). Results showed no difference in the mineralogical composition of clinker as well as no impact on the cement properties. Cembureau [129] highlighted that based on the waste used as AFs, the concentration of individual elements in the final product might increase or decrease. It has little consequence on product quality.

2.4.5 Economic aspects

Bahareh et al. [65] conducted a cost-benefit analysis for installing an RDF plant in Vancouver City. They got the result which indicates the substantial financial profit by using AFs through fossil fuel savings, reduction of landfilling cost, recovered material sale, and employment effect. Rahman et al. [68] reviewed the literature. They found that the cost benefits on production cost due to saving in fuel cost of utilizing various AFs like TDF, plastics waste, sewage sludge, solvent & spent oil, etc., in cement plants have been remarked by many authors. DS Ghosh and SA Ansari [75] presented a case study for the ACC cement plant located in India, and saving was worked out by them based on utilizing 7 t of plastic waste (NCV of 6000 kcal/kg) per day. The outcome of the study showed a saving of INR 9705 per day by replacing coal. Carpio RC and Dos Santos [80] analyzed the mathematical model such as SQP, Genetic Algorithm (GA), and Differential Evolution (DE) to evaluate the cost, quality, and environmental impact of AFs (used tyre, petcoke, etc.) using in the cement production process. They found the opportunity for production cost minimization without loss in cement quality while satisfying environmental and operational restrictions. Ghenai C et al. [83] investigated the combustion of SPL as an AF in a cement plant. They found the most cost-effective solution for disposing of SPL, which is the hazardous waste from the aluminum industry. Chatziaras N [130] highlighted the economic advantages of AFs (RDF, TDF, sewage sludge, MSW, waste-derived fuels), the energy cost contributing a lot (30-40%) in cement production cost; hence the replacement of fossil fuels from AFs may extend the benefits by lowering the production cost. Kumar K et al. [131] presented a case study of a cement plant located in India, where various types of solid AFs i.e., tyre chips, RDF, hazardous waste, etc. were used at a total capacity of 40,000 tons per annum which is about 11% TSR of that plant. Their financial analysis indicates the high Internal Rate of Return i.e. >39% and a very attractive payback period on investment (2 years and 6 months only). Bajtarević A and Hadžikadunić F [132] presented the types of AFs (RDF & TDF) and their consequences of uses in the cement plant. They concluded that the utilization of waste as fuel reduces the overall fuel cost. Nadal M et al. [133] evaluated the impact of disposing of sewage sludge in cement plants as AFs. The evaluation has been done by them based on two benefits (i) Economical cost of health effects and (ii) Economic benefits by saving CO2 emissions in the clinker kiln. They found a substantial drop in the cancer rate after utilizing sewage sludge as AF in cement plant and when converted, this benefit concerning the economic cost of health, a huge saving is achieved. Also, when they evaluated the economic benefits of saving CO2 emissions, a lucrative figure came out. Baidya R et al. [134] studied the number of cases where AFs like ETP sludge, iron sludge, grinding muck, grinding dust, boiler carbon, boiler ash, chemical sludge, brake shoe liner, spent carbon, paint sludge, trade rejects, oily rags, carbon black, etc. were used in Indian cement plants and compared with other waste disposal technology available. The conclusion was made that AFs utilization in cement plants is the most economical waste disposal option due to zero ash generation, less auxiliary equipment required, less investment required for co-processing, etc. Mazza T [135] emphasized that the utilization of waste as AFs in the cement industry is a win-win situation for a waste producer as well as a cement plant. Cement plant gets the benefits of reducing cement production energy costs and CO_2 emissions simultaneously. AFs (RDF, TDF, Biomass, etc.) cost as compared to traditional fuel i.e. coal is almost 5 to 40% less making it more attractive for the cement industry and payback period on investment i.e. <5 years making it more viable [136].

2.4.6 Logistics issues

The economy in logistics of AFs transportation is one of the major challenges due to low-density fuel, high collection and transportation costs, and bailing requirements for long-distance transportation. Moreover, there is a restriction on interstate transportation of hazardous waste in India. Hence, the evaluation of logistic parameters is also an important area of concern [137]. Uddin S et al. [138] studied the techniques of Multi-Criteria Decision Making (MCDM) i.e. Fuzzy Analytic Hierarchy Process (FAHP) and Fuzzy TOPSIS for determining the most optimum supplier out of five numbers, criteria like transportation quality, communication, delivery, chemical labeling, and Material Safety Data Sheet (MSDS) were considered for evaluating the suppliers. De Souza CDR and D'Agosto MDA [139] analyzed the logistics of scrap tyre utilization in the cement industry based on reverse logistics chain and value chain analysis. They also worked out the cost analysis of the scrap tyre in the reverse logistic chain and found that the burning of scrap tyre in the cement plant is the most beneficial option for the socio-economic aspect. Colares-Moreira CD and Mainier FB [140] addressed the challenges of empty cement bag handling at the construction site by implementing reverse logistics concepts by recollecting, bailing, shredding, and co-processing of cement bags into cement kiln from the construction site. Oyola-Cervantes J and Amaya-Mier R [141] applied the reverse logistics concept for the OTR tyre, which is a waste of the mining industry. They proposed a shredder in the mining area for shredding the tyre in the desired size and using shredder material as AF in the power plant. Further, they concluded that this option as beneficial in terms of a social-economic solution. Mutter M [142] highlighted the main four attributes for selecting the suppliers credibility, reliability, understanding (of the cement producer's needs), and commitment.

2.4.7 Occupational health & safety challenges

Occupational health and safety aspects are crucial at every stage of the AF system, from receiving fuels to complete co-processing in the kiln. A safety audit is a must from time to time to ensure safe operation. Wastes like biomedical waste, asbestos, electronic scrap, entire batteries, explosives, corrosives, mineral acid wastes, radioactive wastes, and unsorted municipal garbage are restricted from being used in cement plants [87]. Safety is the most critical aspect of AF handling in a cement plant. AFs include both hazardous and non-hazardous waste. Handling of hazardous waste is more critical and demands strictly following the established standard operating procedure (SOP). The hazard may be toxins, reactive constituents, biological hazards, and ionizing radiation (radioactive materials). The use of AFs in cement plants has increased the potential for accidents and requires greater health and safety procedures to be followed. A wide variety of risk analysis tools can be used for both new and existing processes. Internal and external safety audit by experts is one of the effective tools for finding out the gap in the safety management system [143]. Documents describe the five principles (Principle 13 to 17) related to OH&S. These principles cover the concern of AF pre-processing / co-processing in the plant and clearly states that the site selection should be in such a manner that the chances of risks on human and the environment are minimized, safety and security of site should be well designed, documents and information is must, training should be provided to all levels and emergency and spillover plan should be well prepared [144]. The paper elaborated on the safety & risk associated with different kinds of waste as AFs which covered solid and liquid AFs, as hazardous and non-hazardous AFs. The paper also emphasized that pollution, health, and safety are the critical deciding factor for the success of AFs utilization in cement plants [145]. The document clearly defined the important role of Hazardous waste handling. Various aspects related to safety have been focused on, i.e., the use of PPEs, hazard analysis, the involvement of all stockholders, adequate documents, proper training, emergency plan, medical surveillance, etc. [146]. Handling of hazardous waste safely in cement plant demands adequate emergency and safety equipment and procedure and regular training, safe and sound receiving, storage, processing, and feeding of hazardous wastes, and a well-devoted waste evaluation procedure to assess the health and safety of workers and public, plant emissions, operations and market dynamics [147].

Table 2.4 Operational & system design issues of AFs utilization in cement plant

S.N	Impact Area	AFs Addressed	Method of impact assessment	Impacts	Summary of literature review	References
1	Environment	RDF, agro waste (Biomass), MSW, Scrap tyre, Plastic Waste, Sewage Sludge, Solvent & Spent Oil, Spent pot liner, and other Hazardous Waste	LCA, Laboratory investigation, trial runs in cement plant, plant operating experience, stack monitoring, CFD analysis, mathematical approach such as SQP, GA, DE.	No major negative impacts on the environment have been found by using AFs. However, few cases with TDF, a slightly higher content of Zn, and emission of As2O3 have been reported. Plastic waste also may lead to the emission of HCl.	The majority of authors found the utilization of waste in cement plants is the most suitable option, which reduces GHG emissions, NOx reduction in some cases, landfilling issues, etc. However, quantity and mix are to be decided based on detailed analysis either through software simulation or experimental analysis. Oxygen enrichment is also proposed as an effective technique for the complete combustion of AFs.	[63–72] [73–82] [83–86]
2	Operational & System Design	MSW (RDF), TDF, Hazardous waste, Biomass, Petcoke, Plastic waste	Plant operating experience and Technical Knowhow of original equipment manufacturer	Major impacts during operation are jamming in chutes & hoppers, odor from waste, presence of stone and metals in waste, agglomeration of AFs, difficulty in handling due to high moisture, etc. Inconsistency in AFs	Various authors addressed different types of problems. The majority of operational problems seem to be a result of poor pre-processing of fuel and lacunas at the design stage. These problems can be addressed by close monitoring of Pre-processing operation & considering sufficient inputs of material at the system design stage. The literature explained the possible solution for the various problems. However, no literature is found	[29] [87,92] [88,93,148–151] [94–103] [104–106]

S.N	Impact Area	AFs Addressed	Method of impact assessment	Impacts	Summary of literature review	References
				characteristics because of changes in source further increases the operation challenges during material handling.	to address the chute/hopper jamming problem at the system design stage.	
3	Process	RDF, TDF, MBM, Biomass, Hazardous waste, Whole tyre, carbon black, MBM, Plastic waste, etc.	Laboratory investigation, trial runs in cement plant, Plant operating experience, mathematical modeling, Literature review, etc.	Frequently build-ups in the preheater and kiln increase specific heat requirement, preheater fan power, CO generation, heat losses due to bypass gas extraction, decreases the flame temperature, production rate, refractory life, etc.	Many problems related to the process have been addressed by the authors. The introduction of AFs demands continuous correction, modification, and optimization in the process parameters until the process is established for some specific AFs and their mixes. However, changes in fuel mix again demand process optimization.	[152] [73] [99] [110–115] [116–119]
4	Quality	RDF, MSW, TDF, Paper Sludge, Sewage Sludge, Biomass, Carbon residue, MBM, Hazardous Waste,	Laboratory investigation, trial runs in cement plant and Plant operating experience, etc.	The utilization of AFs may have positive or negative or no impacts on the quality of clinker. It depends on the type of AFs used and their quantity	No major impact on the quality of cement produced has been reported by many authors. However, the raw mix design should be carefully evaluated based on the characteristics of the AF's proposed use. Factors like LSF, SR, and AR should be maintained within the prescribed limits.	[51–52] [120–125] [126–129]

S.N	Impact Area	AFs Addressed	Method of impact assessment	Impacts	Summary of literature review	References
		etc.		(%). The majority of literature indicates no impacts of utilizing AFs on the quality of clinker or cement.	The reactivity of clinker may increase or decrease depending on the combination of AFs used. No major impacts of heavy elements present in AFs on the quality of clinker have been found.	
5	Economic	RDF, tyre chips, Plastic Waste, Sewage Sludge, Hazardous Waste, biomass	Case Studies, Mathematical Modelling, Laboratory Investigation, Cost benefits analysis, Mathematical modeling review of literature	A positive impact has been observed by utilizing AFs in place of fossil fuels due to saving in fossil fuel costs, reduction in landfill requirement, and reduction in the production cost of cement.	The majority of authors found that the utilization of AFs is a worthy solution for waste management on economic aspects. The introduction of AFs may result in reduced production costs and more profitability. Many case studies indicate higher IRR and shorter payback time on the investment made for the AFs system.	[65,68,75,80,83] [130–136]
6	Logistics	Hazardous waste, OTR, used tyre, empty bags, biomass	Techniques of Multi-Criteria Decision Making (MCDM), i.e., Fuzzy Analytic Hierarchy Process (FAHP) and Fuzzy	The logistics of AFs demand special attention and cannot be treated like other bulk materials being used in the cement manufacturing process.	The selection of suppliers and the establishment of logistics emerged as the key parameter for deciding the success and failure of AFs utilization. The majority of authors have promoted the reverse logistics concept for maintaining effective logistics. The selection of suppliers with defined attributes has also been	[137] [138–142]

S.N	Impact Area	AFs Addressed	Method of impact assessment	Impacts	Summary of literature review	References
			TOPSIS, Reverse logistics.		kept on priority, and a mathematical approach for deciding the most suitable suppliers have been recommended.	
7	Occupational Health and Safety issues	Hazardous and Non- hazardous	Case Studies & literature review	Utilization of AFs increases the potential of an Accident if safety instruction SOP do not follow strictly.	Available literature emphasizes that safety is a critical parameter in deciding the utilization of AFs in cement production. It is strongly recommended to follow defined SOPs, use PPEs, carryout Safety Audits frequently, doesn't use restricted waste, carry out hazard analysis, involve all stockholders, maintain adequate documents, train the staff, have an emergency plan, carry out medical surveillance.	[143–147]

The outcome of the above literature review concludes that there are no major negative impacts of AFs co-processing in cement plants on the environment and quality of the produced cement. Utilization of AFs is proven for an economic advantage by reducing production costs. However, the application of AFs has reported some process & operational related issues like jamming in chutes & hoppers, odor from waste, presence of stone and metals in waste, agglomeration of AFs, difficulty in handling due to high moisture, build-ups in preheater and kiln, increases specific heat requirement, preheater fan power, CO generation, heat losses due to bypass gas extraction, decreases the flame temperature, production rate, refractory life, etc.

Further, literature has been reviewed to understand the problems in a transfer chute, the current approach to address the issue, and available solutions.

2.5 Transfer Chute and Its associated problems

The bulk materials handling equipment are common to most industries include belt conveyors, transfer chutes, hoppers, and feeders. Chutes are the connecting pieces in the conveyor systems at transfer points. They are also a mode of channelling and pointing materials between the various storage and process equipment. Chutes are an important part of plants handling bulk materials. Chutes cause more downtime and hence require more attention during the design stage. For a good transfer chute design, it is of utmost importance that the behavior of the material is studied under the operating conditions of the conveyor system to optimize the chute design, thereby averting the incidences of system failure due to material jamming or plugging. Transfer chutes are structure elements made from carbon steel equipped with wear-resistant and flow-assisting liner materials. However, their design depends on the physical properties of the bulk material to be transported and the inclination angle of the receiving belt[153,154]. Fig. 2.3 indicates the typical arrangement of a conveyor to the conveyor transfer section.

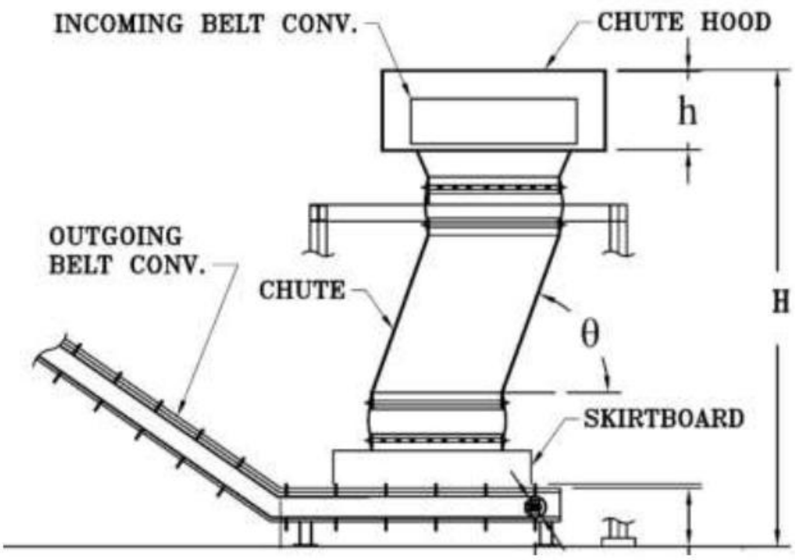


Fig. 2.3 Conveyor to conveyor transfer - A typical arrangement

Optimal conveyor transfer chute designs are a key factor in avoiding expensive chute-related problems which may stop the complete circuit of material handling. Clarity about throughput (flow rate), chute inclination, chute height and other dimensions, material discharge trajectory, and properties of bulk materials to be handled is a must for designing a flawless transfer chute[155]. Poorly designed and maintained transfer points can lead to sever problems in the system. The major problems are spillage, dust generation, material degradation, conveyor belt damage at transfer points, blockage of transfer chutes, impact wear, abrasive wear, and noise generation [156]. The transfer of material from the incoming conveyor to receiving conveyor through a transfer chute generates a lot of noise pollution, sometimes exceeding the exposure limit of 85dB due to the impact of material falling on the chute and the vibrations in the structure[157]. Material spillage occurs due to off-center loading, violent loading, and belt miss tracking. Violent material loading damages skirt seals causing material leakages. Off-center loading causes the material to heap on one side of the belt conveyor and cause spillage as the belt leaves the skirt zone[158]. Proper design of the transfer chute is necessary to minimize belt wear. Each lump of bulk material falling on the belt through the transfer chute must be accelerated to the belt speed. Poorly designed transfer points result in blockages, as shown in Fig. 2.4, cuts in the conveyor belt, abrasive wear, and uneven material distribution[89].

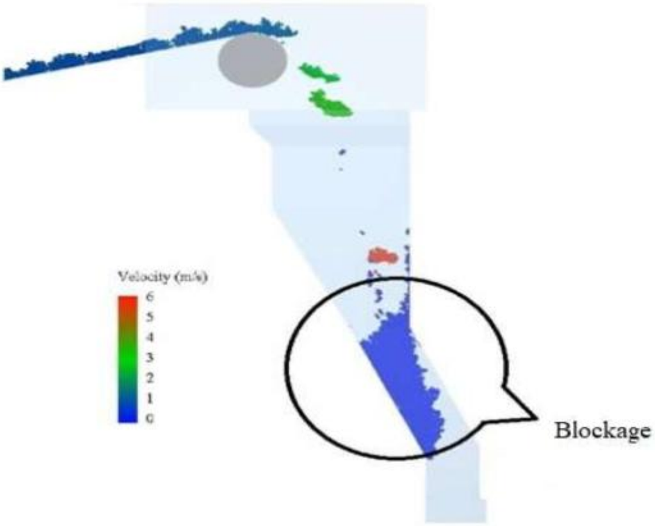


Fig. 2.4 Blockage inside a transfer chute

Material build-up inside the chute is caused by the varying material properties and lack of attention to design parameters such as chute angle, cross-sectional area, exit opening, discharge hood dimensions, chute width, etc., at the design stage. Moisture and fines in the bulk material play an important role in the flowability of the material and must be accounted for at the design stage[159]. The most difficult yet common problem in transfer stations is transfer chute plugging (jamming) while handling sticky and wet materials. Hence the design of the transfer chute has to accommodate various material characteristics[160]. With the advancement and modernization of conveyor transfer points, the transfer chute should be sealed tightly to reduce induced air velocity and dust generation, with a chute design that will smoothly guide the material through the chute with minimum impact resulting in decreasing the wear on the receiving belt and, center loading of the conveyor reducing spillage, combined with a well-sealed skirt board system along with appropriate liners to prevent material plugging[161]. Further, literature has been reviewed to know the reasons for chute jamming, the impact of bulk material properties on flowability, available standard chute design parameters, & tools to address the chute jamming issues to find out the research gap relevant to the present research. One of the reasons for chute jamming is limited knowledge of the physical properties & flow properties of bulk materials and their expected variations at the design stage of the transfer chute. Also, deviation from the recommended standard design guidelines, such as chute inclination, chute width, cross-sectional area, hood height, chute exit opening, etc., leads to chute jamming[162,163]. While reviewing the available literature on the impact of the properties of bulk material on flowability, it was found that apart from moisture, bulk density, and particle size distribution, other parameters like particle shape, angle of repose, and angle of internal friction play an important role in the flowability of the bulk material. Moisture; the researchers have highlighted the impact of moisture on the flowability of bulk materials. A.W. Roberts emphasized that the cohesiveness and adhesiveness of the bulk materials increase with the increase in moisture, which leads to build-up and blockages [164]. D. Hann and Janez concluded that moisture content in bulk materials is a critical parameter determining the properties of the bulk solid's flow. Even minor changes in moisture content substantially impact bulk solid flow properties [165]. Tyler L. Westover and Damon S. Hartley established that materials with large particles, high moisture content, and high elastic limits (high spring back) are particularly problematic for a smoother flow [166].

2.5.1 Transfer Chute Standard Design Parameters

Literature has been reviewed to know the standard design parameters for chute design, such as chute inclination, minimum cross-sectional area, width, existing opening, and hood height required. Almasi A and Jonathan provided basic guidelines applicable to various bulk materials. They recommended that if the valley angle is 65° or even 70°, the bulk material will be properly guided to flow [167,168]. Kazimierz Golka et al. suggested the minimum chute width of 2.5 to 3 times the maximum expected lump size, chute design cross-sectional area should be at least four times greater than the stream cross-sectional area S*= Q/(3600Vd), where Q-conveying capacity in tph, V-conveyor velocity in m/s, and d-material bulk density in t/m^3 , they also proposed the minimum chute inclination $\geq$ tan-1 (μ), where μ is the friction coefficient between bulk solid and chute surface[169]. A. Fritella & A. Smit established that minimum hood height should be half of the belt width and minimum chute exit opening should be 2.5 times of the maximum lump size of the material [156].

2.5.2 Available Solutions for Transfer Chute Problem

Despite their simplicity, transfer chutes need a thorough experience for effective design. A detailed list of problems arising in the chute, along with their solutions, is listed in Table 2.5

Table 2.5 Transfer chute operational problems and their solutions[170]

S. No.	Problem	Solution
1.	Material Spillage	Set skirt boards 12 mm above the belt and add an inner liner to form a labyrinth seal.
2.	Load Zone Turbulence	Provide a curved acceleration gate.
3.	Load Centering	Provide flow training gates

S. No.	Problem	Solution
4.	Poor Skirtboard Seal	Place impact idlers on minimum centers, use the latest type of seal rubber, support belt under seals with continuous pads, and use steel impact idlers except when rubber is mandatory.
5.	Dust Control	Reduce belt speeds, reduce material fall distance, provide flow acceleration gate, provide large enclosures, seal all air entry points, and provide an "adequate" exhaust air system.
6.	Material Degradation	Provide flow acceleration gate, reduce belt speeds and material fall distance.
7.	Chute Wear	Provide the highest grade abrasion resistance lining available, and provide adequate doors and enclosure size to facilitate inspection and maintenance.
8.	Belt Damage From Large Lumps	Provide grizzly bars in the impact zone, provide cushion pads under the belt in the impact zone, and install rip detectors.
9.	Material Build-Up / Plugging	Prevent sticky material from touching chute walls, provide multiple belt cleaners with automatic or mechanical excitation for cleaning, line all contact areas with UHMW plastic, and apply flow aid devices.
10.	Noise	Utilize rubber liners and/or fiberglass chute covers.

When reviewing the further literature to understand the tools available for examining and solving the chute related issues, it was found that many researchers have carried out simulation and modeling to analyze and improve the transfer chute design by resolving various problems like dust emission, wear in the chute, chute jamming & plugging, material degradation, fire, and explosion risks, etc. X.L.Chen et al. demonstrated that CFD (FLUENT) could be used to investigate and improve the chute designs handling Iron Ore with regard to dust emission [171,172]. D.B. Hastie and P.W. Wypych used DEM & Continuum methods to analyze the problems such as dust generation, particle attrition, chute & belt wear, spillage, excessive noise, or blockage while handling polyethylene pellets. They found that both DEM & Continuum methods are suitable [173]. Andrew P. Grima et al. conducted a study on Bauxite (wet and sticky) & found that the cohesiveness and adhesiveness of materials make it difficult to guide it to the receiving belt. DEM can be a resolving tool for the above-said problem [174]. Jason Aldrich and Yijun Zhang examined the flow and transfer of copper ore through conveyors. They found that conveyor belts are damaged due to the acceleration of material to belt speed by friction and wet and sticky material that clogs the chute. DEM was used to modify the transfer chute design and overcome the wear and tear of the belt [160]. G. Dewicki and G.

Mustoe presented that DEM can be an effective tool for analyzing the problem of particle movement, interaction forces, and stresses while handling bulk solids such as copper/gold ore [175]. Ilic D. and Donohue modelled the use of Continuum and DEM as strong tools to handle the problem of wearing belts used in conveyors caused by poor chute design and ignorance of variation in material properties [176,177]. J. Rossow and C.J. Coetzee expended that DEM is a promising technique that can help to predict the flow of a non-cohesive granular material(corn grains) through a transfer chute [178]. Fernando P. et al. presented a case study of a transfer chute design to replace an existing transfer chute (problematic) handling alumina using the suggested modifications based on DEM simulation [179]. A. Mahajan et al. assessed that tumbling's representativeness could test concerning transfer chutes by comparing forces acting on wood pellets in durability tests and transfer chutes using DEM [180]. K. Kukreja et al. suggested the application of DEM software for optimized design of the chute to overcome chute jamming, plugging, wear, and dust generation while handling MSW (RDF), Biomass, and Hazardous waste [29,89].

2.6 Research Gaps Identified

From the above literature reviews following research gaps are identified:

1. Previously, researchers have advocated breakdown maintenance steps for transfer chutes, like cleaning jammed chutes, followed by preventive maintenance steps like installing an air blaster for chute cleaning and sensors that detect agglomeration and jamming of the transfer chute handling alternative fuels in cement plants. The modification in the design of transfer chute handling AFs at the system design & engineering stage to mitigate its issues has not been perceived earlier.

2. Literature review indicates that several of studies have been done to check the suitability of transfer chutes for conventional bulk materials to be handled in the industry, like coal, limestone, various ores, and minerals, even for biomass in some cases. DEM has been used as an effective tool for modelling However, an attempt has yet to be made to develop a common design of transfer chute which can handle AFs (RDF, biomass, tyre chips, plastic waste, sludges, and various other solid hazardous & nonhazardous waste) and their mix available in India.

3. Conventional transfer chute, handling solid alternative fuels in cement plants when completely jammed (caking type accumulation due to poor flowability & high

moisture content of alternative fuels), requires, on average, 85 to 105 minutes for clearing and restarting. The higher downtime required for chute clearance has a negative impact on the operation, quality, environment, and production of cement as the supply of alternative fuels to the rotary kiln is stopped. The industry needs a solution to clean the transfer chute within 10 minutes to avoid AFs feed cut and its negative impact on plant operation. However, No attempt has been made to develop this type of transfer chute design.

CHAPTER 3

VALIDATION OF THE PROBLEM STATEMENT

This chapter validates the problem statement, which has been established through, a survey conducted in the Indian cement industry, AFs technology suppliers, technical consultants, R&D, and Academia working in the field of alternative fuels. The survey has been done to establish how serious chute jamming is in the Indian cement industry and which types of AFs and their characteristics contribute more to the chute jamming problem.

3 Introduction

A survey was carried out to keep the research more focused and relevant to the Indian cement industry, validate the problem statement, and establish the research's precise dimensions. The purpose is to have a decent level of confidence that the problem is a relevant. The survey concentrated on knowing whether the transfer chute jamming issue while handling alternative fuels is a major bottleneck for smooth operation, which types of AFs and their characteristics contribute to the same, what are the expected reasons and what kinds of solutions have been adopted by the industry to overcome the issues.

3.1 Survey Methodology

3.1.1 Selection of Parameters

From the discussion with the experts in alternative fuel system design and operation, various parameters like types of alternative fuels being used, who are technology suppliers, achievable TSR, chute jamming issues, characteristics of alternative fuels, etc., are noted. The critical parameters are then combined according to their nature. The key parameters considered for the survey have shown below in Table 3.1.

Table 3.1 Survey parameters

Survey Parameters	Details Asked
Alternative Fuels Details	• The primary type of solid alternative fuels • Alternative fuels (AFs) being fired in Calciner/ kiln • Thermal substitution rate (Annual Average) % • Plant location • Name of technology supplier/s

Survey Parameters	Details Asked
	• Main equipment • Year of installation
Alternative Fuels Properties	• Bulk density range of AFs in t/m3 (after pre-processing) • Moisture range of AFs in % (after pre-processing) • Particle size range of AFs (after pre-processing) in mm • Net calorific value range of AFs (kcal/kg) • The angle of repose
Alternative Fuels Nature	• Abrasiveness • Corrosiveness • Stickiness • Hazardous
Issues with transfer chute	• Are you facing any problems with the transfer chute during the pre-processing and Co-processing of AFs? • If Yes, what kind of problems are you facing in the transfer chute • Anticipated reasons for problems • Annual hrs spent on maintenance of transfer chute • Whether plant team attempt modification to improve the chute design? (If Yes, please describe in brief)

3.1.2 Survey Design

Since most of the criteria were technical, the evaluation of these criteria was planned to be through a survey. The questionnaire was designed for the assessment of different parameters. Structured questionnaires were prepared, tested, validated, modified, and opinions were collected through a web-based survey. The experts were identified from the cement industry, cement design consultants, alternative fuels system suppliers, cement R&D centres, academicians, etc. Out of 148 cement plants (including five clinkerisation units), around 60 cement plants in India use alternative fuels for co-processing [86]. Hence, a questionnaire was sent to all 60 plants and 40 consultants, R&D Centers, AF system suppliers, academicians, etc.

3.1.3 Outcome of the Survey

Out of 100, a total of 61 responses were received, which is a satisfactory survey research response rate[181]. Fig. 3.1 shows the classification of respondents in percentage:

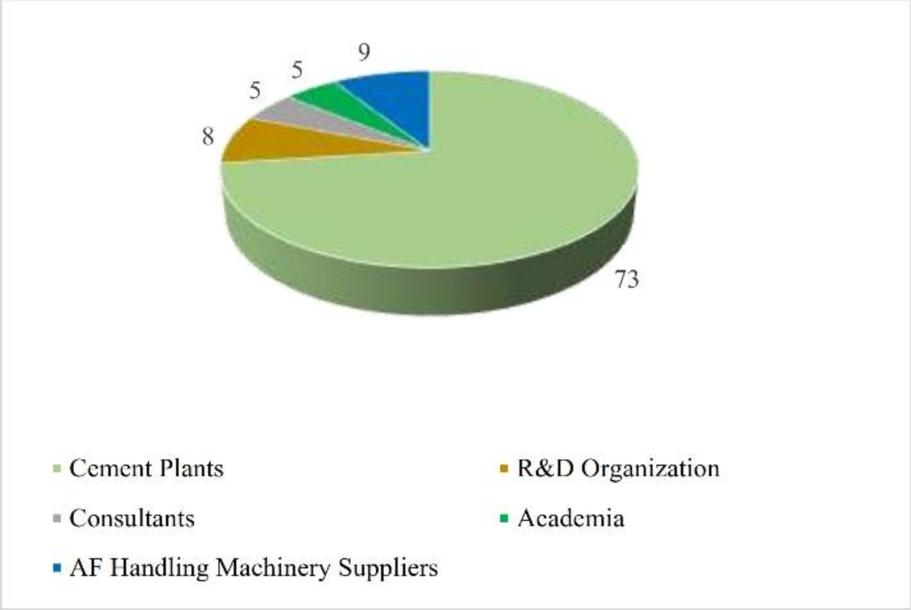


Fig. 3.1 Classification of respondents in %

The above classification indicates a sufficient representation of cement plants from India that uses alternative fuels.

3.1.4 Survey Data Analysis

The advanced data analysis tool, a Python programming language, is used for extensive data analysis to determine what type of alternative fuels are more responsible for chute jamming and what material characteristics lead to chute jamming issues. The raw data collected contains some null values. The data was then cleaned, and various feature engineering techniques were applied to the data using seaborn and matplotlib libraries of Python. The data was visualized by plotting bar graphs against various types of fuels and transfer chute issues. Fig. 3.2 indicates that 48 respondents (78.7%) out of 61 confirmed the problem associated with the transfer chute while handling alternative fuels.

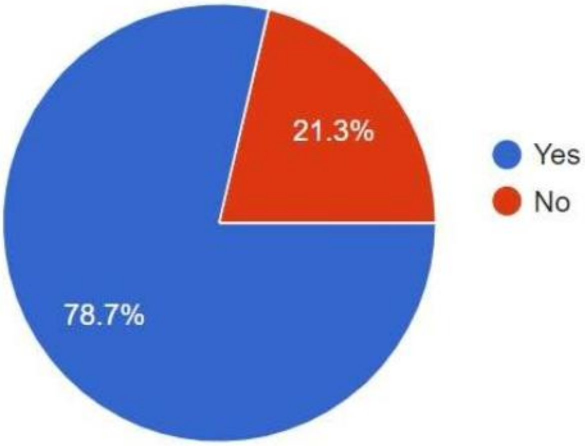


Fig. 3.2 Problem in transfer chute while handling AFs

Further, 52 responses received related to the type of problem faced by the respondents in a transfer chute while handling alternative fuels-

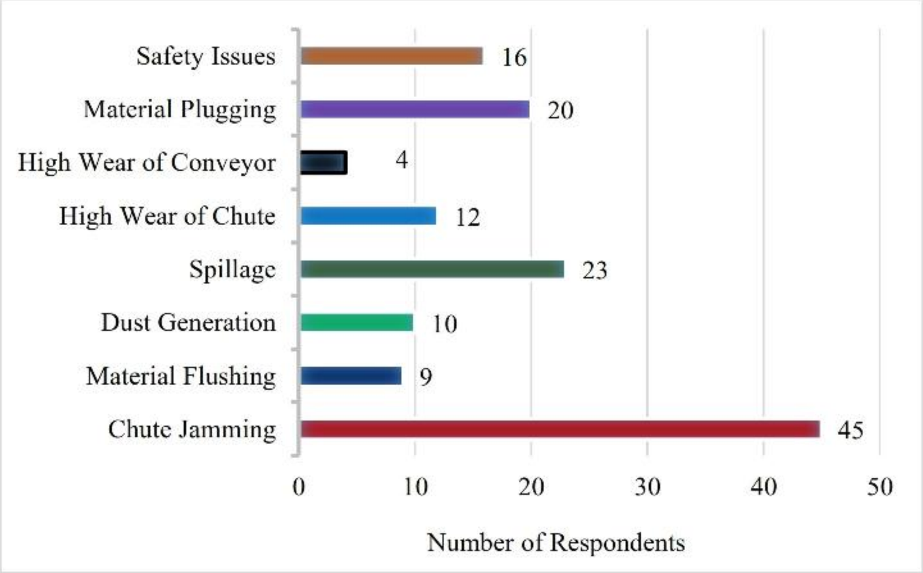


Fig. 3.3 Issues with transfer chute while handling AFs

Fig. 3.3 indicates that jamming is a leading issue with transfer chutes. However, material plugging and spillage was also reported by a substantial number of respondents. Plugging or build-ups also leads to chute jamming. Hence, more than 86 % of total respondents face transfer chute jamming problems. The industry is spending substantial time repairing and maintaining the chute (Fig. 5). The unavailability of the material transport system due to the breakdown of the transfer chute not only involves the cost of maintenance but also hinders the plant operation due to fluctuation in the AF feeding rate, and ultimately variation in the fuel mix ratio. Responses regarding the main cause of chute jamming are shown in Fig. 3.4. Out of 61 who responded about chute jamming issues, 50 shared their anticipated reasons.

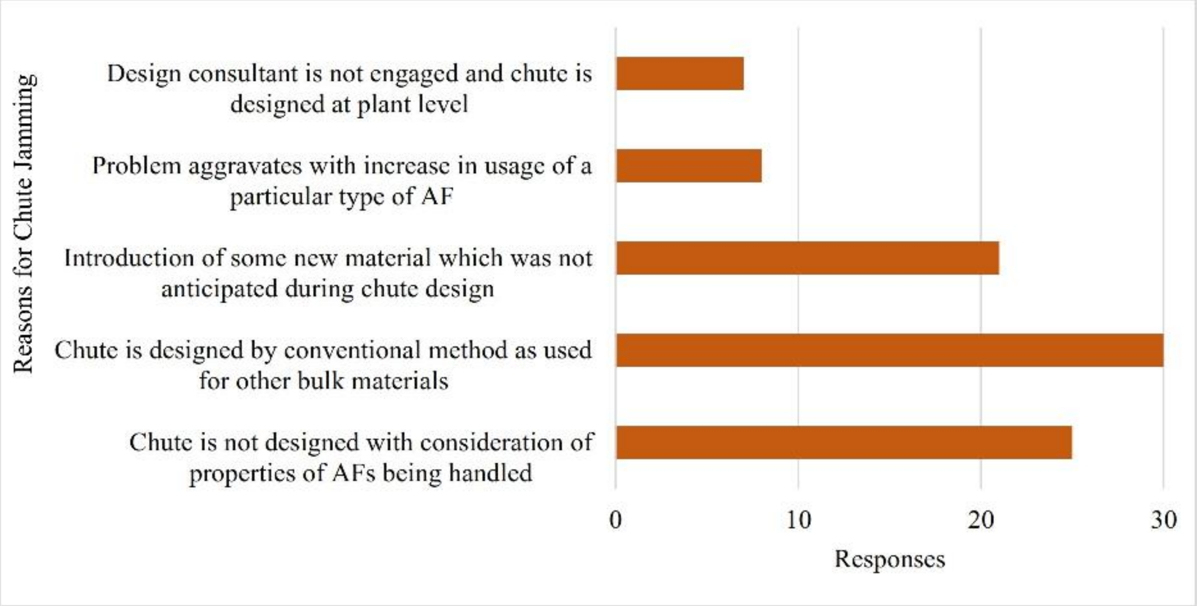


Fig. 3.4 Reasons for chute jamming while handling AFs

Adoption of a conventional approach for chute design is found to be one of the major reasons for chute jamming because the conventional approach is well established in the Indian cement Industry for bulk materials like limestone, coal, bauxite, iron ore, etc., where it is easy to characterize the material properties due to homogeneous nature. However, it does not suit the AFs where the material is heterogeneous, and its properties vary throughout the year based on the source of supply, the content of the mix, etc. Another major reason that emerged from the survey is ignorance of material flow and physical properties like material shape, size, angle of repose, and angle of inclination, because determining these properties are not easy like other bulk materials. The introduction of new material, which was not anticipated during the design of the transfer chute also found to be a reason for chute jamming. It is challenging to anticipate all types of AFs at the time of chute design because cement plants source these materials based on factors like economy, suitability of their raw mix, fossil fuel price, availability, etc. Hence, the chute should be designed with an adequate margin to accommodate a few inappropriate materials too. The survey result also presents establishes that the industry spends substantial maintenance hours for maintaining the transfer chute and clearing the jamming. 48 out of 61 responded and shared the annual maintenance hrs spent to maintain the chute, following Fig.

3.5 indicates that 41 out of 48 are spending 50 hrs to 150 hrs annually for chute maintenance which is a substantial amount for this small component of the material handling system. Plants also reported spending ~60 to 90 minutes to clear the jam.

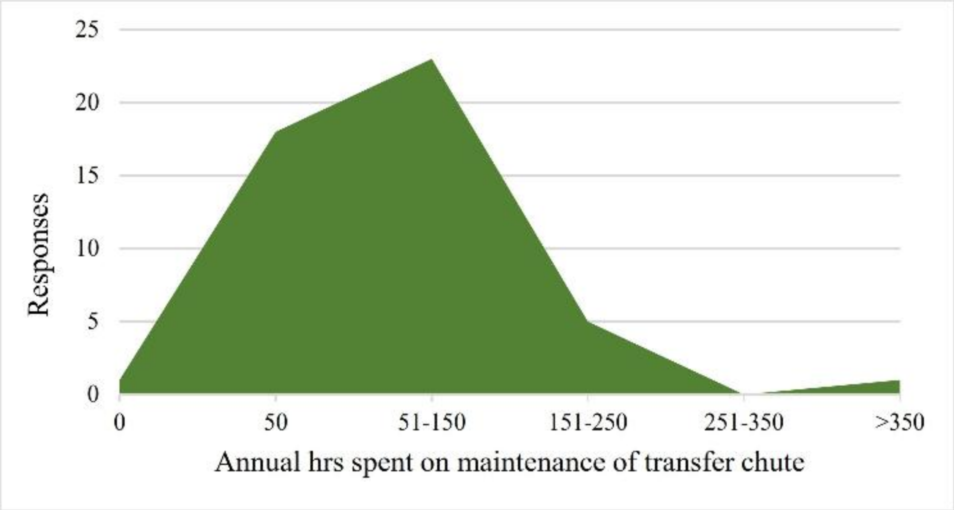


Fig. 3.5 Annual hrs spent on maintenance of transfer chute while handling AFs

Further, bar graphs are plotted to visualize transfer chute issues concerning various alternative fuels. Fig. 3.6 & 3.7 are self-explanatory and indicate the relation between the types of alternative fuels with chute jamming issues. As indicated in Fig. 3.6 & 3.7, it is observed that out of 25 cement plants that are using biomass, only six plants are having jamming issues, whereas out of 24 plants where biomass is not used, nine are facing the issue of chute jamming. Hence, biomass as AF is not a significant contributor to chute jamming. Similarly, Tyre chips are also not contributing to the chute jamming issue. However, RDF, mixed waste, industrial waste, plastic, and sludges contribute significantly to chute jamming.

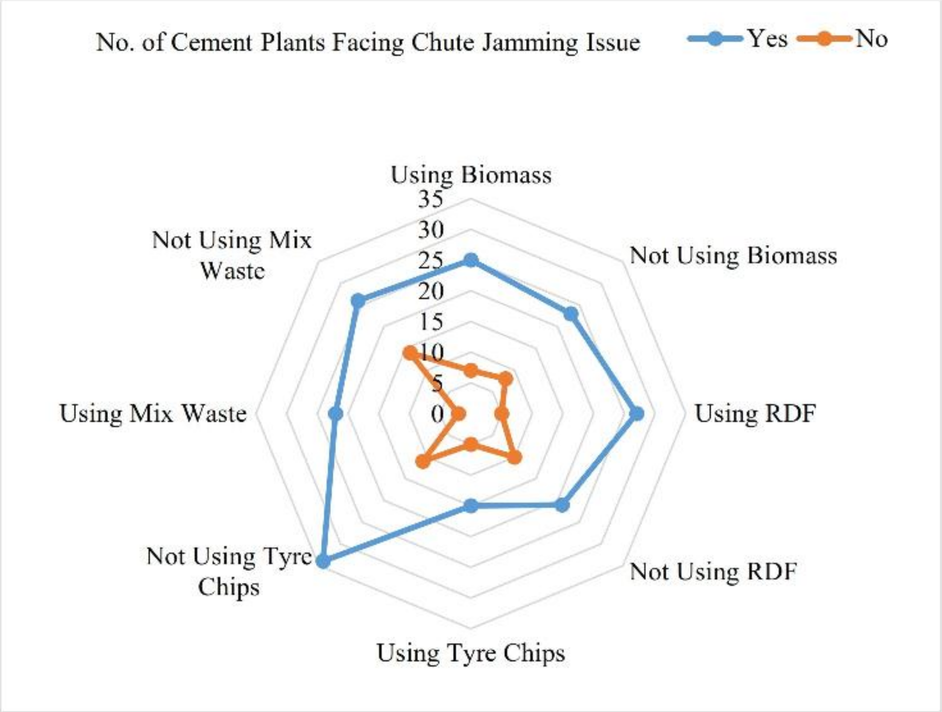


Fig. 3.6 Interrelation between use of biomass, RDF, tyre chips, mix waste, and chute jamming issue

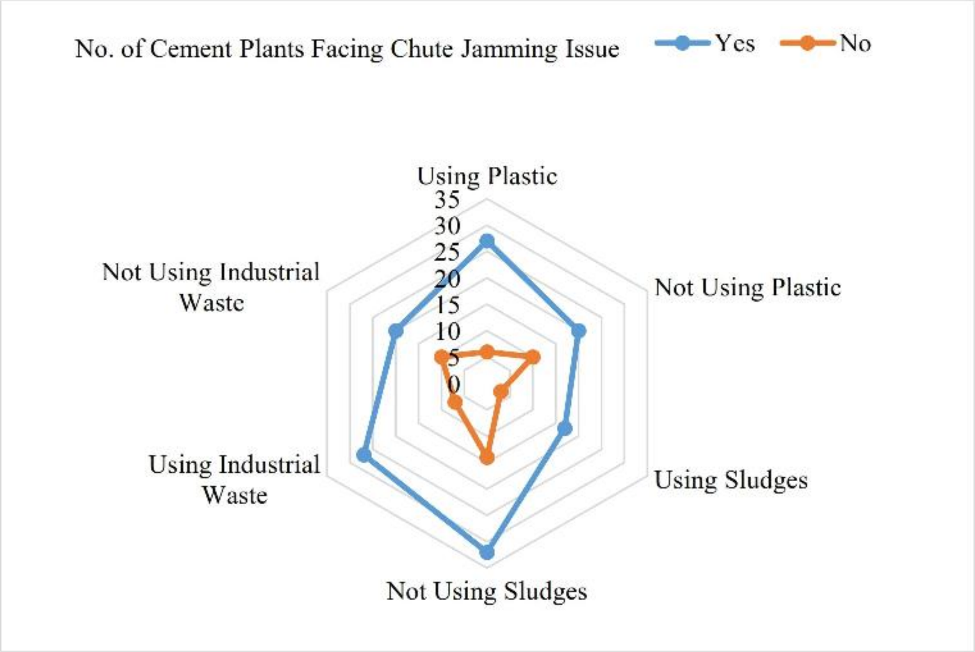
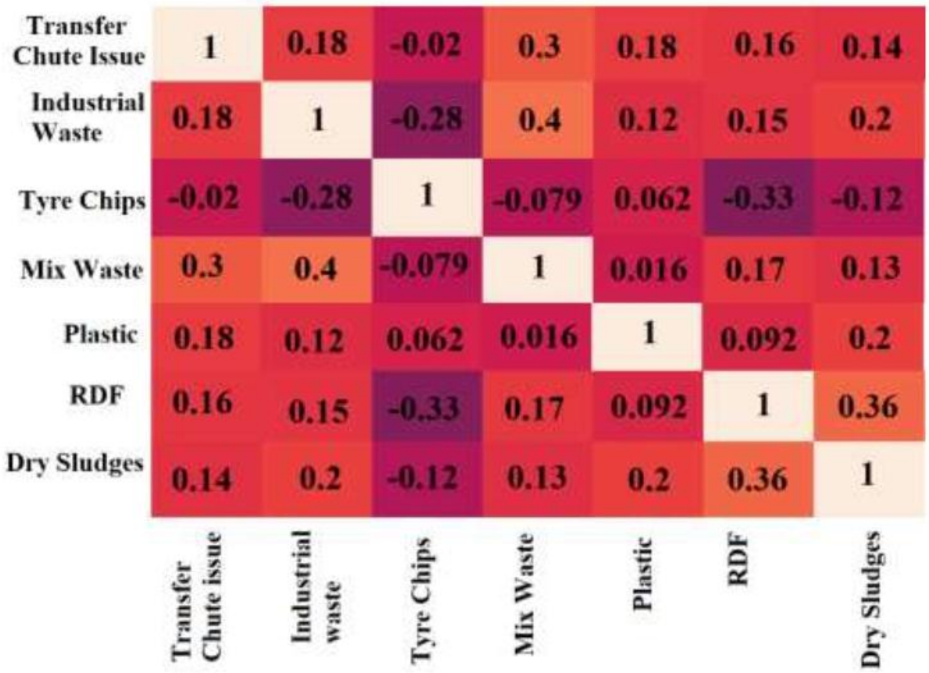


Fig. 3.7 Interrelation between use of plastic, sludges, industrial waste, and chute jamming issue

Further, a correlation heatmap is plotted to identify which type of AFs from RDF, industrial waste, mixed waste, plastic, and dry sludges contribute more to the chute jamming problem.



	Transfer Chute issue	Industrial waste	Tyre Chips	Mix Waste	Plastic	RDF	Dry Sludges
Transfer Chute Issue	1	0.18	-0.02	0.3	0.18	0.16	0.14
Industrial Waste	0.18	1	-0.28	0.4	0.12	0.15	0.2
Tyre Chips	-0.02	-0.28	1	-0.079	0.062	-0.33	-0.12
Mix Waste	0.3	0.4	-0.079	1	0.016	0.17	0.13
Plastic	0.18	0.12	0.062	0.016	1	0.092	0.2
RDF	0.16	0.15	-0.33	0.17	0.092	1	0.36
Dry Sludges	0.14	0.2	-0.12	0.13	0.2	0.36	1

Fig. 3.8 Correlation heatmap of different AFs with transfer chute jamming problem

The correlation heatmap in Fig. 3.8 shows that mixed waste fuel causes more transfer chute jamming problems, followed by industrial waste, plastics, RDF, and dry sludges. From the same correlation, it can also be noted that mixed waste and industrial waste are highly correlated, and if these two fuels mix, it causes more chute jamming problems. Similarly, the chute jamming issue will be more if RDF & dry sludges mix together. Data is further analysed to understand which characteristics of the alternative fuels (corrosiveness, stickiness, abrasiveness, hazardous) cause more chute jamming problems. The result is shown in Fig. 3.8:

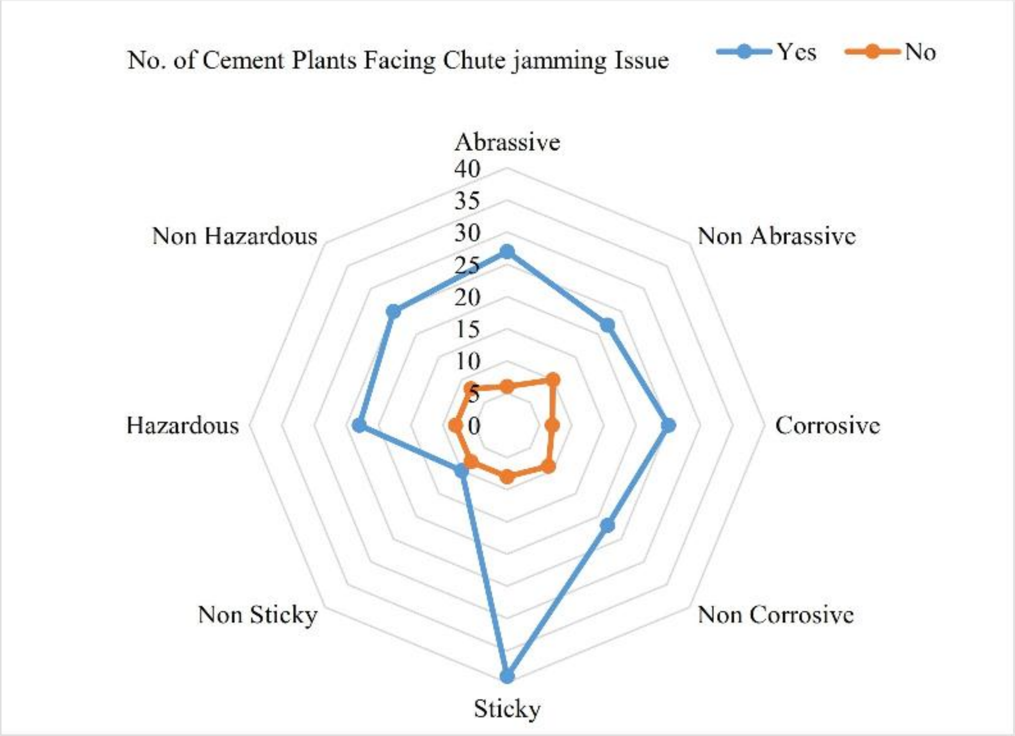


Fig. 3.9 Relationship of AFs characteristics with chute jamming issue

From Fig. 3.9, it can be inferred that the sticky nature of fuel is a major cause of concern related to the transfer chute jamming issue. Further, the respondent also shared the anticipated reasons for chute jamming and their efforts to resolve the transfer chute jamming issues. A total of 50 responses were received to share the anticipated reasons for chute jamming. The majority of respondents shared that the adoption of a conventional method for chute design (used for Limestone, Coal, and other additives), ignorance of inputs properties of AF at the design stage and introduction of new AF have been the primary cause of chute jamming. Further, 29 respondents shared their efforts to resolve the transfer chute jamming issues at their level. Table 3.2 indicates the list of significant changes adopted by respondents and the view of the authors-

Table 3.2 Efforts made by respondents to avoid the chute jamming

S. No.	Efforts made by respondents to avoid the chute jamming	Remarks by authors
1	Chute inclination increase	Depending on the existing layout
2	Falling height changed	Depending on the existing layout
3	Change in mass flow rate through the chute	Not advisable as a reduction in flow rate, reduces the TSR
4	Installation of air blaster in	Not advisable as it is energy-intensive equipment and does

S. No.	Efforts made by respondents to avoid the chute jamming	Remarks by authors
	transfer chute	not effective when the cake formation of AF in the transfer chute
5	Electric hammer fitted on chute wall	Not advisable, as it may damage the chute mother late as well as the liners
6	Provide stainless steel liners to improve the flowability	Adequate liners improve the flowability of material if the other parameters of the chute design are accurate like chute width, inclination, cross-sectional area, exit opening, etc.
7	Bend removed from the transfer chute profile	Depending on the existing layout
8	Installation of chute jamming sensors	A preventive option but not much effective in AFs handling

Table 3.2 indicates that suggestions/modifications suggested by respondents are focused on preventive maintenance steps like installation of air blasters, electric hammers for chute cleaning, and sensors that detect agglomeration and jamming of the transfer chute handling alternative fuels followed by the design medication suit to the site requirement. However, improvement in the design of transfer chute handling AFs at the stage of design & engineering to mitigate its jamming has yet to be perceived.

A detailed survey data may be referred by the following link- https://docs.google.com/forms/d/1kzq95tIQVPmp_6vqBqoQ_jUuJq9nt_L1egd3a2Nr74I/edit#responses

Apart from the above survey done in 2018-19, field visits of cement plants (located in different cement clusters of India) were also carried out in 2022 to assess the issues related to operational & system design being faced by the Indian cement plants when handling AFs & their mix. Data related to the shutdown of the AF system, along with system breakdown hours per annum, have been collected from plants to investigate the operation and maintenance issues while handling alternative fuels in cement plants. The same is indicated in Table 3.3 and Fig. 3.10.

Table 3.3 Details of AF system operational & maintenance issues

Operational & system design issues	AF system breakdown hours per annum				
	Plant-1	Plant-2	Plant-3	Plant-4	Plant-5
Transfer Chute Jamming	60	150	117	63	100
Foreign Particles in AFs	10	5	0	0	20
Dosing System Fluctuation	37	22	0	10	10
Underperformance of Shredder	28	43	33	37	15
Calciner feed chute Jamming	56	27	85	47	66
Breakdown of Grab Crane	0	10	5	10	0
Spillage of material on the conveyor	36	21	35	22	32
The underperformance of weigh feeder	12	5	0	0	10
Break down of conveying system	0	10	0	0	0
Inefficient dust suppression system	0	5	0	0	0
Total Breakdown Hour per Annum	239	298	275	189	253

It is found that the jamming of chutes is a highly problematic area. About 50 to 70% of breakdown hours are due to the chute jamming problem, i.e., Transfer chute and AF feeding chute to Calciner.

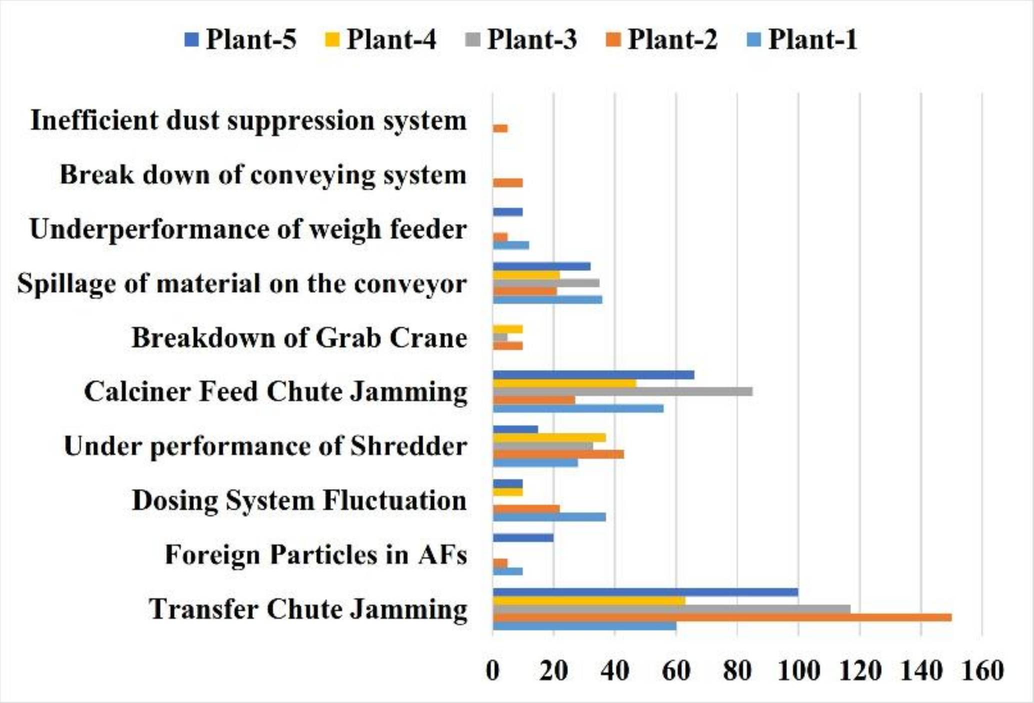


Fig. 3.10 AF system breakdown hours per annum with issues

While discussing the plant personnel, it is noted that the variation in moisture (1% to

40%), heterogeneous characteristics of the AFs, bulk density, particle size, etc., leads to the chute jamming problem. Another major issue observed is the underperformance of the shredder and spillage of material on the conveyor, which accounts for 20 to 30% of breakdown hours. If these issues are appropriately addressed, it may resolve the major operational & maintenance problem related to system design and operation.

Cement plants also shared that the conventional transfer chute, handling solid alternative fuels in cement plants when completely jammed (caking type accumulation due to poor flowability & high moisture content of alternative fuels), requires, on an average, 85 to 95 minutes for clearing and restarting. The higher downtime required for chute clearance has a negative impact on the operation, quality, environment, and production of cement as the supply of alternative fuels to the rotary kiln is stopped. Table 3.4 indicates the data shared by three leading cement manufacturers in India -

Table 3.4 Time required to clean the conventional transfer chute

S. No.	**Activity**	**Duration (minutes)**		
		Plant-A	**Plant-B**	**Plant-C**
1.	Clamping of the chute with chain pulley block	15	15	20
2.	Open the nut-bolts of the chute top & bottom flange	20	20	
3.	Tilting the Chute	10	10	15
4.	Clear the Jamming	15	15	20
5.	Tilting the chute in its original position and matching the flange holes	15	15	15
6.	Tighten the nut-bolts of the chute top & bottom flange	20	15	15
Total Duration (minutes)		**95**	**90**	**85**

The Average time required to clean the transfer chute is 90 minutes. This time is required when it is assumed that the chain pulley block is permanently installed in the transfer tower where the transfer chute is installed and the workforce (two nos. skilled and one no. unskilled) is available immediately.

3.2 The summarized outcome of the survey & field visits

With the help of advanced analytical techniques, survey data has been analyzed, and it is found that alternative fuels such as mixed waste, industrial waste, and RDF are the leading cause of concern for chute jamming. These AFs are being prepared by mixing various wastes either at the cement plant level or at the pre-processing station to achieve desired properties (mainly heat value and other properties like Chlorine content, moisture, etc.) of alternative fuels as the properties of these three wastes are variable and inconsistent due to the heterogeneous nature of the mix, which leads to difficulty in the flow of materials at transfer points. Further, mixing RDF with dry sludges and mixed waste with industrial waste may increase the tendency of chute jamming. Adoption of a conventional approach for chute design, frequent changes in the types of alternative fuels, and lack of consideration of the properties of these wastes while designing the transfer chute are the main reasons for the transfer chute jamming. On the other hand, the stickiness of the materials is characteristic of these AFs, contributing to the jamming issue. It may be one of the reasons that plants are not using flow assistance liners. It can be concluded that despite the very low-cost component of the material conveying system, the transfer chute is creating a major hindrance to achieving high TSR, and it is a must to address this issue at the design & engineering stage of the project to avoid breakdown of complete alternative fuels system. Hence, this research is very much relevant to the Indian cement industry for achieving high TSR. This survey concludes the following-

- Chute jamming is one of the major bottlenecks for increasing TSR in the Indian cement industry, and plants are spending substantial time (50 to 150 hrs per annum) maintaining it.

- About 50 to 70% of breakdown hours related to the operation & maintenance of the AF handling system are due to the chute jamming problem, i.e., the transfer chute and AF feeding chute to Calciner.

- The average time required to clean the transfer chute when it is completely jammed (caking-type accumulation due to poor flowability & high moisture content of alternative fuels) is 90 minutes. This time is required when it is assumed that all resources required to clean the chute are available immediately.

- Mixed wastes, industrial wastes, and RDFs are challenging to handle materials that lead to chute jamming and to be focused more when developing chute design parameters.

- Correct approach of chute design to be adopted, which may include the latest tool of modeling and simulation to get a more practical solution. As the modern problem demands modern solution.

- The source of AFs may vary based on various techno-commercial factors. Hence the chute should be designed to accommodate the wide range of variations in the properties of AFs and their mix.

CHAPTER 4

TRANSFER CHUTE DESIGN- THEORETICAL & DEM APPROACH

This chapter discusses the theoretical techniques for the design of transfer chutes in material handling systems, the limitation of the theoretical approach, various simulation tools available for modeling & simulation, the DEM approach, and their advantages.

4 Transfer Chute Design – Theoretical & DEM Approach

4.1 Transfer Chute Design Process

Transfer chute design is a combination of science & art. Correct transfer chute design fulfills the many requirements in material handling system, i.e., prevent jamming, minimize dust emission & spillage, protect personnel from injury, return belt scrapping, etc. Transfer chute design should consider bulk material characteristics as well as material interaction with various parts of the overall system. In the industry, "rules of thumb" still dominate, including blending of experience and engineering principles[182]. A well-designed transfer point considers the material's flowability during the design process. Chutes are the connecting pieces in the conveyor systems at transfer points. They are also a mode of channelling and pointing materials between the various storage and process equipment. Although it is a small component of a material handling system, poorly designed chutes cause more downtime and require more attention during the design stage. For a good transfer chute design, it is of utmost importance that the behavior of the material is studied under the operating conditions of the conveyor system to optimize the chute design, thereby averting the incidences of system failure due to material jamming or plugging [153,154]. Optimal conveyor transfer chute designs are a key factor in avoiding expensive chute-related problems which may stop the complete circuit of material handling. Clarity about throughput (flow rate), chute inclination, height and other dimensions, material discharge trajectory, and properties of bulk materials to be handled is a must for designing a flawless transfer chute[155].

4.1.1 Conveyor Throughput (Flow Rate)

Conveyor throughput is the critical parameter for transfer chute design. The flow rate for a conveyor system is calculated based on plant capacity and material characteristics. The primary goal of a suitable transfer chute is to transfer all the incoming material from one conveyor to the other without any material losses, either as spillage or dust generation[183].

The mass flow rate depends on the material properties, its velocity, and the cross-sectional area of the transported material. The conveyor flow rate can be calculated by the following method[169]:

Mass Flow: $Q = 3600\rho v S^{*}$, Mgh^{-1} (4.1)

Volumetric Flow: $Q_v = Q/\rho$, $m3h^{-1}$ (4.2)

Chute Flow (Theoretical) $Q_{tv} = 3600 S_i v$, m^3h^{-1} (4.3)

Where S^{*} = Cross-sectional area of the material stream in the chute, m^2

S_i = Cross-sectional area of the chute, m^2

ρ = Bulk solid's density, Mg /m^3

v = Bulk solid's stream velocity, m/s

Tsakalakis K.G. and Michalakopoulos Th. Established the mathematical model for conveyor belt capacity Q (m^3 /h) as a function of the conveyor belt width W, the surcharge angle β_{dyn}, and the roll idlers troughing angle λ[184]

$$Q = 390.24 * W^{2.1473}(-0.0002 * \boldsymbol{\lambda} + 0.0219) * \boldsymbol{\beta}_{dyn} + 0.0408 * \boldsymbol{\lambda}^{0.7903} \ (m^3/h) \quad (4.5)$$

4.1.2 Chute Inclination

The industry has adopted different approaches for selecting the transfer chute inclination for smooth material flow. One approach is to determine the chute inclination angle based on the critical angle. The critical angle is the inclination angle of the material on an inclined plane where it finds equilibrium. The material will begin to move under its weight along the chute if the angle of inclination is slightly increased. The critical chute inclination angle is given by[169]:

$$\sin\alpha > \mu \cos\alpha \quad (4.6)$$

$$\alpha_{min} = \theta_c = \arctan\mu \quad (4.7)$$

Where: α- Chute inclination angle

μ- Coefficient of friction between bulk solids and chute surface

θ_c – Critical angle of chute inclination

The characteristics of the bulk material and the chute surface material or liners should be kept in mind while deriving the chute inclination angle. Variation in friction angle should be considered when determining inclination angle as friction angle varies with varying pressure. With changes in bed depth, friction angle decreases as bed depth increases. The slope or chute inclination angle should be at least 5° larger than the friction angle, i.e. [185].:

$$\theta_{min} = \tan^{-1} [\tan\Phi \, (1 + KvHo/B)] + 5° \qquad (4.8)$$

Where:

Φ = wall friction angle corresponding to Ho

Ho = bed depth

B = chute width

Kv = ratio lateral to normal pressure

The velocity of incoming material after impacting a chute, with respect to the velocity of material before impact, is given by[186]-

$$\frac{V_2}{V_1} = \cos\theta - \sin\theta \tan\Phi \qquad (4.9)$$

Where θ = Angle of incoming material with respect to chute surface,

Φ = Wall friction angle between chute surface and material,

V_1 = Incoming material velocity before impact,

V_2 = Material velocity after impacting chute surface.

For a particular condition, there is a combination of incoming material stream angle (θ) and wall friction (Φ) which reduces the material velocity after impacting chute surface V2 to Zero, i.e. ($\theta + \Phi = 90^o$). A smooth chute surface will lead to lower wall friction. Hence the value of impact angle θ before impacting the chute surface goes to zero.

Another approach to determine the transfer chute inclination is the chute valley angle approach, where the valley angle is determined based on the side wall and back wall angle. The valley angle is the angle created by the side wall with the back wall of the chute. Typically valley angle for a conventional transfer chute is 60 ° to 75°. Fig 4.1 indicates the valley angle, side and back wall angle[182].

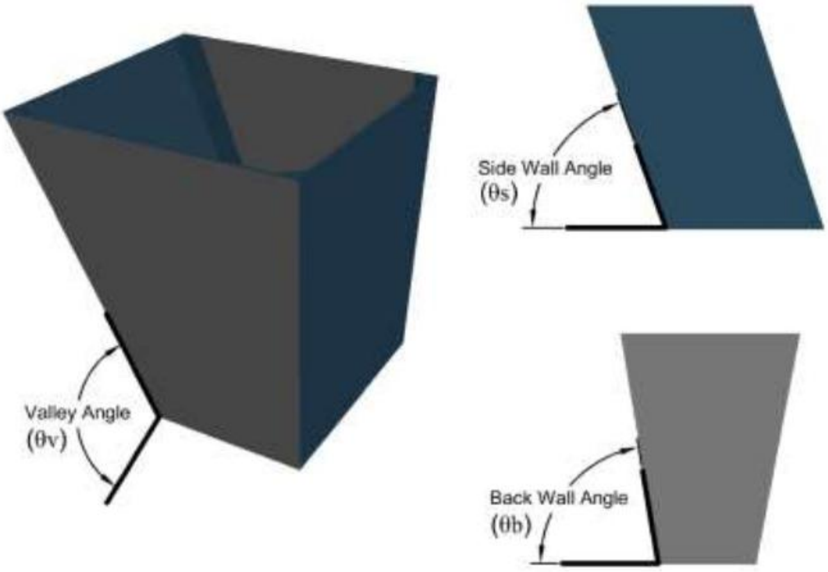


Fig. 4.1 Valley angle, side & back wall angle of transfer chute

The valley angle can be determined by the following equation-

$$\theta_v = \text{arc cot}\left[\sqrt{\cot^2(\theta_b) + \cot^2(\theta_s)}\right] \qquad (4.10)$$

4.1.3 Chute Dimensions

Chute width, cross-sectional area, drop height, chute exit opening, and discharge hood size are the critical dimension of the transfer chute system. Bulk material properties, particle size & shape, bulk density, moisture, etc., are crucial in the design phase. These properties help us decide the geometrical parameters of the transfer chute. Hoods are passive dust control methods in conveyor systems, and adequate literature is available for the design criteria of the hood. The literature recommends that the side plates of the hood should clear the pulley face by a minimum of 50 mm and *hood height* at the material entrance should be at least 0.5 times the belt width to allow material to pass. However, when the material tends to lump formation, the height of the material pass shall be three times of lump size. The chute exit opening should be sized to allow the smooth passage of the bulk material. The *exit opening* of the transfer chute should be at least 2.5 times the maximum lump size of the material and must have an area at least 2.5 times the area of the bulk[156]. The minimum chute width is also recommended as

2/3 of the belt width or a minimum of 2.5 times the largest lump size[182]. The following equation gives the required cross-sectional area for material flow for a design capacity,

$$S^* = Q/(3600\rho v),\ m^2 \qquad (4.11)$$

Where S^*= cross-sectional of the material Stream

Q = Flow rate

ρ = bulk density of the material

v = discharge velocity of material

The cross-sectional chute area should be at least four times of cross-sectional of the material Stream (S^*). The particle size distribution and maximum lump size also play an essential role in defining the cross-sectional chute area. The chute width should be at least 2.5 to 3 times of the cross-sectional area of the material stream[169,182].

Another approach to determine the chute area is given below[156]-

$$\mathbf{Ac} = \frac{2.5.\ Q}{3600.\ Vs.\ \rho} \qquad (4.12)$$

Where Ac = the minimum chute cross-sectional area

Vs = material stream speed or belt speed (m/s)

ρ = bulk density of the material (t/m^3)

Q = belt design capacity (t/h)

Most Chutes have a rectangular or square-shaped cross section as they are easy to fabricate, modify and replace the liners along with the easy installation of various sensors and devices. However, curved chutes have an advantage while handling sticky adhesive material because of the curved surface that lets the material slide. The transfer chute design must be sufficiently steep to slide off the utmost frictional material it is being designed to handle. However, the chute should not be steeper than required to control material velocities and wear.

4.1.4 Material Discharge

Determination of material profile at conveyor discharge is essential for effective transfer chute design, especially the chute geometry and deflector/impact plate position/liner placement. The solid bulk shape preceding the point of tangency on the head pulley of the belt conveyor can be similar to a segment of a circle or a parabolic shape. This parabolic shape of the material can be expressed as a function of material and belt geometry at the idler with a non- dimensional cross-sectional area factor. For material discharge at high speeds, the material burden head height at discharge is assumed to be equal to the head height at the end of the fully troughed idler set. Fig. 4.2 shows the parabolic cross-sectional area and shape of the material burden at discharge[187].

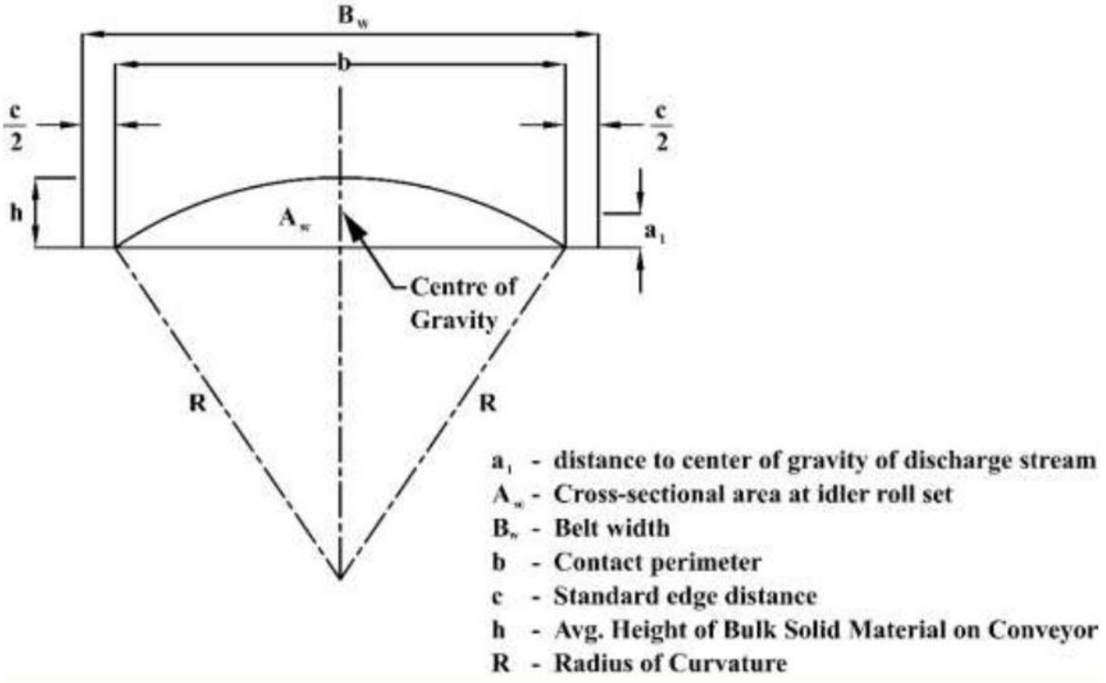


Fig. 4.2 Parabolic material shape at conveyor discharge[187]

The cross-sectional area of the material, A_{sc}, is given by:

$$A_{sc} \approx \frac{2 \cdot b \cdot h}{3} + \frac{h^3}{2 \cdot b} \tag{4.13}$$

The area of the parabolic segment is assumed to be equal to the cross-sectional area of the bulk material burden at the troughed portion of the belt. The height of the cross-sectional profile at the head pulley is given by:

$$h = \frac{A}{(B+C)} \tag{4.14}$$

Where A = Cross-Sectional area.

B = Horizontal length of bulk solid material at a location considered

C = Length of contact between bulk solid material and inclined side of the belt

After the transverse effects in the transition zone, the material burden moves from a troughed belt profile to a flat belt profile at the head pulley before material discharge. The discharge trajectory is influenced by the transition length, idler inclination and geometry, belt speed and head pulley diameter. Material properties influencing discharge trajectory and material burden include particle size, bulk density, internal friction angle, moisture content, and friction and adhesion with the belt conveyor. Material discharge can be categorized into two; Slow speed and high-speed trajectories. The bulk material will wrap around the head pulley by some angle before discharge in case of slow-speed trajectories, whereas for high-speed trajectories, material discharge occurs at the point of tangency between the head pulley and conveyor belt. The trajectory model for material discharge is chosen based on the belt velocity V_b and radius R of the head pulley. Fig. 4.3 shows the trajectory model

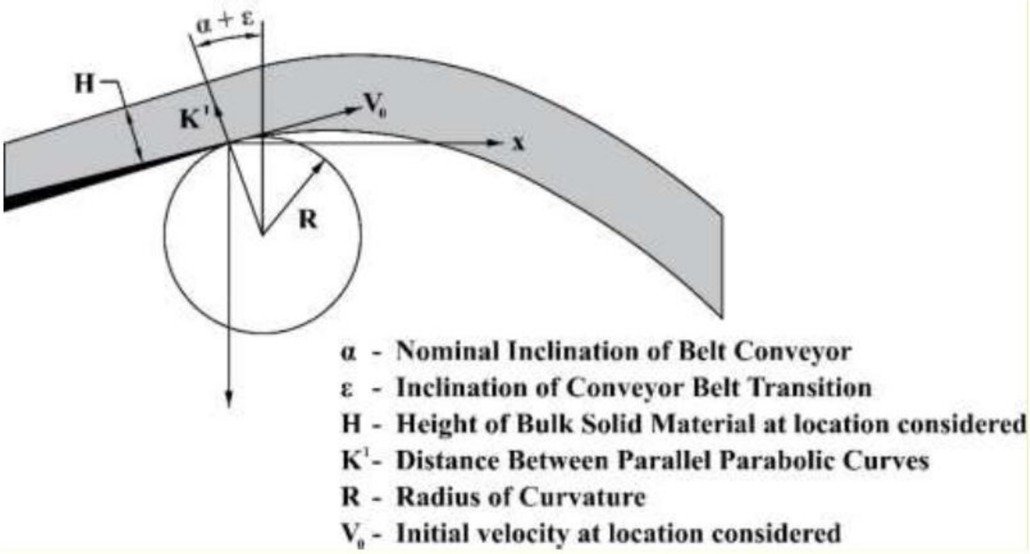


Fig. 4.3 Trajectory model

For non-adhesive materials, the trajectory category can be calculated by:

$$\frac{{V_b}^2}{(R+\frac{H}{2})\cdot g} \geq 1 \tag{4.15}$$

where, $R + \frac{H}{2}$ is the distance from the center of the head pulley to half of the height of the material stream. Under the above conditions, the material will discharge from the belt at a tangency between the conveyor belt and the head pulley. However, if the material is adhesive, the material will wrap around the head pulley at an angle, α_b, from the vertical, which can be calculated by:

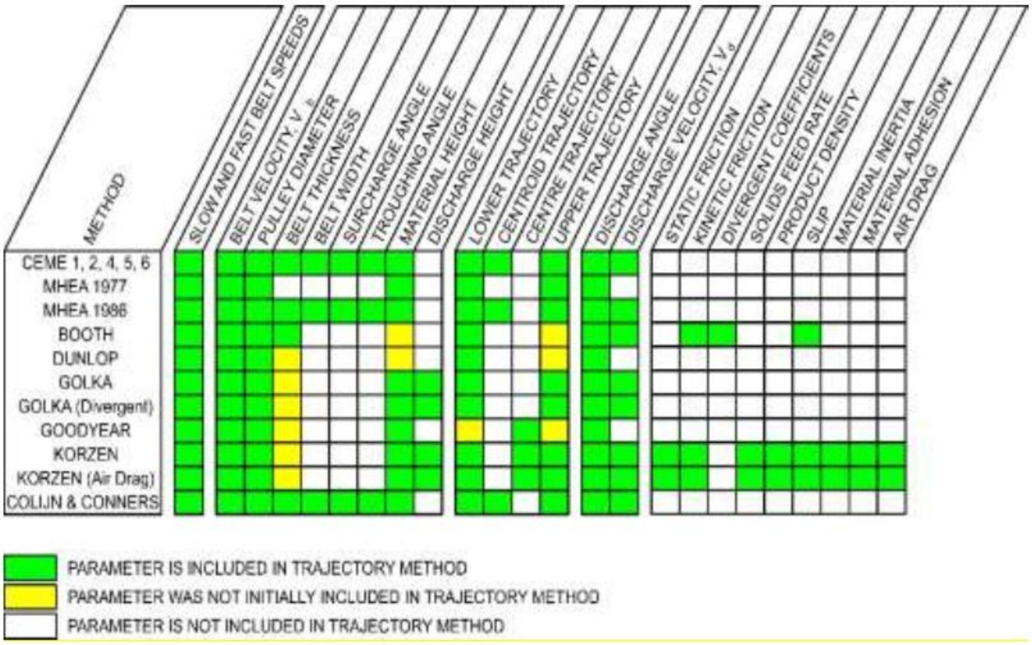
$$\frac{{V_b}^2}{(R+\frac{H}{2})\cdot g} = \cos(\alpha_b) \tag{4.16}$$

The material discharge trajectory can be based on the projectile motion, which can be calculated by:

$$y = \frac{g}{2\cdot V_0^2\cdot cos^2(\alpha+\varepsilon)}\cdot x^2 - \tan(\alpha+\varepsilon)\cdot x \tag{4.17}$$

where α is the belt conveyor inclination angle and, ε is the inclination of the transition zone, V_0 is the material stream velocity given by $V_0=V_b$. The above equation can be used to plot parabolic material trajectories graphically.

Various methods are used to model material discharge trajectories, such as Booth, C.E.M.A, Dunlop, Golka, Goodyear, Krozen, M.H.E.A., Roberts, and Colin &Conners. Dunlop and Goodyear represent the basic material discharge trajectory, whereas Booth, Golka, and Korzen are useful for plotting complex discharge trajectories. Some methods consider the multitude of parameters, such as C.E.M.A. and M.H.E.A., while others incorporate parameters that no others address. Fig. 4.4 shows the comparison of various trajectory methods [188,189].



METHOD	SLOW AND FAST BELT SPEEDS	BELT VELOCITY, V_b	PULLEY DIAMETER	BELT THICKNESS	BELT WIDTH	SURCHARGE ANGLE	TROUGHING ANGLE	MATERIAL HEIGHT	DISCHARGE HEIGHT	LOWER TRAJECTORY	CENTROID TRAJECTORY	CENTRE TRAJECTORY	UPPER TRAJECTORY	DISCHARGE ANGLE	DISCHARGE VELOCITY, V_d	STATIC FRICTION	KINETIC FRICTION	DIVERGENT COEFFICIENTS	SOLIDS FEED RATE	PRODUCT DENSITY	SLIP	MATERIAL INERTIA	MATERIAL ADHESION	AIR DRAG
CEME 1, 2, 4, 5, 6	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	⬜	🟩	🟩	⬜	🟩	🟩	🟩	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
MHEA 1977	🟩	🟩	🟩	⬜	⬜	⬜	⬜	🟩	⬜	🟩	⬜	⬜	🟩	🟩	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
MHEA 1986	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	⬜	🟩	🟩	⬜	🟩	🟩	🟩	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
BOOTH	🟩	🟩	🟩	🟩	⬜	⬜	⬜	🟨	⬜	🟩	⬜	⬜	🟨	🟩	🟩	⬜	🟩	🟩	⬜	⬜	🟩	⬜	⬜	⬜
DUNLOP	🟩	🟩	🟩	🟨	⬜	⬜	⬜	🟨	⬜	🟩	⬜	⬜	🟨	🟩	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
GOLKA	🟩	🟩	🟩	🟨	⬜	⬜	⬜	🟩	🟩	🟩	⬜	⬜	🟩	🟩	🟩	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
GOLKA (Divergent)	🟩	🟩	🟩	🟨	⬜	⬜	⬜	🟩	🟩	🟩	⬜	⬜	🟩	🟩	🟩	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
GOODYEAR	🟩	🟩	🟩	🟨	⬜	⬜	⬜	🟩	⬜	🟨	⬜	🟩	🟨	🟩	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
KORZEN	🟩	🟩	🟩	🟨	⬜	⬜	⬜	🟩	🟩	🟩	⬜	🟩	🟩	🟩	🟩	🟩	🟩	⬜	🟩	🟩	🟩	🟩	🟩	🟩
KORZEN (Air Drag)	🟩	🟩	🟩	🟨	⬜	⬜	⬜	🟩	🟩	🟩	⬜	🟩	🟩	🟩	🟩	🟩	🟩	⬜	🟩	🟩	🟩	🟩	🟩	🟩
COLIJN & CONNERS	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	⬜	🟩	🟩	⬜	🟩	🟩	🟩	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜

🟩 PARAMETER IS INCLUDED IN TRAJECTORY METHOD
🟨 PARAMETER WAS NOT INITIALLY INCLUDED IN TRAJECTORY METHOD
⬜ PARAMETER IS NOT INCLUDED IN TRAJECTORY METHOD

Fig. 4.4 Comparison between various trajectory methods[190]

Fully understanding the material behavior is of utmost importance for the successful design of a transfer chute. Incorrect trajectory predictions can lead to various detrimental issues in the material handling system. In the absence of a correct material trajectory, there is no way to adequately determine the angle of incidence. The Korzen method of material trajectory has the most parameters that can affect the material trajectory, such as material shape and size, static and kinetic wall friction, bulk density, and adhesive stress, which affect trajectory profiles[188,189].

4.2 Limitation of Theoretical Approach for Transfer Chute Design

The theoretical approach for chute design is acceptable when the bulk materials are easy to flow and have consistent properties. Transfer chute design parameters are established for common bulk materials being handled in the industry, i.e., limestone, coal, ores, etc. However, the conventionally designed chute does not perform well when the material has frequent variations in its properties like particle size, shape, bulk density, moisture content, heterogeneity, etc., depending upon the source of the material seasonal impact. Hence, the theoretical approach has limitations in predicting the flow of material in a dynamic environment. A few limitations are-

- Chute design can be a highly complex process, and theoretical approaches may only be able to capture some of relevant parameters and factors involved. For instance, the behavior of materials in chutes is influenced by a range of factors, such as the velocity, density, size, and shape of the particles, as well as the roughness of the chute surface. The theoretical approach may not be able to account for all these factors, resulting in inaccurate design predictions [191]

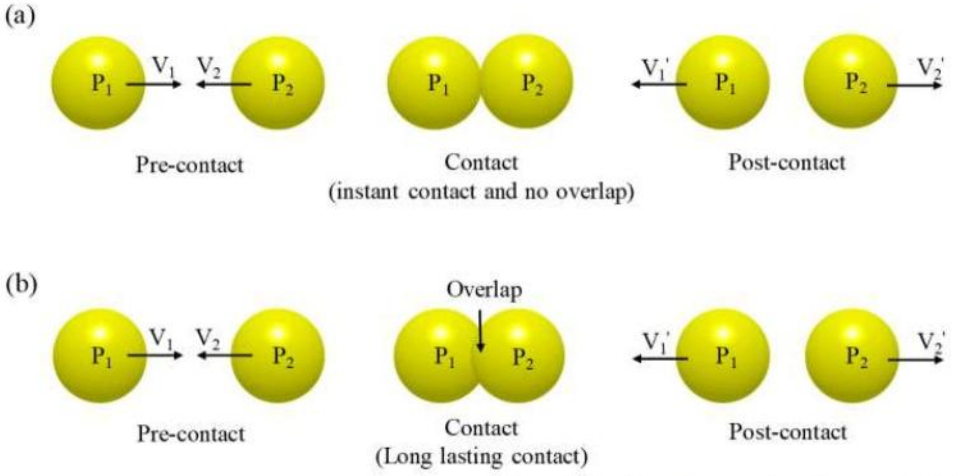
- The inability to accurately measure the velocity, solid fraction, and granular temperature distributions inside such flows hinders experimental work in this field. Theoretical approaches are based on fixed mathematical models that cannot be easily adapted to changes in operating conditions or design requirements [192].

- Transfer chute design with a theoretical approach for non-linear transfer points is complex due to difficulty in maintaining the material speed, predicting trajectory, and considering variation in the material properties[182].

- Chute design is influenced by external factors such as the environment, equipment, and material handling practices. Therefore, more than the theoretical approach is required for accurate chute design. Chutes are designed to handle a variety of materials and operating conditions, and the design must be flexible enough to accommodate these variations. Theoretical models may be unable to account for these variations, resulting in suboptimal or ineffective[162].

4.3 DEM approach of transfer chute design

Two main modeling methods are well known when it comes to simulating particle systems, i.e., Continuum (Eulerian) and discrete (Lagrangian). Modeling substances with the continuum approach method assumes that it is continuous and completely occupy the space fills. Consequently, the behavior of individual particles is ignored, and the resulting constitutive equations are solved numerically. When compared to the continuum method, the discrete model method considers every single particle as an individual unit and represents granular material as an idealized assembly of particles. The complete macroscopic system behavior results from individual particle interactions; as a result, the discrete method is very good for studying changes occurring at the scale of particle diameter and simulating the bulk behavior of particles. DEM programs have gained popularity in recent years due to their ability to analyze and visualize the bulk material interaction in material flow. The application of DEM in research and analysis of transfer chutes has been most documented. DEM has been applied for handling solid materials in hoppers, bins, mixers, screw conveyors, vibrating screens, grinding, rod and sag mills, landscape modeling, and bucket and chain conveyors [193,194]. Around 20 years ago, DEM was first applied to transfer chutes. Hustrulid and Mustoe, and Hustrulid carried out innovative investigations, establishing a quantitative description of solid bulk flow through a transfer point as well as investigating belt wear, tensions, and velocities. These studies were some of the first to acknowledge the use of DEM as a technique for visualizing transfer chute flow [163]. Using algorithms for contact detection and applying appropriate contact models, DEM software is capable of computing forces acting on particles. Accelerations, velocities, and positions are then worked out using Newton's laws of motion and numerical integration. There are two main methods of discrete simulations: hard-sphere and soft-sphere approaches. The hard-sphere approach assumes the interaction forces to be spontaneous and the momentum of particles exchange only through collisions. Forces between particles are not clearly considered. The other approach is of soft-sphere in which it is assumed that particles are firm but small overlaps are allowed to characterize deformations during particle contact. The soft-sphere method is the most common and accurate approach[195]. Fig. 4.5 explains the phenomena of soft and hard-sphere contact mechanism[196]-



V1 and V2: the velocity of each particle before contact;
V1' and V2': the velocity of each particle after contact

Fig. 4.5 Simple schematic diagram of (a) hard-sphere model and (b) soft-sphere model

The DEM simulation and analysis technique considers the rotational and translational motion equations of the particles. The mathematical model covers the interaction between particles, particles and walls and non-contacting forces like electrostatic, liquid bridges, van der Waals, etc., as shown in Fig. 4.6. The governing equations are given by [197], as follows:

The translational motion-

$$m_i \frac{dv_i}{dt} = \sum_j F_{ij}^{C} + \sum_j F_{ik}^{nC} + F_i^{f} + F_i^{g} \qquad (1)$$

For rotational motion-

$$I_i \frac{d\omega_i}{dt} = \sum_j M_{ij} \qquad (2)$$

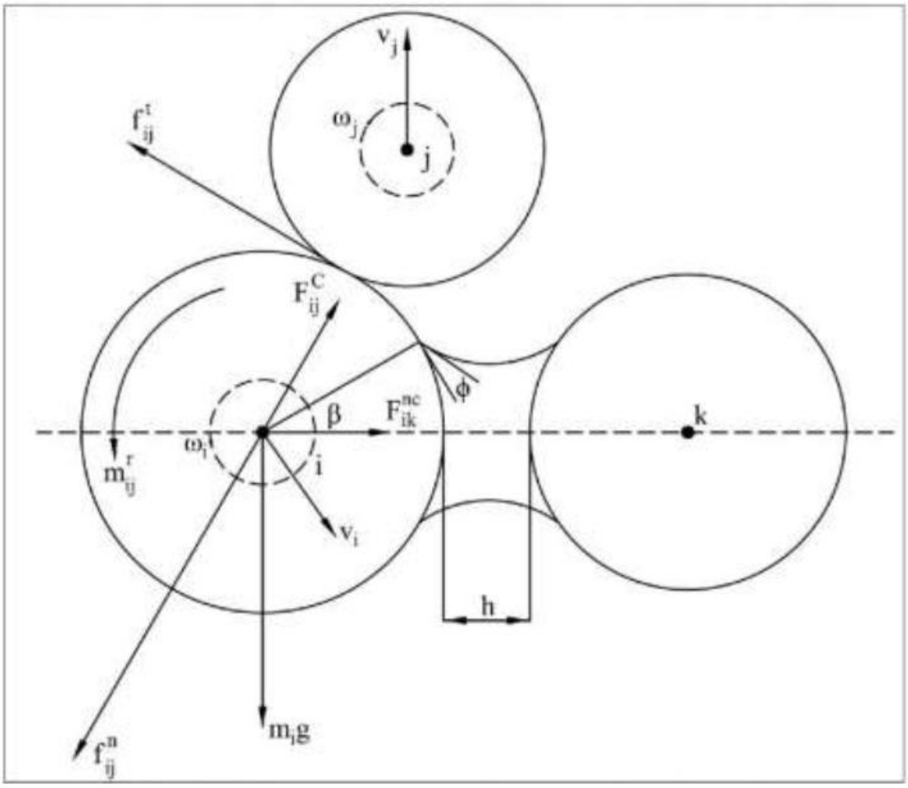


Fig. 4.6 Various forces acting on particle i & j and between not-contacting particle *k*

Hence, there are two types of forces between particles, i.e., contact and non-contacting. The particles are often not in direct contact but are in contact over a finite area because the particles deform when in contact, similar to two rigid bodies overlapping slightly within the DEM. The contact forces can be distributed over a tangential plane as well as one normal plane. The equation for Normal Force and Tangential force is indicated in Table 4.1 [197]:

Table 4.1 Contact force between particles

Force models	Normal force	Tangential force
Linear spring–dashpot Model	$f_n = -K_n \delta_n n_c - C_n \left(v_c . n_c \right) n_c$	$f_t = -K_t v_c^t + C_t \left(v_c \times n_c \right) \times n_c$
Simplified Hertz–Mindlin and Deresiewicz model	$f_n = -\frac{4}{3} E^* \sqrt{R^*} \left(\delta_n \right)^{3/2} n_c$ $-C_n \left(8m^* E^* \sqrt{R^* \delta_n} \right)^{1/2}$ $. \left(v_c . n_c \right) n_c$	$f_t = -\mu \left\| f_{n,e} \right\| \left(1 - \left(1 - \left\| v_c^t \right\| / \delta_{\max} \right)^{3/2} \right) \hat{v}_c^t$ $+2C_t \left(1.5 \mu m * \left\| f_{n,e} \right\| . \sqrt{1 - \left\| v_c^t \right\| / \delta_{\max}} / \delta_{\max} \right)^{1/2}$ $. \left(v_c \times n_c \right) n_c$
Walton and Braun's model	$f_n = \begin{cases} -k_1 \delta_n n_c, \dot{\delta}_n \geq 0 \\ \text{(loading)} \\ -k_2 \left(\delta_n - \delta_{n0} \right) n_c, \dot{\delta}_n < 0 \\ \text{(unloading)} \end{cases}$	$f_t = \begin{cases} f_t' + k_t^0 \left(1 - \frac{f_t - f_t^*}{\mu f_n - f_t^*} \right)^{1/3} \Delta v_c^t \\ \text{if } \dot{v}_c^t \text{ in initial direction} \\ f_t' + k_t^0 \left(1 - \frac{f_t^* - f_t}{\mu f_n - f_t^*} \right)^{1/3} \Delta v_c^t \\ \text{if } \dot{v}_c^t \text{ in opposite direction} \end{cases}$ where $f_t = \left\| f_t \right\|, f_n = \left\| f_n \right\|$.

Further, non-contact forces such as Van der Waals, liquid bridge, and Electrostatic force are also active between the particles and important when fine particles and moisture exist in the material. It may affect the packing and flow behaviors of the material. The equation for non-contact forces is indicated in Table 4.2 below [197]:

Table 4.2 Non-contact force between particles

Cohesive Force	Origin	Formula
Van der Waals force	Molecular dipole interaction	$F^v = -\frac{A d_p}{24 h^2} \hat{n}ij$
Electrostatic force	Coulomb force	$F^e = -\frac{Q^2}{16 \pi q_0 h^2} \left(1 - \frac{h}{\sqrt{\left(R^2 + h^2 \right)}} \right) \hat{n}ij$
Liquid bridge force (static)	Surface tension	$F^l = -\left[2\pi \gamma R \sin\phi \sin\left(\theta + \phi \right) + \pi R^2 \Delta p \sin^2 \phi \right] \hat{n}ij$

4.3.1 Overview of DEM Contact Models

In DEM, granular solid bulk materials are represented as an assembly of particles that interact with one another by the rules of physics. The various types of particle interactions occurring during the DEM approach are shown in Fig. 4.7[196]

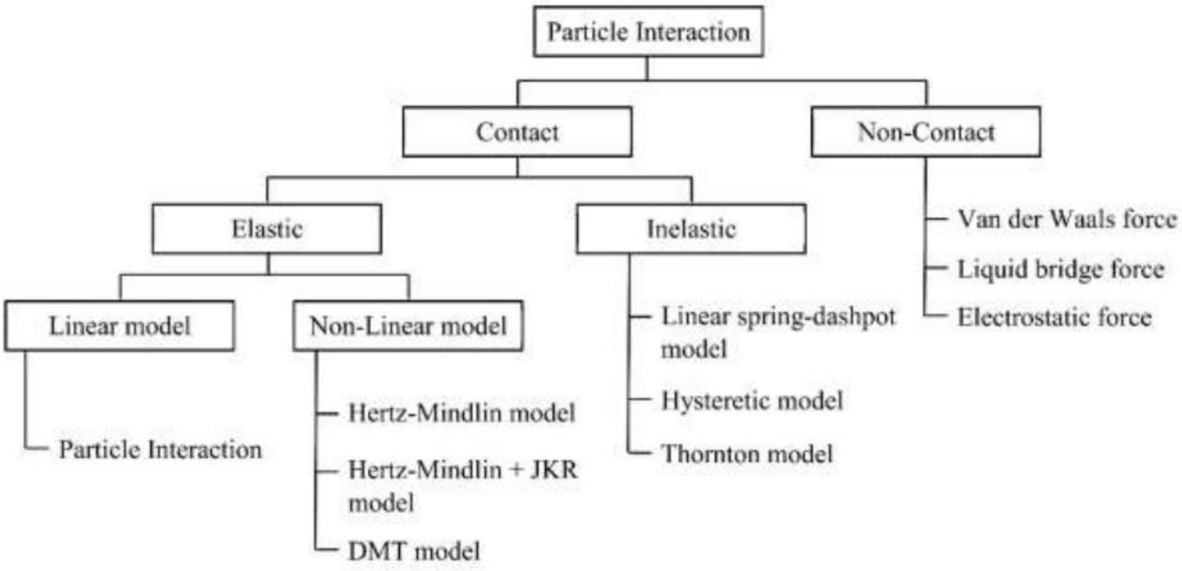
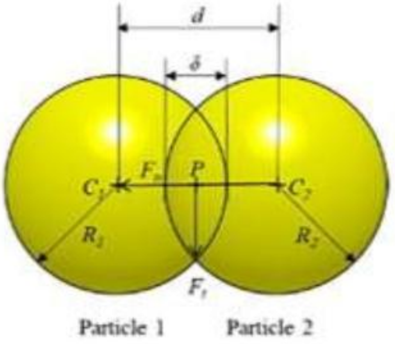


Fig. 4.7 Contact models used in DEM based on particle interaction

Material modeling in DEM requires a detailed understanding of particle interactions with varying load conditions. Correct physical parameter values for particulate materials and adequately chosen and utilized physical models of particle interaction are essential as inputs for DEM modeling. DEM considers a wide range of particle interactions such as viscous, dry friction, elastic, and adhesive interaction. Viscosity, plasticity, and dry friction simulate energy dissipation, while elastic theory simulates energy accumulation at the contact points. Fig. 4.8 indicates the interaction between two particles in the DEM approach[198].

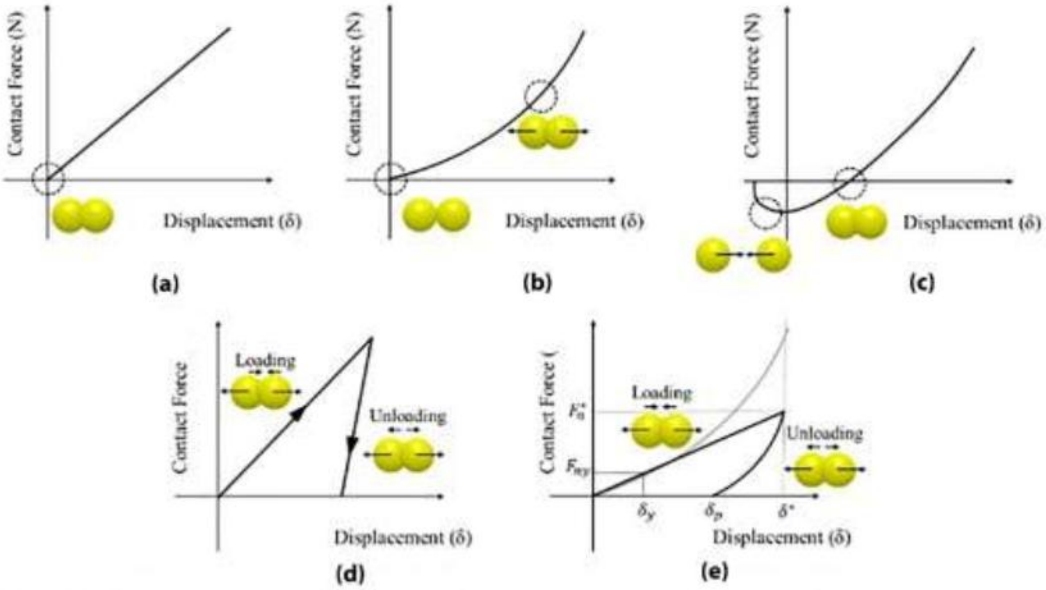


C_1: The center of particle 1;
C_2: The center of particle 2;
R_1: The radius of particle 1;
R_2: The radius of particle 2;
d: Distance between the C_1 and C_2;
δ: The overlap between particle 1 and particle 2;
P: The center point of overlap;
F_n: The contact force in the normal direction;
F_t: The contact force in the tangential direction.

Illustration of normal and tangential force involved in the contact between particles.

Fig. 4.8 Normal and tangential forces in between particles

Force and displacement between particles in the various contact models are indicated in Fig.4.9 [196]



Relationship between force and displacement in various models: **(a)** Linear spring model, **(b)** Hertz-Mindlin model, **(c)** Hertz-Mindlin + JKR model, **(d)** hysteretic model and **(e)**Thornton model

Fig. 4.9 Force and displacement between particles in the various contact models

Table 4.3 Contact models and their application

S. No	Types of Model	Application	Reference
1	Linear spring model	The linear spring model is based on the fact that during the contact of particles, the energy is not consumed, and the contact is considered completely elastic. In most practical cases, however, some kinetic energy is dissipated by plastic deformation and/or some kinetic energy is converted to another energy. Therefore, a linear spring model has a limitation in application to particle contact modeling in industrial applications.	[196]
2	Linear spring dashpot model	To simulate & analyze the fine material fluidization a	[199]
3	Hertz-Mindlin Contact Model	Various manufacturing processes such as milling, blending, granulation, and coating in the industry.	[196]
4	Hertz- Mindlin with JKR (Johnson, Kendal, Roberts)	This model describes the adhesive theory using a balance between stored elastic energy and loss of surface energy. It is used to model materials where adhesion is caused due to the liquid bridge or capillary forces. Model is widely used in the industry to solve various process and design-related issues involving bulk solids with cohesive properties	[196]
5	Hysteretic model	The model has been used in the pharmaceutical industry to study cohesion and segregation during blending.	[196]

The chapter concludes that various researchers have done exhaustive work to establish the design parameters of the transfer chute. Chute inclination, cross-sectional area, chute exit opening, minimum width, etc., can be calculated based on the theoretical approach shared by many researchers. The theoretical approach of transfer chute design adopted by the researchers is the combination of thumb rules followed by the industry for a long and the engineering principle. Chute design can be a highly complex process, and theoretical approaches may only be able to capture some of the relevant parameters and factors involved. The inability to accurately measure the velocity, solid fraction, and granular temperature distributions inside such flows hinders experimental work in this field. Theoretical approaches are based on fixed mathematical models that cannot be easily adapted to operating conditions or design requirements changes. Discrete Element Modelling (DEM) has emerged as a proven simulation tool to develop the transfer chute design, especially when the material is complex to handle.

However, selecting correct input parameters and contact model is most important to get accurate results. References are available for transfer chute design with the help of DEM, where Hertz- Mindlin with JKR contact model has been used to simulate the complex materials having adhesive and cohesive characteristics. The outcome of this chapter advocates that the DEM will be the more accurate approach for transfer chute design when handling alternative fuels like RDF, biomass, hazardous waste, industrial waste, and mixed waste, where the variation range in the properties of the material is wide and all the material to be handled by the single material handling system.

CHAPTER 5

MODELING AND SIMULATION

This chapter discusses the selection of software for DEM simulation, a case study from a cement plant to validate the accuracy of selected software, design & development of transfer chute design parameters based on simulation results, suitable to handle multiple types of alternative fuels & their mix without any jamming issue.

5 Modeling and Simulation

5.1 Selection of Software

Various software is available for DEM simulation; ROCKY DEM (Ansys), EDEM (Altair Engineering Inc.), and STAR CCM+ (Siemens Digital Industries Software) are some of the proven proprietary software. LIGGGHTS and LAMMPS are open-source DEM software that demands coding knowledge and complex computation. Outcome of the research shall be useful for the Indian cement industry to handle the transfer chute jamming issue. Leading cement manufacturing group Ultratech Cement Limited came forward to provide the support for simulation work. M/s Ultratech Cement Limited extended its support for simulation work through EDEM software. At the initial research phase, M/s CAEZEN Technologies, Bangalore, also extended their software support to NCB. EDEM is proven software, and exhaustive case studies are available for transfer chute simulation and design improvement for various bulk materials. However, any case study covering alternative fuels, especially RDF, mixed, Industrial, and hazardous waste, could not be found on DEM. Hence, validating the software for any of the AFs mentioned above is a must.

5.2 Validation of Software

In order to move ahead to the simulation of the new chute design, it was necessary to validate whether the selected simulation software could handle the various properties of alternative fuels. Hence, a case study was taken from an Indian cement plant located in the western part of India. The cement plant selected for the case study has a full-fledged, eco-friendly AFs feeding system. AFs were being unloaded by self-tapping trucks/hydraulically operated truck tipplers and transported with the help of belt conveyors and bucket elevators to the pre-calciner. As shown in Fig. 5.1 AFs feeding system was fully automatic and controlled through Programmable Logic Controllers (PLC). Apart from various environmental benefits, the enhanced usage of AFs also provides cost benefits to the plant over conventional fuels, as the cost of AF per 1000 kcal was Rs. 1.00 to 1.1 compared to conventional fossil fuel, i.e., Rs. 1.2 to 1.6.

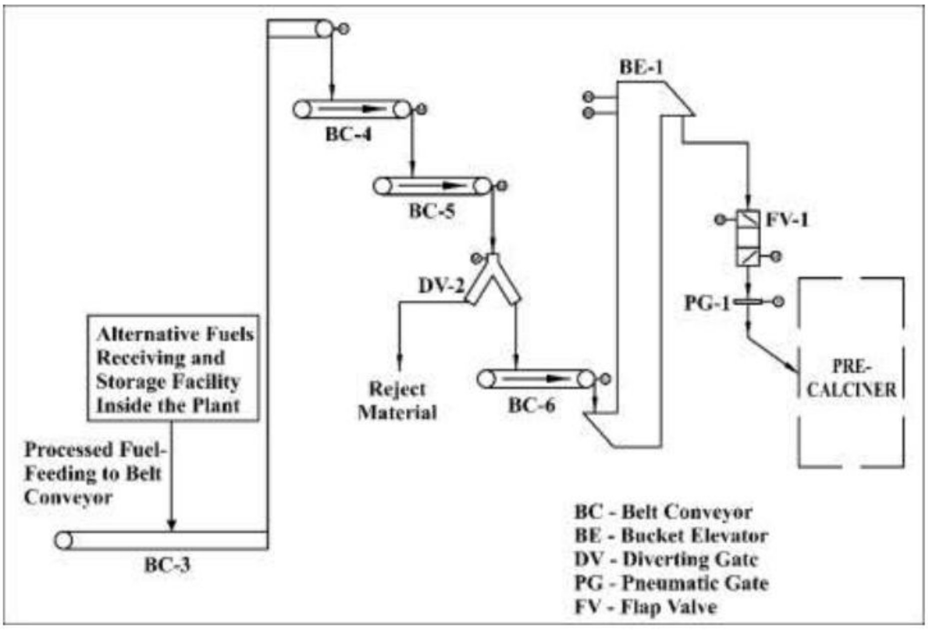


Fig. 5.1 Existing alternative fuel feeding system

Table 5.1 indicates the operational conditions of AFs conveying system

Table 5.1 Operational conditions of AFs conveying system

Parameters	Value
Material Carrying Capacity (t/h)	7.50 to 10.00#
Incoming Belt Velocity (m/s)	1.00
Conveyor Belt Width (m)	0.80
Belt Conveyor Head Pulley Diameter (m)	0.40
Belt Conveyor Inclination (deg.)	13.85
Belt Conveyor Trough Angle (deg.)	35.00
Hood Entry Width (m)	1.00
Outgoing Bucket Elevator Velocity (m/s)	1.00
The vertical height of the transfer chute from hood discharge flange to the bucket elevator feeding flange (m)	3.00
Chute Inclination from Horizontal (deg.)	60.00

Depending on the types of AFs

The plant reported jamming issues in the transfer chute, which is feeding RDF from the belt conveyor (BC-6) to the bucket elevator (BE-1) as shown in Fig. 5.2:

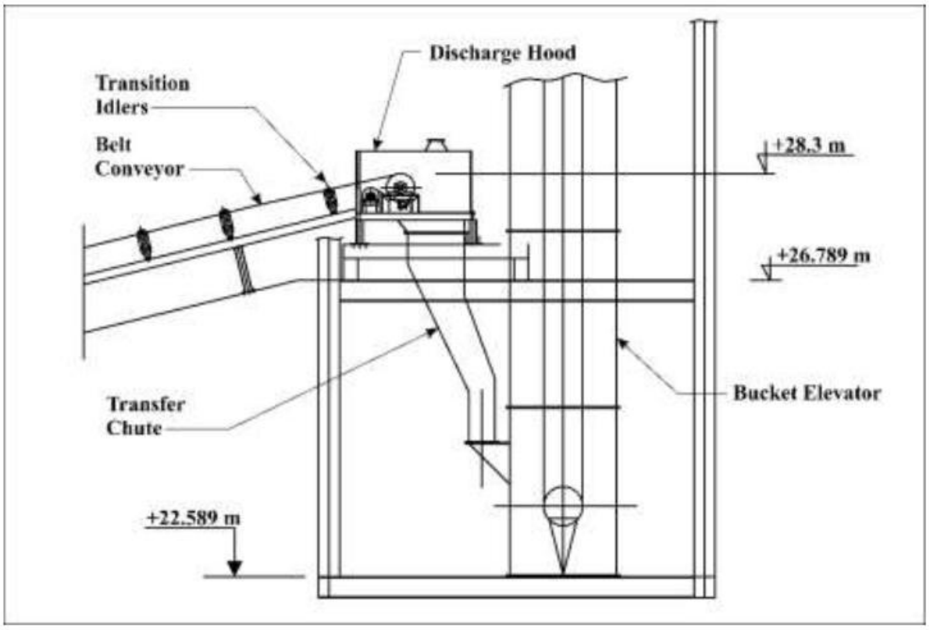


Fig. 5.2 Existing transfer chute arrangement

The plant reported an average 150 hrs maintenance requirement per annum to clear the chute jamming and shared that the problem occurs due to variations in RDF physical properties, especially high moisture. The chute is rectangular and made of a mild steel plate conforming to IS 2062. DEM simulation tool has been adopted to analyze and resolve the chute jamming issues. As per the literature, DEM modeling & simulation is a proven technique where 3D CAD models can be imported into DEM simulation. The steps followed to analyze and fix the issues with the existing transfer chute and its modification to get an improved chute design are described in Fig. 5.3:

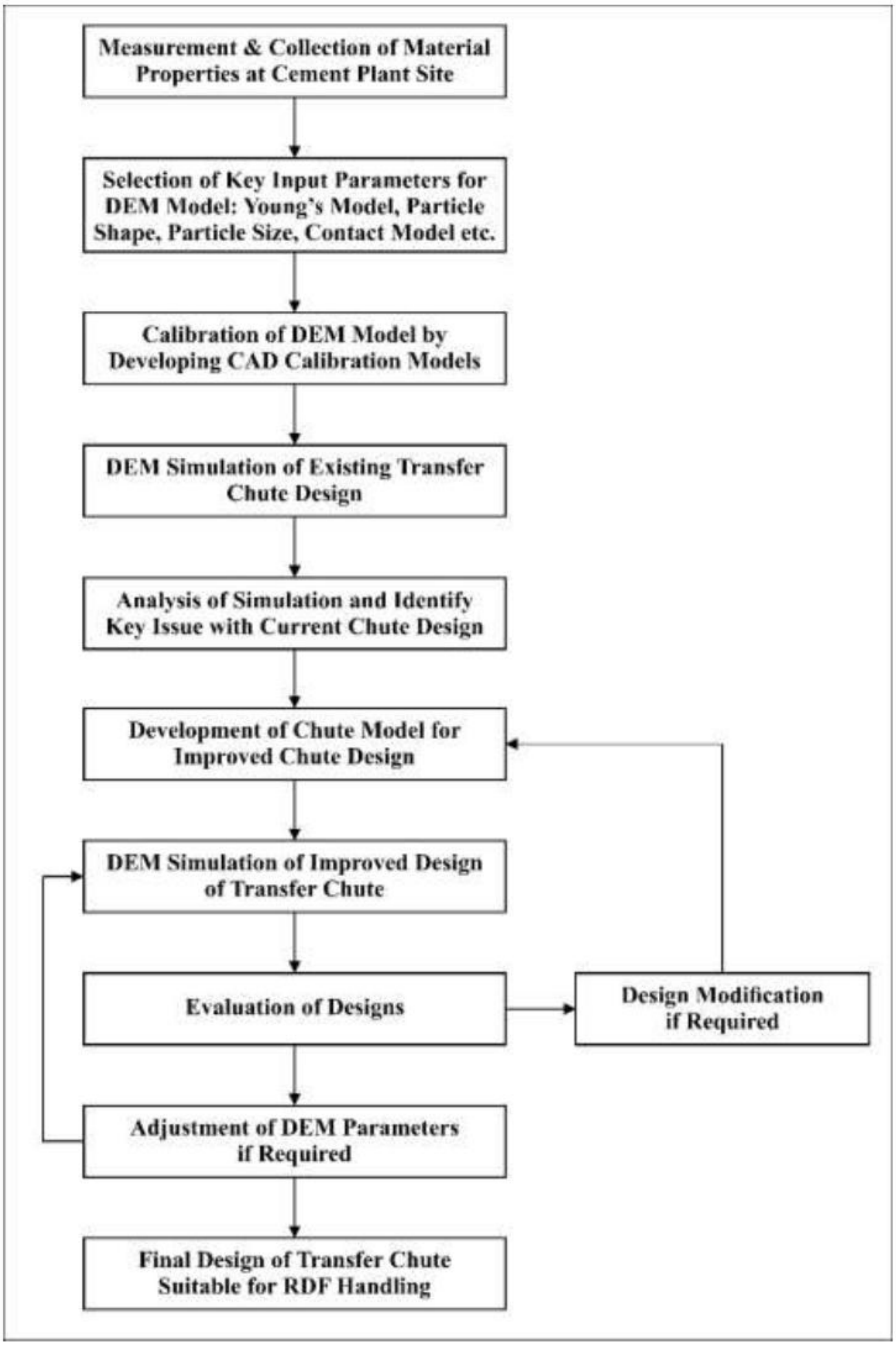


Fig. 5.3 Methodology for chute design simulation and improvement

5.2.1 Collection and Measurement of RDF Properties at the Site

RDF properties collected from the site are shown in Table 5.2;

Table 5.2 Properties of RDF

S. No.	Properties	Value
1.	Composition of RDF	Paper, wood, cloth, plastic, etc.
2.	Particle Size Distribution (Typical)	<30 mm (10%) >30 mm and < 60 mm (80%) >60 mm (10%) (maximum 70mm)
3.	Bulk Density	0.10-0.20 t/m^3
4.	Moisture content	Variation from 20% to 35%
5.	Calorific Value (NCV)	2500 to 3000 kcal/kg
6.	Particle Shape	Uneven

Data on moisture, bulk density, particle size distribution, and particle shape was readily available. However, the angle of repose and the angle of internal friction were determined at the site. The angle of repose (θR) was determined at the site with the help of a magnetic inclinometer. For determining θR, the material sample (RDF) was filled into a cylinder pipe (PVC) and then emptied on a flat surface by lifting the pipe slowly. The acute angle that the heap makes with horizontal is the repose angle. Site measurement indicate the value of θR as ~ 60 degrees, as shown below Fig. 5.4 and Fig. 5.5:

Fig. 5.4 Determination of angle of repose at site

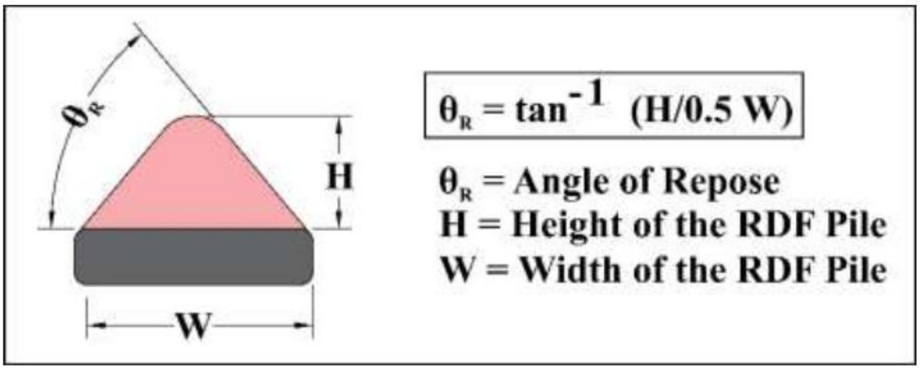


Fig. 5.5 Calculation of angle of repose at site

For cross-checking the angle of repose, which is measured through a magnetic inclinometer, a ruler and a tape were used to measure the height (H) and width (W) of the pile of RDF. To measuring tape was kept next to the RDF pile to measure the height. Further tape was extended carefully to the top of the RDF pile to measure the height without disturbing the pile. The direct shear test was conducted at the laboratory on the direct shear tester for RDF to determine the angle of internal friction, cohesion, and adhesion. A graph (Fig. 5.6) is plotted between shear stress and normal stress. The internal friction angle is found to be 38.66 degrees.

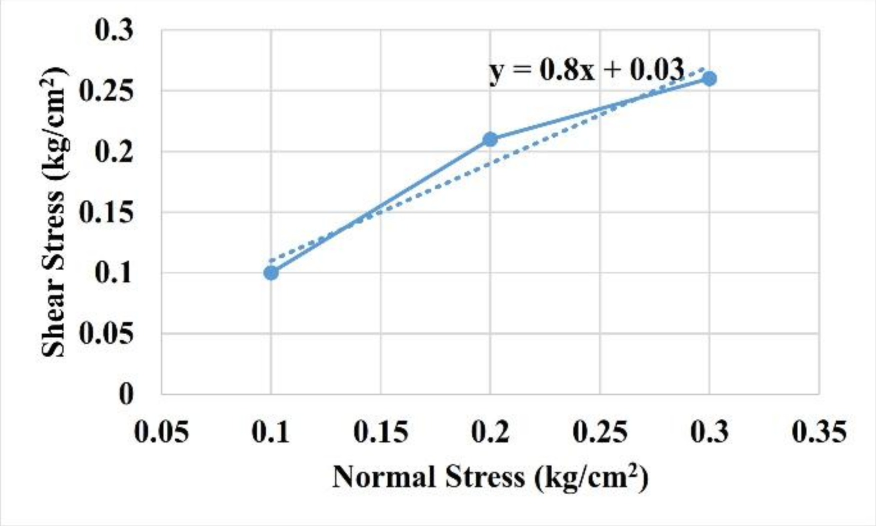


Fig. 5.6 Determination of angle of internal friction

The angle of inclination (θi) is determined by putting some amount of bulk material onto a flat plate of liner material (or mother plate material), rotating the plate about one edge slowly until the bulk material over the plate starts to slide, and then measure the angle of inclination (through inclinometer) of the plate with respect to the horizontal plane. Site measurement indicated (Fig. 5.7) that the value of θi is 30 degrees.

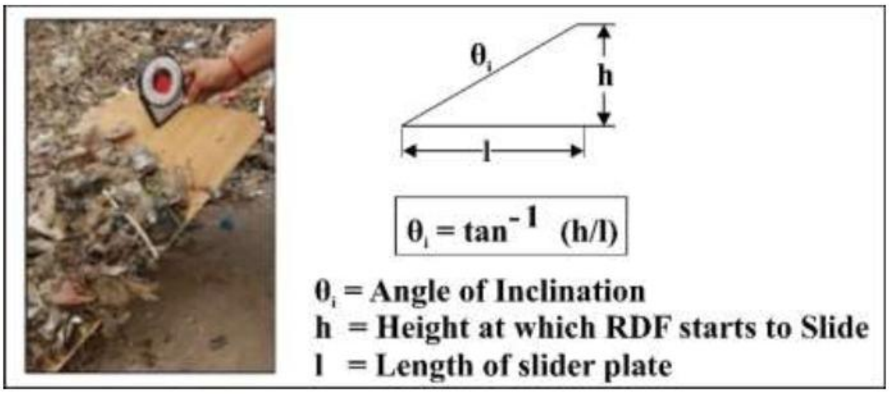


Fig. 5.7 Determination of angle of inclination at site

As concluded in the literature review, a slight variation in properties such as moisture, bulk density, and particle size may significantly impact the flowability of bulk materials. Hence, it is essential to understand variations of received RDF at the plant site throughout the year. Data related to these variations were collected from the cement plant for the last year. Fig. 5.8 & 5.9 indicate the graphical representation of variation in the above physical properties:

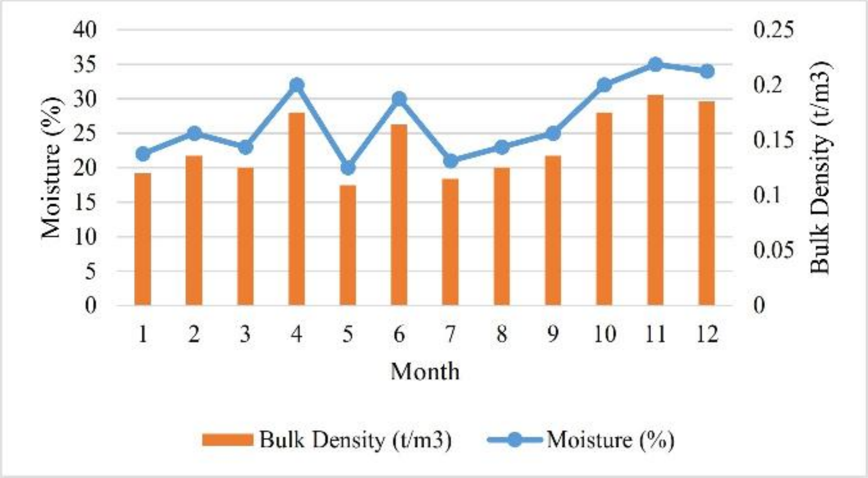


Fig. 5.8 Variation in moisture content & bulk density of RDF

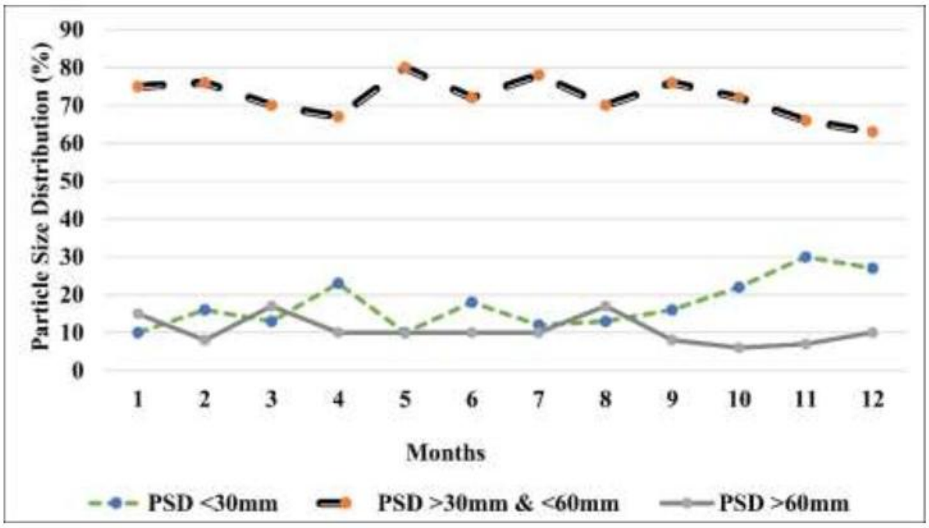


Fig. 5.9 Variation in particle size distribution of RDF

Fig. 5.8 & 5.9 indicate the inconsistency of the physical properties of RDF being received by the cement plant. On investigating the reasons for the wide range of variation in these properties throughout the year, plants reported that they have multiple sources for RDF. These sources have different RDF preparation processes & techniques, which leads to variation. Further, it was also informed that the storage time of RDF at the plant site and transportation distance from the plant also contributes to the variation of these properties. For a better understanding of the interrelation between these physical properties, a regression analysis is carried out, and its trend has been plotted in Fig.5.10 & 5.11:

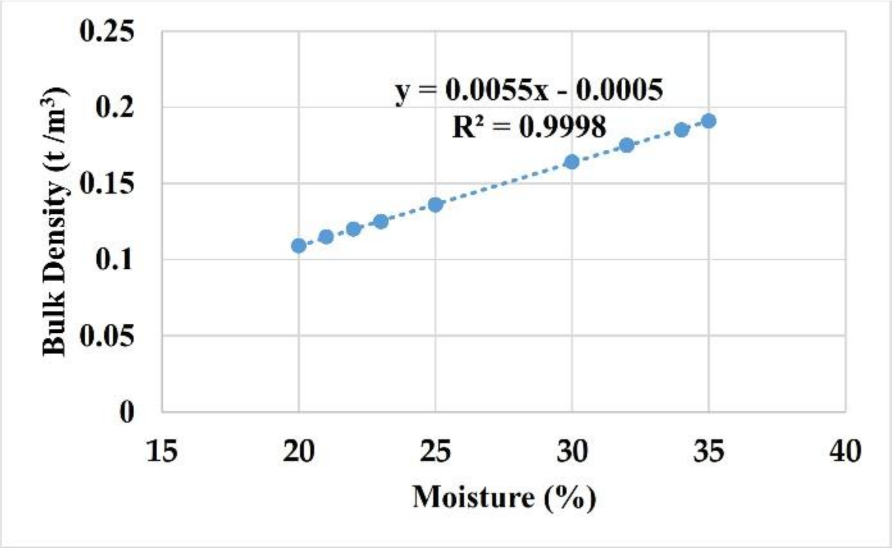


Fig. 5.10 Interrelation between bulk density and moisture content

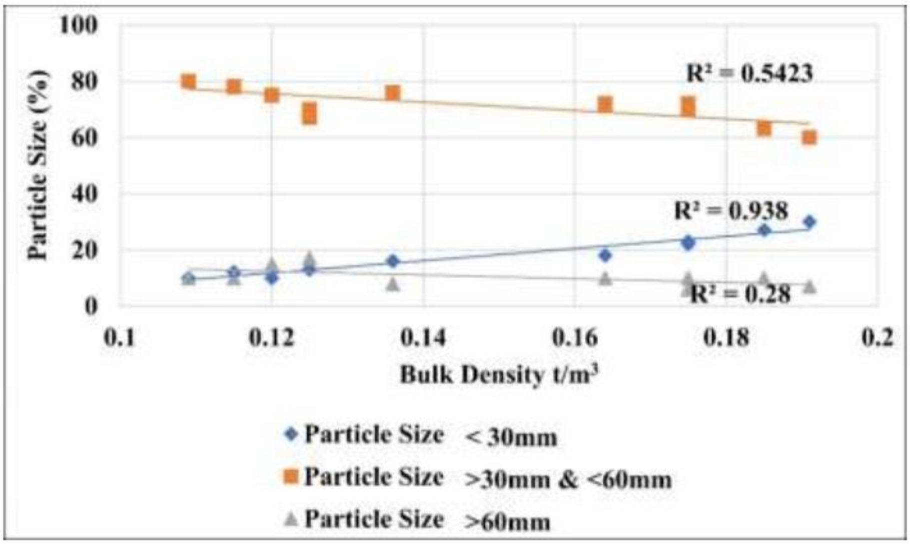


Fig. 5.11 Interrelation between bulk density and particle size distribution

Fig. 5.10 & 5.11 indicate that bulk density, moisture, and particle size are interlinked. With the increase in moisture, bulk density also increases. Particle size <30mm has a more significant impact on bulk density. If this variation is not considered in the initial design, it may create issues in the flow through the transfer chute. While reviewing the properties of RDF collected from/ measured at the cement plant, it was observed that RDF is a very cohesive material with variations in physical properties throughout the year. This variation was not considered at the system design stage, resulting in a chute jamming issue. Table 5.3 indicates the possible impacts of physical properties variation on the flowability of material in the chute.

Table 5.3 Impact analysis of measured physical properties of RDF on flowability

S. No.	Parameters	Literature outcome	Authors' Observations	Whether controllable at the plant level
1	Moisture Content	Moisture has a direct impact on flowability, and frequent variation may result in jamming & blockage of the chute [164–166]	A wide range of variations was found in the monthly average moisture of RDF, from 22% to 35%. Hence, it may be a significant cause of chute jamming.	Partially with the mixing of other low moisture AFs at plant level. However, the moisture content of purchased RDF is not controllable as it depends on

S. No.	Parameters	Literature outcome	Authors' Observations	Whether controllable at the plant level
				different sources.
2	Bulk Density	Carr's Compressibility Index (CCI) is a good indicator of flowability. With the increase of index value, the flowability decreases. [200,201]	Tapped density of RDF was determined in the laboratory and found CCI from 26.5 to 32%, which indicates poor flowability of the material.	Partly by mixing with other AFs. However, Major AFs, i.e., Biomass/agro waste, have low density.
3	The angle of Repose (**θ_R**)	The angle of repose (**θ_R**) directly indicates material flowability. With an increase in **θ_R**, flowability decreases [202].	**θ_R** was determined by the site measurement and found ~ 60 deg. The value of AoR indicates that the material is very cohesive and further tends to jam in the transfer chute.	No
4	Particle Size	Materials with large particles and high moisture content are particularly problematic [165,166,201,203]	Moisture in RDF can be very high- sometimes at the level of 35% in a particular month. Increased moisture and large size of particles cause chute jamming issues.	No control on the particle size of RDF received at Cement Plant.
5	Particle Shape	The effect of particle shape has a more significant impact than particle size on the flow property of materials [165,204,205]	Particle shapes in RDF are very irregular due to heterogeneous composition. Hence, more interlocking of materials occurs.	No control on the particle shape of RDF received at the cement plant.
6	The angle of Internal	The angle of internal friction is the indicator	The determined value, i.e., 38.66 degrees,	No, as the particle size and shape is

S. No.	Parameters	Literature outcome	Authors' Observations	Whether controllable at the plant level
	Friction (θ_I)	of internal friction between particles to particles. Both particle size and shape may impact θ_i. [206]	indicates the higher value of θ_i and higher value of internal friction, which creates more resistance for flow.	not controllable.

From Table 5.3, it can be noted that RDF has poor flowability with high cohesiveness and adhesiveness. Heterogeneous composition, varying size, and shape of the material contribute to the resistance inflow. Monthly average variation in moisture, bulk density, and particle size distribution also contribute to the current jamming issues in the transfer chute. The variation in RDF properties has not been accounted for during system design. To understand the phenomena of contact and non-contact forces between the RDF particles and their impact on flowability of material through the transfer chute, a 3D CAD model of the transfer chute was developed using existing general arrangement & fabrication drawings and subsequently imported into the EDEM software. Fig. 5.12 shows the 3D CAD model of the existing transfer chute: -

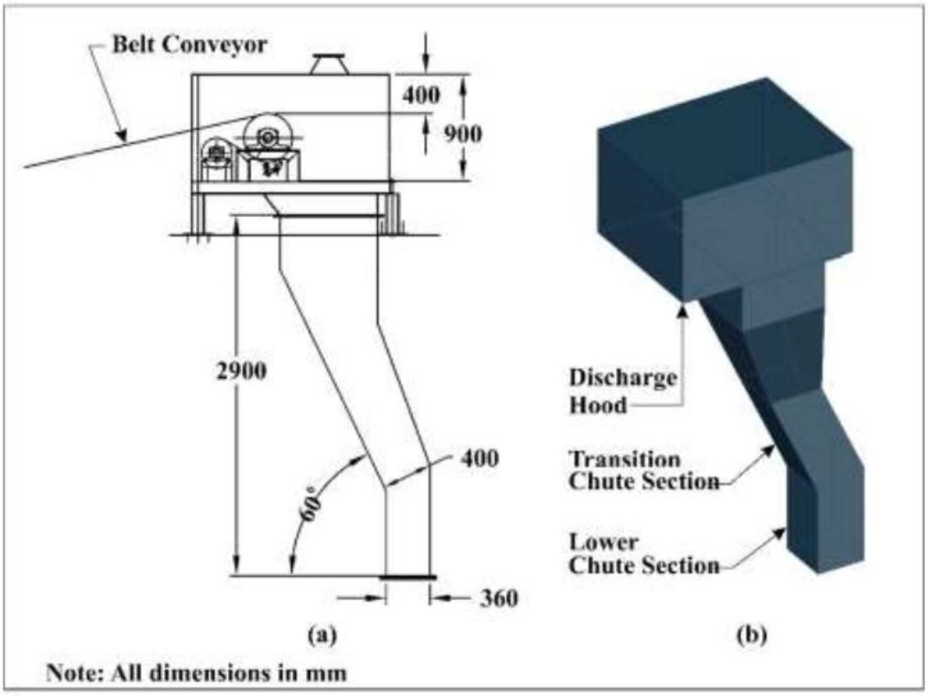


Fig. 5.12 (a) 2D drawing and (b) CAD model of existing transfer chute

For developing the simulation in EDEM, various inputs related to particle characteristics, the interaction between particles, particles to chute wall, particles to belt conveyor, etc., are important to define the right input conditions for accurate simulation output. The coefficient of Restitution (CoR), Coefficient of Static Friction (CoS), Coefficient of Rolling Friction (CoRF), Young's modulus, and Poisson's Ratio are the key inputs for DEM simulation in EDEM. CoR is the ratio of the final to the initial relative speed between two objects after they collide. CoS represents the maximum static frictional force between the surfaces in contact before the movement starts to the normal force. CoRF indicates the force resisting the motion when a body rolls on a surface. Poisson’s ratio is a measure of the lateral expansion compared to longitudinal contraction for longitudinal load or ratio of strain to longitudinal strain, and Young's modulus is, in essence, the stiffness of material [207].

Table 5.4 indicates the key inputs considered while doing the simulation work:

Table 5.4 Key inputs considered for DEM simulation in EDEM

S. No.	Physical Parameters	Unit	Value	Remarks
1	Young's modulus - mild steel (Chute Body Material)	GPa	182	[208]
2	Young's modulus – Conveyor Belt	GPa	100	[208]
3	Young's modulus – RDF	GPa	0.001	
4	Poisson's Ratio mild steel (Chute Body Material)		0.3	[208]
5	Poisson's Ratio Conveyor belt		0.45	[208]
6	Solid Density-Mild Steel	t/m^3	7.8	[208]
7	Solid Density-Conveyor Belt	t/m^3	0.95	[208]
8	Solid Density-RDF	t/m^3	0.6 – 1.6	Through Calibration method in EDEM*
9	RDF to RDF interaction Properties			
(a)	Coefficient of Restitution		0.1	
(b)	Coefficient of Static Friction		0.8	
(c)	Coefficient of Rolling Friction		0.1	
10	RDF to Belt interaction Properties			
(a)	Coefficient of Restitution (CoR)		0.1	
(b)	Coefficient of Static Friction (CoS)		0.6	
(c)	Coefficient of Rolling Friction (CoRF)		0.1	
11	RDF to Chute interaction Properties			

S. No.	Physical Parameters	Unit	Value	Remarks
(a)	Coefficient of Restitution		0.1	
(b)	Coefficient of Static Friction		0.9	
(c)	Coefficient of Rolling Friction		0.15	
12	Angle of Inclination (**θ_i**)	degree	30	Determination at the plant site
13	Angle of repose (**θ_R**)	degree	60	
14	Particle size distribution	mm (%)	<30 (17.5), >30 & <60 (71.5), >60 (11)	Average Particle Size Distribution based on Table-3
15	Particle shape		Irregular	
16	Contact Model Used**		Hertz-Mindlin with JKR V2	[174,180,196,209]
17	JKR Surface Energy			
(a)	RDF - RDF	J/m^3	80	
(b)	RDF – Chute wall	J/m^3	77	
(c)	RDF to Rubber belt	J/m^3	0	
18	Bonded model properties			
(a)	Normal Stiffness per unit area	N/m^3	1e+07	
(b)	Shear Stiffness per unit area	N/m^3	1e+06	
(c)	Normal Strength ()	Pa	2e+15	
(d)	Shear Strength ()	Pa	2e+15	
(e)	Bonded Disk Scale		1.2	

* Three types of calibrations are done, i.e. (1) Bulk Density Test- To Know the Particle Density of RDF, (2) Angle of repose test -To know the interaction properties like CoR, CoS, CoRF for bulk material to bulk material), (3) Angle of inclination (AoI) test-To know the interaction properties like CoR, CoS, CoRF for bulk material to belt and bulk material to the chute.

** *Many researchers have adopted The Hertz-Mindlin with JKR model that considers both characteristics of the material, i.e., adhesiveness and cohesiveness. This combination of the model represents the opposite force due to the pulling force that results from the adhesion effect of the particles when contact between particles is initiated. Also, it* *predicts a larger contact area than the contact area determined through conventional Hertz theory due to cohesion. The application of this model suits the RDF as it is highly adhesive and cohesive in nature.*

The challenge faced during the simulation of the transfer chute for RDF handling was the irregular shape of the RDF particles. The RDF constitutes the combustible mix of different materials like paper, plastic, biomass, cloths, etc. It is challenging to create the actual shapes of RDF particles. However, particles have been collected from the number of samples to get a more realistic particle flow in simulation. In the EDEM, a feature to create meta-particles is available to form the desired particle shape and size by combining various spherical particles. Hence, the particles of RDF were developed, as shown in Fig. 5.13 & 5.14, which show the dimensions of the randomly selected particles of RDF and their meta-particles developed in EDEM:

Fig. 5.13 Dimensions of RDF particles collected from samples

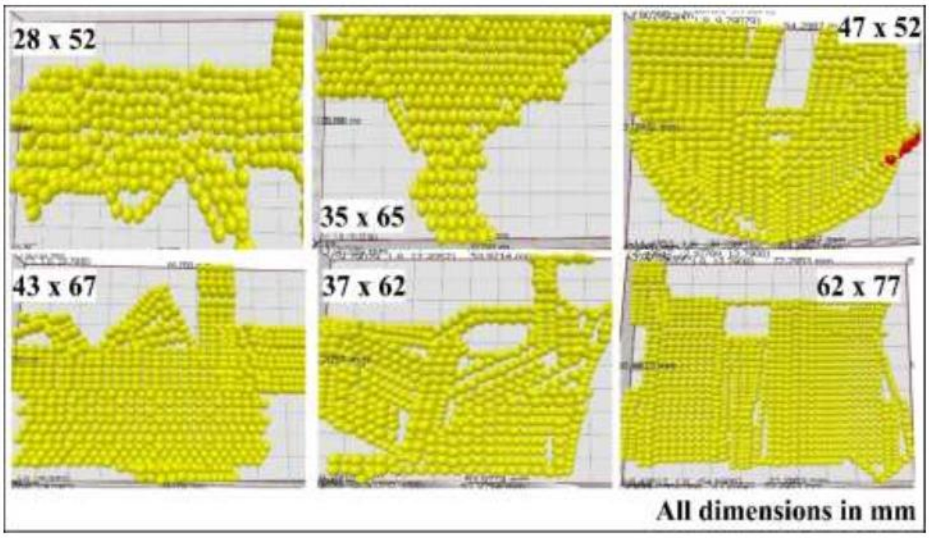


Fig. 5.14 Development of meta-particles in EDEM

Based on the input specified in Table 6, meta-particles were developed as shown in Fig. 5.15, simulation was done in EDEM, and the result is shown in Fig. 5.16.

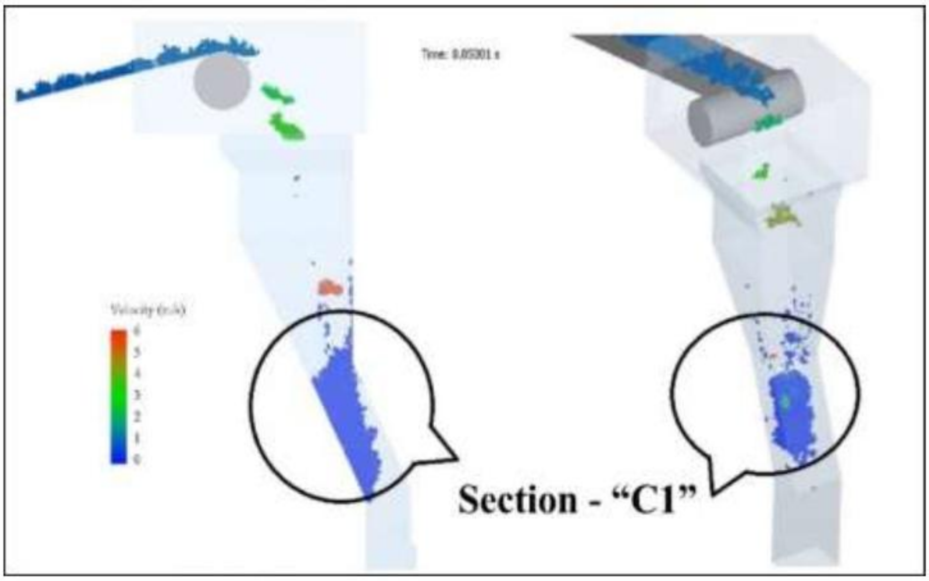


Fig. 5.15 Simulation results for original transfer chute arrangement

Fig. 5.15 indicates the chute jamming at a cross-section "C1". When discussed with the plant, they confirmed the problem in the transfer chute at the same location. Simulation validated the problem being faced by the cement plant. A design evaluation has been done to check the design parameters of existing chute design vs. standard guidelines specified in the literature. Table 5.5 indicates the results

Table 5.5 Analysis of existing chute design for key parameters

Parameters	Formulas / Reference Values	Calculated Values	References	Measured Values for Existing Chute
Chute Hood Height at the material entrance	Minimum 0.5 X Belt Width	0.5 * 800= 400 mm	[156]	400 mm
Chute Body (minimum Cross-Sectional Area for material pass)	minimum four times of S* S*= Q/(3600Vd), where S*- Cross-sectional area of the material stream inside the chute. Q-conveying capacity in tph, V-bulk solid stream velocity in m/s, and d-material bulk density in t/m^3	0.12 m^2 (minimum)	[169]	0.16 m^2
Chute Exit (Spoon)	The exit opening is 2.5 times the maximum lump size of the material	2.5 X 125* =312mm	[156]	360 mm
Chute Valley Angle	As a rough guideline applicable to many materials, using a surface inclined at 65° or even 70° of valley angle will properly guide bulk materials. Valley angles below 55° are risky	Not applicable	[167,168]	60°
Chute Widths	Minimum width of three times the maximum expected lump size	3 X 125 (maximum lump size) =375 mm	[168,169]	420 mm

** Average lump size reported by the plant and observed by the author during the site visit.*

From Table 5.5, while comparing the existing chute dimensional parameters with the standard design guidelines available in the literature, it can be observed that one of the leading causes of flow problems in the transfer chute is the low angle of inclination (60 degrees) which causes the material to decelerate and form a stagnant area. EDEM predicts the material flow through the lower section of the transfer chute, where there is a slow build-up of RDF, leading to eventual plugging. Due to the low inclination angle, the cross-sectional area at C1 suddenly contracts, which causes the material to build up and plug against the other side quickly. Due to the chute cross-section area's sudden contraction, the material build-up starts and causes jamming of the material flow. The cohesive and adhesive properties of RDF may be the reason for jamming. Also, the standard design guidelines may apply for conventional bulk materials but demand some optimization for challenging materials like RDF.

5.3 Chute Design Improvement by DEM

Transfer chute design improvement attempt was made based on the followings:

- Recommendations available in the literature for improving chute design,
- Shared by the respondents during the survey (as discussed in Chapter 3),

The following options have been evaluated for the improvement of the transfer chute design (1) changing the chute design, (2) changing the degree of slope, (3) removing the bend, (4) providing stainless steel (SS) liners, (5) electric hammer fitted on chute body, (6) Changed the flow rate in the chute by changing belt conveyor speed, (7) Flap gates are introduced for proper flow, (8) discharge chute angle modification, (9) Chute changed and the obstruction removed, (10) making smooth discharge, (11) installed air blasters in the chute for flow improvement, (12) Height and degree changed. The information collected is summarized in Table 5.6 and examined for suitability in improving the current chute design.

Table 5.6 Summary of recommendations depicted by survey

S. No.	Suggestions	Possibility in existing transfer chute design	Remarks
1.	Chute design changed	Yes	The least cross-section area where the jamming occurred can be enlarged.
2.	Change in Chute Inclination angle	Yes	The existing chute inclination is 60 degrees, which can be increased to 70 degrees as the layout permits.
3.	Remove the bend	No	No bend in the existing chute design
4.	Provide SS liners	Yes	Ultra-High Molecular Weight Polyethylene (UHMWPE) liners can be

S. No.	Suggestions	Possibility in existing transfer chute design	Remarks
			used in place of SS liners, which have the least friction coefficient and support smooth flow [210].
5.	Changed the flow rate in the chute by changing the belt conveyor speed	No	The system is designed at a specific capacity of AF transport; hence reduction in flow rate will reduce the thermal substitution rate (TSR). Hence, it is not recommended.
6.	Obstruction removed	No	No obstruction in the existing chute design.
7.	Electric hammer fitted on chute body	No	Recommended only when design changes are not adequate to avoid jamming.
8.	Installation of air blasters in the chute	No	Recommended only when design changes are not adequate to avoid jamming.
9.	Height of chute	No	Layout constraints.
10.	Installation of blockage sensors	Yes	To avoid shutdown time due to jamming of the chute.

Once the critical problems were identified, two new concept designs were developed using 3D CAD as shown in Fig. 5.16 and 5.17.

The existing chute design has been modified for (1)-Angle of inclination, (2)-Enlargement of the cross-sectional, and (3)-Using the flow assisting liners.

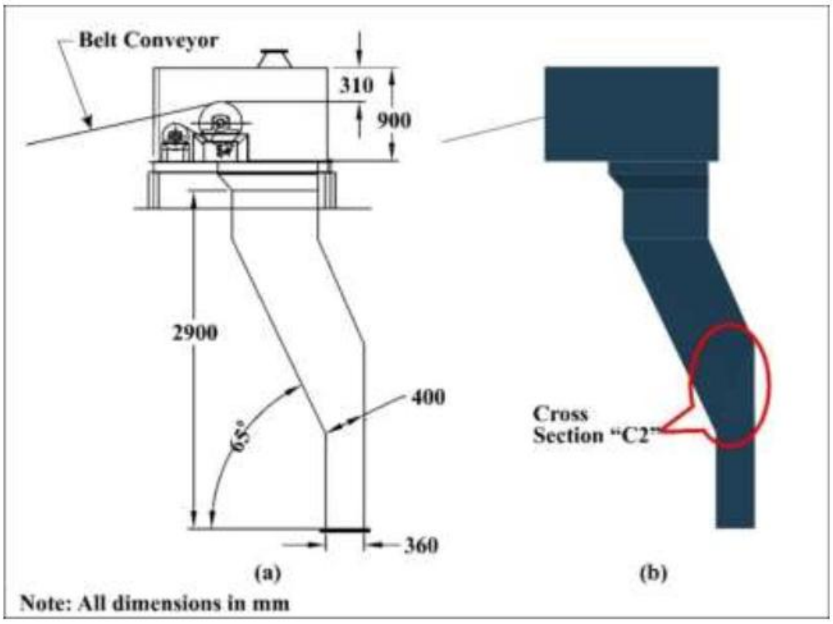


Fig. 5.16 (a) 2D drawing and (b) CAD model of modified chute design-1

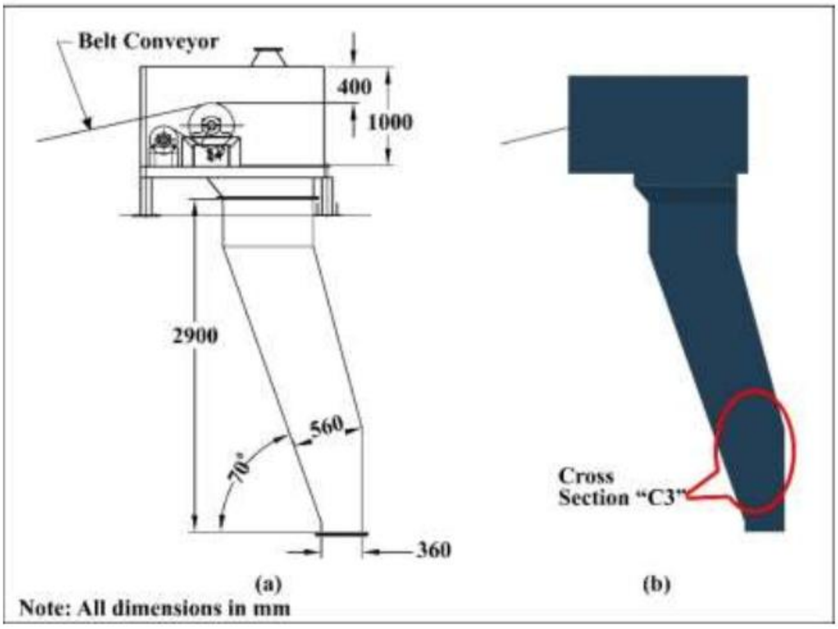


Fig. 5.17 (a) 2D drawing and (b) CAD model of modified chute design-2

New designs were developed based on the literature review and survey outcome., Table 9. The comparative Table 9 indicates a comparison between the design parameters of the existing chute v/s and proposed design-1 & 2:

Table 5.7 Parameter comparison between existing & proposed chute designs

Parameters	Unit	Existing Chute	Proposed Design-1	Proposed Design-2
Chute vertical Height	mm	2900	2900	2900
Chute Inclination	Degree	60	65	70
Chute Exit Opening	mm	360	360	360
Minimum Cross Section area	mm^2	C1=0.16	C2=0.15#	C3=0.29#
Minimum Width	mm	400	380	540
Chute Hood height at the material entrance	mm	400	400	500
Liners		No	UHMWPE (10mm thick)	UHMWPE (10mm thick)

Excluding Liners

In the modified design-1, the cross-section area where the RDF was getting jammed is not increasing; hence design-1 was not considered for further simulation work. Again, EDEM was deployed to investigate/evaluate the possible changes in chute design to achieve improvement with the current structure where changes would be feasible and can be implemented. The main design criteria needed to decide on the best technical concept to achieve the desired objectives were an easy flow of RDF, easy maintainability, accessibility, installation, and the least estimated cost. To improve the flow of material out of the lower section of the transfer chute, the angle of inclination of the chute increased from 60 deg to 70 deg, and increased the cross-sectional area “C1” to “C3”.

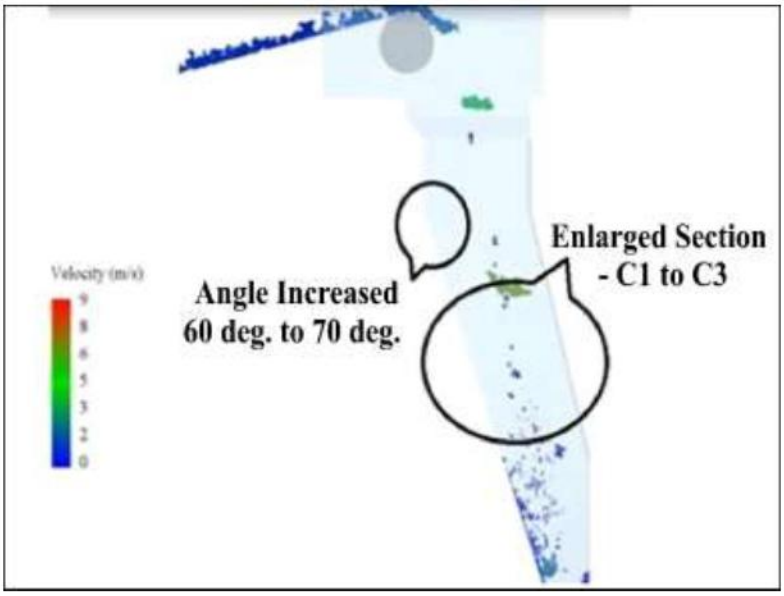


Fig. 5.18 Simulation of modified transfer chute design using EDEM

Fig 5.18, taken from the EDEM simulation, displays the smooth flow of RDF material without any material build-up at cross-section C1. This was achieved by incrementing the inclination of the discharge chute from 60 degrees to 70 degrees. This supported the smooth flow of RDF material, whereas applying UHMWPE liners, which have the least friction coefficient, helped avoid the sticking of RDF (having high moisture) to the chute wall. Since the chute's outlet area is attached to the inlet of the bucket elevator, it cannot be enlarged and is one of the limitations of the modified transfer chute design. However, the modified transfer chute is suitable for the current RDF handling capacity with the existing input parameters like particle size density, moisture, bulk density, angle of repose, and inclination angle.

5.4 The outcome of the case Study

The study shows how DEM can be an effective design tool to model and visualize complex RDF flow through the chute. When the simulation results of the existing transfer chute were discussed with the plant, they also confirmed the problem at the same location in the transfer chute. Simulation validated the problem being faced by the cement plant. DEM has evolved as a suitable design mechanism to model and predict complex material flow behaviour where 2D continuum theories are difficult to be applied. Excellent qualitative relation between the DEM simulations and site observations of an existing chute design was found, proving the accuracy and value of DEM methods in identifying the issues in the design of the given system before it is installed on-field. However, further simulations were carried out to improve the transfer chute design handling RDF with varying properties. Simulation results indicate that the inclination angle of the chute should be at least 70 degrees for RDF (lightweight with high moisture), which is adhesive and tends to stick to the chute wall. Further, RDF, also being cohesive (the tendency of lump formation), needs adequate cross-section and width for its smooth flow. This study recommends that the preferred chute width 4.3 to 4.5 times the lump size, and the cross-sectional area should be 10 to 11 times the S* (Cross-sectional area of the material stream inside the chute) to accommodate the lumps that can be formed. The calculation of area S* does not consider the formation of lumps while flowing through the chute. The study recommends that a factor describing lump size should be accounted for in calculating the cross-sectional area of the chute. Another area of concern is the lining material inside the chute. The cement industry has focused on wear-resistance liners to handle clinker, limestone, slag, and other abrasive materials. However, RDF demands flow assistance liners instead of wear resistance; because of this, it is recommended to have UHMWPE liners that have a low friction coefficient. Table 5.8 indicates the comparison between literature-suggested design parameters derived from the case study carried out on EDEM-

Table 5.8 Result comparison of current study with available literature

Design Parameter	Available literature	References	Outcome of the Case Study
Chute Valley Angle	55° to 70°	[167,168]	70°
Chute Width (Min.)	3 times the lump size	[168,169]	4.3 to 4.5 times the lump size
Chute Hood Height at the material entrance	Minimum 0.5 * Belt Width	[156]	Minimum 0.6 * Belt Width
Cross-Sectional Area	Minimum four times of S* where S*- Cross-sectional area of the material stream inside the chute.	[169]	10 to 11 times of S*

The major difficulty faced during the simulation was creating the particle shape of RDF as it combines different combustible fractions like paper, plastic, wood, and cloth. EDEM's multi-sphere technique helped model the irregular shapes to achieve high accuracy during simulation work.

5.5 Design of Transfer Chute for Multiple AFs & their mix

During the validation of the software, design parameters for transfer chute handling RDF were established through modeling & simulation on DEM. The outcome of the case study was taken as the base to start the simulation work for transfer chute design suitable for various AFs & their mix. Fig. 5.19 indicates the steps followed for the same

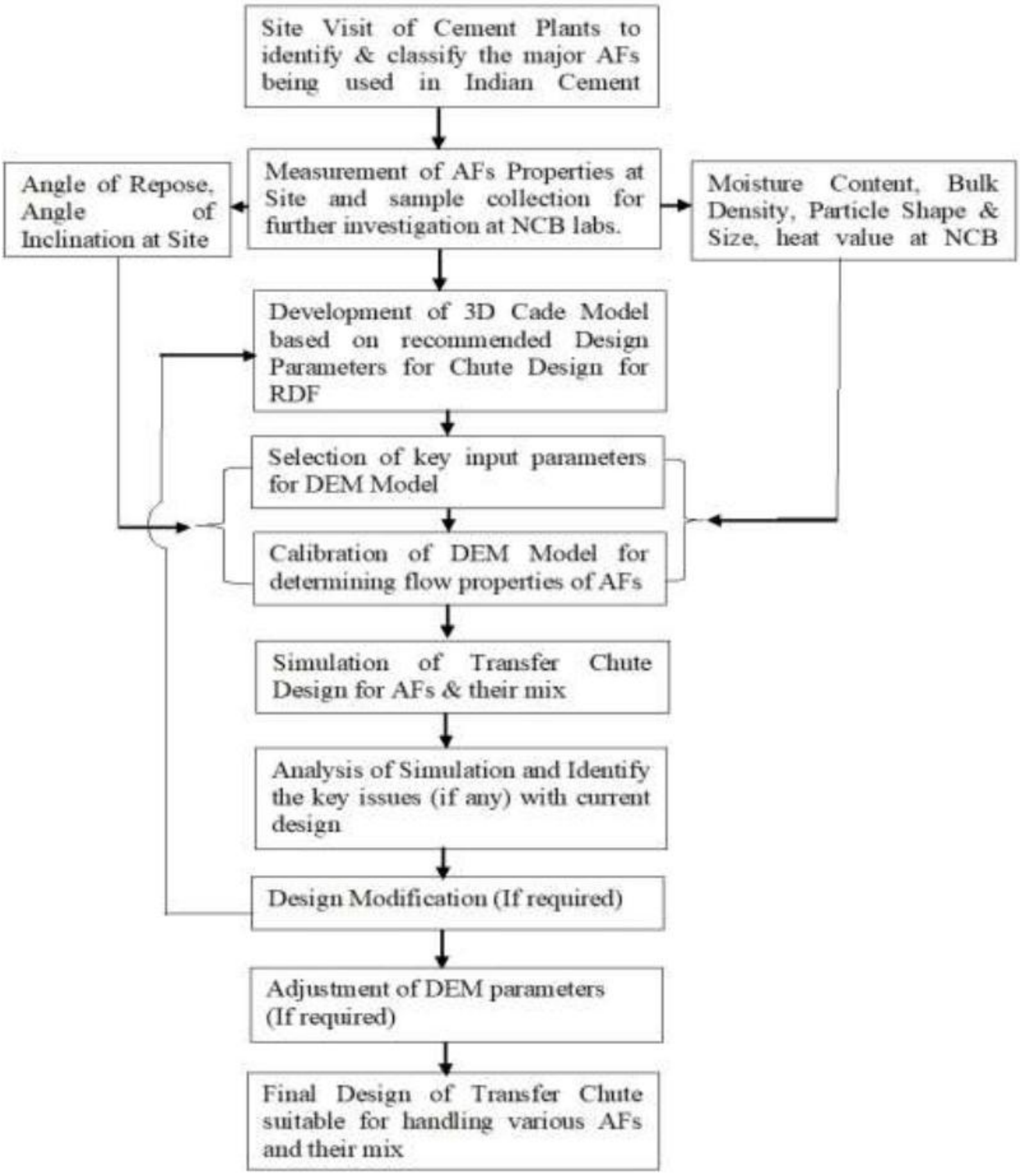


Fig. 5.19 Methodology for chute design simulation and improvement.

5.5.1 Identification & Classification of Major AFs & Their Properties

Table 5.9 indicates the list of major AFs being used by the seven nos. cement plants visited; apart from these identified AFs, plants are also using other waste like Spent Pot Lining (SPL), FMCG waste, nut shells, oil-bearing soils, pulp sludge, oil sludges, etc. as AFs. However, the quantity of these could be more substantial and hence not considered in the below table. Further, AFs have been classified into four categories, as shown in Table 5.9, based on the generation source.

Table 5.9 Identification & classification of major AFs & their properties

SN.	AFs Name	Angle of Repose (deg)	Angle of Inclination (deg)	Bulk density (t/m^3)	Maximum Moisture (%)	Particle Size (mm)
Alternative Fuels (Type-I)-Society Waste						
1	RDF-1	60	30	0.20	35	<30 (10 %) 30 to 50 (80 %) >50 to 90 (12%)
2	RDF-2	47	35	0.25	23	<30 (8 %) 30 to 50 (12%) >50 to 90 (80)
3	MLP	45	26	0.1	<5	<30 (80 %) 30 to 50 (20%)
Alternative Fuels (Type-II)-Biomass & Agro Waste						
4	Wood chips	41	35	0.28	10	<30 (16.3 %) 30 to 50 (87.7%)
5	Biomass Pellets	23.7	14	0.45	10	6 dia x 24 length
6	Bagasse	30	28.5	0.11	24	<30 (63 %) 30 to 50 (37%)
7	Parali	26	20	0.09	10	<30 (100%)
Alternative Fuels (Type-III)-Industrial Waste						
8	Tyre Chips	40	35	0.5	0	<50 (100%)
9	Footwear Waste	35	24.5	0.12	0	< 50 (100%)
10	ETP Sludge	33	23.7	0.4	<5	<30 (60%), 30 to 50 (40%)
Alternative Fuels (Type-IV)-Mixed Waste						

SN.	AFs Name	Angle of Repose (deg)	Angle of Inclination (deg)	Bulk density (t/m^3)	Maximum Moisture (%)	Particle Size (mm)
11	Mixed Solid Waste (MSW-1)	50	45	0.2	25	<30(20%) 30 to 50 (20 %) >50 to 90 (60%)
12	Mix Solid Waste (MSW-2)	43	27.5	0.23	30	<30 (5 %) 30 to 50 (30 %) >50 to 90 (63, %), >90 (2%)
13	Mix Solid Waste (MSW-3)	50	40	0.4	35	<30 (30 %) 30 to 50 (70 %)
14	Mix Solid Waste (MSW-4)	45	37	0.28	30	<30 (40 %) 30 to 50 (30 %) >50 to 90 (30 %)

Further, the Angle of Repose (AoR) and Angle of Inclination (AoI) were determined at the plant site with the use of a magnetic inclinometer, slide plate, and scale as indicated in Fig. 5.20. For determining AoR, the material sample was filled into a cylinder PVC pipe and then emptied on a flat surface by lifting the pipe slowly. The acute angle that the heap makes with horizontal is the repose angle. However, for AoI, a flat plate (mild steel/ UHMWPE) was used, rotating the plate about one edge slowly until the bulk material over the plate started to slide, and then measuring the angle of inclination (through inclinometer) of the plate with respect to the horizontal plane-

(a) Angle of Inclination

(b) Angle of Repose

Fig. 5.20 Determination of angle of inclination and repose

5.5.2 Development of 3D CAD Model

A 3D CAD model was developed (Fig. 5.21) based on the suggested parameters (Table 5.8) to start the simulation in DEM software. UHMWPE liners are considered to protect the chute wall and enhance the flowability of AFs. Table 5.10 indicates the basic conveyor dynamics considered for the simulation of input and exit conveyors:

Table 5.10 Belt conveyors dynamics considered for simulation

S. No.	Parameters	Unit	Value
1.	Belt width	mm	800
2.	Belt Speed	m/s	1.00
3.	Drive Pulley (Head pulley) diameter	mm	500
4.	Belt Conveyor Inclination	deg	13
5.	Belt Conveyor Trough Angle	deg	35

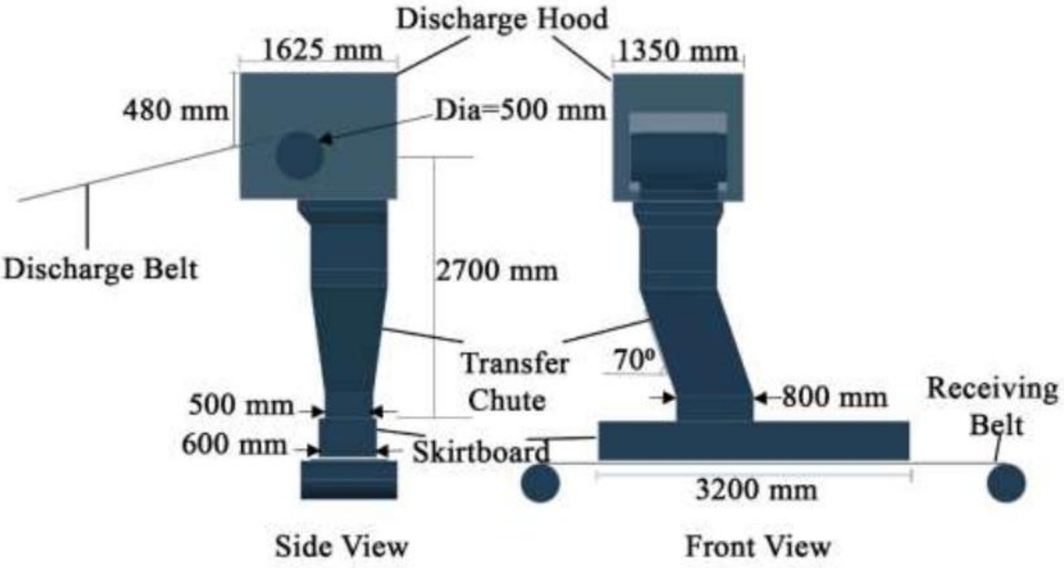


Fig. 5.21 3D CAD model of transfer chute

5.5.3 Selection of key input parameters for the DEM Model

Material properties play a vital role in the complete analysis of a transfer chute system. The variation, if not considered, may create issues in the material flow through the transfer chute, and it is more critical when focused on alternative fuels. Factors such as particle shape, angle of repose, and angle of internal friction significantly impact on the flowability of bulk materials in addition to moisture, bulk density, and particle size distribution. Additionally, DEM simulations need material and geometry interaction attributes to model the chute design[89]. Table 5.11 indicates the key inputs considered for the simulation of the transfer chute for various AFs and their mix. Simulation properties like Young modulus, Poisson's ratio, and solid density taken from literature, the Coefficient of Static Friction determined based on the AoI value, Coefficient of Restitution & Coefficient of Rolling Friction is found through calibration in DEM software based on the AoR value. Further, the moisture content is determined at the NCB laboratory. Accordingly, the value of Surface Energy is decided.

Table 5.11 Key inputs considered for DEM simulation

SN.	Physical Parameters	Unit	RDF-1	RDF-2	MLP	Wood Chips	Biomass Pellets	Bagasse	Parali	Tyre Chips	Foot wear Waste	ETP Sludge	MSW-1	MSW-2	MSW-3	MSW-4
1	Young's modulus - mild steel (Chute Body Material)	GPa	182[208]													
2	Young's modulus – Conveyor Belt	GPa	100[208]													
3	Poisson's Ratio mild steel (Chute Body Material)		0.3 [208]													
5	Poisson's Ratio Conveyor belt		0.45 [208]													
6	Solid Density-Mild Steel	t/m³	7.8 [208]													
7	Solid Density-Conveyor Belt	t/m³	0.95[208]													
8	Solid Density-material	kg/m³	700[89]	700 [89]	926[211]	380[212]	1011[213]	1530[214]	450[215]	535[216]	100 [217]	560[218]	700			
9	Poisson's Ratio (Material)		0.25[89]		0.43[219]	0.43[220]	0.33 [213]	0.15[214]	0.4[221]	0.4[216]	0.26 [222]	0.2	0.25[89]			
10	Material to material Interaction Properties															

SN.	Physical Parameters	Unit	RDF-1	RDF-2	MLP	Wood Chips	Biomass Pellets	Bagasse	Parali	Tyre Chips	Foot wear Waste	ETP Sludge	MSW-1	MSW-2	MSW-3	MSW-4
(a)	Coefficient of Restitution		0.1	0.1	0.5	0.1	0.4	0.55	0.35	0.1	0.35	0.35	0.35	0.35	0.35	0.15
(b)	Coefficient of Static Friction		0.8	0.6	0.58	0.47	0.25	0.68	0.38	0.48	0.45	0.44	1.00	0.52	0.83	0.75
(c)	Coefficient of Rolling Friction		0.1	0.1	0.01	0.05	0.01	0.1	0.01	0.1	0.05	0.01	0.15	0.15	0.15	0.1
11	Material to Belt interaction Properties															
(a)	Coefficient of Restitution (CoR)		0.1	0.1	0.5	0.1	0.4	0.55	0.35	0.1	0.35	0.35	0.35	0.35	0.35	0.15
(b)	Coefficient of Static Friction (CoS)		0.6	0.6	0.5	0.47	0.25	0.68	0.38	0.48	0.45	0.44	1.00	0.52	0.83	0.75
(c)	Coefficient of Rolling Friction (CoRF)		0.1	0.1	0.1	0.05	0.01	0.1	0.01	0.1	0.05	0.01	0.15	0.15	0.15	0.1
12	Material to Chute interaction Properties															
(a)	Coefficient of Restitution		0.1	0.1	0.5	0.1	0.4	0.55	0.35	0.1	0.35	0.35	0.35	0.35	0.35	0.15
(b)	Coefficient of Static Friction		0.9	0.6	0.58	0.47	0.25	0.68	0.38	0.48	0.45	0.44	1.00	0.52	0.83	0.75

SN.	Physical Parameters	Unit	RDF-1	RDF-2	MLP	Wood Chips	Biomass Pellets	Bagasse	Parali	Tyre Chips	Foot wear Waste	ETP Sludge	MSW-1	MSW-2	MSW-3	MSW-4
(c)	Coefficient of Rolling Friction		0.15	0.1	0.01	0.05	0.01	0.1	0.01	0.1	0.05	0.01	0.15	0.15	0.15	0.1
13	Angle of Inclination (θ_i)	degree	30	35	26	35	14	28.5	20	40	24.5	23.7	45	27.5	40	37
14	Angle of repose (θ_R)	degree	60	47	45	41	23.7	30	26	35	35	33	50	43	50	45
15	Moisture Content	%	35	23	<5	10	10	24	10	0	0	<5	25	30	35	30
17	Contact Model Used	Hertz-Mindlin with JKR V2[89]														
18	Surface Energy															
(a)	Material to Material	J/m^3	80	80	10	25	10	30	15	0	0	10	80	80	15	35
(b)	Material to Chute wall	J/m^3	77	77	5	20	5	25	15	1.4	1.4	5	77	77	15	35
(c)	Material to Rubber belt	J/m^3	0	0	0	0	0	0	0	0	0	0	0	0	0	0

5.5.4 Simulation of Transfer Chute Design for AFs & their mix

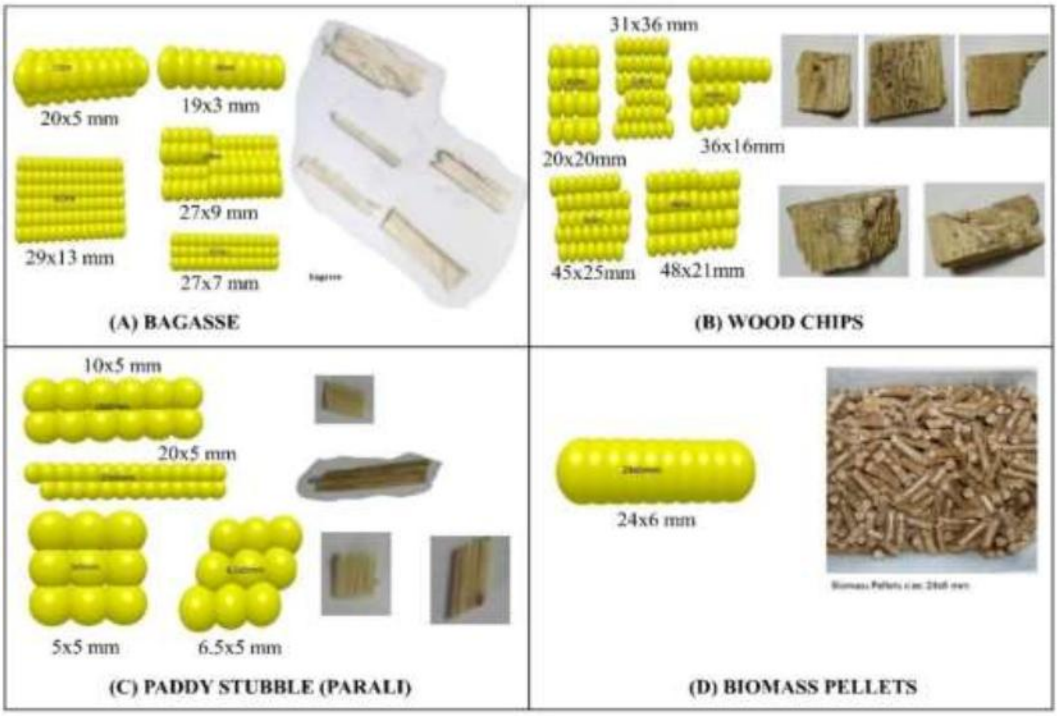
Meta-particles were created as shown in Fig.5.22, 5.23, 5.24, and 5.25 for AFs materials along with their actual shapes and dimensions.

(A) MULTI LAYER PLASTIC (MLP)

(B) REFUSED DERIVED FUEL (RDF-2)

(C) REFUSED DERIVED FUEL (RDF-1)

Fig. 5.22 Developed particle shapes in EDEM for society waste



(A) BAGASSE

(B) WOOD CHIPS

(C) PADDY STUBBLE (PARALI)

(D) BIOMASS PELLETS

Fig. 5.23 Developed particle shapes in EDEM for agro and biomass waste

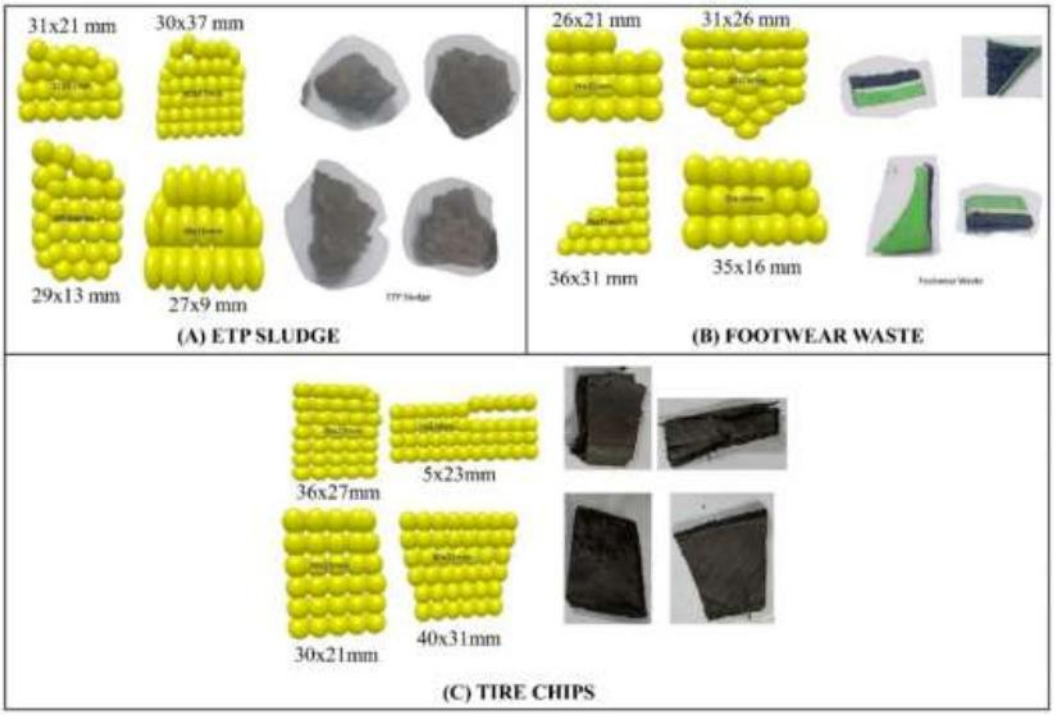


Fig. 5.24 Developed particle shapes in EDEM for industrial waste

Fig. 5.25 Developed particle shapes in DEM for mixed waste

Once all the necessary inputs given in Table 5.11 were set in EDEM simulator, the simulation was run for the desired duration. After completion of the simulation, the results are analyzed in the post-processor section. The post-processing section shows the material flow rate inside the system and the simulated behavior of the material throughout the transfer chute. The simulation images of the various AFs have been shown in Fig. 5.26, 5.27, 5.28, and 5.29.

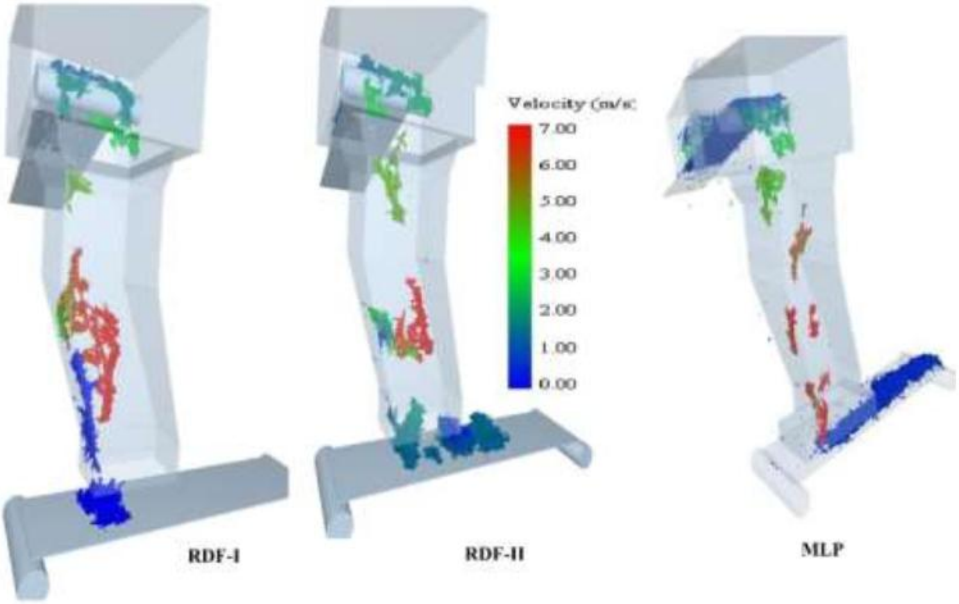


Fig. 5.26 Simulation results for society waste

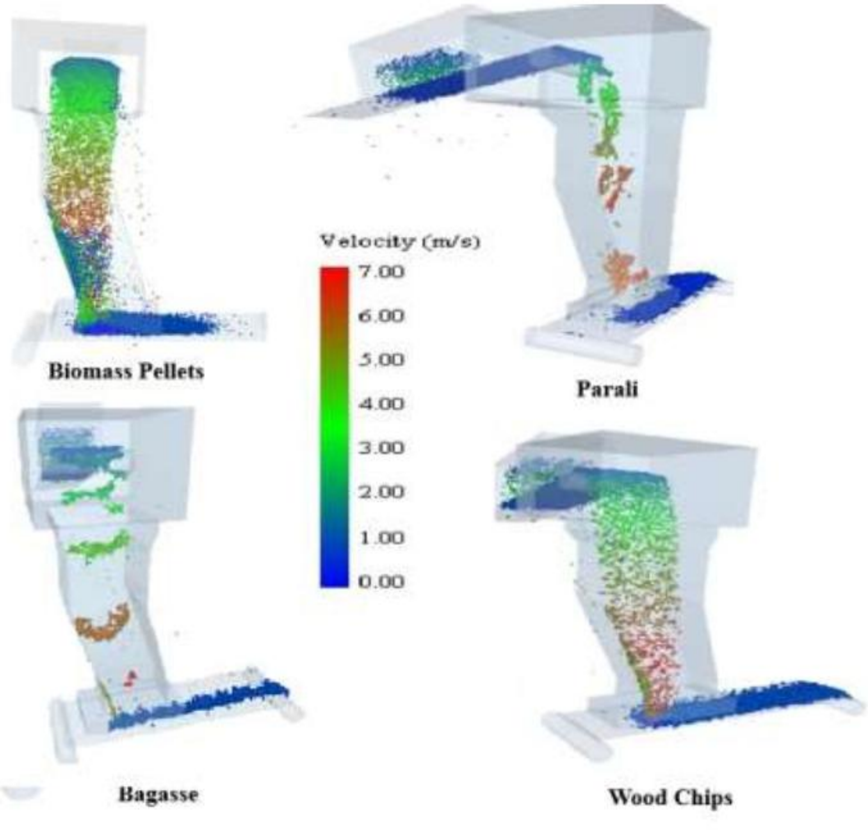


Fig. 5.27 Simulation results for agro & biomass waste

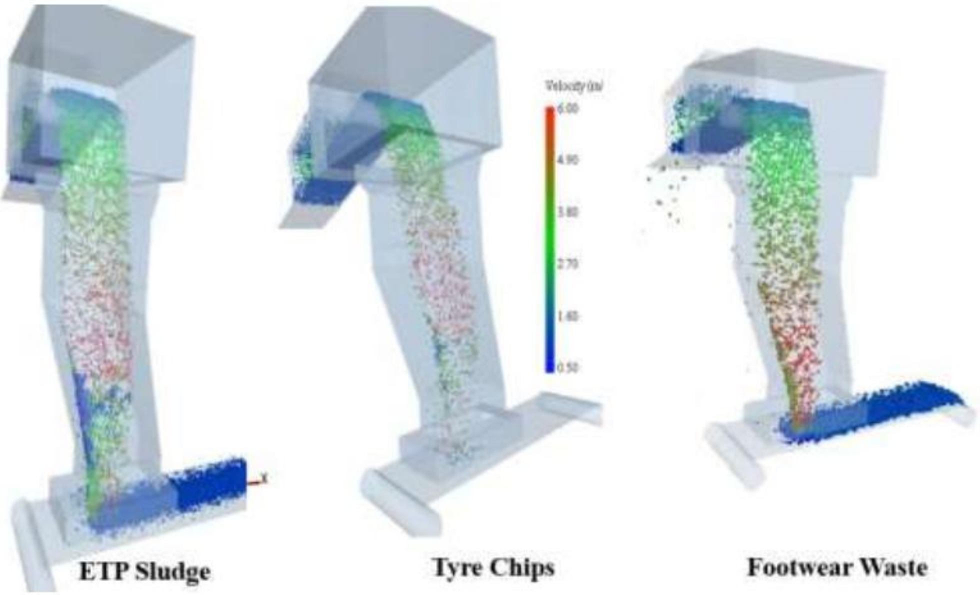


Fig. 5.28 Simulation results for industrial waste

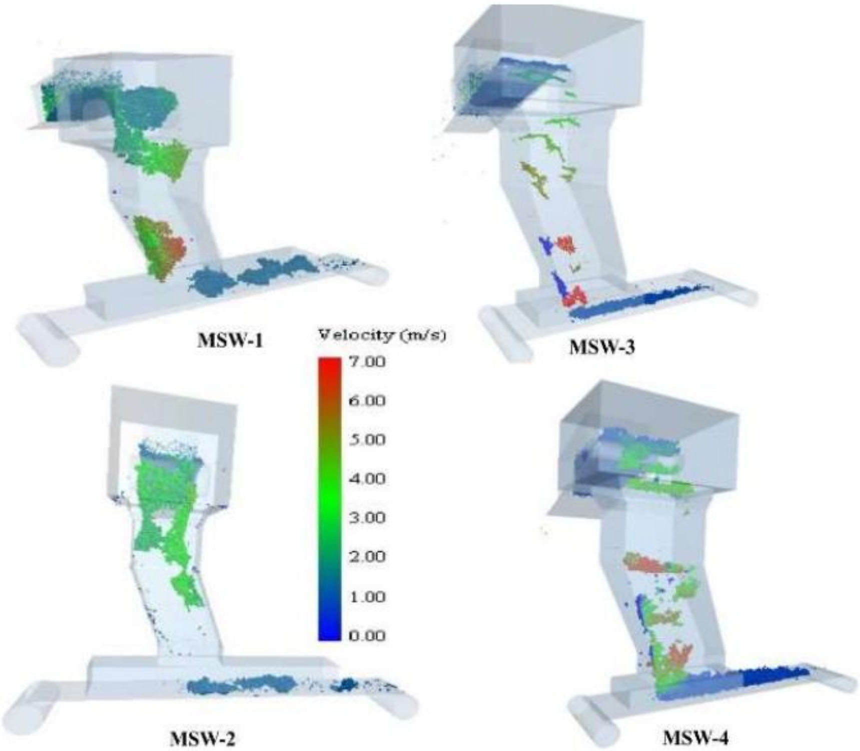


Fig. 5.29 Simulation results for mixed waste

5.5.5 Outcome of Simulation

Simulation results show that there is no chute jamming in any case, and the chute design parameters indicated in Table 5.8 for RDF handling are also suitable for the various alternative fuels used by Indian cement plants having variation in the bulk properties of the following range-

Table 5.12 Ranges of AFs properties

S. No.	Bulk Properties	Range	Unit
1.	Angle of Repose	23.7 to 60	deg
2.	Angle of Inclination	14 to 45	deg
3.	Bulk density	0.11 to 0.50	t/m^3
4.	Maximum Moisture	0 to 35	%
5.	Particle Size	5-100	mm

Simulations show that the AFs like RDF, Mixed Solid Waste, and high moisture biomass (bagasse & Parali) are flowing in surges. However, there is no jamming. Other dry or low moisture AFs like footwear waste, tyre chips, dry ETP sludge, biomass pellets, and wood chips have a smooth flow from the transfer chute. Although there is no jamming in a transfer chute, however in the case of RDF-1, MSW-3 & ETP Sludge, some material appears to be stuck on the corners of the chute wall, as shown in Fig. 5.26, 5.28 & 5.29. The corners are made at the connection of the transfer chute wall at 90 deg angle; it is the area where the material appears to be stuck. Further, to improve the transfer chute design, a slight modification is done at the corners, as shown in Fig. 5.30. The corners are modified in such a way that the material gets more space to flow through the corners.

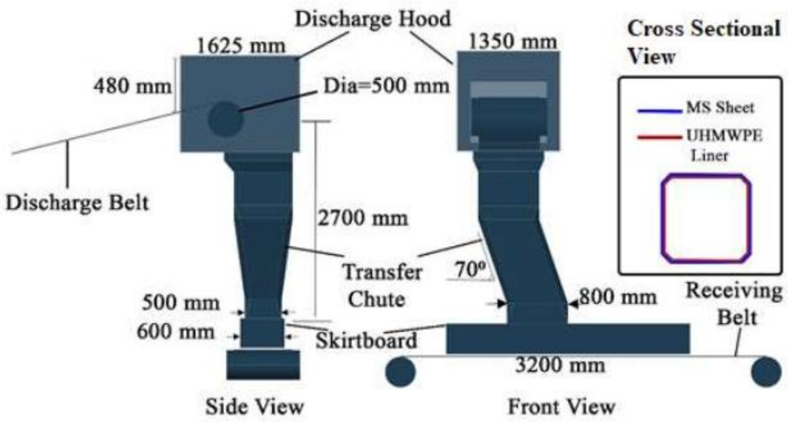


Fig. 5.30 CAD model for modified transfer chute design

With these modified corners, simulations have been done again for RDF-I, MSW-3 & ETP Sludge. The results are indicated in Fig. 5.31, demonstrating no material accumulation at corners. The particle velocity at corners, which was near zero in the previous design, seems to be in the range of 2 to 3 m/sec with this modification and provides momentum for the free flow of the material.

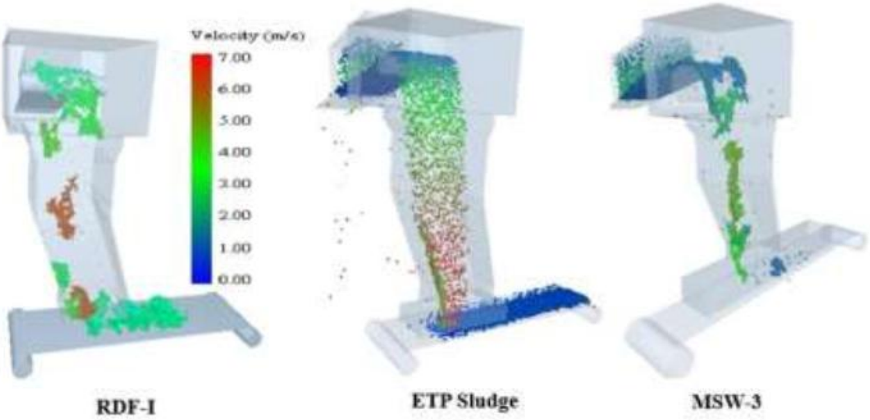


Fig. 5.31 Simulation results with modified transfer chute

Fig. 5.31, 5.32, 5.33 & 5.34 indicates the mass flow rate derived from simulation results. A high fluctuation in mass flow rate through the transfer chute at the beginning of the belt conveyor is noted, which takes ~ 15 to 12 seconds to get the desired mass flow rate.

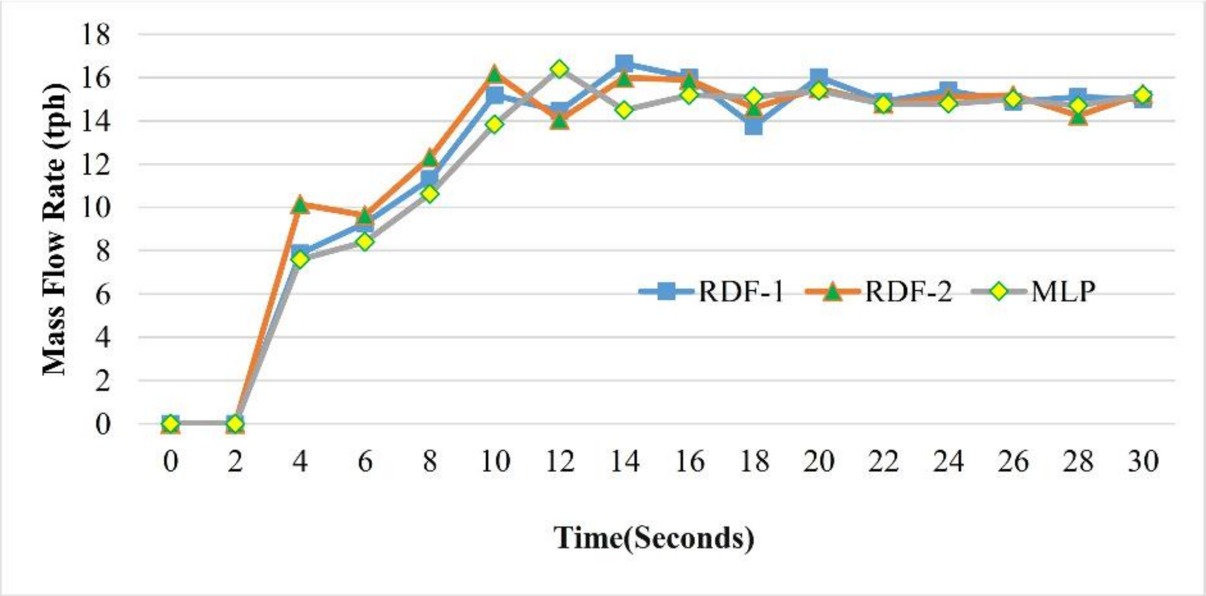


Fig. 5.32 Mass flow rate in transfer chute-AF (Type-I)

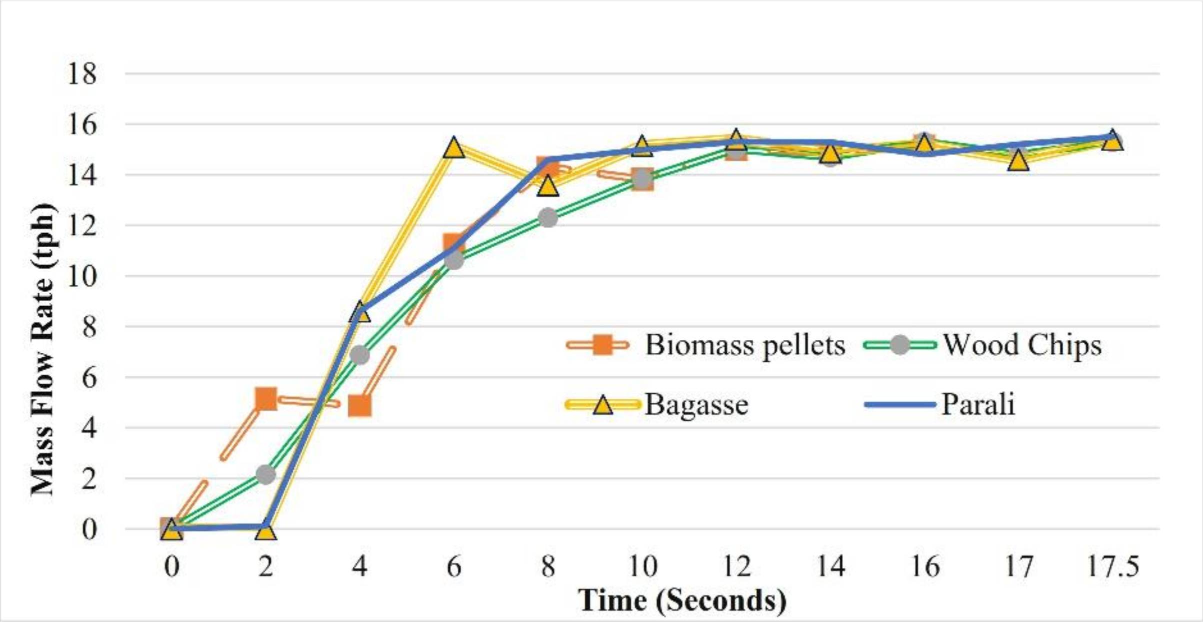


Fig. 5.33 Mass flow rate in transfer chute-AF (Type-II)

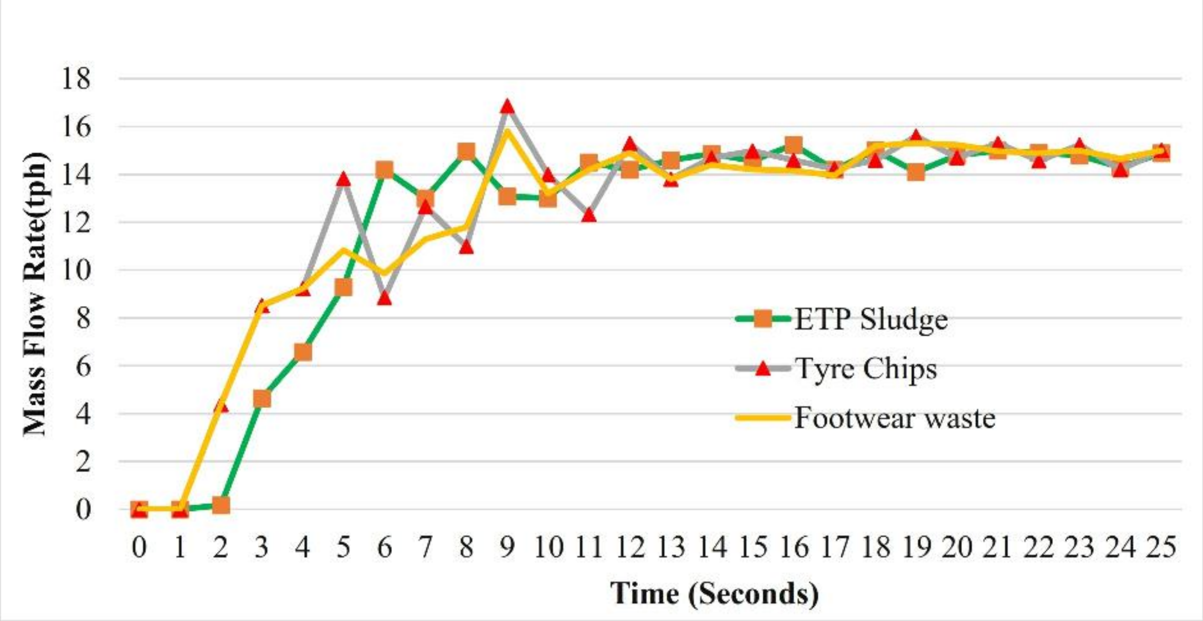


Fig. 5.34 Mass flow rate in transfer chute-AF (Type-III)

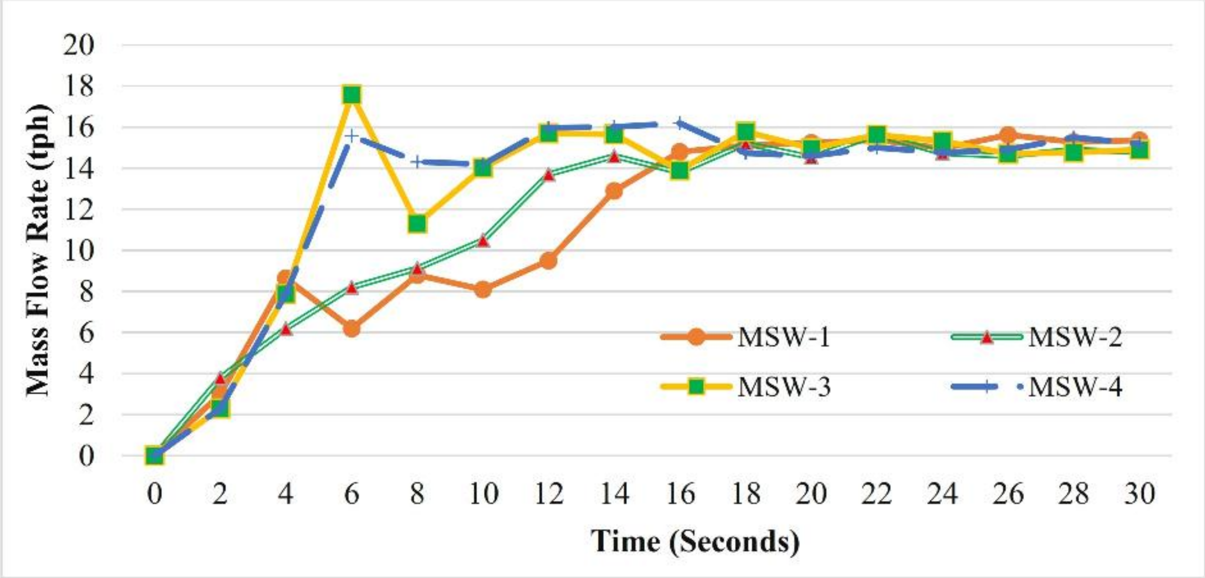


Fig. 5.35 Mass flow rate in transfer chute-AF (Type-IV)

The theoretical mass flow rate through the transfer chute can be derived from the following formula[169]

$$Q = (3600 \text{ v Si}) \text{ m}^3/\text{hr}, \quad (1)$$

As indicated above, the mass flow rate depends on the cross-sectional area of the chute, which is fixed and the same for all materials. However, fluctuation in mass flow rate through the transfer chute at the initial operation results from high cohesions in some alternative fuels like RDF, MSW, and bagasse, making the lumps on the conveyor fall at a higher speed as compared to the individual particle. AFs like MLP, Wood chips, biomass pellets, footwear waste, and semi-dry ETP sludge have a smooth transition from fluctuated flow rate to a smooth flow rate. MLP, which is dried and has the least particle variation, achieved the constant mass flow rate at the earliest.

Further, the precise calculation of the material's trajectory from a conveyor's head pulley is crucial to the intricate design of conveyor transfers. To assess the location of the liner in the transfer chute, particle attrition, chute wear, dust generation, spillage, chute obstruction, and excessive noise are just a few of the adverse effects of inaccurate trajectory path predictions that can occur during a conveyor transfer owing to faulty design parameters[223]. Discharge trajectories (theoretical) were calculated for all alternative fuels considered in the current study based on the CEMA, and Fig. 5.36 indicates the AFs discharge trajectory results [187]. When these results were compared with simulation results and actual discharge of material at the site, it was found that all three matched for easy-flowing materials like biomass pellets, woodchips, footwear waste, etc. However, discharge trajectories do not match accurately for heterogeneous materials like RDF, MSW, and other high moisture materials. High moisture content, irregular shape & size, and heterogeneity in the composition of AFs make them more cohesive. Hence literature suggests considering the adequate factor for the cohesiveness of the material when determining the discharge trajectory.

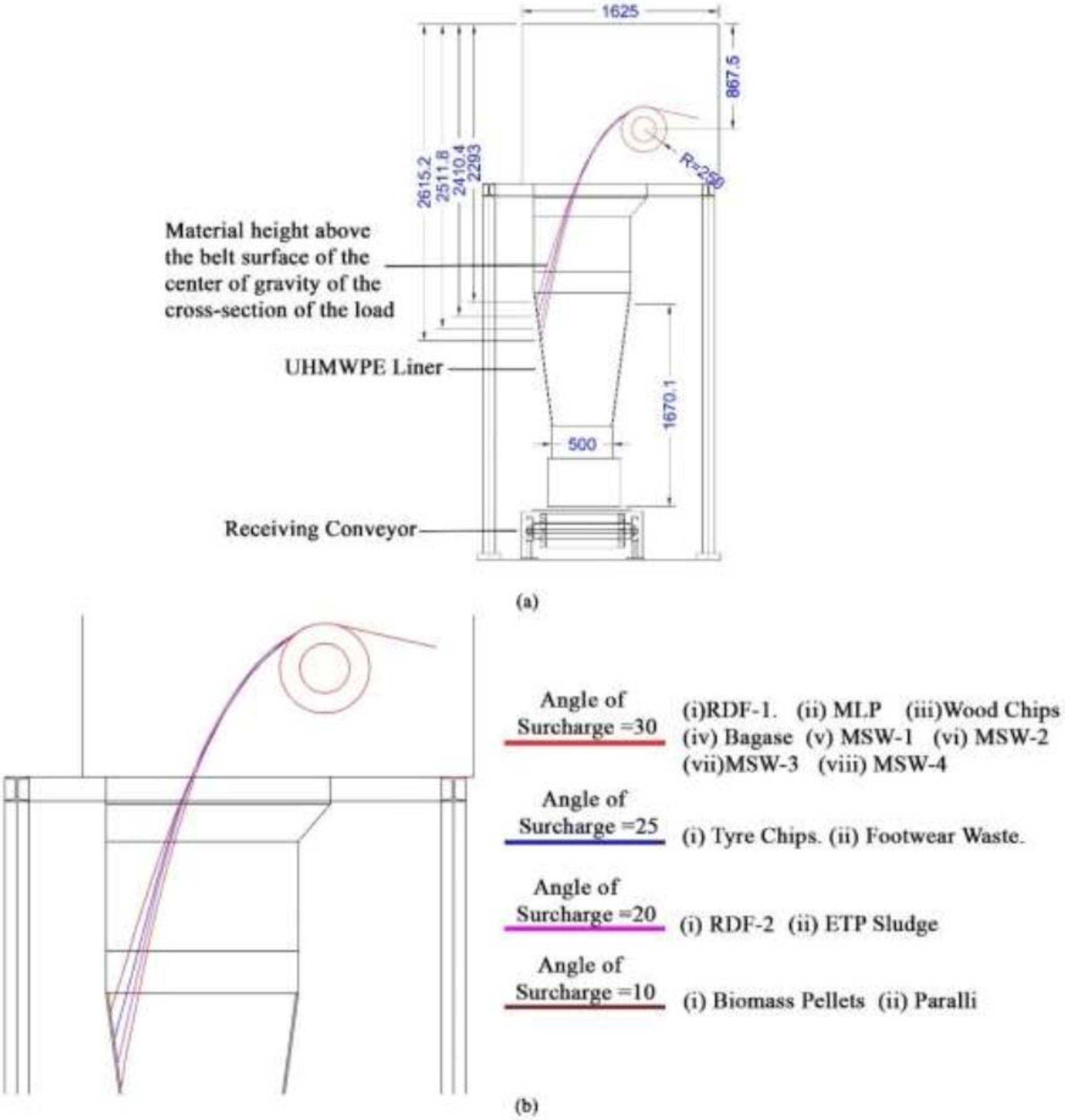


Fig. 5.36 Material trajectories for different alternative fuels

Further, the discharge trajectory of alternative fuels (cohesive materials) can be calculated based on the critical velocity and accurate trajectory velocity. The critical velocity and velocity of the lower & upper path of the bulk solid's stream can be determined by the following [169].

$$V_{cr} = \{r_1.(g.\cos(\omega_1) + \frac{\sigma_a}{\rho.h})\}^{0.5} \tag{2}$$

$$v_2 = v_1.[(1+ \frac{2.h}{r_1})]^{0.5} \tag{3}$$

Based on the critical velocity, an appropriate case for cohesive materials may be selected and the trajectory velocity of the material stream at the selected time ‘t’ can be calculated from the following equations:

Horizontal velocity $$v_{1x} = v_1.\cos(\omega_1) \tag{4}$$

$$v_{2x} = v_2.\cos(\omega_2) \tag{5}$$

Vertical velocity $$v_{1y} = v_1.\sin(\omega_1) + g.t.(1+\varepsilon_1) \tag{6}$$

$$v_{2y} = v_2.\sin(\omega_2) + g.t.(1+\varepsilon_2) \tag{7}$$

Trajectory velocity $$v_1 = (v_{1x}^2 + v_{1y}^2)^{0.5} \tag{8}$$

$$v_2 = (v_{2x}^2 + v_{2y}^2)^{0.5} \tag{9}$$

Material discharge trajectory calculated based on the above equations shall be more representative of cohesive alternative fuels. Still, it cannot be taken as the base for transfer chute design as the AFs properties change frequently based on the source of material, seasonal impact, its storage time at the pre-processing station & cement plants, and continuous changes in the mixed recipe of the fuel by the plant to suit the raw materials. Hence, it is recommended that flow assisting liners (UHMWPE) should cover the entire transfer chute wall to avoid jamming. The simulation tool, DEM, may provide the design parameters for the worst scenario by considering maximum moisture, large particles, a wide range of AoI and AoR, etc. When the chute is designed for the worst condition, the issues related to spillage, wear, and dust generation may be avoided.

The chapter established the design parameters of the transfer chute capable of handling multiple types of alternative fuels covering, RDF, Biomass, Agro waste, Industrial Waste, etc. This study is useful for Indian cement plants targeting high TSR and wishing to use various types of waste (having heat value) available as alternative fuels. The conclusions drawn from the outcomes of this chapter are-

- Design parameters available for transfer chute design, handling RDF is also suitable for handling other alternative fuels such as MLP, tyre chips, mixed solid waste, footwear waste, ETP sludge, biomass, and agro waste.

- Simulation results show that RDF-1, MSW-3, and ETP Sludge get stuck on the corners of the transfer chute wall. A small modification at the corners is required to ensure the smooth flow of these materials through the transfer chute. The corners are modified in such a way that the material gets more space to flow through the corners.

- A high fluctuation of material flow rate for RDF, MSW, and high moisture alternative fuels due to the higher cohesiveness of the material. DEM has predicted this complex material flow behavior and excellent qualitative relation between the DEM simulations and site observations.

- Material discharge trajectory calculated theoretically does not predict the accurate behavior of difficult flowing AFs like RDF, Mixed Solid Waste, and other highly moist materials; these materials' properties frequently change due to various reasons such as changes in the source of material, seasonal impact, extended storage and often changes in the recipe of the fuel mix. Hence, it is recommended that flow assisting liners (UHMWPE) should cover the entire transfer chute wall to avoid jamming.

CHAPTER 6

DESIGN AND FABRICATION OF TRANSFER CHUTE SYSTEM

The current chapter discusses the development of the experimental setup of a material discharge through a transfer chute system and the experimental procedure in detail. The technical specifications of the transfer chute and associated conveying equipment have been finalized based on the simulation results. The complete system was fabricated in a workshop located in Faridabad, Haryana (India), under continuous supervision and erected at National Council for Cement and Building Materials, Ballabgarh, for further experiments.

6 Design and Fabrication of Transfer Chute System

6.1 Purpose and Description of the Experimental Setup

The main purpose of developing the experimental test setup was to validate the transfer chute design parameters in real scenarios with various alternative fuels and varying operating parameters. In the previous chapter, the transfer chute design was simulated on **15 types** of alternative fuels and their mix; hence, transferring of these materials through the transfer chute without any jamming issues is the whole purpose of this experiment.

The experimental setup is a close circuit material circulation system consisting of 4 nos. conveyors (BC-1 to 4), and four nos. transfer chutes (TC-1 to 4). Fig. 6.1 shows the arrangement of the system:

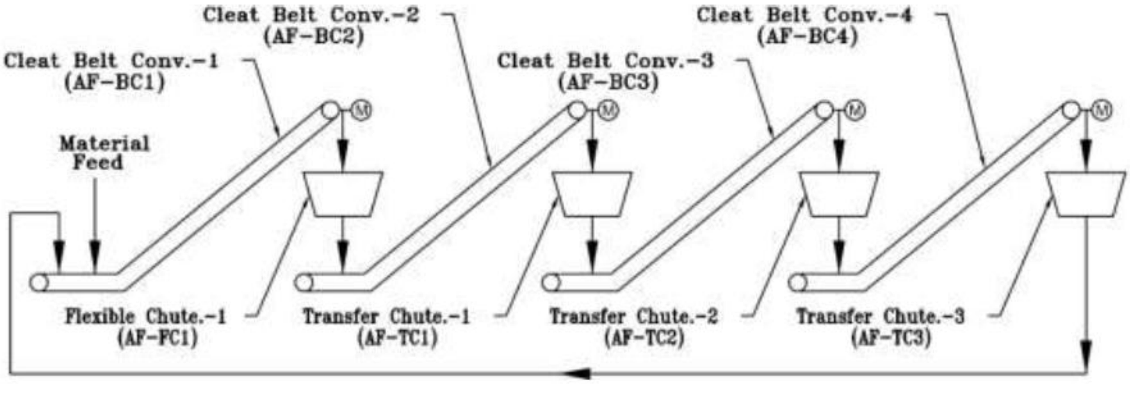


Fig. 6.1 Flowsheet of experimental set up

Fig. 6.2 to 6.6 shows the plan and various side views of conveying system.

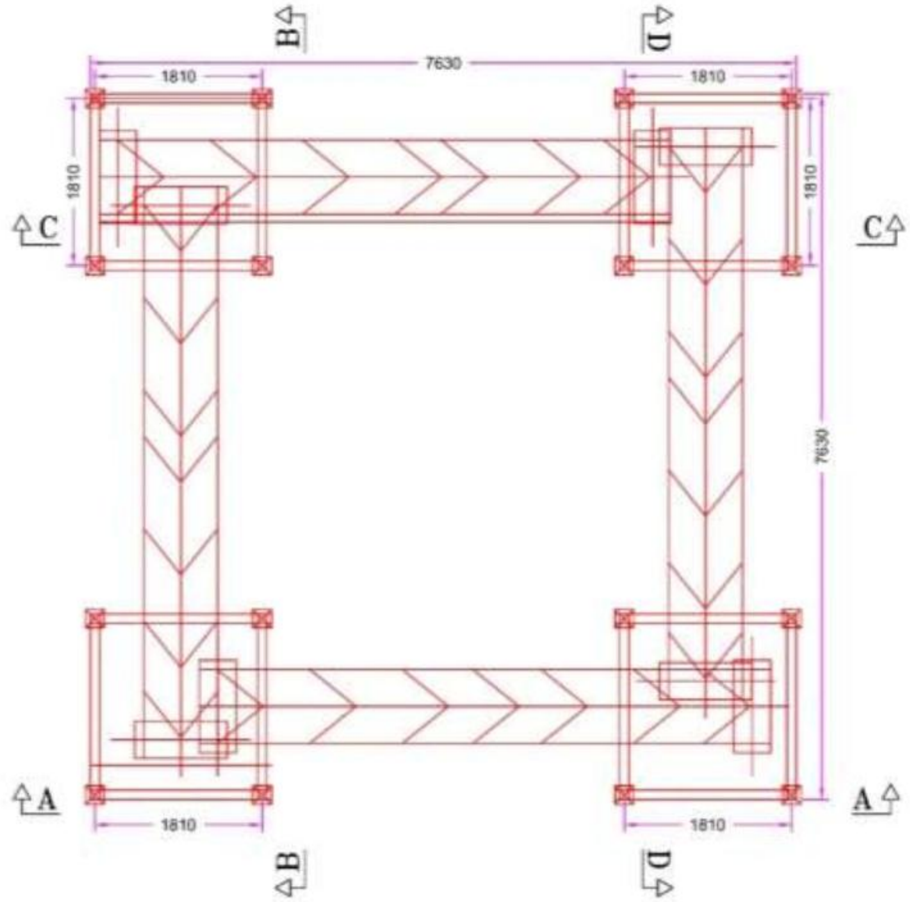


Fig. 6.2 Plan view of experimental setup

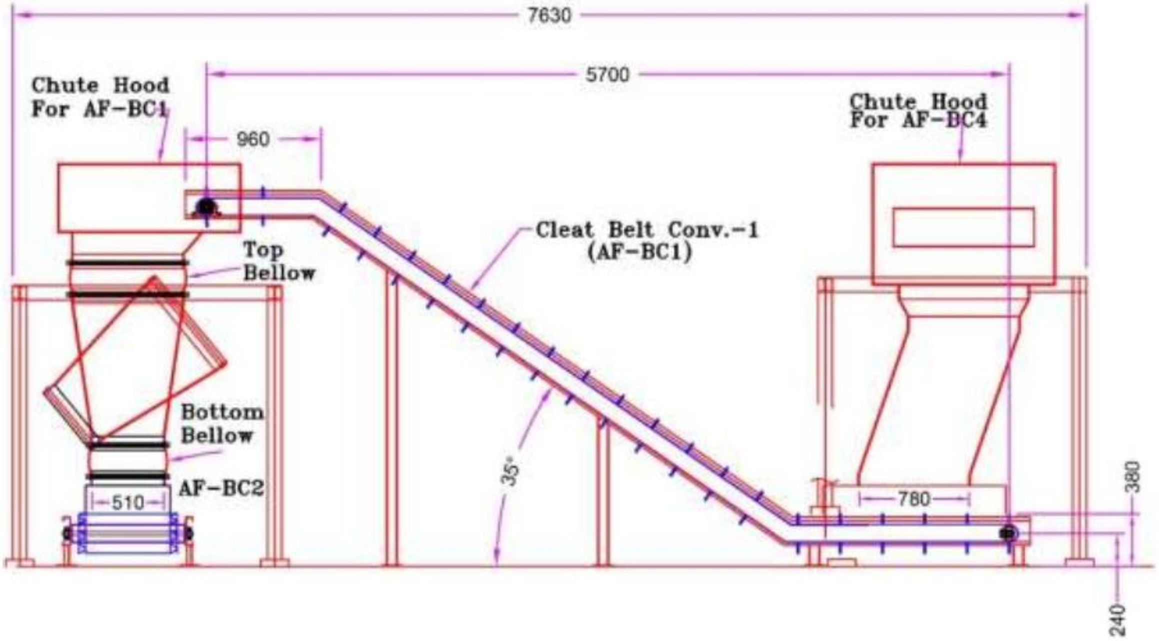


Fig. 6.3 General arrangement (Section AA) of experimental set up

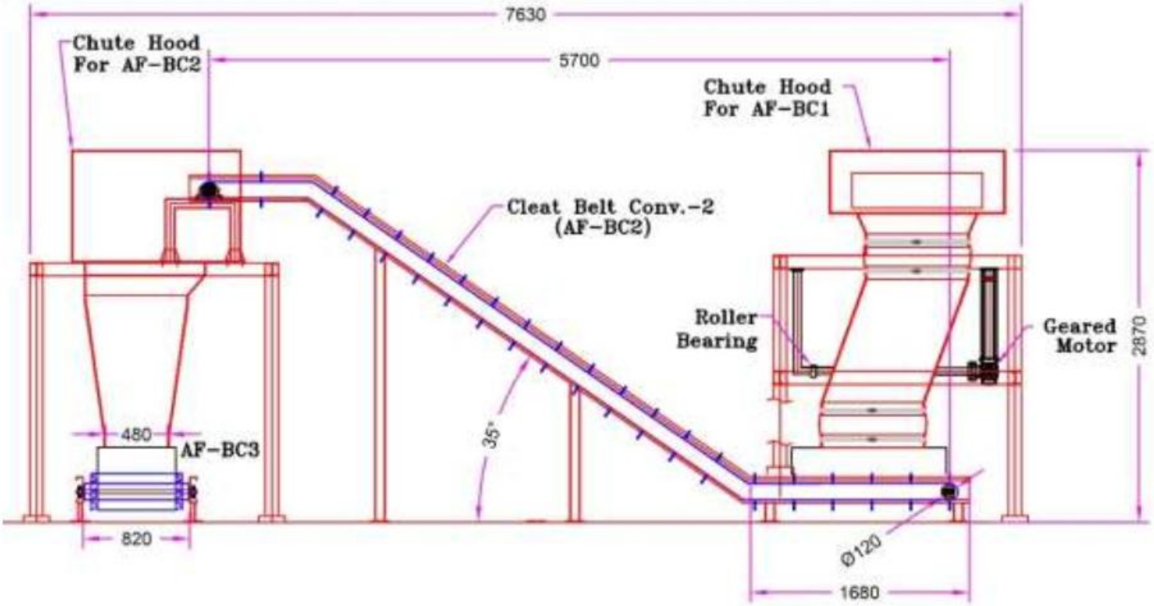


Fig. 6.4 General arrangement (Section BB) of experimental set up

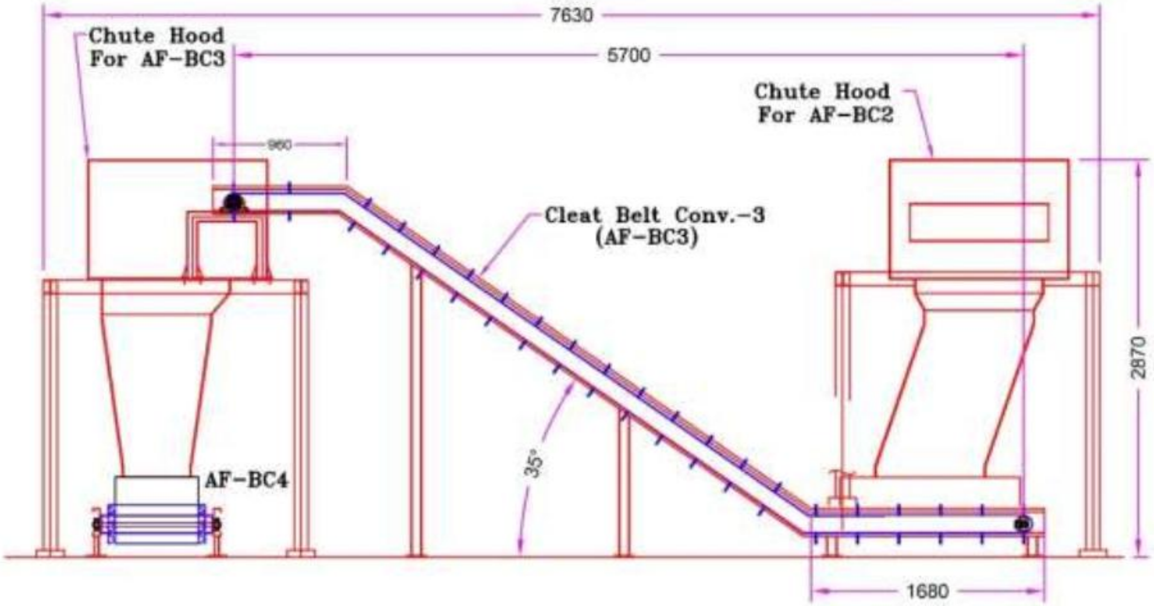


Fig. 6.5 General arrangement (Section CC) of experimental set up

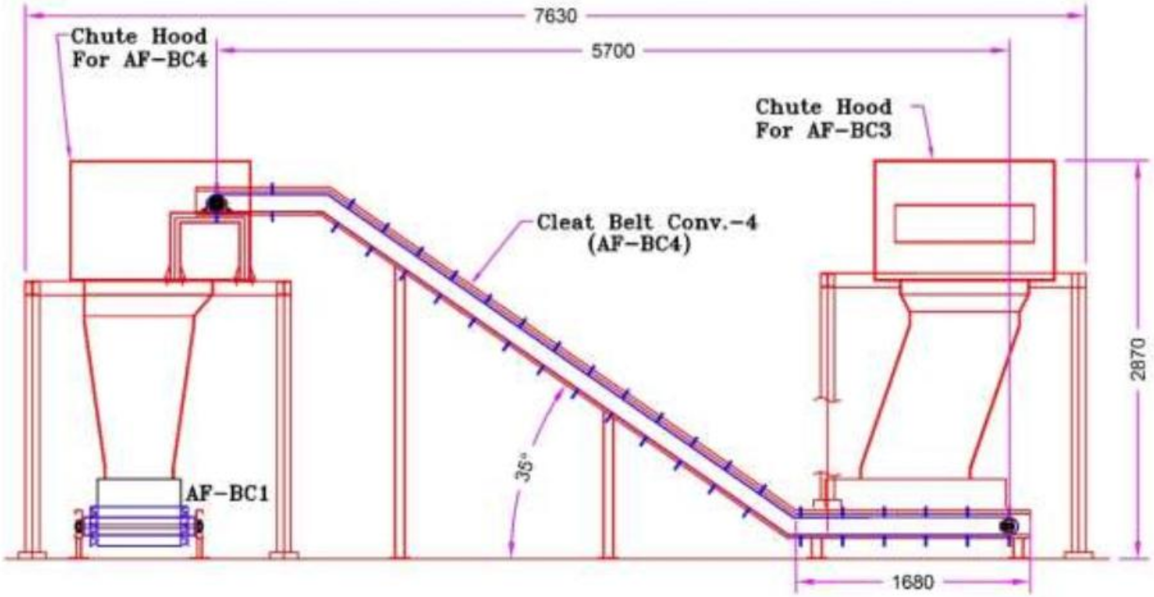


Fig. 6.6 General arrangement (Section DD) of experimental set up

6.2 Technical Specification of the Experimental Setup

To achieve a high inclination in limited available space, cleat belt conveyors have been selected for the following specifications based on the simulation results:

Table 6.1 Technical specification of belt conveyor

Conveyor Capacity	15 tph (max)
Conveyor numbers	4 nos. (BC-1 to BC-4)
Belt Speed	0.5 to 1.5 m/sec (Through VFD)
Belt Thickness	5mm
Belt Length (C-C)	5.7 meter
Belt Elevation	~ 2.6 meter (@ 35° inclination)
Belt Width	800 mm (effective width 600mm)
Belt type	PVC Belt, Oil resistant and fire retardant
Cleat Height	50 mm
Bulk Density of AFs	0.2 to 0.8 t/m^3
Particle Size of AFs	1 mm (Min.) to 80 mm (Max.)

Transfer Chutes: As indicated in Fig. 6.3 to Fig. 6.6, four nos. transfer chutes were considered in the experimental setup to make the circuit a closed loop for material circulation. Design parameters of all four nos. transfer chutes have been considered in line with the simulation result recommendations in Table 6.2.

Table 6.2 Design parameters of transfer chute

Design Parameter	Recommended Value	Considered for Experiments
Chute Valley Angle	70°	70°
Chute Width (Minimum)	4.3 to 4.5 times the lump size	480 mm (4.3 times of maximum lump size)
Chute Hood Height at the material entrance	Minimum 0.6 * Belt Width	480 (0.6 times of belt width)
Cross-Sectional Area	Minimum 10 to 11 times of S*	375 mm^2(13 times of S*)

The technical specification of the transfer chute is indicated in Table 6.3.

Table 6.3 Technical specification of transfer chutes (4 nos.)

Dimensions	As per Fig 5.3 to 5.6
Base Material	4 mm Mild Steel Sheet (IS2062)
Liners	8 mm UHMWPE liner
Chute Jamming Sensors	Photoelectric sensor

Research also approached one critical issue of transfer chute cleaning, as highlighted in Chapter 3, where plants reported that when there is jamming in the transfer chute, it takes 85 to 95 minutes to clear the chute jam, which leads to the followings-

- Process disturbance due to feed cut of alternative fuels
- Loss in production due to raw mix composition
- Low TSR and high carbon footprint due to higher fossil fuel consumption
- Higher maintenance cost
- Higher production cost

Plants further reported that if they get any system that can clean the chute within 10 to 12 minutes, they may operate the AF system with storage in a pre-bin located on the calciner floor and may avoid stoppage of the AF handling system. This research also addressed the chute cleaning issue and provided a solution, i.e., "*Flexible Transfer Chute*" that may facilitate the chute cleaning in <10 minutes instead of 85 to 105 minutes. Fig 6.7 & 6.8 indicates the components & typical working principle of the proposed flexible chute design-

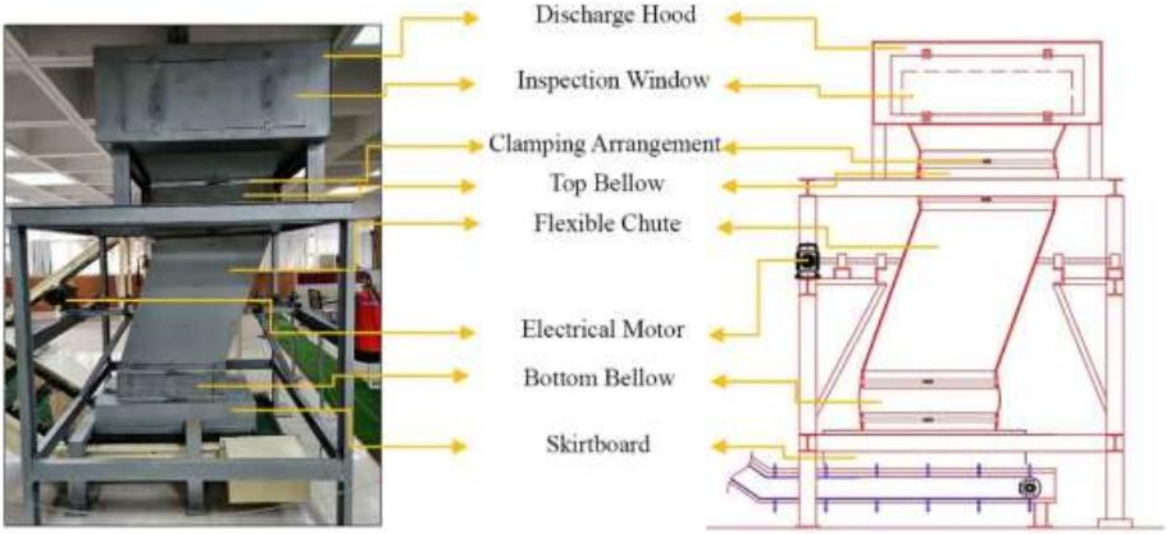


Fig. 6.7 Flexible chute components

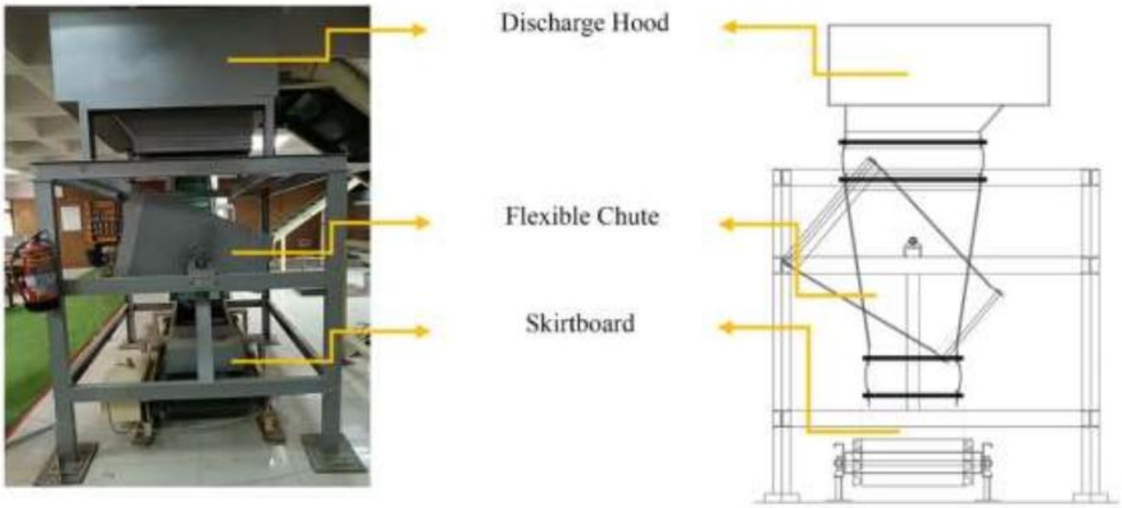


Fig. 6.8 Flexible chute working principle

Instead of flange and bolting at the top and bottom connection of the transfer chute, two flexible connections have been introduced with clamping, which facilitates the fast cleaning of the chute and avoids the stoppage of the entire AF handling and feeding system. A detailed discussion and its comparison with conventional transfer chute is discussed in Chapter 7

6.3 Fabrication of Experimental Setup

6.3.1 Fabrication of Transfer Chutes

- ***Sheet marking, cutting, and welding***

A 2D design was prepared in AutoCAD software for the chute's manufacturing. A local fabrication workshop was involved in the fabrication of the chute. Mild steel sheets with a thickness of 4 mm were used to build the chute walls, and the proper shapes were cut from the metal sheet. The sheets were then welded together to create the appropriate shape and size. An oxy-fuel gas cutter was used for cutting metal sheet, as it gives good cutting quality. Mild steel with excellent impact strength, ductility, weldability was employed to construct the transfer chute.

The different sections of the transfer chute are as follows: -

- Chute hood
- Transition chute section
- Lower chute section & Skirting

The parameters considered while cutting of mild steel sheet are given below:

Table 6.4 Parameters for transfer chute designing

S. No.	Parameters	Unit	Dimensions
1.	Chute vertical Height	mm	2900
2.	Chute Inclination	Degree	70
3.	Chute Exit Opening	mm	480
4.	Minimum Width	mm	480
5.	Chute Hood height at the material entrance	mm	480


(a) (b)

Fig. 6.9 Marking (a) and cutting (b) of MS sheet for chute wall

Manual Metal Arc Welding (MMAW) was employed to join the mild steel sheets together. The welding was completed in two stages: first, the transfer chute was assembled with the help of E7018 electrodes, and then the transfer chute supporting structures were assembled with the help of E6013 electrodes at the NCCBM premises under supervision. The electrodes were selected based on their properties, weld bead qualities, and strength of the weld. The difference between the 6013 and 7018 electrodes are as follows [2]:

Table 6.4 Comparison between electrodes 6013 & 7018

Electrodes	6013	7018
Flux Coating	High Titania Potassium	25% Iron Powder Low Hydrogen
Tensile Strength	60,000 psi	70,000 psi
Welding Position	All Positions	All Positions
Welding Current	AC/DC	AC/DC (Usually DC)
Arc Characteristics	Smooth	Smooth
Penetration	Shallow to Medium	Shallow to Medium
Fill	Medium	Medium to Wide
Slag Type	Light, Easy to Remove	Thick
Special Applications	Sheet Metal	High-Carbon Steels, Low-Alloy/High-Strength Joints

The chute was fabricated in three parts (1) Chute Hood, (2) Transition Chute Section, (3) Lower chute Section as indicated in Fig 6.10

(a) (b)

Fig. 6.10 Fabrication of transfer chute parts (a) chute hood (b) transition section

- ***Fitting of Liners***

As recommended in Chapter 5, Ultra-High Molecular Weight Polyethylene (UHMWPE) was selected for lining the transfer. The speed of the belt conveying system in the research spans from 0.5 to 1.5 m/s, and simulation findings suggest that the transition chute section is where the material affects the greatest. Hence, 8 mm UHMWPE liners are used and installed with the help of M8 countersunk bolts, as indicated in Fig. 6.11.

Fig. 6.11 Installation of UHMWPE liner sheets in the chute

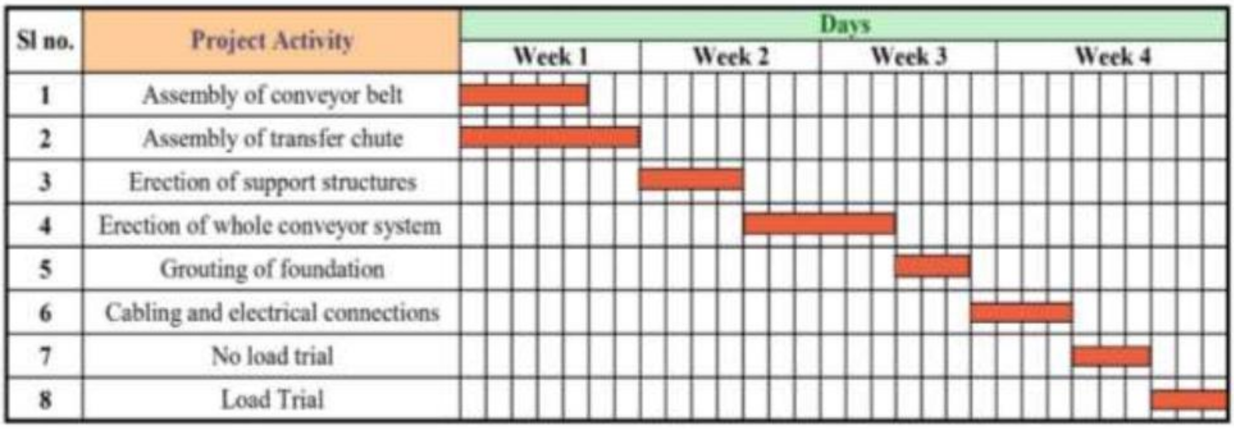
- ***Assembly of Fabricated chute components***

Under supervision, the components of the transfer chute were assembled at NCB, Ballabgarh, Haryana. The chute hood was on top, followed by the transition chute section and the lower chute section, all held together by nuts and bolts, followed by the erection of the supporting structures. Four transfer chutes were erected, and one of the transfer chutes had a rotation mechanism powered by a geared motor (flexible chute) to facilitate the easy cleaning of the chute in case of jamming, as discussed above.

Fig. 6.12 Assembly of transfer chute

6.4 Construction, Erection, and Commissioning of Transfer Chute System at NCCBM, Ballabgarh

It took four weeks to complete the installation of the experimental setup at NCB. An activity chart was prepared for the timely erection and commission of the system as indicated below:



Sl no.	Project Activity	Week 1	Week 2	Week 3	Week 4
1	Assembly of conveyor belt	🟥			
2	Assembly of transfer chute	🟥			
3	Erection of support structures		🟥		
4	Erection of whole conveyor system		🟥	🟥	
5	Grouting of foundation			🟥	
6	Cabling and electrical connections			🟥	🟥
7	No load trial				🟥
8	Load Trial				🟥

Fig. 6.13 Planned activity chart for installation of experimental setup

i. Erection Activity

➢ *Installation of Transfer Chute*

The chute construction was then completed by first constructing the support structure using MS channels. The discharge hood was then mounted on top, followed by the transition chute, and the bottom segment of the chute was then joined to the transition chute section. A fork lift has been used to erect the chute structure and chute-

Fig. 6.14 Installation of transfer chute

- ***Installation of Belt Conveyors***

The conveyor system's initial installation began with the conveyor belt and deck plate assembly with the support frame using countersunk nuts and bolts. The support channels were then joined together using metal arc welding, and the connection with the support frame and conveyor belt was established using countersunk nuts and bolts. A geared motor with a gear ratio of 7.5 and a power rating of 1.5 kW was used to power up the conveyor belt system's driving pulley. Since there are four conveyor belt systems, the identical erection procedure was followed for each.

Fig. 6.15 Assembly of conveyor belt

Fig. 6.16 Erection of complete system

ii. Safety Aspects

- ***Fire hazards***

Because the methods utilized in the system's assembly and construction might create or start a fire or be hazardous to human life, hence the protective gear worn by workers at all times when executing these duties. Protective gloves, jackets, dust masks, and safety helmets with safety goggles or glasses were the major protective equipment advised for these types of procedures. A fire extinguisher was kept near the working area.

- ***Health hazards.***

Maintain a safe distance while assembling the conveyor chute system since the components used in the system are heavy and might cause injuries if handled carelessly. A limited barrier system was used to prevent unauthorized entry.

Poisonous gases or particles are generated during the welding, cutting, and painting processes; thus, industrial-scale exhaust fans were installed to ventilate the space, and wear a mask was avoid breathing such toxic gases.

6.5 Electrical & Instrumentation System

Power Supply system

An electrical control panel is installed along with the conveyor system to control the conveyors through VFDs and get feedback through various sensors. The panel is energized through 3 phase 415 V 50 11z AC power supply controlled through a four-pole 32 A MCB. The power is then fed to two no's, VFDs to control the speed of conveyors and one VFD, which controls the movement of the flexible chute. In case of jamming of the flexible chute, the VFDs receive the signal from the field device and photo sensor, which subsequently stops the conveyors. The major components inside the control panel are described as under.

Variable Frequency Drive

Variable frequency drives were selected to control the speed of conveyor belts to facilitate the experiments. All motors selected are 3 Phase induction motors with VFD. Table 6.7 indicates the drive list

Table 6.7 Drive list

Equipment Number	Equipment Description	kW Rating	Current rating (Amp)	Motor Type	Starter
AFBC1	Belt Conveyor	1.5	3.45	Induction	VFD
AFBC2	Belt Conveyor	1.5	3.45	Induction	VFD
AFBC3	Belt Conveyor	1.5	3.45	Induction	VFD
AFBC4	Belt Conveyor	1.5	3.45	Induction	VFD
AFFC1	Flexible Chute	0.37	1.09	Induction	VFD

MCB (Miniature Circuit Breaker)

The primary function of an MCB is to switch off the circuit, i.e., to open the circuit (which has been connected to it) automatically when the current passing through it (MCB) exceeds the value for which it is set. It can be manually switched ON and OFF as, similar to a standard switch, if necessary.

Main Switch in the panel

Main switches are elementary switching and protective devices for safe machine control. They can be used, for example, as repair switches to quickly switch off large machines and systems so that maintenance work can be carried out safely.

Relays

It is a protection device installed in a panel. It sends a command to the circuit breaker to cut-off the circuit in case of any fault condition.

On Delay Timer

In on delay timer, the timer changes its contacts after reaching the preset time (On delay time). As its name suggests, the timer contacts changeovers after some delay. It means the timer does not change over its contacts until the preset time is reached.

SMPS (Switching Mode Power Supply)

SMPS is an electronic power supply system that uses of a switching regulator to transfer electrical power effectively.

Push Buttons

Push buttons can be explained as simple power-controlling switches of a machine or appliance. These are generally metal or thermoplastic switches intended to grant easy access.

Photo Sensors

A photoelectric sensor is a device used to determine the distance, absence, or presence of an object by using a light transmitter, often infrared, and a photoelectric receiver.

Instruments Used

To monitor the motion of belt conveyors, Zero Speed Switches were installed on non-drive pulleys of conveyors. Further, photoelectric type chute jamming sensors were used to get the indication about chute jamming, Table 6.8 indicates the instrument list.

Table 6.8 Instrument list

Equipment Number	Equipment Description	Instrument
AFBC1	Belt Conveyor	Zero Speed Switch (ZSS-1)
AFBC2	Belt Conveyor	Zero Speed Switch (ZSS-2)
AFBC3	Belt Conveyor	Zero Speed Switch (ZSS-3)
AFBC4	Belt Conveyor	Zero Speed Switch (ZSS-4)
AFFC1	Flexible Chute	Jamming Sensor (JS-1)
AFTC2	Transfer Chute	Jamming Sensor (JS-2)
AFTC3	Transfer Chute	Jamming Sensor (JS-3)
AFTC4	Transfer Chute	Jamming Sensor (JS-4)

6.6 Load Trial Runs

On completion of the erection of the entire system, a load trial was carried out with biomass for 12 hrs. During the load trial, conveyors were fine-tuned for the belt alignment and dust generation points. After running for 12 hrs, it was found that the system operation was satisfactory and further experiments could be done.

The parameters of load trials are mentioned in Table 6.9

Table 6.9 Details of load trials

S. No.	Description	Value
1	AF Handled	Agro Waste (Parali)
2	AF Properties	Bulk Density 0.10 t/m^3 Moisture 8 % Particle Size (2D max) 20 mm AOR 26.56 degree AOI 20 degree
3	Conveying capacity	8 tph
4	Belt Speed	0.5 m/s (min), 1.5 m/s (max)
5	Conveyor drive power (Operating)	1.5 kW
6	Noise Level Recorded	67 dB (min speed), 80 dB (max speed)

Fig. 6.17 shows the load trials for biomass on an experimental setup installed at NCB

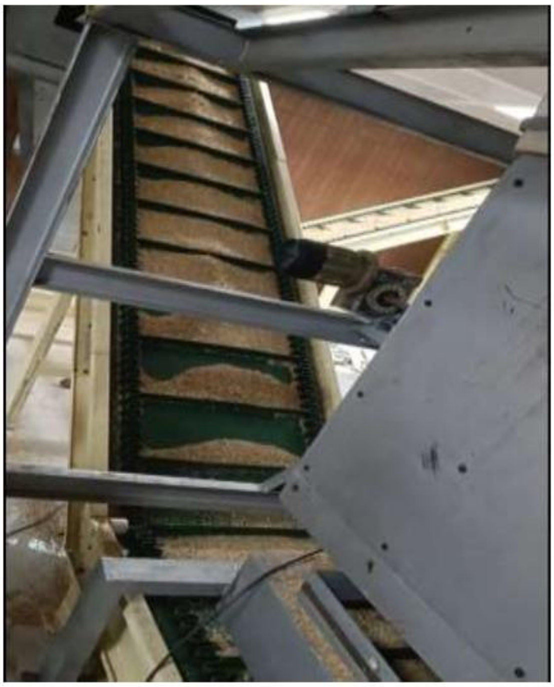


Fig. 6.17 Load trial on experimental setup for biomass

6.7 Apparatus/instruments used for experiments

For the transfer chute system, high-quality, accurate, and calibrated instruments / apparatus were used for measuring the different parameters, viz. angle of repose, angle of inclination, the mass of the material, wear rate, particle size distribution, wear rate, etc. The description and specification of the instruments used for measuring the data are given below.

a) ***Sieves***

The classification of alternate fuels based on their particle size is crucial in transfer chute design because different particle sizes have different flow properties. Inconsistent particle sizes can cause blockages, uneven burning, and other operational problems. The use of sieves enables the classification of alternate fuels based on size, and sieves can be designed to meet specific size requirements for the fuel being used. In the process, sieves of various sizes, such as 30 mm, 50 mm, and 90 mm square size holes and 42.43 mm, 70.71 mm, and 127.28 mm length of diagonals, are stacked in a particular order, with the smallest size at the bottom followed by the larger sizes. The sizes of Seives have been selected based on the maximum particle size, which can be co-processed in the cement industry. The material is then added to the stack of sieves using a constant volume container and weighed to ensure accuracy. The stack is then agitated, allowing the material to redistribute according to particle size. Each sieve is then removed and weighed to determine the proportion of the load for each particle size. The process is repeated for all sample materials. Fig. 6.18 shows the selected sieve for the experiment and their stacking for classification of material size-

Fig. 6.18 Different sizes of sieves used in experimentation

b) *Sliding plates*

In order to determine the angle of inclination of the AFs used in experiments, Mild Steel (MS) and UHMWPE liner sheets of 1 mm and 8 mm thickness were utilized, as shown in Fig. 6.19. These sheets were bolted with each other on wood support to provide a rigid structure so that angle of inclination experiment could be performed easily. The material was loaded onto the plates using a cylindrical container with a constant volume and radius throughout its length. A magnetic inclinometer was then positioned at the edge of the plate to measure the angle of inclination. By using a magnetic inclinometer, accurate measurements of the angle of inclination were obtained as soon as the sample materials started to slide on the MS and UHMWPE liner sheets. The angle of inclination was determined to compare the value with the value considered in the simulation while designing the transfer chute. The angle of inclination was calculated for various moisture levels.

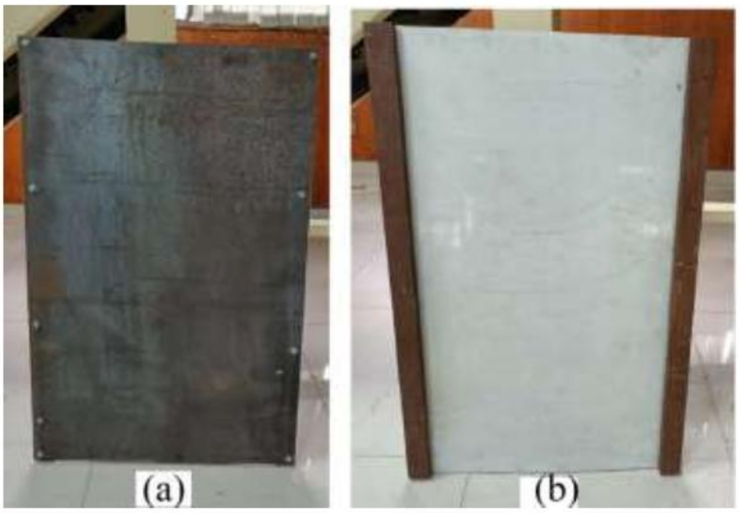


Fig. 6.19 (a) MS sliding sheet (b) UHMWPE liner sliding sheet

c) *Magnetic Inclinometer*

A *magnetic inclinometer* is a device that can accurately determine the angle of inclination of a surface. In the experiments conducted, a magnetic inclinometer was utilized to measure the angle of inclination of the sample materials as they slid down the MS and UHMWPE liner sheets (Fig. 6.20). The readings obtained from the magnetic inclinometer were crucial in determining how the moisture content, particle shape, particle size, and other properties of the sample materials affected their flow behavior and angle of inclination.

Fig. 6.20 Magnetic inclinometer used in experiments

d) Weighing Scale

Using a weighing scale in the experiment was crucial in measuring the weight of the sample materials required for loading onto the belt conveyor system and calculating the mass flow rate during the experiment. The weighing scale used in experiments can measure up to 500 kg of weight up to the two decimal values (refer to Fig. 6.21). This allowed the calculation of the bulk density of materials at varying moisture contents as the materials were tested at different mass flow rates of 3, 5, 8, 10, and 15 tph. The weighing scale was essential in achieving/determining the desired mass flow rate for each test.

Fig. 6.21 Weighing scale used in experimentation

e) Chute Jamming Sensor

Photoelectric sensors were used to indicate the chute jamming during the experiment. These sensors are installed at strategic points in the system where material blockages or jams are likely to occur (Fig. 6.22). Sensors are designed to detect any obstructions in the flow of materials and alert operators or automated systems to take corrective action to prevent downtime, equipment damage, or safety hazards.

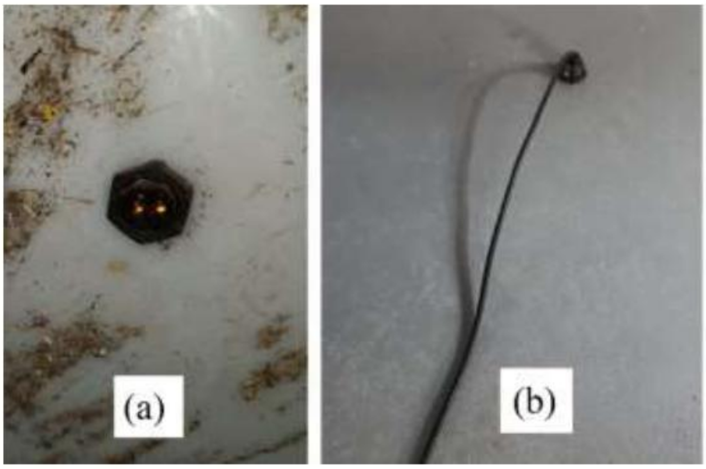


Fig. 6.22 Chute jamming sensor (a) internal view, (b) external view

Table 6.10 indicates the technical specification of the chute jamming sensors

Table 6.10 Specification of chute jamming sensor

Description	Specification
Type	Photoelectric
Make	Omron
Supply Voltage (Volt)	10 to 30
Operation Mode	Light-On or Dark-On
Operating temperature range (°C)	-25 to 55

f) Noise level meter

A noise level meter consists of a microphone, preamplifier, and signal analyzer that works together to measure sound pressure levels and calculate various noise metrics, such as A-weighted decibels (dBA), which are commonly used to assess human exposure to noise. The sound level measured in the room during experimentation was 78 dB on average. Fig. 23 & Table 6.11 shows the Noise Level Metera and its specifications, respectively-

Fig. 6.23 Noise level meter

Table 6.11 Specification table of noise level meter

Model No:	**SVAN 945A**
Measuring range for the LEQ levels (with the error <0.7 dB)	24 dB - 137 dB
Measuring range for the Peak values (with the error <0.7 dB)	68 dB – 140 dB

g) Template to measure wear rate

In the study, a template made from a 2 mm thick machined MS sheet and 1016 mm long (Fig. 6.24) was fabricated and to be used for measuring the wear rate of the UHMWPE liner plate in the transfer chute. The template was placed on the liner plate, and the feeler gauge was used to measure the depth of the groove created due to the movement of bulk materials on the liner plate. The depth of the groove represents the amount of material removed from the liner plate, and this measurement is used to calculate the wear rate.

Fig. 6.24 Template to measure wear rate of transfer chute Liners

The feeler gauge (Fig. 6.25) set used included a range of metal strips, each of which has a specific thickness, ranging from 0.01 mm to 1 mm. These strips are stacked together in a holder, making selecting the appropriate size for a given measurement easy.

Fig. 6.25 26 blades feeler gauge used for measuring wear rate

The feeler gauge was used along with template to measure the wear rate of the UHMWPE liner. Specification table for feeler gauge:

h) The Straight scale

A straight scale was used for precision measuring to facilitate the measurement of height for the calculation of sample material. Typically made of durable materials such as plastic or metal, the scale features a flat strip with markings or graduations that indicate units of measurement in centimeters. The scale measured the height (for the angle of repose calculation) up to 60 cm (Fig. 6.26). With the help of measuring tape and scale, the angle of repose of sample materials was calculated. The readings for the angle of repose were noted down at different moistures for all the sample materials used in the experimentation.

Fig. 6.26 Straight scale used for the measurement of the angle of repose

i) Measuring Tape

The measuring tape used is a flexible strip of metal marked with measurements and used to measure distance or length. The measuring tape was used to accurately measure the distance of the outermost radius of the pile of the material sample. The measuring tape used was able to measure lengths up to 5 m, with the markings of measurements in inches and centimeters (Fig. 6.27).

Fig. 6.27 Measuring tape used for measuring angle of repose

j) Uniform water sprayer bottle

The purpose of a water sprayer bottle is to apply a controlled amount of liquid to a specific area or surface. The four nos. bottle were used to add moisture content to sample materials for the experiments. Each bottle can hold water up to 2 liters of water.

Fig. 6.28 Uniform water sprayer bottle

CHAPTER 7

RESULTS AND DISCUSSION

In the current chapter, the performance assessment of the newly designed transfer chute is carried out on the experimental setup (conveyors & chutes) using alternative fuels (AFs) & their mix with different parameters. The results obtained by experimentation are discussed in detail. Transfer chute design is validated on experimental setup for two essential features, i.e., Time required to clean the chute if the chute is jammed. In the end, a comparative analysis of simulation results with experiments outcome was also carried out, and a detailed analysis was done to evaluate the techno-economic advantages of this research work for the Indian cement industry.

7 Results and Discussion

7.1 Experimental Procedure Adopted

As discussed in Chapter 6, an experimental set-up comprising four (4) nos. conveyors and four (4) nos. transfer chutes was installed at NCCBM, Ballabgarh, India. Transfer chute design parameters for experimental set-up were selected in line with simulation results, discussed in Chapter 5, and a unique feature was incorporated in one of the transfer chutes (out of 4) to validate the flexibility of the transfer chute for fast cleaning, in case the chute is jammed (discussed in Chapter 6). The experiments were carried out for 40 days in January-February 2023. On request, various cement plants/aggregators of India voluntarily sent the AFs to NCB. However, various industrial and agro wastes were purchased from the local market for experimentation trials. The various parameters mainly moisture, heat values, particle size distribution, bulk density, repose angle, angle of inclination and their characteristics are shown in Table 7.1.

Table 7.1 List of AFs collected from cement plants and industry

S. No.	Alternative Fuel	Source	Composition	Particle Size Distribution (mm)	Bulk Density (t/m^3)	Source Moisture (%)	NCV (kcal/kg)	AOR (deg)	AOI (deg)
1.	RDF-1	Plant-1	Mix of cloths, plastic, paper, wood etc.	<30 (12%), 30 to 50 (57%), >50 to 90 (24%) >90 (7%)	0.205	16.82	3169	46.45	35.70
2.	RDF-2	Plant-2	Mix of cloths, plastic, paper, wood etc.	<30 (32%), 30 to 50 (51%), > 50 to 90 (11%) >90 (6%)	0.215	43.09	3342	47.65	36.20
3.	RDF-3	Plant-3	Mix of cloths, plastic, paper, wood etc.	<30 (29%), 30 to 50 (56%), >50 to 90 (12%) >90 (3%)	0.213	33.39	5085	52.53	38.80
4.	RDF-4	Plant-4	Mix of cloths, plastic, paper, wood etc.	<30 (13%), 30 to 50 (59%), >50 to 90 (21%), >90 (7%)	0.193	23.62	5670	48.25	36.70
5.	RDF-5	Plant-5	Mix of cloths, plastic, paper, wood etc.	<30 (15%), 30 to >50 (54%), 50 to 90 (23%) >90 (8%)	0.221	14.94	3488	49.12	38.60
6.	Tyre Derived Fuel (TDF)/Tyre chips	Plant-3	Shredded tyre free from dust and stone	<50 mm (100%),	0.610	0.36	8493	39.14	34.30

S. No.	Alternative Fuel	Source	Composition	Particle Size Distribution (mm)	Bulk Density (t/m^3)	Source Moisture (%)	NCV (kcal/kg)	AOR (deg)	AOI (deg)
7.	Agro Waste	Locally purchased from Faridabad, Haryana	Paddy stubble (Parali)	<30 (100%)	0.110	10.95	3007	25.44	19.90
8.	Multilayer Plastic (MLP)	Tiffot Private Ltd., Kunnukara, Kerala	Shredded plastic	<30 (87%) >30 to 50 (13%)	0.100	0.70	7640	32.38	29.70
9.	Footwear Waste	Purchased from Footwear Industry, Faridabad, Haryana	Shredded hawai chappal	<30 (83%) 30 to 50 (17%)	0.122	0.59	4396	34.17	23.40
10.	Bagasse	Locally purchased from Faridabad, Haryana	Waste of sugarcane	<30 (72%) 30 to 50 (28%)	0.105	23.82	3229	29.57	27.30
11.	ETP Sludge	CETP, Faridabad, Haryana	Dry sludge from common effluent treatment plant	<30 (45%) 30 to 50 (55%)	0.437	0.18	1224	32.07	24.70

The AFs received/purchased from the industry at NCB, Ballabgarh is shown in Fig. 7.1

Fig. 7.1 AFs received / purchased from industry

As concluded in Chapter 3, AFs like RDF, industrial waste, and mixed solid waste are mainly associated concerned with chute jamming. Hence, once the experiments were completed for the above 11 nos. waste as indicated, mixed wastes were also prepared in the proportions suggested by the industry experts as indicated in Table 7.2.

Table 7.2 List mixed waste prepared for experimental study

S. No.	Alternative Fuel	Composition	Bulk density (t/m^3)	Moisture (%)	NCV (kcal/kg)	AOR (deg)	AOI (deg)
1.	Mixed Waste-1	Saw Dust (25%), Parali (75%)	0.141	14.46	3767	32.80	25.20
2.	Mixed Waste-2	Saw Dust (20%), Parali (65%),	0.138	14.87	3506	33.20	25.50

S. No.	Alternative Fuel	Composition	Bulk density (t/m^3)	Moisture (%)	NCV (kcal/kg)	AOR (deg)	AOI (deg)
		Bagasse (10%), Wood Chips (5%)					
3.	Mixed Waste-3	Saw Dust (20%), Parali (55%), Bagasse (8%), Wood Chips (5%), MLP (12%)	0.136	13.37	3880	33.25	26.50
4.	Mixed Waste-4	RDF-1 (50%), RDF-2 (25%), RDF-3 (25%)	0.209	27.53	3750	48.42	37.00
5.	Mixed Waste-5	RDF-1 (25%), RDF-2 (25%), RDF-3 (25%), RDF-4 (25%)	0.207	29.20	5200	48.76	36.80
6.	Mixed Waste-6	RDF-1 (20%), RDF-2 (20%), RDF-3 (20%), RDF-4 (20%), RDF-5 (20%)	0.209	26.47	4785	49.25	37.30
7.	Mixed Waste-7	Mixed Waste-6 (90%) Parali (10%)	0.198	24.80	4607	44.90	34.50
8.	Mixed Waste-8	Mixed Waste-6 (80%), Parali (10%), MLP (10%)	0.188	22.26	4893	43.30	32.60

The performance of the newly designed transfer chute was evaluated using 11 types of AFs and eight types of mixed waste. This allowed for a more diverse range of AFs to be tested, which in turn helped identify potential issues or variations in the performance of the chute when handling different types of materials. Furthermore, using materials from multiple sources ensured that the chute could handle materials from different geographical locations in India. This can be particularly important in industries where materials may have varying properties depending on their source or location. The AFs were classified into three categories RDF (5 nos.), Mixed Solid Waste (8 nos.), and Industrial & Agro waste (6 nos.). Experiments were carried out for the followings objectives-

- Validation of design parameters of a newly developed transfer chute,
- Performance of liners selected for transfer chute,
- Validation of flexible feature of newly developed transfer chute for fast cleaning.

7.2 Experiments for Validation of Design Parameters of Transfer Chute

The objective of the experiment for validation of design parameters was to assess the performance of the newly designed chute for any jamming when handling different AFs & their mix with a wide range of variations in the properties. The performance of the transfer chute was evaluated with the consideration that if the chute is jammed, it will have the following indication in the system-

- The mass flow rate passing through the transfer chute will decrease gradually,
- The power drawn by the conveyor will decrease when the material is stuck in the chute,
- The quantity of material will decrease on the conveyor, which can be observed physically

Accordingly, the performance of the transfer chute was evaluated by varying the mass flow rate, moisture content, operating time, and conveying speed.

7.2.1 Results obtained at varying mass flow rates at constant moisture

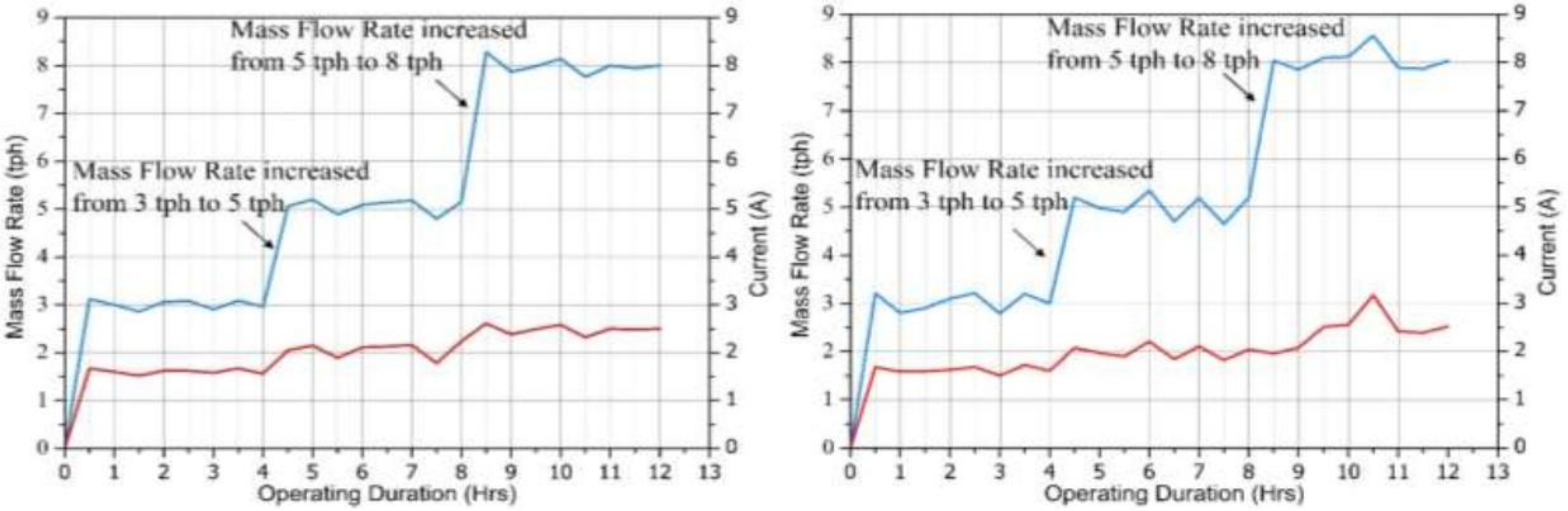
During the first set of experiments, the performance of the transfer chute was evaluated by varying the mass flow rate of the AFs at the moisture obtained from the source. The experimental setup was designed to handle 15 tph @ bulk density 0.6 t/m^3. The system was capable of achieving a maximum 8 tph capacity for lightweight materials (bulk density 0.1 t/m^3 to 0.23 t/m^3) like RDF, agro waste, mixed waste and MLP, and 15 tph for TDF (tyre chips) & EPT Sludge (bulk density 0.610 to 0.437 t/m^3). Experiments for RDFs, agro waste, footwear waste, and MLP began with a mass flowrate of 3.00 tph for initial 4 hrs; after that, feed increased upto 5 tph and 8 tph for another 4, 4 hours without changing the moisture to evaluate the chute performance at an increased mass flow rate. ETP sludge and TDF were operated with a flow rate of 5.00 tph at source moisture for initial 4 hrs; after that, the feed was increased up to 10 tph and 15 tph for another 4, 4 hours without changing the moisture. Experiments were done for 12 hrs for each material at varying mass flow rates and constant moisture (source moisture), as the plants reported that the jamming in the transfer chute might arise at any time between 30 minutes to 2 hours of operation, depending on the AF properties and response of the conventional transfer chute. Hence, the reading of the mass flow rate & conveyor current is recorded manually every 30 minutes to plot the graphs between mass flow rate, current consumed, and duration of the operation. Fig. 7.2 shows the pictures of experiments for various AFs received /purchased from the industry

RDF-1 RDF-2 RDF-3 RDF-4 RDF-5 Tyre Chips

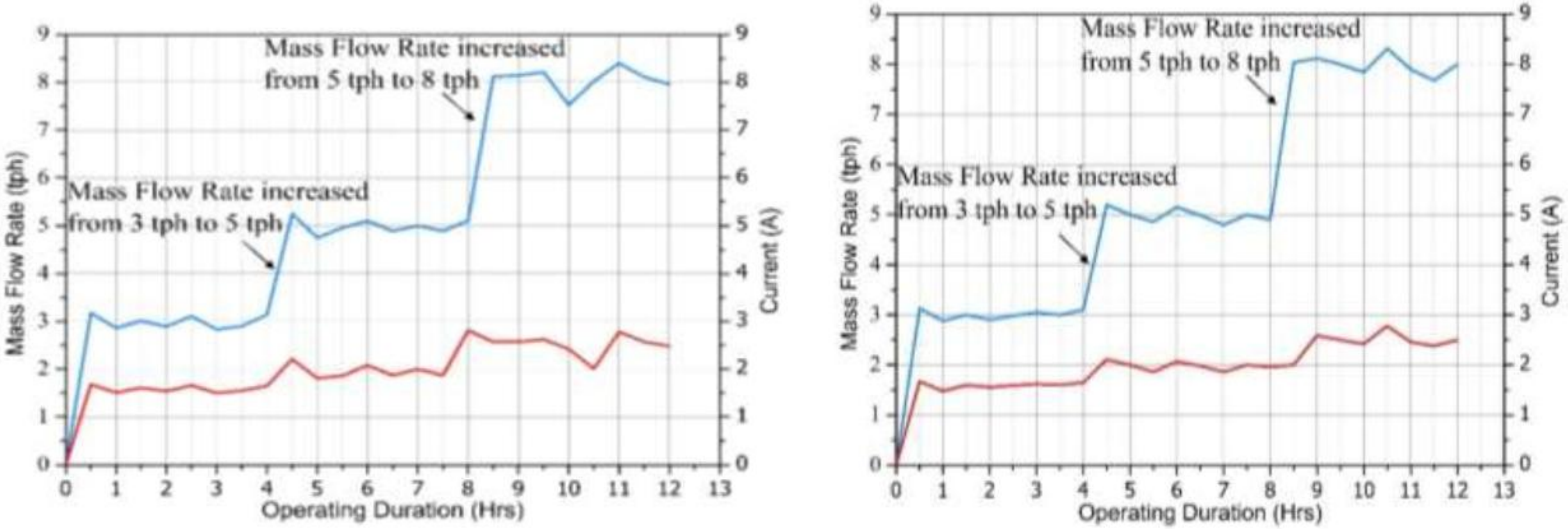
ETP Sludge Parali MLP Footwear Waste Bagasse

Fig. 7.2 Experiments for AFs received from the industry at varying mass flow rates

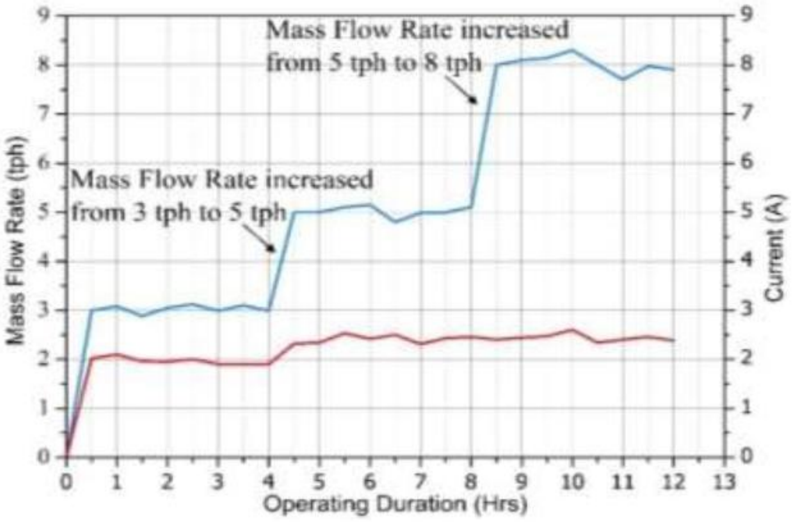
Fig. 7.3, 7.4 & 7.5 indicates the performance of the newly designed transfer chute, handling RDFs, MLP, footwear waste, agro waste, ETP sludge, and TDF with varying mass flow rate and constant moisture content. Fig. 7.3 (a) to (e) shows the impact of the increased mass flow rate of RDFs through the transfer chute at constant moisture content. Results indicates that the mass flow rate has fluctuated for RDFs at every operating capacity. This fluctuation is more in the case of RDF-2 & 3. The mass flow rate of RDF fluctuates within the range of -3 to +4 % in the case of RDF-1, RDF-4, and RDF-5 (moisture 16.82, 23.62 and 14.94%) and -6 to +7 % for RDF-2 & 3 (moisture 43.09 and 33.29). It can be observed that for each RDF (1 to 5), the fluctuation is in the same range at every capacity (3, 5, 8 tph), which varies individually among one another. The possible reasons for these fluctuations may be the heterogeneity of RDFs, uneven particle size & shape, and the higher moisture content, which tends to create lumps due to agglomeration. Variations in the motor current recorded during the experiments were in proportion to mass flow rate fluctuation. The noise levels of the system recorded during the experiment were in the range of 76 to 78 dB. Many foreign materials like stone and metal were found in the RDF-1 and removed manually during the experiment.



(a) RDF-1 (b) RDF-2



(c) RDF-3 (d) RDF-4



(a). RDF-1 (Moisture content = 16.82 %)

(b). RDF-2 (Moisture content = 43.09 %)

(c). RDF-3 (Moisture content = 33.39 %)

(d). RDF-4 (Moisture content = 23.62 %)

(e). RDF-5 (Moisture content = 14.94 %)

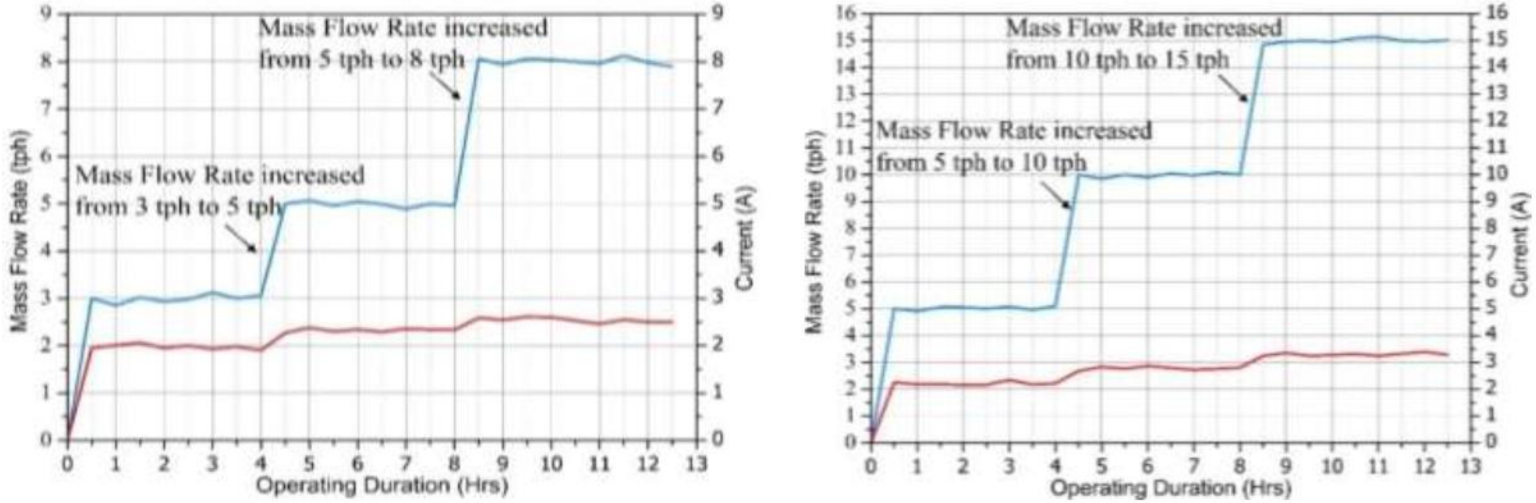
━ **Mass Flow Rate**

━ **Current**

(e) RDF-5

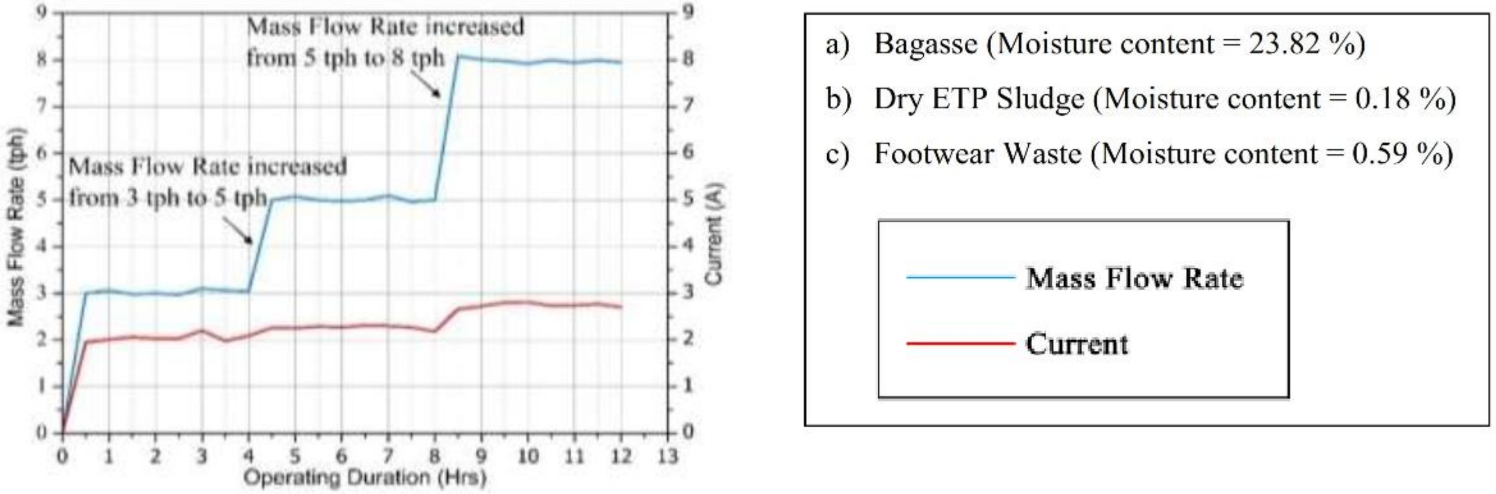
Fig. 7.3 Transfer chute performance for RDFs at a varying mass flow rate

Fig. 7.4 & 7.5 indicate the impact of the increased mass flow rate of Bagasse, dry ETP sludge, footwear waste, TDF, parali, and plastic waste through the transfer chute at constant moisture content. It can be noted that MLP, footwear waste, dry ETP sludge, and TDF have moisture <1%, have the least variation in particle size distribution, and demonstrate negligible fluctuation in mass flow rate at different operating capacities. The fluctuation in the mass flow rate was recorded in the range of ±2%, and the operating current was also stable for the majority of the duration. However, a slight fluctuation in current is observed at some moments, which may be due to the line voltage fluctuations. Parali and bagasse, although having comparatively high moisture when compared to MLP, footwear waste, dry ETP sludge, and TDF, no higher fluctuation (-2 to +3%) is observed. One of the reasons may be the homogeneity of material and well-distributed particle size and shape.



(a) Bagasse

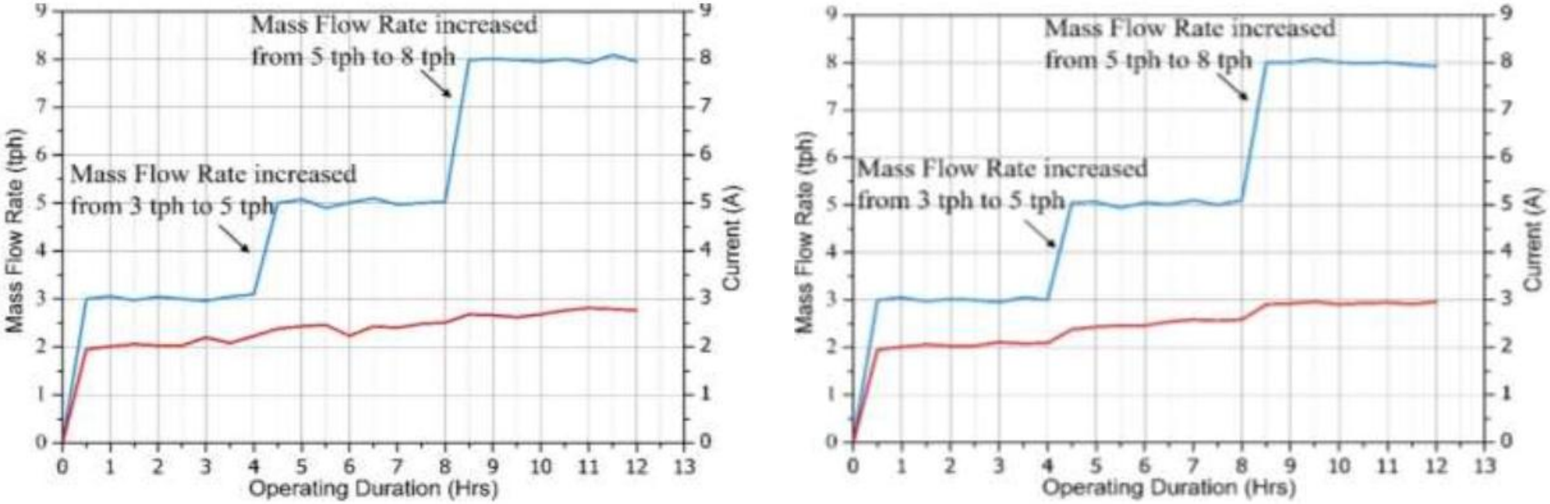
(b) Dry ETP Sludge



a) Bagasse (Moisture content = 23.82 %)
b) Dry ETP Sludge (Moisture content = 0.18 %)
c) Footwear Waste (Moisture content = 0.59 %)

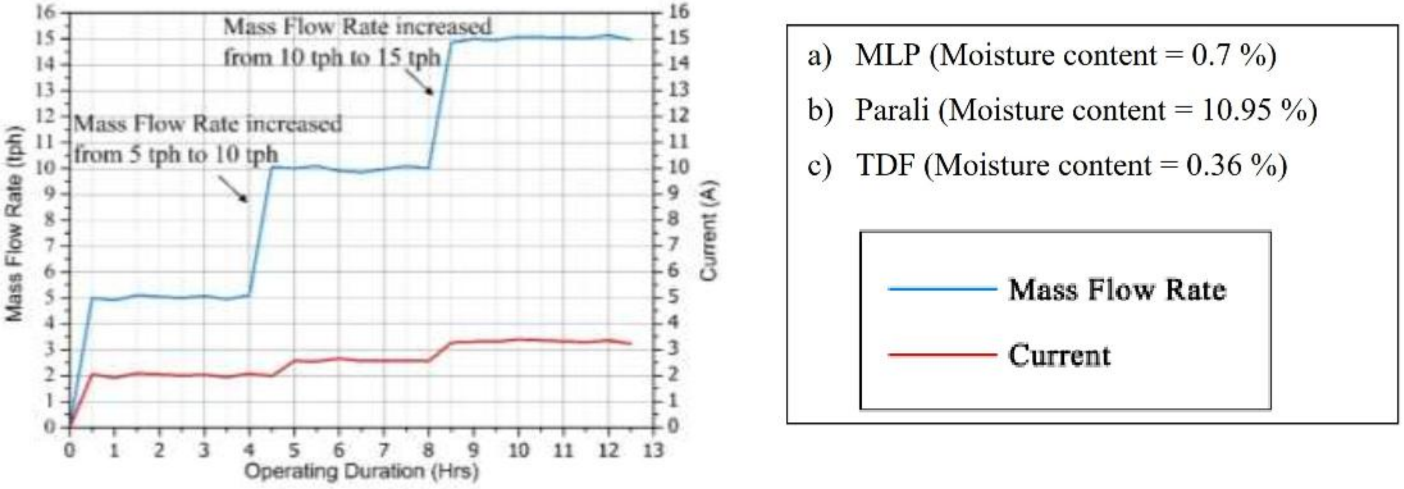
(c) Footwear Waste

Fig. 7.4 Transfer chute performance for bagasse, ETP sludge, and footwear waste at a varying mass flow rate



(a) MLP

(b) Parali



a) MLP (Moisture content = 0.7 %)
b) Parali (Moisture content = 10.95 %)
c) TDF (Moisture content = 0.36 %)

(c) TDF

Fig. 7.5 Transfer chute performance for MLP, parali, and TDF at a varying mass flow rate

Fig. 7.3, 7.4 & 7.5 indicates that with the increase in mass flow rate of AFs (RDF, MLP, footwear waste, dry ETP sludge, TDF, and agro waste), no chute jamming have been observed with new chute design even after 132 hours of operation. However, RDFs are more challenging to handle, and with the increased moisture, fluctuation in mass flow rate is increased mainly due to lump formation (agglomeration effect). Fig. 7.6 shows the internal condition of the transfer chute after carrying out the above experiments.

Fig. 7.6 Chute condition after an experiment for RDFs, industrial & agro waste at varying mass flow rates

As shown in Fig. 7.6, the flexible transfer chute was tilted to inspect the internal condition of the chute liners. It was found that no material was stuck on the chute liners, but a thin layer of dust was seen on one wall (where AFs impacted directly). Most of particles in the layer were of ETP sludge that became sticky due to the moisture content of RDF, which was used just before ETP sludge. Liners were well within their position, and all bolts were found tight enough. The corners of the transfer chute were also found clean.

Further, to compare the performance of the newly designed transfer chute with the conventional chute design being followed in the industry and discussed in Chapter 5, a temporary transfer chute (Fig. 7.7) was fabricated in-house with the following design parameters indicated in Table 7.3:

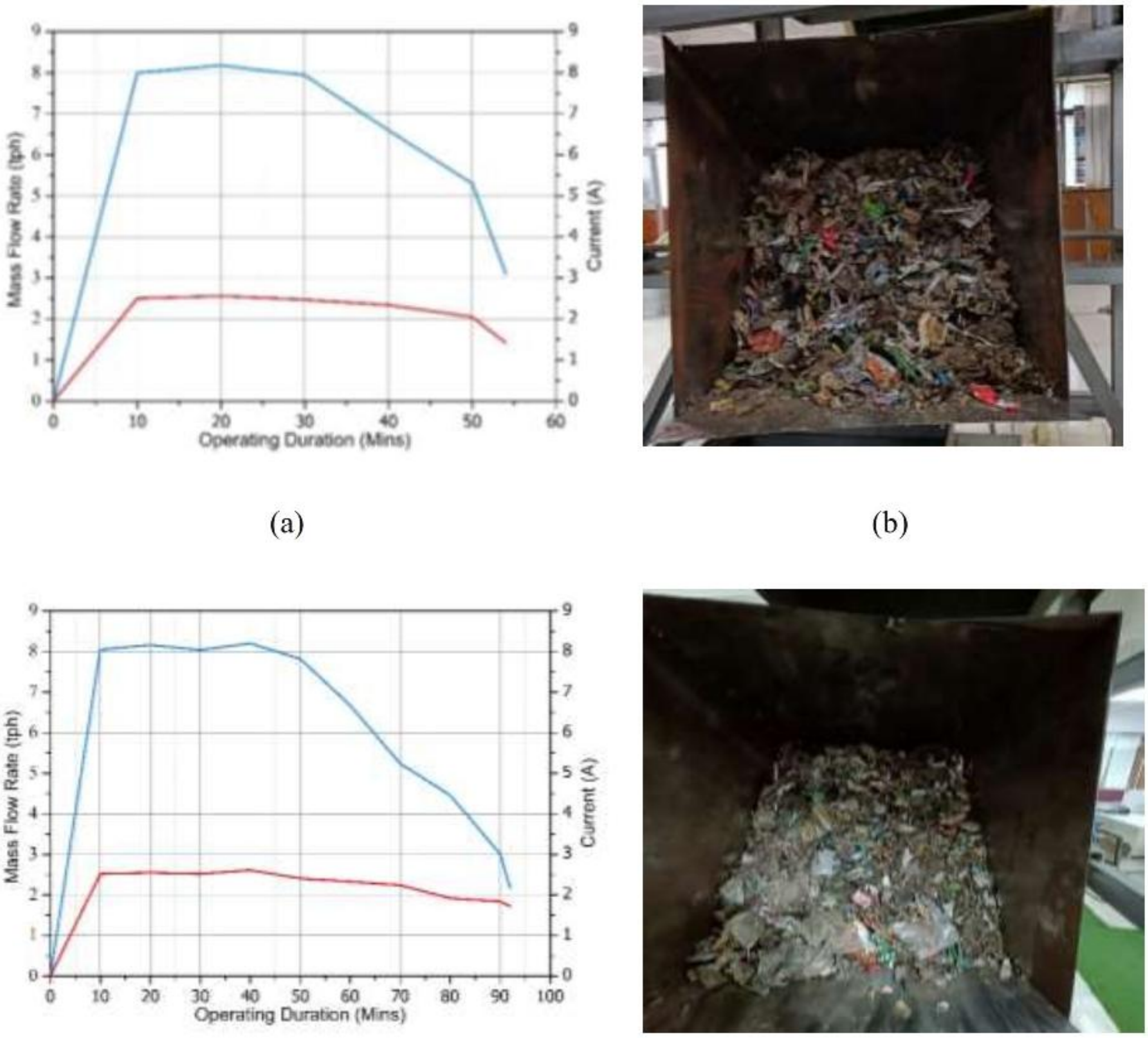
Table 7.3 Design parameters of the conventional chute

Parameters	Unit	Value	Remarks
Chute vertical height	mm	1500	
Chute inclination	Degree	65	The industry is using 60 to 65 degree
Chute exit opening	mm	400	
Cross Section area	mm^2	0.16	
Width	mm	400	
Liners		No	Mother plate 2 mm Mild Steel Sheet


(a) (b)

Fig. 7.7 (a) Fabricated conventional transfer chute (b) Conventional transfer chute inserted in the newly designed flexible chute

Further, to check the performance of conventional transfer chute RDF-2, 3 & RDF-4 (having moisture 43.09, 33.09% and 23.62 % was selected to operate for 4 hrs each at 8 tph. The mass flow rate was noted every 10 minutes. It was observed that the conventional transfer chute did not jam for the RDF-4 at 23.62% moisture for the entire 4 hours duration. However, the chute did not sustain the smooth flow for RDF-2 & 3 and got completely jammed for both materials. For RDF-2 (moisture 43.09%), it was observed that the mass flow rate started to decrease substantially after 30 minutes and decreased continuously till the last reading was recorded at 50 minutes and got completely jammed at 54 minutes. Similarly, for RDF-3 (moisture 33.29%) decrease in the mass flow rate was observed at 50 minutes which decreased continuously till the last reading was recorded at 80 minutes and got completely jammed at 92 minutes. Fig. 7.8 indicates the impact of mass flow rate on the performance of conventional transfer chute.



(a) (b)

(c) (d)

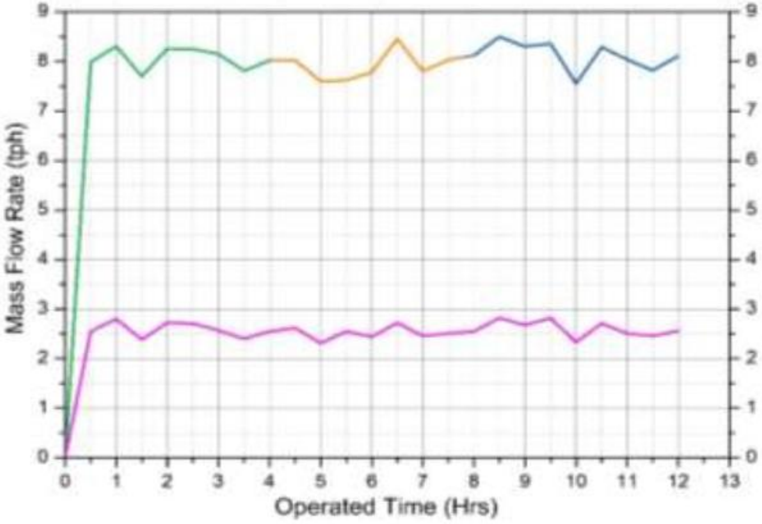
Fig. 7.8 Conventional transfer chute performance for (a & b) RDF-2, (c & d) RDF-3

The conventional chute performed satisfactorily for RDF-4 (moisture 23.62%). However, the chute got jammed within 92 minutes for RDF-3 (moisture 33.29%) & within 54 minutes for RDF-2 (moisture 43.09%). Hence, the industry's conventional chute design parameters work satisfactorily with RDF having moisture ~20 %, which can not be ensured at all times. Most RDF supplied to the industry has 30 to 40%moistur, whereas conventional chute does not perform well, and plants have to add some dry biomass to avoid chute jamming. The process to adding biomass to reduce the moisture and increase the flowability is known as impregnation

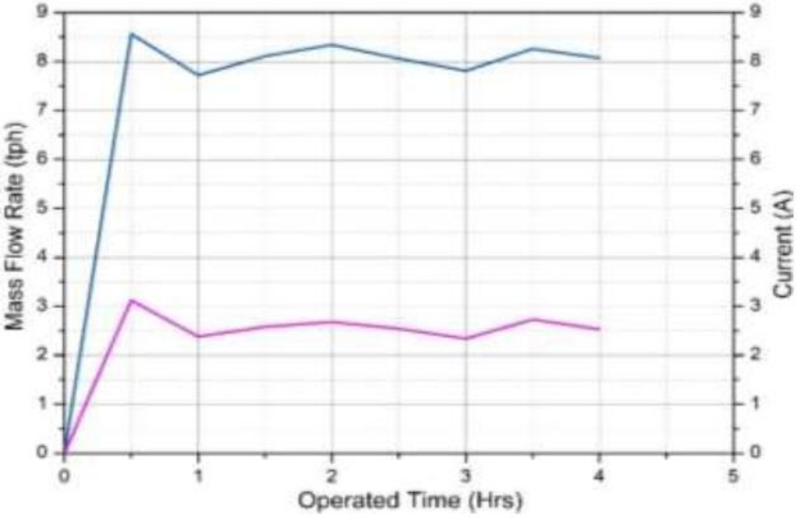
7.2.2 Results obtained at varying moisture and constant mass flow rate

Increase in moisture content leads to increase in angle of repose of bulk solid materials resulting in reduction of flowability. However, along with moisture, other properties of bulk solids also contribute to decide the flowability like particle size, shape, constituents of mix etc. As the majority of AFs are mix of various materials, having wide range of variation in particle size, shape, composition which cannot be altered, the moisture content is the only property which a plant can manage with the use of impregnation. Impregnation demands good quality biomass as well as extra resources for preparation. Cement plants prefer low moisture AFs for easy handling and minimal operational issues. On the other hand high moisture AFs provides the benefits of NO_x reduction.

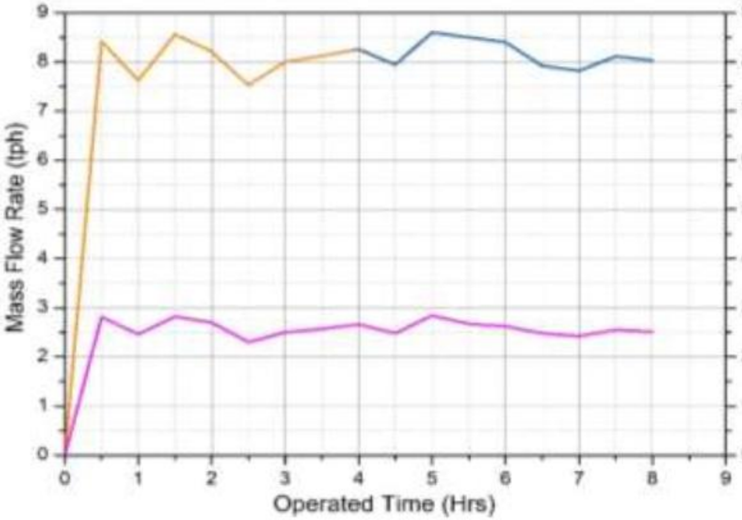
These experiments aim to assess the performance of the newly designed transfer chute at higher moisture levels (up to 45%). The experiments were carried out using RDF-1, 3, 4, 5, parali, bagasse, and ETP sludge at a constant mass flow rate of 8 tph adding the moisture to the levels of 20, 30, and 45% for the duration of 4 hrs each. RDF-1 & 5 having source moisture <20% was operated at 20, 30 and 45% moisture, whereas RDF-3 (33.39% source moisture) was operated at 45% moisture. RDF-4 (23.62% source moisture) was operated at 30% & 45% moisture level. ETP sludge which has tendency of stickiness with the handling equipment, hence moisture addition in ETP sludge started with 10%. This increment in moisture content was achieved by uniformly spraying the calculated amount of water on the belt conveyors. Some of the AFs like TDF, MLP, and footwear waste, for which the moisture level in plants is consistent, have not been considered for this experiment. RDF-2 with source moisture of 43.09 % was also not considered, as it was already operated at 43% moisture at 8tph capacity in the previous experiments. Further, all the eight nos. mixed waste, having moisture range between 13.37 to 29.20%, were also operated up to 45% moisture at a constant flow rate of 8 tph to assess the transfer chute performance.



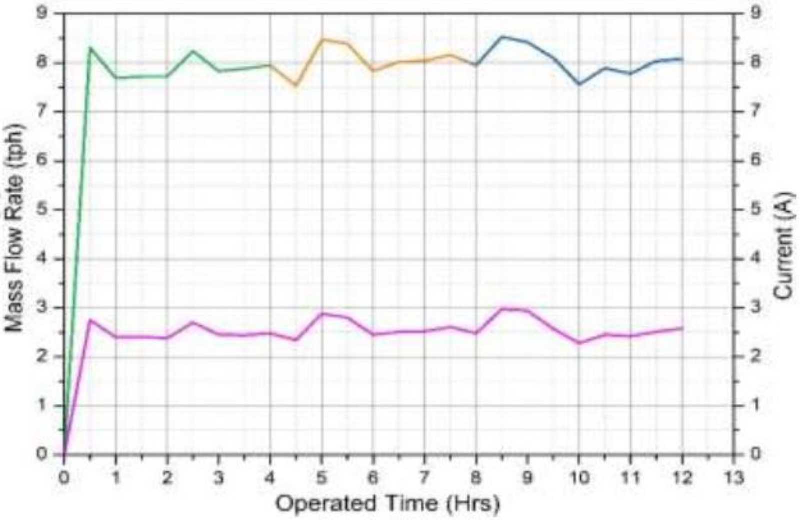
(a) RDF-1



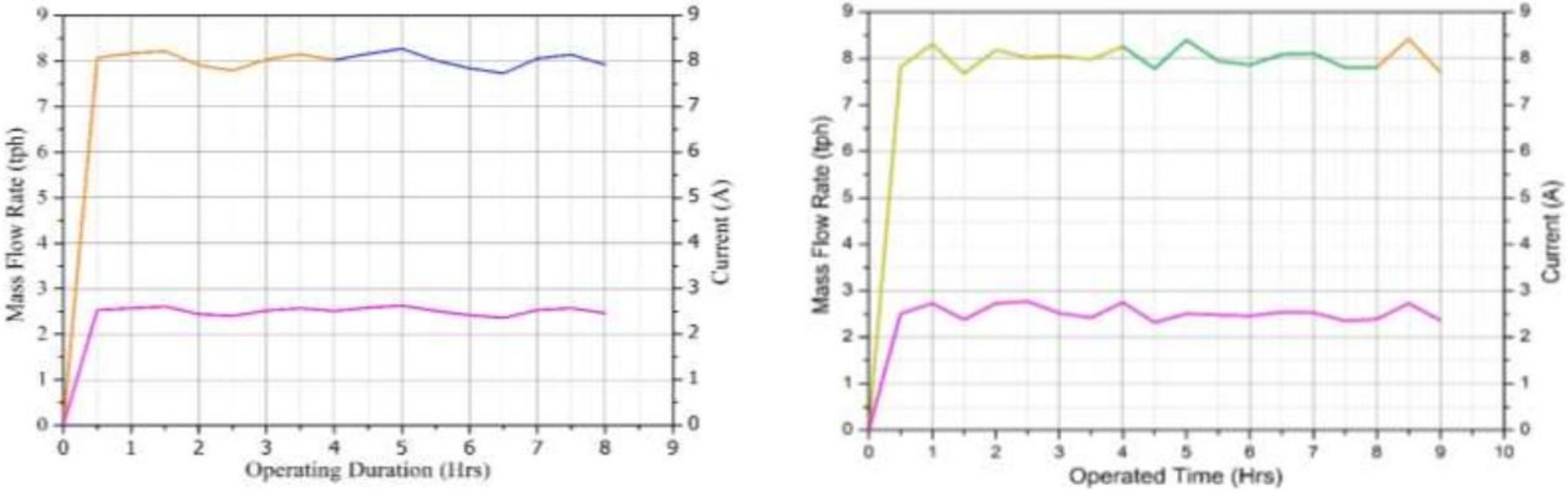
(b) RDF-3



(c) RDF-4

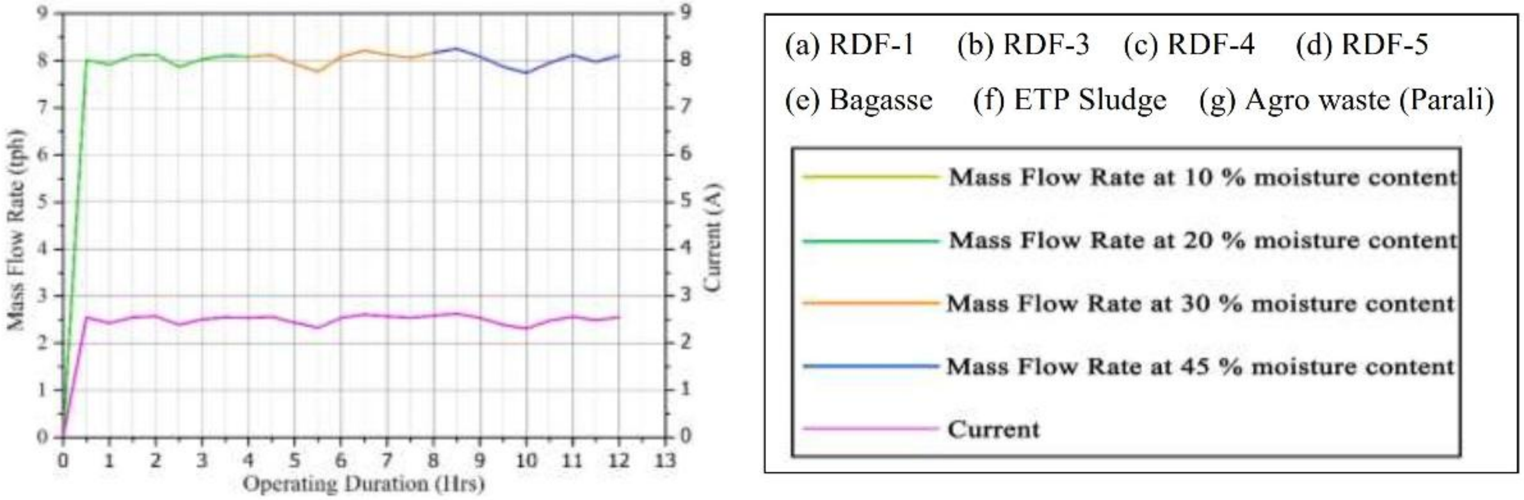


(d) RDF-5



(e) RDF-Bagasse

(f) ETP Sludge



(g) Parali

Fig. 7.9 Chute performance at varying moisture for RDFs, parali, bagasse, and ETP sludge

As shown in Fig. 7.9 (a to d), with increase in moisture of RDFs, the mass flow rate fluctuation increases, but no jamming is observed in the newly designed transfer chute. At high moisture, high fluctuation of mass flow rate was recorded, indicating lump formation; the same was observed on the conveyors also. Mass flow rate fluctuation for RDF-1 & 5 was recorded within the range of -3.75 to +3.89% at 20% moisture, which increased in the range of -5.00 to + 7.00% and -6.00 to +7.50 % at 30% & 45% moisture respectively. Similarly, when RDF-3 was operated at 45% moisture, the recorded mass flow rate fluctuation was -3.50 to 7.00%. When RDF-4 was operated at 30% & 45% moisture and mass flow rate fluctuation was -5.87 to +7.00 & -2.25 to +7.50% respectively. However, after operating the conveying system for a few hours, it is observed that the fluctuation in mass flow rate starts to settle, which may happen due to the breaking of the lumps into smaller sizes after passing multiple times through the transfer chute. It was observed that the big size lumps with dimensions ~200 mm could pass easily through the newly designed transfer chute, which was higher than the value considered during the simulation for chute design. This experiment indicates that with increased moisture, the flowability of RDFs reduces due to heterogeneity, high cohesiveness & adhesiveness but no chute jamming has been recorded even upto 45% moisture content Fig. 7.9 (e & g) indicates that parali and bagasse could be operated smoothly even at higher moisture up to 45% and no significant fluctuation in mass flow rate (± 3.5%) have been observed. However, ETP sludge started to stick on belt conveyors at 30% moisture; still, experiments were done for ETP sludge for an hour at the same moisture as shown in Fig. 7.9 (f). Fig. 7.10 indicates the internal condition of the transfer chute after running AFs at higher moisture content.

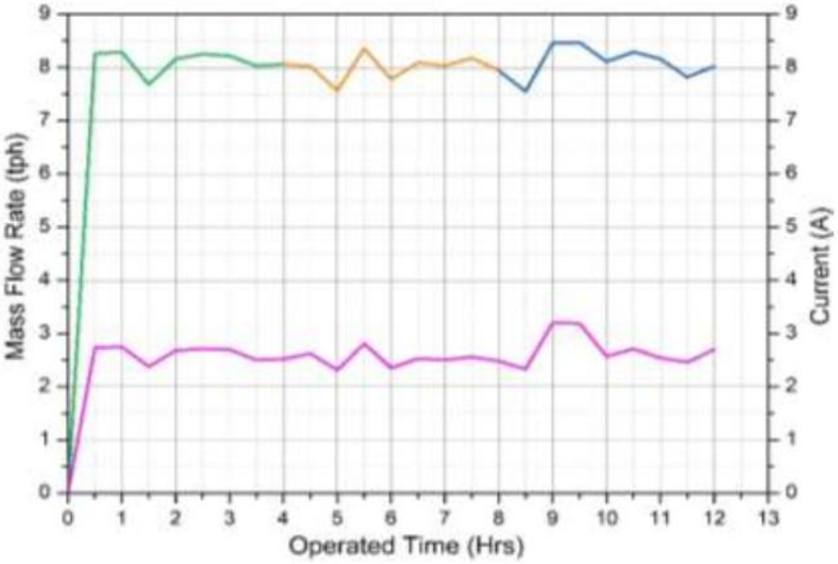
Fig. 7.10 Chute internal condition after running AFs at higher moisture

Fig. 7.10, the flexible transfer chute was tilted to inspect the internal condition of the chute liners. It was found that a thin layer of ETP sludge stuck on chute liners. Apart from ETP sludge, other AFs could not be found on liners. Experiments suggested that ETP sludge should not be used at higher moisture and appropriate dry bulk material (preferably biomass) should be used for impregnation to reduce the moisture level <20%. Although the newly designed transfer chute was capable of handling ETP sludge at 30% moisture, at this moisture content, ETP sludge started sticking on the conveyor belt and formed a sticky paste. Further, experiments were carried out for eight nos. for Mixed Solid Wastes (MSW). There is no standard recipe for the preparing mixed solid waste in Indian cement plants. Plants prepare the MSW based on the available AFs in that geographical location to achieve the desired heat value, Chlorine & Alkalies content and to control the moisture for easy handling. Fig. 7.11 & 7.12 shows the pictures of experiments carried out for various MSWs prepared at NCB based on the suggestions received from plant experts and the performance of the transfer chute was recorded at 8 tph at varying moisture.

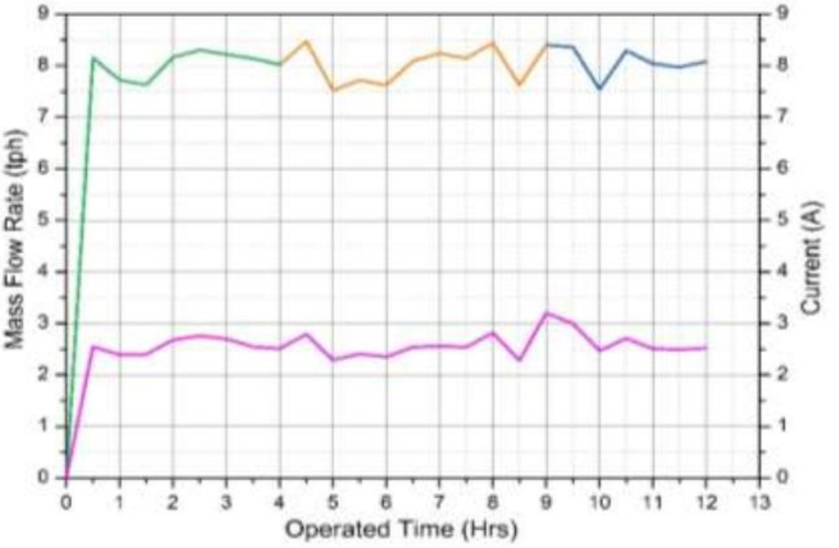
Mixed Waste-1 Mixed Waste-2 Mixed Waste-3 Mixed Waste-4

Mixed Waste-5 Mixed Waste-6 Mixed Waste-7 Mixed Waste-8

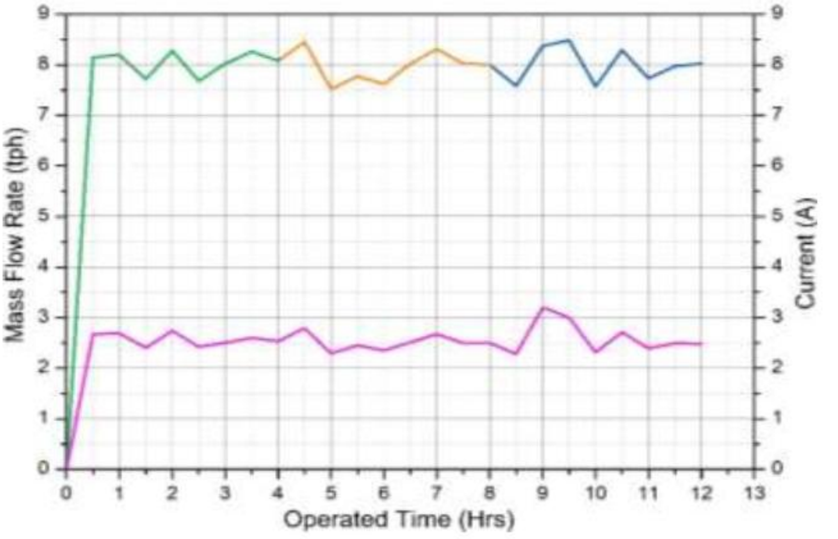
Fig. 7.11 Experiments for mixed solid waste prepared at NCCBM



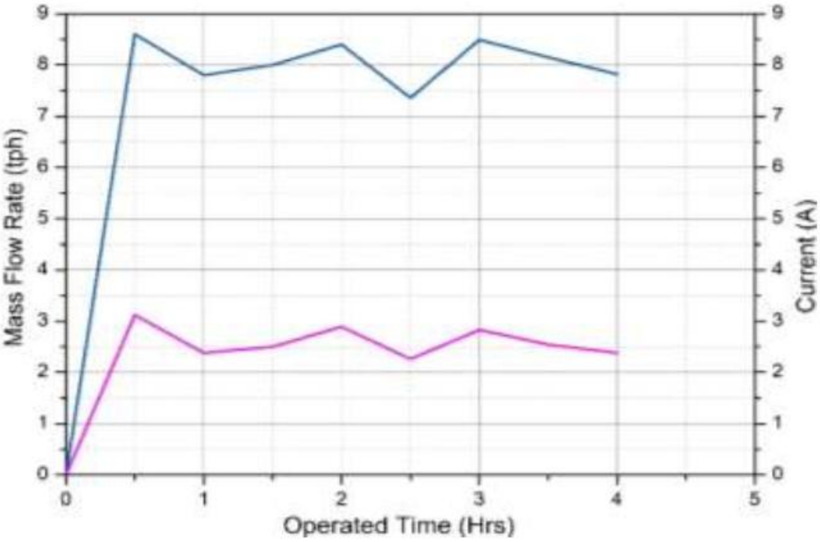
a. MSW-1



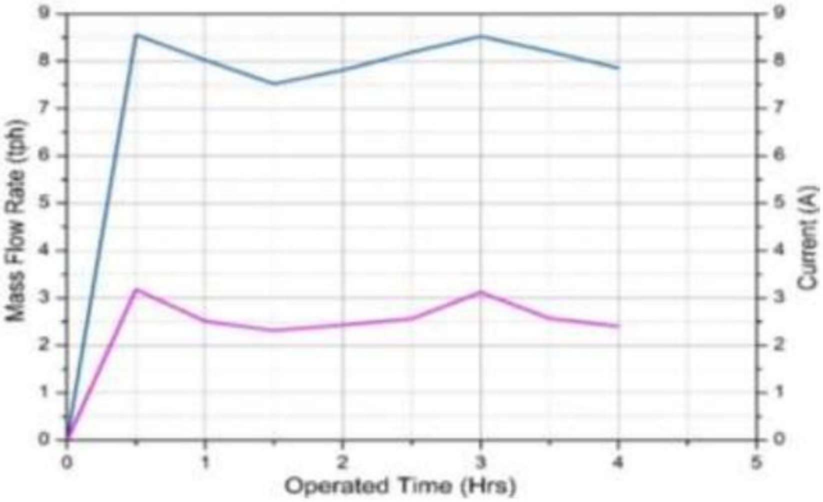
b. MSW-2



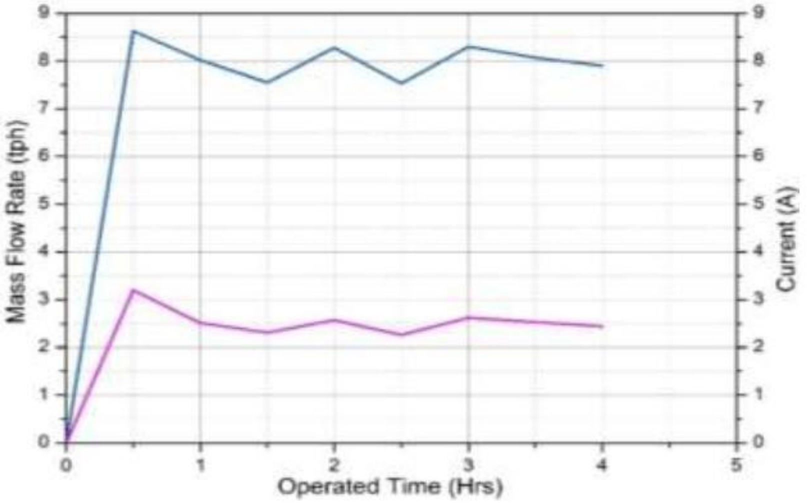
c. MSW-3



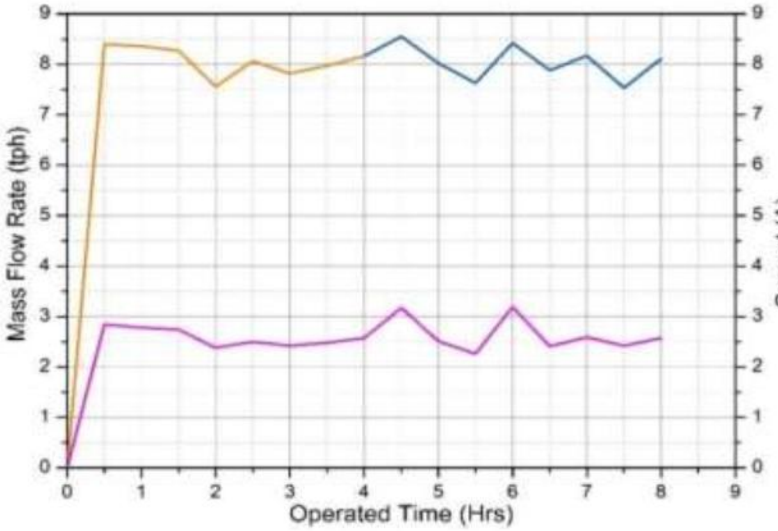
d. MSW-4



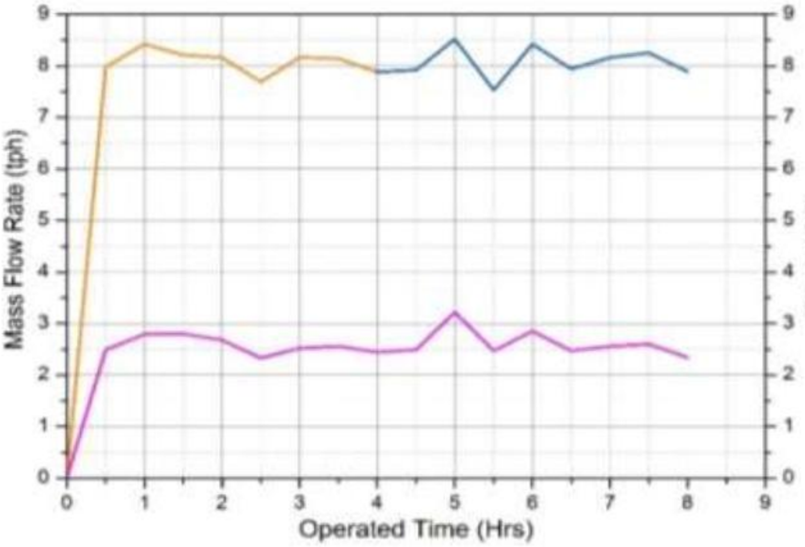
e. MSW-5



f. MSW-6



g. MSW-7



h. MSW-8

— **Mass Flow Rate at 10 % moisture content**
— **Mass Flow Rate at 20 % moisture content**
— **Mass Flow Rate at 30 % moisture content**
— **Mass Flow Rate at 45 % moisture content**
— **Current**

Fig. 7.12 Chute performance at varying moisture for mixed solid wastes

MSW-1, 2, and 3 are the mix of biomass & agro waste, operated for 4 hrs each at 20%, 30%, and 45% moisture. It was observed that the mass flow rate fluctuation was recorded within the range of -3 to +5% as shown in Fig. 7.12 (a to c). MSW-4, 5, and 6 (have moisture 26.47 to 29.20 %) operated at 45% moisture for 4 hrs, where the mass flow rate fluctuation was recorded within the range of -6 to +8% as shown in Fig. 7.12 (d to f), which is high as compared to MSW-1,2&3. Further, MSW-7 & 8 which are the mix of RDFs, biomass & agro waste with moisture content <25%, have been operated for 4 hrs each at 30% & 45% moisture content. It was observed that with the addition of biomass, the fluctuation in mass flow rate reduces in the range of -1 to +2 % when compared with MSW-4, 5 & 6. The recorded value for mass flow rate fluctuations for MSW-7 & 8 was 4 to 5.5 % (at 30% moisture) and 6 to 6.87% (at 45% moisture) as shown in Fig. 7.12 (g & h). The experiment shows that the newly designed chute did not jam for any MSW material, even at 45% moisture content. In the experiment, moisture content was restricted up to 45% maximum due to various considerations in cement plant operation. Cement plants do not prefer to use AFs with moisture exceeding 40% as it demands some energy for water evaporation, increasing the combustion time while decreasing the process efficiency and production capacity.

The experiments established that the newly designed transfer chute performed well at a higher moisture content of up to 45%. The total 15 nos. AFs & their mix have been operated for a total of 129 hours without jamming or any other trouble with the transfer chute.

Further to check the performance of the transfer chute at 45% moisture for biomass & agro-waste material i.e., MSW-3 was carried out at 8 tph for 4 hours duration as shown in Fig. 7.13. The mass flow rate was noted every 10 minutes. It was observed that the conventional transfer chute did not perform well for MSW-3. However, the chute did not get jammed during 4 hours of operation, but mass flow started to decrease with time, and when the internal was inspected, it was found that the substantial material was stuck on the chute wall which may lead to the chute jamming in long-running.

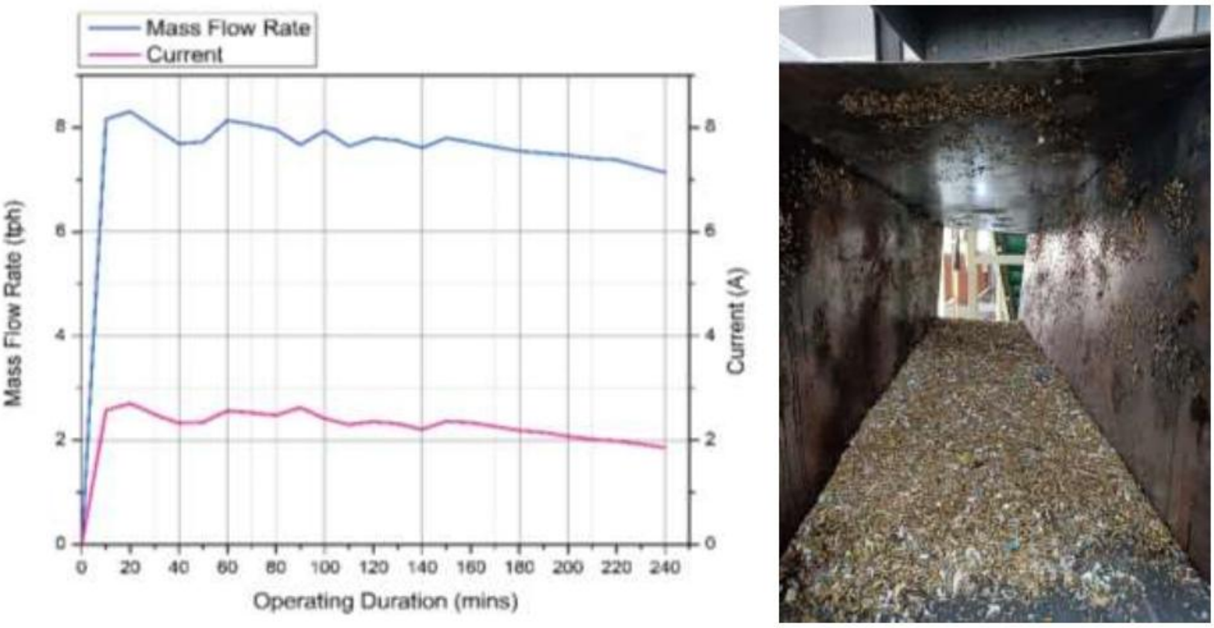


Fig. 7.13 Conventional transfer chute performance for MSW-3 at 45% moisture

7.2.3 Chute Performance at Varying Conveying Speed

Varying the speed of the belt in a transfer chute can significantly impact on the material flow behaviour. The transfer chute should perform well at optimum belt speed, and the role of the transfer chute is to ensure the well-distributed material discharge on the belt conveyor. The experiments were carried out to identify the optimal belt speed for a given material at which the newly designed transfer chute performs well. The materials were tested at three different conveying belt speed ranges: 0.5 to 0.8 m/s, 0.9 to 1.2 m/s, and 1.3 to 1.5 m/s using VFD. This was likely done to determine how the varying speed of the belt would affect the behaviour of the materials being conveyed through the transfer tower. When the speed is too high, the material does not have enough time to settle on the belt accumulated on the right-hand side of the belt. Conversely, when the speed is too low, the material has more time to settle on the belt, causing it to accumulate on the left side. This can result in reduced conveyor capacity, increased power consumption, and more significant wear and tear on the belt and other components of the conveyor system. Due to differences in bulk density, different AF demands different optimum belt speeds.

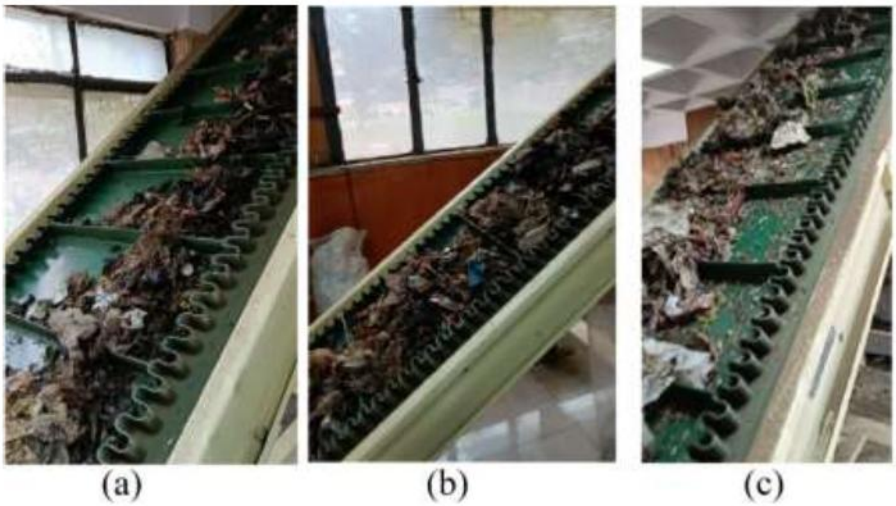


Fig. 7.14 RDF discharge profile on the conveyor at varying belt speed (a) 0.5 to 0.7 m/s, (b) 0.8 to 1.2 m/s, (c) 1.3 to 1.5 m/s

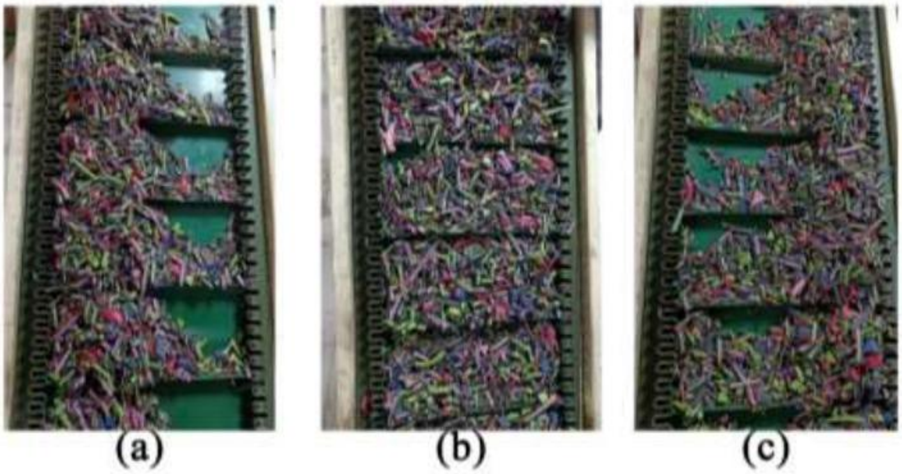


Fig. 7.15 Footwear discharge profile on the conveyor at varying belt speed (a) 0.5 to 0.7 m/s, (b) 0.8 to 1.2 m/s, (c) 1.3 to 1.5 m/s

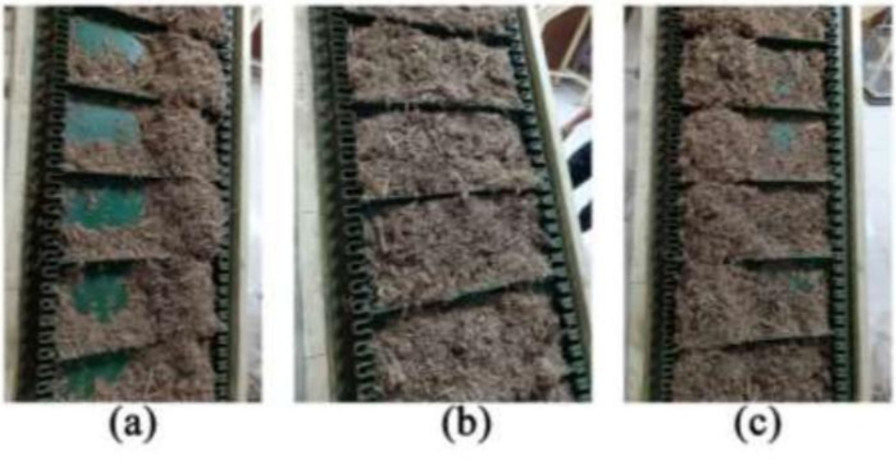


Fig. 7.16 Bagasse discharge profile on the conveyor at varying belt speed (a) 0.5 to 0.7 m/s, (b) 0.8 to 1.2 m/s, (c) 1.3 to 1.5 m/s

RDF, biomass, and footwear waste were selected for experimentation (Fig. 7.14, 7.15, 7.16), and the results indicate that the behaviour of the sample materials was speed-dependent when passing through the transfer chute. It was observed based on the experiments that AFs operate well at the conveying speed of 0.8 to 1.2 m/s. However, 1.0 to 1.2 m/s is the optimum conveying speed, which keeps the material well distributed on the discharge conveyor. This optimum speed, apart from well-distributed material on the discharge conveyor, also provides other benefits like fugitive dust emission and wear of chute liners and conveyor components.

7.3 Liners Wear Rate

Ultra-high molecular weight polyethylene liners are used to protect the mother plate of the chute wall and assist the flow of AFs. The performance of liners was assessed for flowability (based on AoI) and wear rate. It was found during the experiment that with these types of liners, most of AFs start to slide at an angle of 2 to 3 degrees less when compared to mild steel. A wear measurement template made from a 2 mm thick and 1016 mm long machined MS sheet was used to measure the wear rate. A flexible chute was used for measuring the liner wear of all four-side walls indicated as 1,2,3,4 and marked in Fig. 7.17

Fig. 7.17 Marking of liners in the flexible chute for wear measurement

Further, data related to the wear of these liners were recorded as shown in Table 7.4 at the following intervals-

Table 7.4 Wear rate of UHMWPE liners

S. No.	Description	Duration (hours)	Wear (mm)			
			1	2	3	4
1.	After running all RDFs (5 nos.) at varying the mass flow rate and constant moisture	60	<0.01	<0.01	<0.01	<0.01
2.	After running of AFs at varying mass flow rates and constant moisture	72	<0.01	<0.01	<0.01	<0.01
3.	After running RDF-1,3,4 & 5 at varying moisture content	36	<0.01	<0.01	<0.01	<0.01
4.	After running bagasse, parali, and ETP sludge at varying moisture content	29	> 0.01 & <0.02	> 0.01 & <0.02	<0.01	<0.01
5.	After running mixed waste (8 nos.) at varying moisture content	64	> 0.01 & <0.02	> 0.01 & <0.02	<0.01	<0.01
Total Operational Hours		**261**				

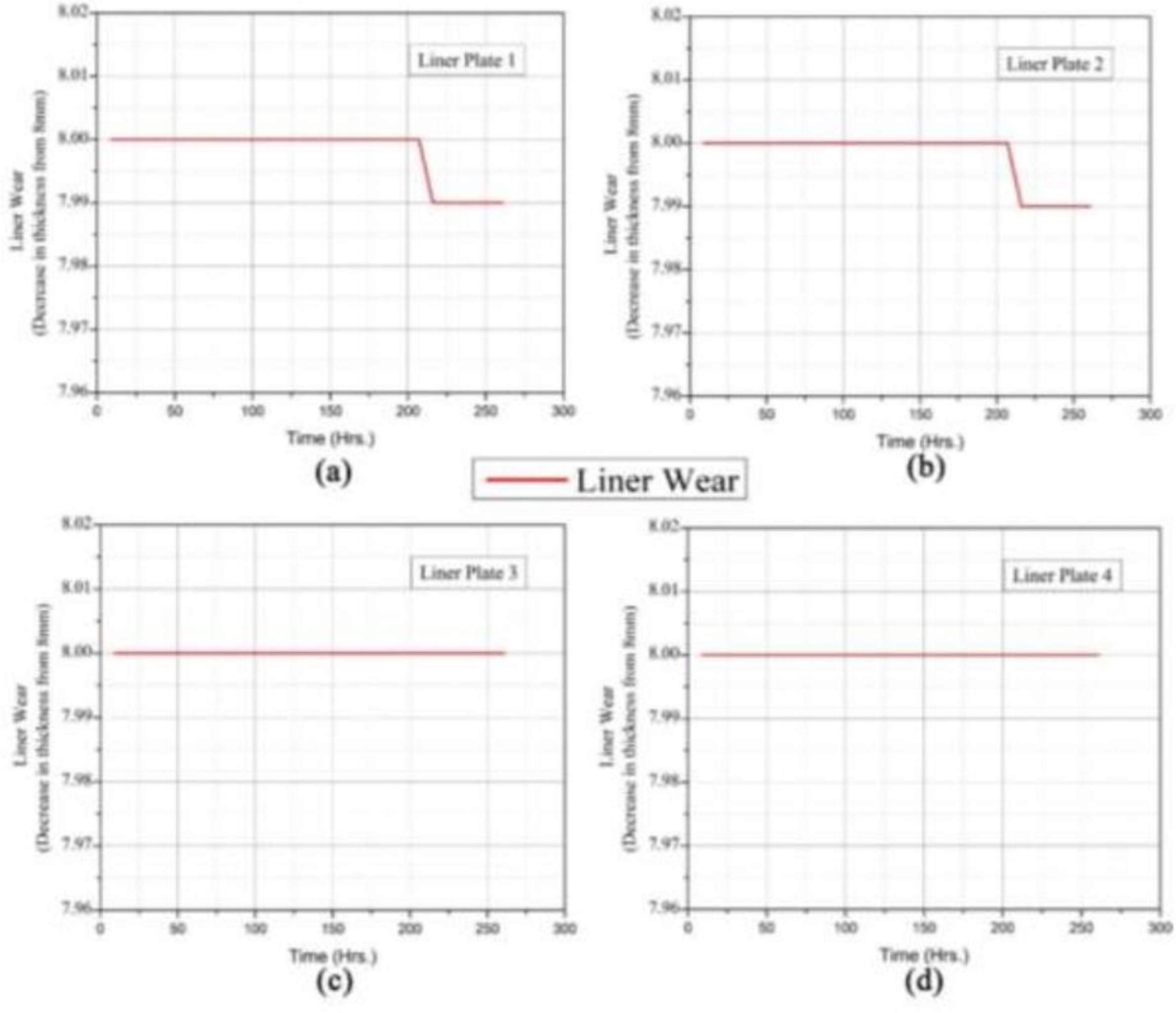


Fig. 7.18 Wear rate of UHMWPE liners

The results of wear rate as shown in Fig. 7.18 (a) to (d) highlight that applying these types of liners for AFs application can be beneficial. If we consider the recorded wear rate as the basis for the valuable life calculation of liners, these liners may provide a life of 50,000 hrs with 5 to 6 years of plant operation. Besides good wear resistance and flow assistance quality, these liners are cost-effective and light weights. Except for ETP sludge at high moisture (30%), no other materials were found sticking on the liners. However, for ETP sludge operation at 30% moisture, the thickness of the layer stick on the liners was considered negligible compared to conventional MS/SS liners used in the cement industry. Available literature also supports the application of these liners where high resistance to corrosive chemicals is needed. Hence, for hazardous waste also, these types of liners can be used. Indian cement plants use many agro wastes, which contain silica and cause the high wear of liners. The research outcome indicates that the wear can be reduced substantially by replacing MS/SS liners with UHMWPE liners.

7.4 Comparison of Experimental Results with Simulation

Comparing the simulation and experimental results is an essential step in evaluating and validating the accuracy of the simulation model. The transfer chute design, developed from simulation, is based on the 14 nos. AFs, including RDFs, MSWs, MLP, TDF, biomass & agro waste, ETP sludge, and footwear waste, whereas the experiments were carried out for 19 nos. AFs, including all types of AFs considered during simulation. The comparison between AFs properties considered in simulation and experiments is indicated in Table 7.5, which shows that the experiments cover all the range of AFs considered during simulation, and experimental results can be compared with simulation results.

Table 7.5 AFs properties considered in simulation & experiments

S. No.	Bulk Properties	Unit	Value	
			Simulation	Experiments
1.	Bulk density	t/m^3	0.09 to 0.50	0.100 to 0.610
2.	Moisture content	%	0 to 35	0.18 to 45
3.	Angle of inclination	deg	14 to 45	19.90 to 38.80
4.	Angle of repose	deg	23.7 to 60	25.44 to 52.53
5.	Particle size variation	mm	5-100	1-100
6.	Conveying speed	m/s	1.0	0.5 to 1.5

Fig. 7.19 indicates the mean value along with the range (standard deviation) of input data for simulation as well as experiments.

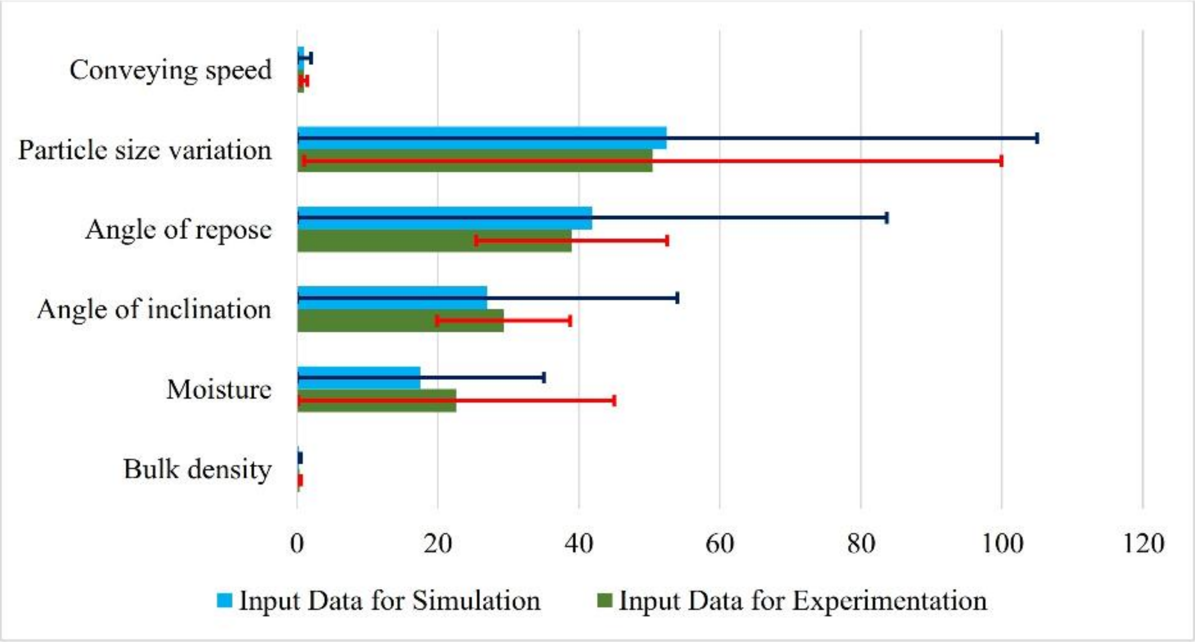


Fig. 7.19 Comparison of AFs properties considered in simulation & experiments

In comparing experimental data, measured in hours, with simulation data, measured in seconds, the difference in the time scale is because it is often not feasible to run simulations for the same length of time as experimental tests due to the computational resources required. For instance, even for simulations lasting just 15-30 seconds, it may take 15-20 days to complete with a high-configuration hardware system. The purpose of the simulation was to get an indication of material flow and the tendency to stick on chute walls/liners when passing through the transfer chute. The time duration of the simulation of the stabilized material flow was taken and compared with the experimental data. By doing so, the performance of the transfer chute was effectively compared with the simulation to capture the behaviour of the system accurately.

To facilitate the comparison, the duration of material runs in simulation & experiments was divided into parts, and the stabilized part of the simulation was compared with the experimental results. Notably, the absence of jamming during the experimental run of materials allowed for a meaningful comparison with the stabilized part of the simulation.

Specifically, the simulations were conducted for 20-30 seconds, during which the material flow rate stabilized within 12-20 seconds, depending on the type of AFs and this stabilization period provided 8 to 12 seconds of data which can be compared with the data obtained from the experimental results.

The properties of materials are influenced by a variety of factors such as their source, geographical location, processing method, and the presence of impurities, etc. As a result, it can be challenging to ensure that the material considered during the simulation and the one used for experimentation are precisely the same. However, the following materials (RDF, MSW, Parali, and TDF) having comparable properties between experiments & simulations as shown in Table 7.6, were considered to analyze the results

Table 7.6 AFs selected for comparing the results for simulation & experiments

Bulk Properties	**Unit**	**S**	**E**	**S**	**E**	**S**	**E**	**S**	**E**
		RDF-1	**RDF-3**	**MSW-2**	**MSW -8**	**Parali**		**TDF**	
Bulk density	t/m^3	0.20	0.213	0.23	0.188	0.09	0.110	0.50	0.610
Moisture content	%	35.00	33.39	30.00	22.26	10.00	10.95	0.00	0.36
Angle of inclination	degree	30.00	38.80	27.50	32.60	20.00	19.90	35.00	34.30
Angle of repose	degree	60.00	52.53	43.00	43.30	26.00	25.44	40.00	39.14
Particle size	mm	<90	<90	<100		<30		<50	

S-Simulation, E-Experiment

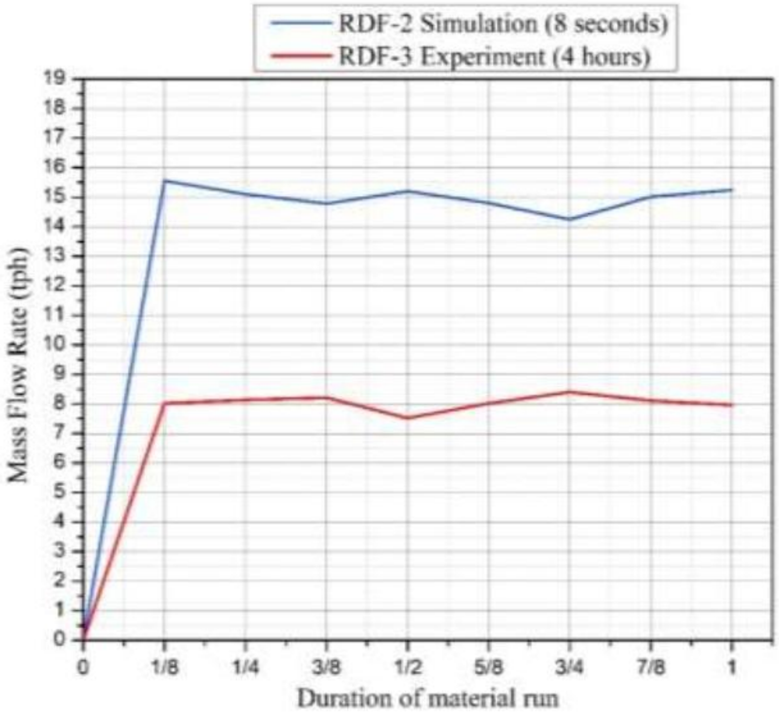


Fig. 7.20 RDF flow through the chute, simulation vs. experiment

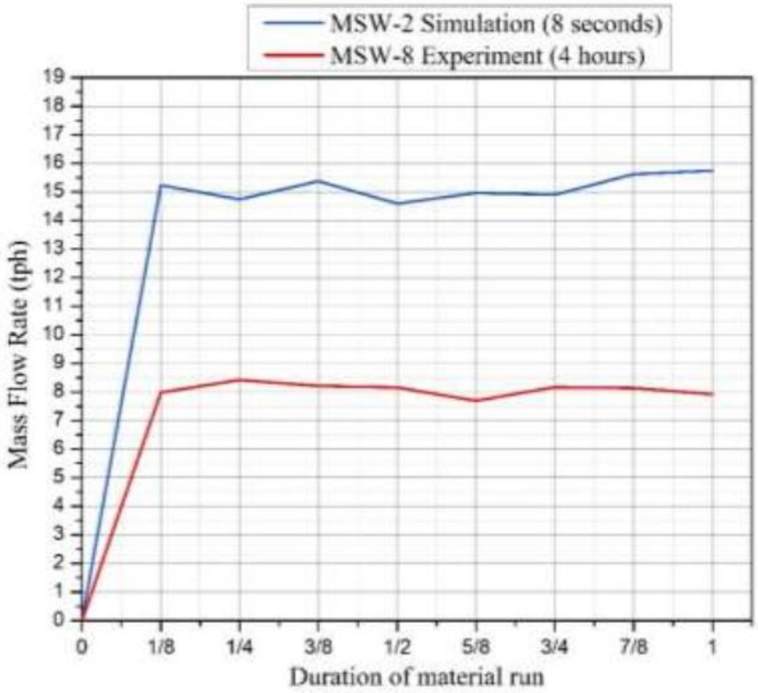


Fig. 7.21 MSW flow through chute, simulation vs experiment

Fig. 7.20 indicates a fluctuation trend in the mass flow rate of RDF-2 & RDF-3, which represent simulation and experiment results and are comparable. RDF-2, the simulation results indicate the fluctuation in mass flow rate from ±7 % in stable conditions (from 23sec to sec30), where the fluctuations in mass flow rates are recorded within the range of ± 6% during an experiment of 4 hours. Simulation for RDF-2 was done at a 15 tph mass flow rate where the 800mm belt conveyor was considered; however, experiments were done at 8 tph for 4 hours duration where the effective width available was 600mm, but in both cases, the design parameters for transfer chute was selected accordingly.

Similarly, Fig. 7.21 indicates a fluctuation trend in the mass flow rate of MSW-2 & MSW-8, which represent simulation and experiment results, respectively, are comparable. MSW-2, the simulation outcome, shows the fluctuation range ± 5% in stable conditions (from 23 sec to sec 30), where the fluctuations in mass flow rates are recorded within the range of ± 6% (4 hours operation) during the experiment. Although the AoR for the material is at par, however, a minor difference observed in the results may be the influence of other properties like bulk density and AoI.

Fig. 7.22 indicates the fluctuation trend in the mass flow rate of Parali, which is comparable in simulation as well as experiments. The simulation outcome shows the fluctuation range ± 2% in stable conditions (from 13 sec to sec 20), where the fluctuations in mass flow rates are recorded within the range of ±1% during the experiment. Similarly, for TDF, as indicated in Fig. 7.23, the operating mass flow rate in simulation and experiments were 15 tph, and both show the fluctuation in mass flow rate in the range of ± 3%.

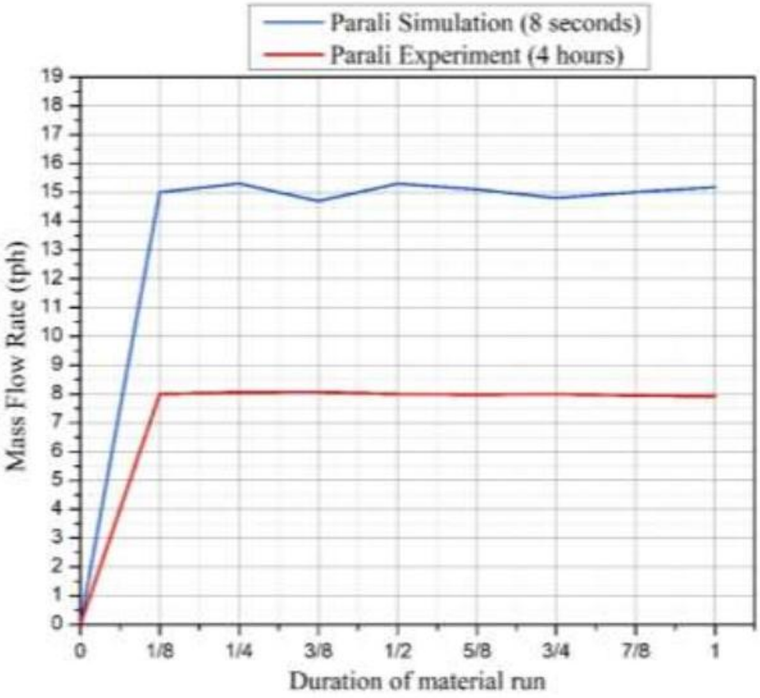


Fig. 7.22 Parali flow through chute, simulation vs experiment

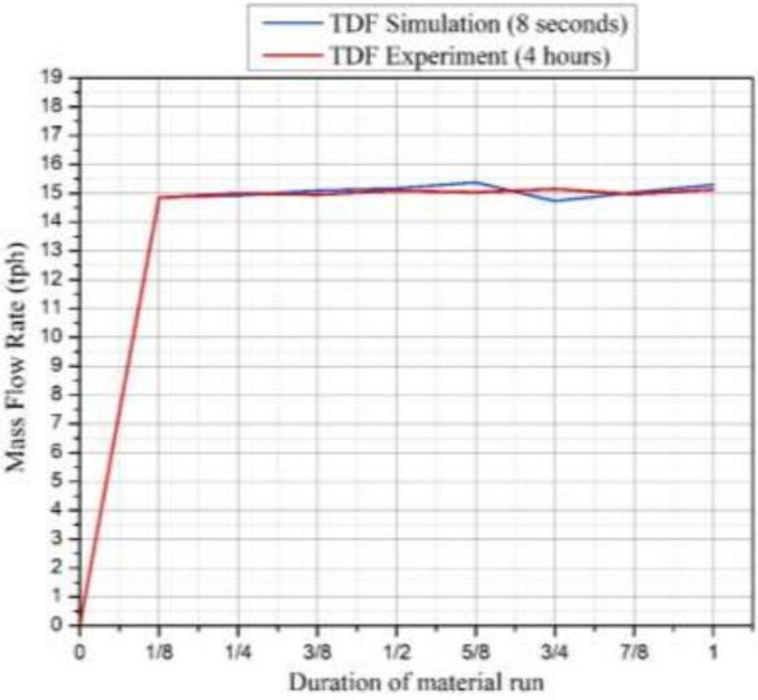


Fig. 7.23 TDF flow through chute, simulation vs experiment

Hence, the comparison shows that the simulation and experimentation are at par. The flow of TDF and parali are smooth, and MSW & RDF have slight fluctuation due to their material characteristics. However, in all the conditions, the newly designed transfer chute performed well in simulation as well as in experiments.

7.5 Validation of the flexible feature of the transfer chute for fast cleaning

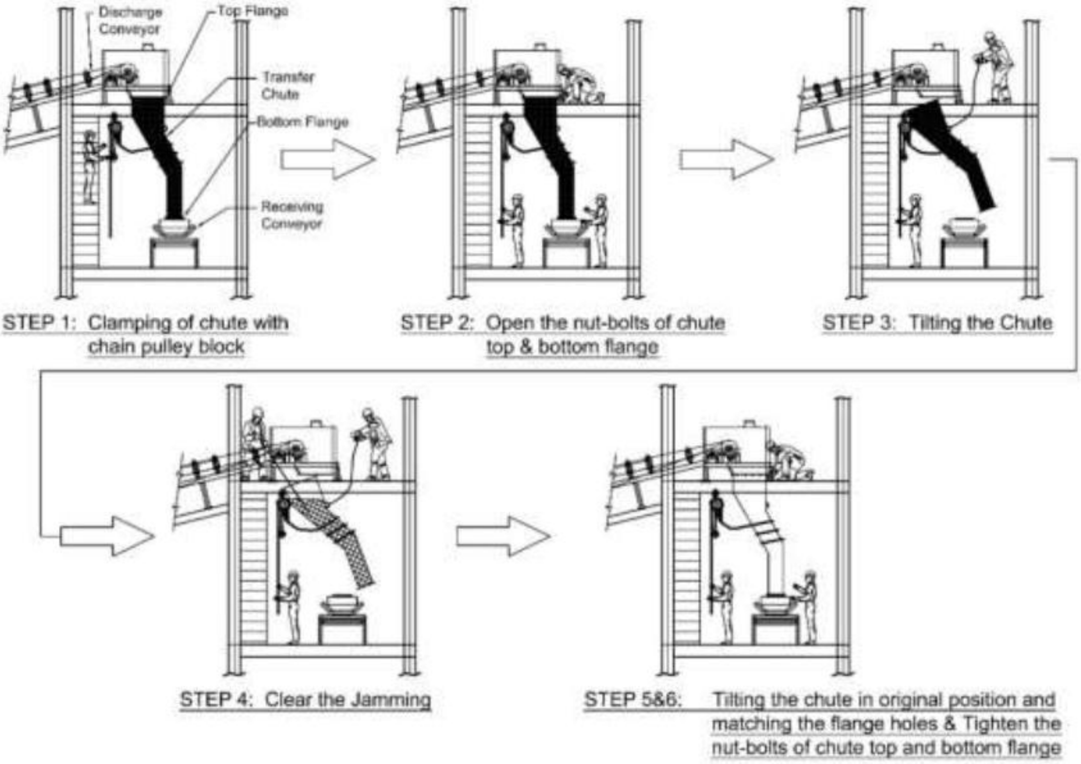
Flexibility in the transfer chute is one of the significant outcomes of this research work. In cement plants, a flexible transfer chute handling AFs, with an arrangement of the electrical geared motor along with a rotating/tilting arrangement, facilitates the clearing of the completely jammed chute within **6 minutes** compared to the conventional method, which takes **a minimum of 85 minutes**). The component and the functioning of the flexible transfer chute developed under this research is discussed in Chapter 6. Here, the comparison of conventional transfer chute with the flexible chute is discussed.

Conventional transfer chute, handling solid alternative fuels in cement plants, when completely jammed (*caking type accumulation due to poor flowability & high moisture content of alternative fuels*), requires, on average, 85 to 105 minutes for clearing and restarting (discussed in Chapter 3). The higher downtime required for chute clearance harms the operation, quality, environment, and production of cement as the supply of alternative fuels to the rotary kiln is stopped. Table 7.7 indicates the average time required to clear the jammed transfer chute (discussed in Chapter 3) -

Table 7.7 Time required to clean the conventional transfer chute

Step no.	Activity	Average Time (minutes)
1.	Clamping of the chute with chain pulley block	15
2.	Open the nut-bolts of the chute top & bottom flange	20
3.	Tilting the Chute	10
4.	Clear the Jamming	15
5.	Tilting the chute in its original position and matching the flange holes	15
6.	Tighten the nut-bolts of the chute top & bottom flange	15
Total time required (minutes)		**90**

The average time required to clean the transfer chute is 90 minutes, assuming the chain pulley block is permanently installed in the transfer tower, and manpower (Two nos. skilled and one no. unskilled) is available immediately. Fig. 7.24 shows the systematic steps to clean the transfer chute with the conventional process.



STEP 1: Clamping of chute with chain pulley block

STEP 2: Open the nut-bolts of chute top & bottom flange

STEP 3: Tilting the Chute

STEP 4: Clear the Jamming

STEP 5&6: Tilting the chute in original position and matching the flange holes & Tighten the nut-bolts of chute top and bottom flange

Fig. 7.24 Conventional process of transfer chute cleaning

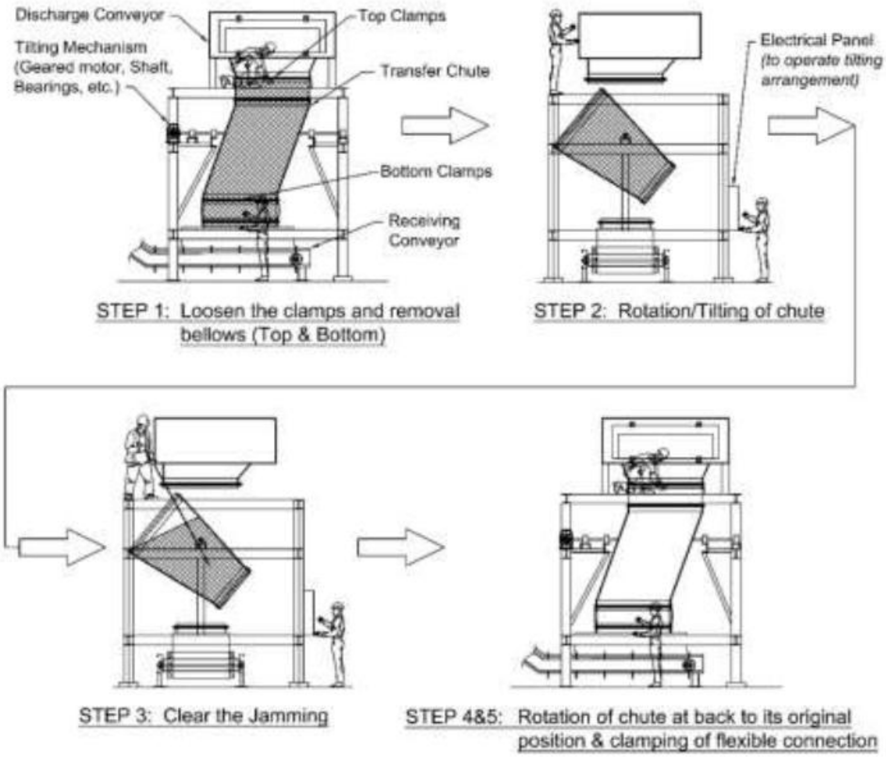
During the experiment, it was found that by using a flexible motorized tilting/rotating chute the jamming of solid alternative fuels is cleared in a very short time, i.e., 6 minutes, as compared to the conventional technique. It is to be noted that buffer storage of 10 minutes for alternative fuels is available in the bin (hopper) near the cement rotary kiln/calciner firing points, and the time elapsed for clearing the chute is 6 minutes, stopping the alternative fuels feeding system to the rotary kiln and calciner is not required. Table 7.8 indicates the process for cleaning the transfer chute with a flexible chute arrangement-

Table 7.8 Chute cleaning with flexible chute

Step no.	Activity	Duration (minutes)	Manpower Requirement
1.	Loosen the clamps and remove bellows (Top & Bottom)	1	

Step no.	Activity	Duration (minutes)	Manpower Requirement
2.	Rotation/Tilting of the chute	1	One no. skilled manpower & one no. unskilled
3.	Clear the Jamming	2	
4.	Rotation of chute at back to its original position	1	
5.	Clamps of flexible connection	1	
Total Duration (minutes)		**6**	

Fig. 7.25 & 7.26 shows the systematic steps to clean the transfer chute with a newly developed flexible transfer chute.



STEP 1: Loosen the clamps and removal bellows (Top & Bottom)

STEP 2: Rotation/Tilting of chute

STEP 3: Clear the Jamming

STEP 4&5: Rotation of chute at back to its original position & clamping of flexible connection

Fig. 7.25 Steps to clean the transfer chute with flexible transfer chute

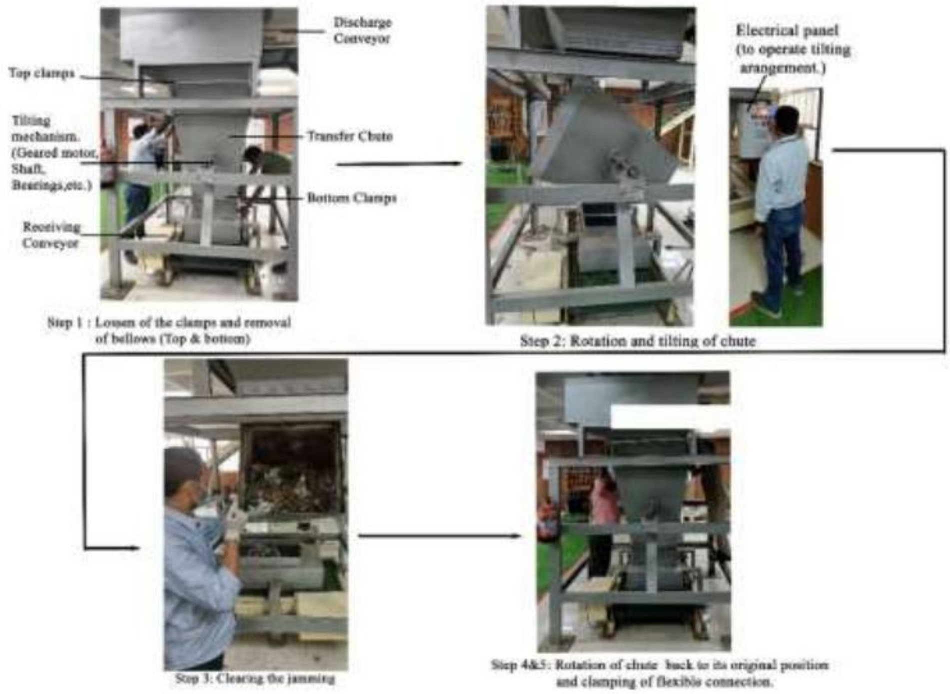


Fig. 7.26 Pictorial presentation of flexible transfer chute cleaning (to be added)

Currently, plants use two methods to clean the transfer chute if jammed while handling AFs- (1) the Conventional approach, as discussed in Fig. 7.24, (2) Installing an air blaster or hammering on the chute wall. Table 7.9 compares the existing two methods with the newly developed flexible transfer.

Table 7.9 Flexible transfer chute comparison with existing methods

Parameters for Comparison	Conventional Process	Air blaster and hammering	Flexible Transfer Chute
Method to detach the transfer chute from the circuit	Opening of Top & Bottom Flange Bolts	Not required	Through quick-releasing clamp
Chute dismantling from the circuit	Through chain pulley block	Not required	Not required
Manpower Required	Two nos. skilled & 1 no. unskilled	Not required	One no. skilled & one no. unskilled
Effectiveness of methods/devices	High when the chute is completely jammed	Effective when the chute is partly/locally Jammed	High when the chute is completely jammed

Parameters for Comparison	Conventional Process	Air blaster and hammering	Flexible Transfer Chute
Safety aspect	Lesser safe, more human interference	Safe, involves less human interference	Safe, involves less human interference
AFs feed cut in the circuit	Yes	No	No

The flexible transfer chute reduces the transfer chute downtime, increasing its reliability by reducing the time and workforce required to de-clog the chute, thereby lessening stoppages of the alternative fuel feeding system of the kiln/ calciner and having no negative impact on plant operation.

7.5.1 Techno-economic benefits of flexible transfer chute.

Flexible transfer chute contributes to techno-economic benefits by avoiding alternative fuel-feeding cuts to the cement rotary kiln system. Table 7.10 elaborates on the example of a 1.0 MTPA capacity cement plant using coal as the primary fuel (65%) and other solid wastes as an alternative fuel (35%)

Table 7.10 Techno-economic benefits of flexible chute in a cement plant

S.No.	Parameters	Value	Unit	Remarks
		Cement plant operational data		
1.	Clinker production capacity	125	tonnes per hour (tph)	1 million tonnes per annum (24 hrs operation per day and 330 days per annum)
2.	Specific Heat Consumption (SHC)	700	kcal/kg clinker	Indian Average SHC
3.	Total thermal energy requirement	87500000	kcal/hr	
4.	Thermal Substitution Rate	35	%	Thermal energy replace by alternative fuels
5.	The heat is taken from the coal	56875000	kcal/hr	
6.	Average Cost of Coal	2.5	INR/1000 kcal	Average NCV 5000 kcal/kg

S.No.	Parameters	Value	Unit	Remarks
7.	The heat is taken from the AFs	30625000	kcal/hr	
8.	Average Cost of Alternative Fuels	1.0	INR/1000 kcal	Average NCV 2500 kcal/kg
When the feed of AFs is cut due to chute jamming for 90 min once a week				
a)	**Impact on Fuel Cost**			
1.	Additional coal is fired due to the unavailability of Alternative fuels	6.125	tph	To achieve 30625000 kcal/hr
		431.812	tonnes of coal per annum	Total 47 stops of 90 minutes each due to jamming (330 days plant operation)
2.	**Additional Cost of Fuel**	**3238593.75**	**INR per annum**	Additional Cost= Cost of Coal-Cost of Alternative Fuel
b)	**Impact on Production Loss**			
1.	Loss of clinker	3.64	Tonnes per stoppage	5 minutes per stoppage due to Fuel Changeover from Alternative fuel to coal when the chute is jammed
		171.55	Tonnes per annum	
2.	**Cost impact due to production loss**	**223015**	**INR per annum**	INR 1000/tonne due to loss of profit in cement sale
c)	**Carbon footprint**			
1.	**Reduction in CO_2 Emission**	**791.65**	**Tonnes of CO_2/annum**	Carbon Content in Coal is 50%

S.No.	Parameters	Value	Unit	Remarks
2.	**Required Trees to be planted to compensate above CO_2 emission**	**~25000**	**Nos.**	31 to 46 trees to compensate for 1.00 tonne of CO_2 emission

The 1.00 MTPA Cement plant chute jamming problem creates a loss in the total cost of ***~INR 35.00 Lakhs per annum,*** along with an additional ***792 tonnes of CO_2 emission***. However, in the current trend in India, the preferable size of cement plant is ***3.00 MTPA***. Hence the losses contributed in terms of cost is INR ***1.00 Crores (USD 1,22,000) per annum*** and ***CO_2 emission of ~ 2400 tonnes per annum*** which has a significant impact on the profitability of cement production as well as the sustainability of the cement plant.

The impact of current research is evaluated at the National level, considering due advantages of the newly designed transfer chute for achieving high TSR. At present Indian cement industry is having total installed capacity of 594.14 MTPA, with cement production of around 361 million tonnes (60% capacity utilization) and clinker production of 255.6 MTPA at 0.71 clinker factor[1]. The total fuel requirement for producing 255.6 MTPA is ~38 MTPA (at NCV of 5000 kcal/kg fuel). Fig. 7.35 indicates the scenario of CO_2 mitigation potential at the National Level in different scenarios

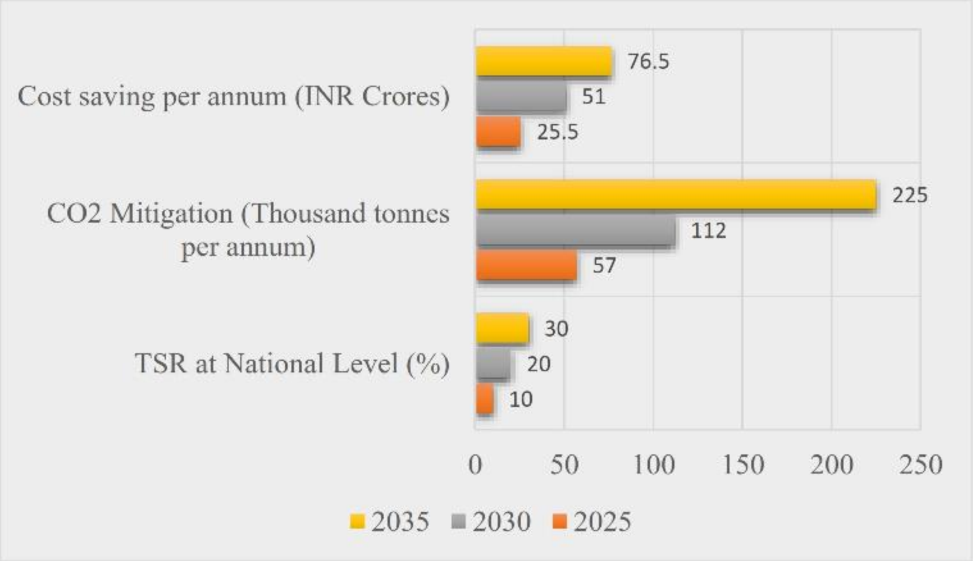


Fig. 7.27 Flexible transfer chute benefits in cement plants at the national level

While estimating the above, the following benefits are not considered, which add another value to current research work-

- Benefits for safe disposal of waste by achieving high TSR.
- Saving the precious land being utilized for landfills
- Avoid losses due to fluctuations in the fuel mix ratio and quality of the product
- Impact of cost benefits by using AFs, when compared to fossil fuel cost
- Less dependency on imported fuel
- Safe operation due to the least interference of human

CHAPTER 8

CONCLUSION AND FUTURE SCOPE OF THE WORK

This chapter discusses the conclusion drawn from the present research work and also presents the possibility for the future scope of the work.

8 Conclusions and Future Scope of the Work

8.1 Conclusions

In this research work, an assessment has been carried out to understand the issues related to conventional transfer chute handling multiple types of AFs & their mix in Indian cement plants. Based on a literature review and survey carried out in the Indian cement industry, it was found that the transfer chute is a major bottleneck for achieving high TSR, and cement plants are spending substantial time and cost to maintain it. It was found that the cement plants still use the conventional approach for chute design (based on the thumb rules), which could not succeed for transfer chutes handling AFs with a wide range of variation in their properties. It was found that all these variations must be necessarily accounted for at the stage of chute design. The survey study also concluded that RDF, mixed solid waste, and industrial waste are the major contributors to transfer chute jamming. The research gaps in the literature review highlighted, that substantial design parameters are not available for such type of transfer chute, and previously, researchers have advocated breakdown maintenance steps for transfer chutes like cleaning jammed chutes followed by preventive maintenance steps like installing an air blaster for chute cleaning and sensors that detect agglomeration and jamming of the transfer chute handling alternative fuels in cement plants. The modification in the design of transfer chute handling AFs at the system design & engineering stage to mitigate its issues has yet to be perceived. It was also noted that technical know-how available from other countries could not be implemented directly in the Indian scenario as the waste composition & its characteristics are entirely different. DEM was found to be the most preferred simulation tool for transfer chute design; however, substantial literature is not available for the application of DEM while handling AFs in cement plants. DEM was used to simulate various AFs like RDF, MLP, agro waste/biomass, tyre chips, footwear waste, ETP sludge, and mixed solid waste in a transfer chute presently used in cement plants. Based on the simulation results, the design parameters of the transfer chute capable of handling multiple types AFs & their mix were determined. An experimental setup comprising of 4 nos. conveyors and four nos. transfer chute was fabricated & installed to validate the design parameters derived from the simulation. The chapter-wise conclusions are given below-

8.1.1 Problem, Causes & Impact

An industrial survey was conducted under the current research to establish the problem associated with transfer chute jamming, its causes, and its impact on Indian cement plants using AFs (Chapter 3). The survey concludes that transfer chute jamming is one of the major bottlenecks for achieving high TSR in Indian cement plants. 78.7% of respondents from Indian cement plants, R&D institutes, and technology suppliers confirmed the issue related to the transfer chute. Plants spend substantial time (50 to 150 hrs per annum) and money to maintain it. About 50 to 70% of AF handling system breakdown hours are due to the chute jamming problem, i.e., (1) Transfer chute and (2) AF feeding chute to Calciner. Alternative fuels, such as RDF, mixed waste, and industrial waste, are difficult to handle materials that lead to chute jamming and to be focused more when developing chute design parameters. The survey also concludes that the cement plants are using the conventional approach for chute design (proven for other bulk materials like limestone, coal, additive and corrective material), which could not work well; it was suggested that the latest tool of modeling and simulation to be adopted for a more practical solution.

8.1.2 Simulation of the New Transfer Chute Design

In Chapter 6, the modeling and simulation of the transfer chute design were carried out using DEM-based simulation tools. The simulation results concluded that the guidelines/thumb rules available in the literature related to transfer chute design parameters are suitable for conventional bulk materials but require optimization for AFs. A total 15 nos. simulations have been carried out under this research work, and the recommended design parameters from simulation for the major AFs such as RDF MLP, TDF, mixed solid waste, footwear waste, ETP sludge, biomass, and agro waste are

- Chute Valley angle (70°),
- Chute width (min 4.3 to 4.5 times the lump size),
- Chute hood height at the material entrance (min 0.6 * belt width),
- Cross-sectional area (10 to 11 times of S, Where S- Cross-sectional area of the material stream inside the chute) and

- UHMWPE liners for smooth flow.

8.1.3 Performance of Newly Designed Transfer Chute

In Chapter 7, the performance of the newly designed transfer chute was assessed on an experimental setup (a close circuit system comprising of four nos. belt conveyors and 4 nos. transfer chute) installed at NCB, Ballabgarh. The objective of the experiments was to validate the design parameters of the newly designed transfer chute in various dynamic conditions of AFs, such as varying mass flow rate, moisture content, conveyor speed, and achievable wear rate of the liners selected. The performance of the newly designed transfer chute was evaluated for 19 types of waste through experiments carried out for 261 hours, and the following results were found-

- The flow of AFs was analyzed at varying mass flow from 3.0 to 15.0 tph at constant moisture. The flow of materials like bagasse, dry ETP sludge, footwear waste, TDF, parali, and MLP was smooth through the transfer chute. Slight fluctuation in the mass flow rate of RDFs was observed due to material heterogeneity, varying particle size & shape, and higher moisture content, which tends to create lumps due to agglomeration. However, the newly designed transfer chute did not jam and performed well for all AFs, including RDFs, in all dynamic conditions, whereas the conventional chute got jammed within 90 minutes for RDFs having moisture beyond 30%.

- The experiments were also carried out at a constant mass flow rate and varying moisture content up to 45 %; with the increase in moisture of RDFs, the mass flow rate fluctuation increases due to lump formation; the same was observed on the conveyors also, but no jamming is observed in the newly designed transfer chute. It was observed that the big size lumps of RDFs with a dimension of 200 mm could also pass easily through the newly designed transfer chute, which was higher than the value considered during the simulation for chute design. This experiment indicates that with increased moisture, the flowability of RDFs reduces due to heterogeneity, high cohesiveness & adhesiveness but no chute jamming has been recorded even up to 45% moisture content. Parali and bagasse could be operated smoothly even at higher moisture up to 45%, and no significant fluctuation in mass flow rate has been observed. However, ETP sludge started to stick on belt conveyors at 30% moisture. Still, experiments were done for ETP sludge for an hour at 30% moisture. Experiments suggested that ETP sludge should not be used at higher moisture and appropriate dry bulk material (preferably biomass) should be used for impregnation to reduce the moisture level <20%. Although the newly designed transfer chute was capable of handling ETP sludge at 30% moisture, at this moisture content, ETP sludge starts sticking on the conveyor belt and forms a sticky paste.

- Further, experiments were carried out for eight nos. for Mixed Solid Wastes (MSW) prepared from RDFs, Biomass, Agro waste, and MLP based on the recommendation received from cement plants. The experiment shows that the newly designed chute did not jam for any of MSW material, even at 45% moisture content. In this research, moisture content has been restricted up to 45% maximum due to various considerations in cement plant operation. Cement plants do not prefer to use AFs with moisture content beyond 40%, As it demands some energy for water evaporation, increasing the combustion time and decreasing the process efficiency and production capacity.

- The results of wear rate are motivating for the application of these types of liners for AFs application. If we consider the recorded wear rate as the basis for the valuable life calculation of liners, these liners may provide a life of 50,000 hrs at least or 5 to 6 years of plant operation.

- The newly developed transfer chute performed well during the experiment for the AFs having a wide range of variation in the material properties, such as bulk density (0.10 to 0.61 t/m^3), moisture content (Dry to 45%), angle of inclination (19.9° to 38.6°), angle of repose (25.44° to 52.53°), and particle size (Fine powder to 100mm).

- The results of experiments were compared with the simulation for RDFs, MSWs, agro waste, and TDF, which shows that the results are at par. The flow of TDF and parali are smooth, and MSW & RDF have slight fluctuation due to their material characteristics. Still, in all the conditions, the newly designed transfer chute performed well in simulation as well as in experiments.

8.1.4 The uniqueness of the research

Flexibility in the transfer chute (Chapter 7) is one of the major outcomes of this research work. In cement plants, a flexible transfer chute handling AFs, with an arrangement of the electrical geared motor along with a rotating/tilting arrangement, facilitates the clearing of the completely jammed chute within **6 minutes** compared to the conventional method, which takes **a minimum of 85 minutes**. The higher downtime required for chute clearance harms the operation, quality, environment, and cement production as the supply of alternative fuels to the rotary kiln is stopped. This problem will further aggravate as the AFs utilization increases in the Indian cement industry. With the flexible chute, it is recorded that the jamming of solid alternative fuels is cleared in a very short time, i.e., 6 minutes, as compared to 85 minutes in the conventional technique. At the same time, 10 minutes of buffer storage of alternative fuels is usually available in the bin (hopper) near the cement rotary kiln/calciner firing points. Therefore, the 6 minutes time duration required for clearing the chute and stopping the AFs feeding system to the rotary kiln and calciner is not required.

8.1.5 Techno-economic impact of research

The impact of current research is evaluated at the National level, considering due advantages of the newly designed transfer chute with flexible arrangement for achieving a high Thermal Substitution Rate (TSR) in Indian cement plants. At present Indian cement industry is having total installed cement production capacity of 594.14 MTPA, with cement production of around 361 million tonnes (60% capacity utilization) and clinker production of 255.6 MTPA at 0.71 clinker factor in 2022-23. The total fuel requirement for producing 255.6 MTPA is ~38 MTPA (at NCV of 5000 kcal/kg fuel). The research outcomes shall contribute to the Indian cement industry in achieving the high TSR and accruing its associated benefits, such as saving in cost ~Rs. 25 to 76 Crores per annum and reduction in CO_2 emission to the tune of 57,000 to 225000 tonnes per annum at an average % TSR value of 10% to 30% by 2035. Other benefits of current research will be the safe disposal of waste by achieving high TSR, saving in the precious land being utilized for landfills, avoiding losses due to fluctuation in the fuel mix ratio and quality of the product, impact of cost benefits by utilizing AFs, when compared to fossil fuel cost, less dependency on imported fuel and safe operation due to least interference of human.

8.2 Future scope of the work

In the present work, the design and development of the transfer chute capable of handling multiple types of AFs & their mix without jamming have been done. The followings are the future scope of the work:

- Design and development of the chute feeding AFs to Calciner may be carried out. An industrial survey carried out under this research work highlighted that about 50 to 70% of system operation and maintenance breakdown hours are due to the chute jamming problem, i.e., (1) Transfer chute and (2) AF feeding chute to Calciner. Transfer chute design parameters are available now as the outcome of this research work. However, research for chute design for AFs feeding to calciner may be carried out.

- Design and development of the transfer chute covering the fugitive dust emissions and wear characteristics while handling AFs & their mix may be carried out.

- Current research work covers the ETP sludge; however, further research may be done to assess the transfer chute performance while handling other hazardous waste like oil sludge, paint sludge, oil-bearing soil, sewage sludge, etc.

- Long-term assessment for UHMWPE liners may be carried out to assess their useful life, compatibility with AFs, and chemical reactivity with hazardous waste.

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LIST OF PUBLICATIONS

Patent

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Book Chapter

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BRIEF BIOGRAPHY OF THE CANDIDATE AND SUPERVISORS

About the candidate

Kapil Kukreja completed his B.E. Degree in Mechanical Engineering from Maharana Pratap College of Technology, Gwalior, Madhya Pradesh in 2004. He obtained his master's degree in Energy and Environment Management from the Indian Institute of Technology, Delhi in the year 2015. He joined BITS Pilani as a Part-time Ph.D. student in the Mechanical Engineering department in 2018.

He is working as Group Manager and Programme Leader-Project Engineering & System Design in National Council for Cement and Building Materials (NCB), Ballabgarh, Haryana (An R&D Organisation under the administrative control of Ministry of Commerce and Industry, Govt. of India). He has total 18+ yrs of experience in the field of system design, project engineering & management. He rendered his services to Holtec Consulting Pvt Ltd., Gurgaon, Haryana (2007 to 2014), ACC Cement, Chaibasa, Jharkhand (2006 to 2007), JK White Cement, Gotan, Rajasthan (2005 to 2006) and National Steel And Agro Industry Limited, Indore, Madhya Pradesh (2004 to 2005). He Joined NCB in 2014. During his professional career, he has successfully completed various international assignments including Belgium, Germany, Poland, Japan, China, Vietnam, Mongolia, Sri Lanka, Congo, Oman, Saudi Arabia etc. He is the Member of BIS Committee MED-7 & MED-18. During his doctoral research he has published a patent, various research papers in internationals journals of repute, book chapter and many technical papers in international conferences. He also received the Best Scientist Award of NCB in the year 2016.

About the Supervisor

Dr. Manoj Kumar Soni is a Professor in the Mechanical Engineering department and coordinator of the Centre for Renewable Energy and Environment Development (CREED) at Birla Institute of Technology and Science (BITS), Pilani. He is a B.E. (Mechanical), M.E. (Thermal Power Engineering), and Ph.D. in Energy Efficiency. He was a faculty at VNIT Nagpur before joining BITS Pilani in 2002 with 27+ years of teaching and research experience.

His research interest includes solar thermal, thermal engineering, renewable energy, and energy efficiency. He has co-authored three books, viz, Indian and International adaptations of the world-renowned book **"Fundamentals of Thermodynamics, Claus Borgnakke, Richard E. Sonntag."** He recently published a book on "**Prime Movers and Fluid Machines**." He has published 30+ research articles in high-impact factor international journals, two book chapters, and 24 papers at international conferences. He has filed three patents, two Indian and one USA. He has delivered keynote addresses at various international conferences and workshops. He has also conducted faculty development workshops.

Recently, he has been appointed as a **member of the Advisory board** for the ArcelorMittal Nippon Steel India - Academy for Skill Development.

As a research team member, he visited P.T. Indo Bharat Rayon, Indonesia, an Aditya Birla Group unit, in 2011. In 2015, he was awarded a Summer Scholarship under the university immersion scheme of BITS Pilani. He visited the University of South Florida, Tampa, and Columbia University, New York.

He is the recipient of the prestigious Dr. Shirin Gadhia Sustainability Award 2019 from Eco Center ICNEER, Vadodara. He also received **Stifterverband Scholarship from Institut für Werkzeugmaschinen und Fertigungstechnik, Technische Universität, Braunschweig, Germany**, in 2019 for visiting **TU Braunschweig** for one week of his research work.

He was a **Jury member** for the **9th Manufacturing Today Conference and Awards 2021**, organized by **Aditya Birla Group, ManufacturingToday**, and **LOCTITE**. Also, a jury member of the **4th, 5th and 6th VDMA Manufacturing Excellence Award** (Energy Efficiency & Conservation - Large Category), organized by **Verband Deutscher Maschinen- und Anlagenbau (**VDMA) India., which is the India office of The German Engineering Federation (VDMA).

He has a particular interest in spirituality and has mixed the philosophies of spirituality and thermodynamics. He has delivered special lectures on ***Thermodynamics- A philosophy of life*** and ***A date with entropy*** at various institutes. The students, academicians, and industries greatly appreciate his coveted lecture on ***Spiritual thermodynamics***. He delivered his ***Spiritual Thermodynamics*** talk at the University of South Florida, Tampa, USA; the University of Balearic Islands, Spain; and Universidade do Algarve, Faro, Portugal. Four of his seven Ph.D. students in the energy and solar thermal field have graduated successfully. He has guided over 50 M. Tech. and first-degree thesis. He has experimented with many pedagogical innovations, like team-based and game-based learning, in his various courses.

At BITS, he is actively involved in Work Integrated Programs Division for industrial collaborations. He was a coordinator of various collaborative programs: B.S. and B.Tech Power Engg (Aditya Birla Group, NTPC, NDPL, THDC, ESSAR Power, Tata Power, JSW Energy), B.S. and B.Tech Process Engg (Aditya Birla Group Cement Business UltraTech, Hindalco Industries, Birla Cellulosic, Indogulf Fertilizers, Vedanta Aluminium), B.S. Engg Design (L&T iES, Vadodara), M.S. Engineering Management (Mahindra & Mahindra), M.S. Embedded Systems (L&TiES), M.S. Pharmaceutical Operations & Management (Wockhardt), M.S. Manufacturing Management (Vedanta Aluminium), and M.S. Automotive Engg Programs (Tata Technologies).

He is a Fellow of the Institute of Engineers (FIE) and a Life Member of the International Solar Energy Society (ISES), the Indian Society for Heat and Mass Transfer (ISHMT), and the Energy and Fuels Users Association of India (ENFUSE). He is an associate member of Solar Cookers International, USA, and a Senior Member of the Universal Association of Mechanical and Aeronautical Engineers (UAMAE).

About the Co-Supervisor

Dr. Bibekananda Mohapatra is an Advisor & Consultant-CMO Cell, UltraTech Cement Limited and former Director General, National Council for Cement and Building Materials, Ballabgarh, Haryana, India. He previously, served as Vice President & Corporate Quality Head of Ambuja Cement Limited under the banner of LafargeHolcim and held several key positions in Vikram Cement Works (UltraTech Cement Ltd) under Aditya Birla Group, OCL India L. Research Institute - Dalmia Institute of Scientific and Industrial Research (DISIR)

He is enriched with 13 years of research and over 22 years of industry experience with strong academic relations with premier institutes. He has cross functional experience in development of low carbon cements and clinker, mineralogy & microstructure of cement and concrete, product development & diversification, advanced comminution techniques, energy & environment improvement and Total Quality Management. Previously, Dr Mohapatra made pioneering contribution in the field of co-processing of AF in cement industry in India. He did his M.Sc in Chemistry from Utkal University, Odisha and PhD from Sambalpur University, Odisha. Dr B.N. Mohapatra has guided one PhD student in the area of Portland Limestone Cement. Dr B.N. Mohapatra is Chairman of Cement Sectoral Committee of Bureau of Energy Efficiency (BEE), Govt. of India, member of Expert Appraisal Committee-Industry-1 sector 292 by Ministry of Environment, Forest and Climate Change (MOEF&CC), Govt. of India, member of Committee for Sustainability of fly ash management system by Central Pollution Control Board (CPCB), nominated by NITI Aayog, Govt. of India as Member of Low Carbon Technology Committee, Circular Economy in Gypsum & handling of waste, member of Research Council of CSIR- National Physical Laboratory (NPL), member of Various Technical Committees of Bureau of Indian Standards (BIS), DISIR, member of Academic Council of AKS University, Satna, member of Board of Studies of Khallikote Autonomous College, Berhampur. He has received Lifetime Achievement Award for the year 2021 by Indian Concrete Institute. He has published more than 130 technical papers in Journals/Conference. He has authored a book on "Application of X-Ray Diffractometry in Cement Quality Control System"