CHAPTER - 01

INTRODUCTION

1.1 General

Over the past few years, human activities have caused a major crisis for the global economy. This search for ever-increasing needs has inevitably intensified stress on our finite natural resources, including fossil fuels, soil, and the environment. This great demand for these natural resources has necessitated massive production across various industries (Obuzor et al., 2011). The consequence of this intensified industrial production has been the generation of vast quantities of waste, posing a serious environmental threat. Both human activities and industrial processes have contributed to this growing waste issue. To manage the escalating volume of generated waste and explore opportunities for waste utilization effectively, the concept of geopolymerization has emerged.

1.2 Need for the Geopolymer

This section explored the essential reasons for introducing the concept of geopolymers. The following points underscore the significance of incorporating geopolymers.

1.2.1 Scenario of Waste in India

Based on the latest United Nations data as per Worldometer elaboration the estimated population of India by the year 2023 would be 1,428,627,663 (i.e. 1428 million) people. The approximate growth rate of 18.01% population has increased from 2011 to 2023. Due to this rapid population growth, escalating urbanization, and improved living standards resulting from technological advancements have substantially increased the volume and variety of solid waste produced in various sectors, including industrial, mining, domestic and agricultural (Pappu et al., 2007).

The anticipated global waste output by 2050 is expected to reach 27 billion tonnes annually, with Asia currently accounting for one-third of this total. Notably, China generates between 0 to 0.49 kg of waste per capita daily, while India's per capita/day waste generation falls within the range of 0.50 to 0.9 kg. Projections suggest that India's waste generation could range from 334 to 661 MT per day between 2016 and 2050, underscoring the pressing need for effective waste management strategies in rapidly growing economies (Kumar and Agrawal, 2020). On a global scale, waste generation reached an estimated 12 billion tonnes in 2002, with industrial waste accounting for 11 billion tonnes and municipal solid waste (MSW) contributing 1.6 billion tonnes to this staggering figure. Yoshizawa et al. (2004) highlighted that an annual production of approximately 19 billion tonnes of solid waste was anticipated by the year 2025. This trend underscores the growing significance of sustainable waste management strategies and practices.

It is worth noting that, on an annual basis, Asia contributes a significant 4.4 billion tonnes of solid waste to the global total, and among this amount, municipal solid waste (MSW) accounts for 790 million tonnes (MT). Notably, about 48 million tonnes, equivalent to 6% of this MSW, is generated with in India, as reported by Yoshizawa et al. (2004) and the Central Pollution Control Board (CPCB) in 2000. In India, an estimated 143,449 MT of municipal solid waste (MSW) are generated daily. Of this amount, approximately 111,000 metric tonnes are collected, while about 35,602 metric tonnes undergo treatment, as reported by Kumar et al. (2017). The quantity of municipal solid waste (MSW) generated is influenced by various factors such as living standards, the scale and nature of commercial activities, dietary habits, as well as geographical and climatic conditions. Additionally, the influx of migrants seeking opportunities exacerbates this situation.

According to recent data from the MNRE Report, India currently generates approximately 145 million tonnes of waste annually, with projections indicating a potential increase to approximately 260 to 300 million tonnes per day by the year 2047. Data from the Central Pollution Control Board (CPCB) indicates that around 117,644 MT of waste are collected, with only approximately 49,401 MT being treated, as reported by Ahluwalia and Patel in 2018.

More recent data from CPCB (2020-21) indicates that India generates a daily average of 160,038.9 tonnes of solid waste. Fig 1.4 represented the state wise generation of solid waste. In anticipation of the year 2047, it is projected that India's Municipal Solid Waste (MSW) generation will experience a substantial surge, reaching the mark of 300 million tonnes, necessitating a land area of 169.6 square kilometres for waste disposal. This is a significant increase from the 20.2 square kilometres allocated in 1997 to manage 48 million tonnes of waste (CPCB, 2000**)**. These statistics highlight the mounting waste management challenges and the imperative for sustainable solutions.

The Central Pollution Control Board (CPCB) of India provided the information that a notable exponential increase in per capita waste generation, escalating from 0.26 kilograms per day to 0.85 kilograms per day (CPCB India, 2018a)**.** Unfortunately, an estimated 80% to 90% of municipal waste is disposed of in landfills without the adoption of appropriate management protocols. Moreover, the open burning of waste is a prevalent practice, resulting in severe environmental repercussions, including air, water, and soil pollution, as articulated by Ahluwalia and Patel (2018) and Joshi and Ahmed (2016). This situation underscores the urgent need for more sustainable waste management approaches to mitigate these environmental issues.

Mining activities play a substantial role in the generation of vast quantities of waste materials. These encompass overburden waste material, mine residues, seepage water from mine and various other process-related wastes. India's mineral resource landscape is quite diverse, with the country producing a total of 95 different minerals (Metals and Mining industry in India). Worldwide, there exist approximately 3,500 operational mining waste sites, which encompass areas like waste rock dumps and tailing dams. The annual production of solid waste originating from primary mineral and metal production surpasses 100 billion tons, with noteworthy disparities depending on the specific commodity type. As reported by Shome et al. (2021), this range spans from several times the mass of valuable elements like iron and aluminium ores to several million times for rarer elements such as gold ore. Significant industrial waste generation, as noted by Heath et al. (2014), along with substantial sediment accumulation, as indicated by Lirer et al. (2017), poses eco-problems and contributes to greenhouse effect. Comprehensive waste management and sustainability measures are imperative in addressing these issues.

Electricity serves as the fundamental cornerstone of the modern world, with global finance relying on it both directly and indirectly. The generation of electricity has been reliant on coal as a primary fuel source since the 1920s, leading to the production of substantial quantities of fly ash and related byproducts. India, currently ranked as the third-largest hydroelectric power producer globally, following China and the USA, faces a distinctive challenge in this context. Indigenous coal resources in India typically have a lower grade and higher ash content, falling within the range of 30% to 45%. Consequently, India generated an additional 226.13 million tons of fly ash in the fiscal year 2019-20 and 270.82 million tons in 2021-22 emphasizing the magnitude of the challenge posed by the disposal and management of these substantial waste volumes. (Report on Fly Ash Generation at Coal / Lignite Based Thermal Power Stations and Its Utilization in the Country for the Year 2021 – 22). The unused fly ash and the bottom ash transferred to the ponds which is called pond ash. Since pond ash is the residue after the combustion of coal in thermal power plants, its properties depend upon the coal used and may vary from one power plant to other power plants. Heavier unburnt ash, collected at the bottom of the surface is called bottom ash and it constitutes around 20% of total ash generated at a power plant. According to a report by Yousuf et al. (2020), India is confronted with an alarming situation, with approximately 65,000 acres of land occupied by ash ponds. These ash ponds will yield an additional ton of ash in coming years. The need for responsible ash management and safe disposal practices is evident in light of these statistics. Table 1.1 represents the generation of Pond Ash in India in the year 2021-22

Table: 1.1 Pond Ash Generation During the year 2021-22

Pond ash Generation at a power plant	Unused Fly ash + Bottom ash
Total fly ash generations	270.82 million tons
Bottom ash generated	20% of The Total Ash Generated (270.82 million tons) 54.164 million tons
Unutilized Fly ash	4.05% of Total Ash generated (270.82 Million tons) 10.96 million tons
Total pond ash generated	Unutilized fly ash+ Bottom ash 54.164+10.96 65.132 million tons

Besides electricity, the iron and steel industry plays a crucial role in the nation's economy, contributing significantly to modernization and economic growth. The per capita consumption of steel is a crucial yardstick for assessing socio-economic development and living standards within a nation. Steel retains as primary engineering material. The cumulative production of steel, comprising alloy, stainless, and non-alloy varieties, has experienced remarkable growth in India. In 1951, the production was a modest 1.1 million tonnes, but it has surged to an impressive 96.204 million tonnes in recent years. This substantial expansion underscores the pivotal role of the iron and steel industry in the nation's advancement. The production of crude steel amounted to 109.14 million tonnes in 2019-20 and slightly decreased to 103.54 million tonnes in 2020-21. This substantial steel production, accompanied by pig iron manufacturing, leads to the substantial generation of a byproduct known as slag. In the course of pig iron production in a blast furnace and in the steel manufacturing process at a steel melting shop, slag is generated as fluxes interact with impurities in the iron ore. In an integrated steel plant, the manufacturing of one tonne of steel leads to the generation of 2-4 tonnes of waste materials encompassing solid, liquid, and gaseous forms. Integrated steel plants produce significant quantities of waste materials, with one of the major byproducts being blast furnace (BF) iron slag. The quantity of slag generated during pig iron and steel production can vary, primarily depending on the raw material's constituents and the type of furnace used. The scenario of ore feed containing iron levels between 60% and 65%, the generation of blast furnace slag usually falls within the range of 300 to 540 kilograms per tonne of pig or crude iron manufactured. In steelmaking processes, around 150 to 200 kilograms of slag are generated per tonne of liquid steel produced. This emphasizes the need for efficient management and utilization of these slag byproducts (Indian Minerals Yearbook 2021). Following Fig 1.1 provides plant-wise capacity of iron and steel slag in the country.

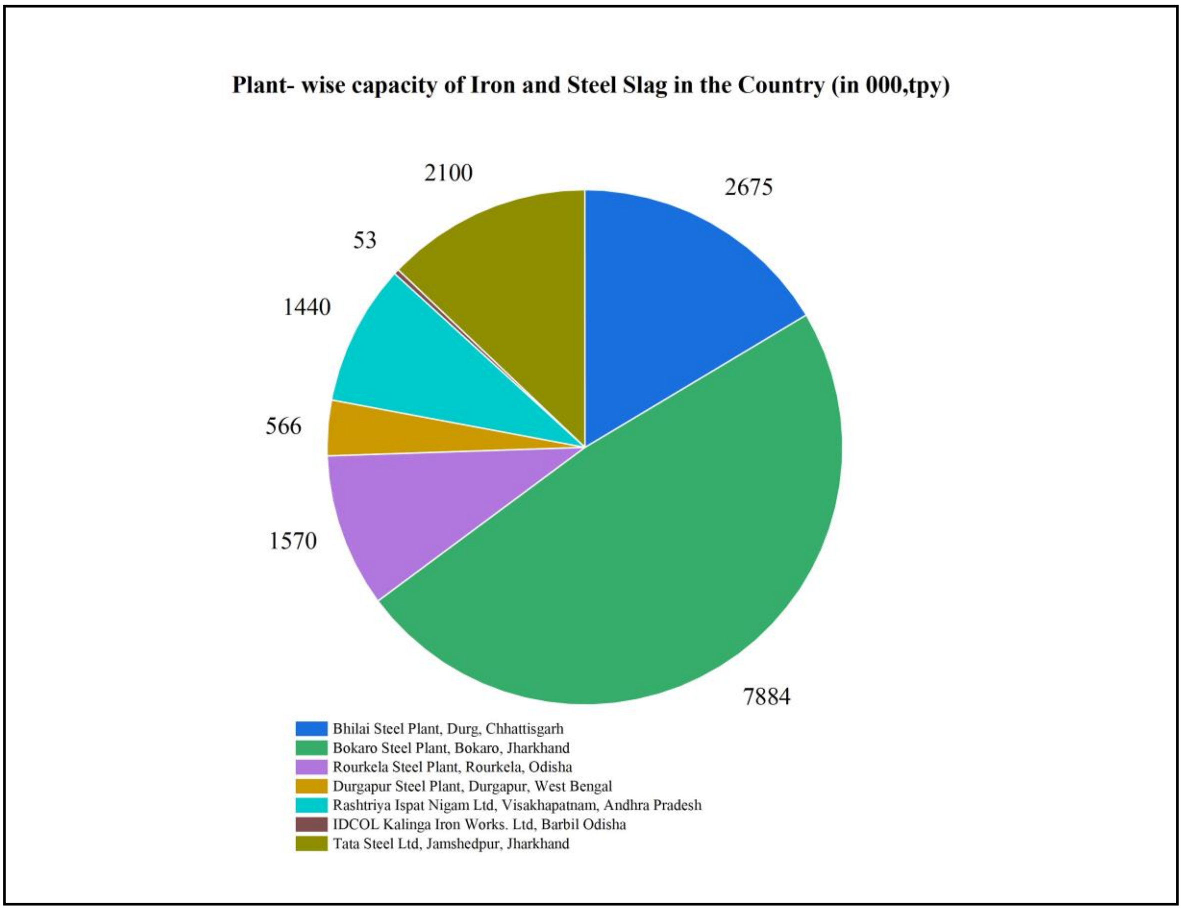


Fig: 1.1 Plant-wise Capacity of iron and steel slag in the country

The production of slag accounts for approximately 10% of the overall steel production (Aydin and Baradan, 2014). Presently, India's annual iron slag production totals around 12 million tons. It's noteworthy that India holds the position of being the world's fourth-largest steel producer.

Following steel, the production of aluminum contributes significant importance in advancing modern society. The commercial production of aluminum primarily involves two key processes. The initial step is the extraction of alumina through the Bayer process, followed by the second step, which entails the electrolysis of alumina in Hall-Heroult electrolytic cells to yield aluminum alloy. The process of extracting alumina from bauxite raises significant environmental issues, primarily concerning the considerable waste by product referred to as

Red Mud (Altundogan et al., 2000). India ranks seventh among the countries with the largest bauxite reserves. The production of red mud varies from 55% to 65% of the processed bauxite, depending on the bauxite's quality. The amount of red mud generated per tonne of alumina produced can vary, typically ranging from 1.5 to 2.5 tonnes, depending on factors such as the source of bauxite and the efficiency of the alumina extraction process (Samal et al., 2013). Approximately 140 million tonnes of red mud (RM) are generated annually. India's red mud production during the year 2021-22 & 2020-21 is detailed in the Fig 1.2 & 1.3 (Guidelines for Handling and Management of Red Mud Generated from Alumina Refineries).

Every year, millions of tons of industrial waste are generated, posing significant environmental challenges due to inadequate storage and safe disposal methods.

This waste contributes to soil and water pollution in the vicinity of processing sites. One substantial source of waste is the quarry industry, which produces vast amounts of waste in the form of quarry dust (QD). About 25% of the milled material comprises granite stone

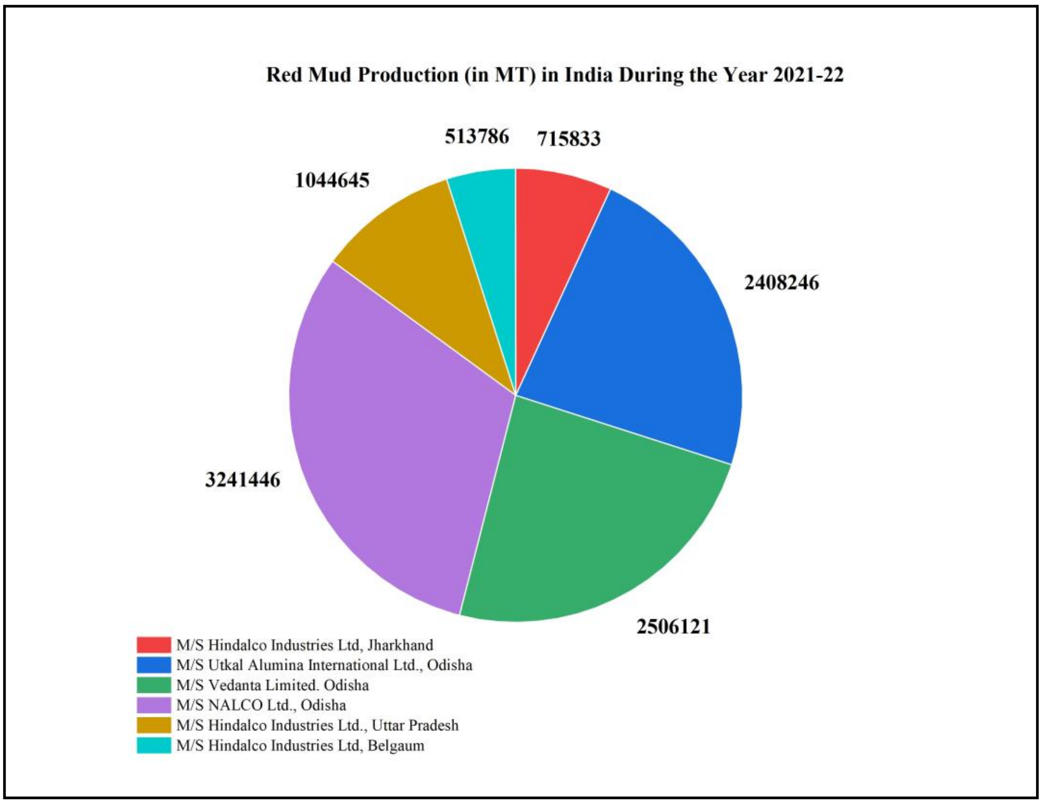


Fig: 1.2 Red Mud Production During the year 2021-22 in India

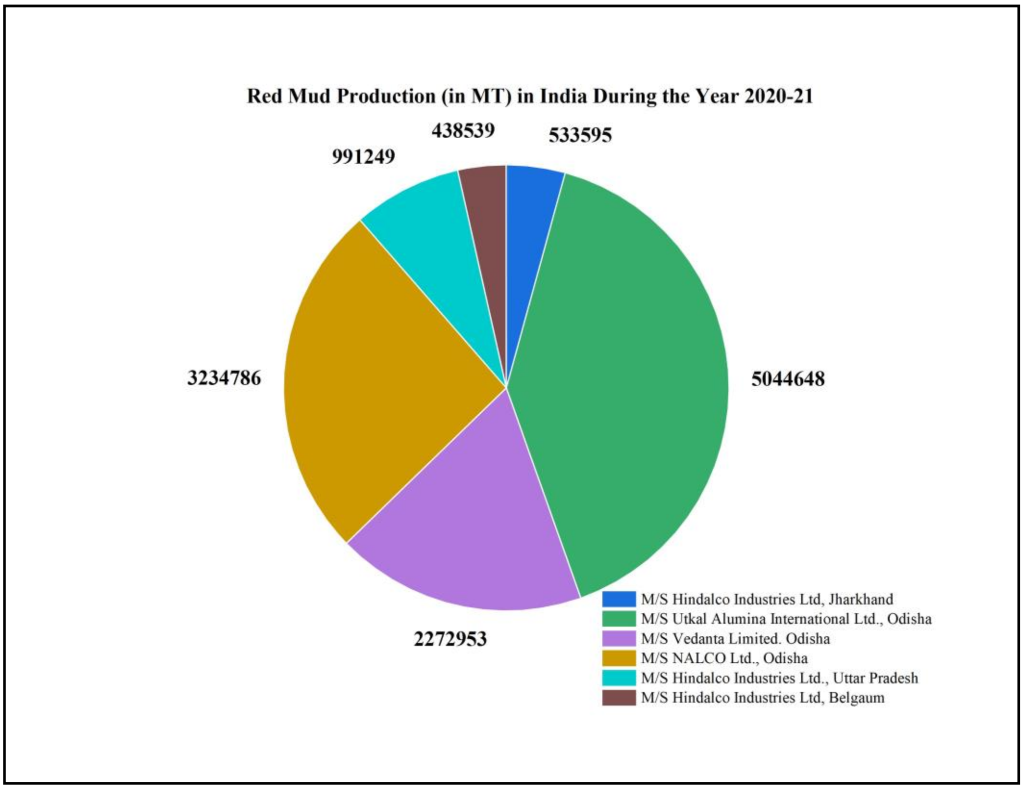


Fig: 1.3 Red Mud Production During the year 2020-21 in India used in crushers to create a coarse mix (Basar et al., 2016). Geothermal power plants generate approximately 50,000 tons of waste annually during electricity production using water and steam extracted from the ground (Gomez-Zamorano et al., 2016). In Kerala, the production of terracotta tiles results in roughly 20,000 tons of damaged or broken tiles each year (Usha et al., 2016). Among the largest waste producers is the metallurgical industry, which generates various types of waste, including (a) sinter dust and sludge from the sintering process, (b) blast furnace dust and sludge during the blast furnace process, (c) steelmaking powder from electric arc steelmaking furnaces, (d) blast furnace and steelmaking slags, and (e) ceramic chips.

The calcium carbide residue (CCR), a waste product obtained as a by-product of the acetylene production process through the hydrolysis of calcium carbide is available in large amounts and has been identified as one of the calcium additives. (Phetchuay et al., 2014).

Bagasse and rice husks are significant byproducts of the waste industry. Indian sugar mills generate an estimated 45 million tons of bagasse annually, with bagasse ash comprising approximately 4.6% of the total bagasse production. Rice husk, a crucial byproduct of rice milling, is produced in over 75 countries worldwide, with a global annual production of approximately 116 million tons. Rice husks are primarily used as furnace fuel, leading to a high rice husk ash (RHA) content ranging from 16% to 23% (Thind et al., 2012).

In India, waste dealers and collectors involved in household waste management gather significant amounts of recyclable materials each year, including 1.2-2.4 million tons of paper, 2.4-4.3 million tons of cardboard and mixed paper, 6.5-8.5 million tons of scrap metal, and 4-6.2 million tons of other recyclable materials (Nandy et al., 2015). Fig 1.4 represented the state wise solid waste generation during the year 2020-21 (Annual Report on Solid Waste Management, 2020-21, CPCB, Delhi). Conversely, the global community continues to grapple with issues of global warming and climate change caused by factors such as carbon dioxide emissions, greenhouse gases, and various forms of pollution. To address these challenges, sustainable and environmentally friendly approaches like geopolymer technology have emerged. Geopolymer technology offers a promising solution that not only reduces energy consumption but also mitigates CO_2 emissions by utilizing industrial waste and by-products (Usha et al., 2016).

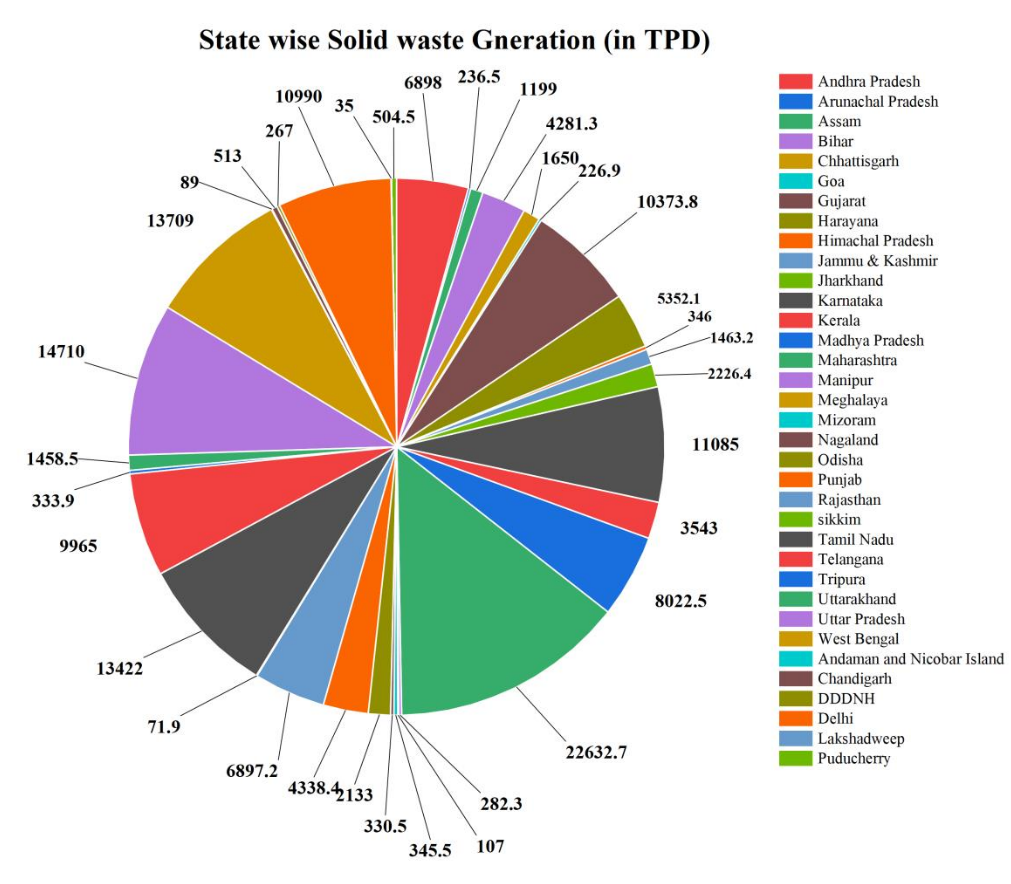


Fig: 1.4 State wise Solid Waste Generation in (TPD)

The detrimental effects of cement production can be mitigated through practices such as recycling secondary cementitious materials and enhancing the environmental friendliness of industrial waste (Chaunsali et al., 2011). Incorporating these waste materials into the cement and concrete industry not only alleviates environmental issues but also leads to cost savings in waste management, minimizes waste generation, curbs greenhouse gas emissions, preserves valuable resources, and diminishes the disposal of clinker waste in landfills (Wongsa et al., 2017). (Ranjbhar et al., 2014) also examined the ecological ramifications of cement production, emphasizing that each ton of cement manufacture results in the release of approximately 0.7 to 1.1 tons of carbon dioxide. Cement, ranking third after aluminum and steel in terms of production volume, significantly contributes to CO2 emissions. Nevertheless, the substitution of cement with materials like fly ash & Pond ash from thermal power plants, GGBFS (Ground Granulated Blast Furnace Slag) from steel plants, Silica fume and other cementitious alternatives offers a viable strategy for curtailing carbon dioxide emissions.

Annually, industrial operations yield a multitude of waste materials, many of which remain underutilized or considered nonviable. This accumulation of waste not only presents storage dilemmas but also compounds environmental issues, with detrimental consequences for the surrounding areas. In recent years, there has been an amplified consciousness of the extensive quantity and diverse nature of hazardous wastes and their profound implications for human health (Islam et al., 2015).

Joseph Davidovits' introduction of geopolymers in 1978 marked a pivotal moment that kindled enthusiasm for crafting sustainable materials. This was achieved through geopolymerization processes involving alkali-activated solutions, often leveraging diverse sources of silica and alumina. These sources typically encompass substances like sodium hydroxide and sodium silicate.

An innovative inorganic geopolymer binder, devoid of any Portland cement content, has emerged as an environmentally responsible alternative. This geopolymer exhibits commendable characteristics, including rapid strength development, heightened durability, exceptional hardness, and enhanced fire resistance.

The yearly global production of ash amounts to approximately 500 million tons which has majority originating from fly ash, representing a substantial 75-80% of the total. The issue of fly ash disposal has raised environmental apprehensions. Numerous researchers have diligently explored the use of fly ash as a valuable resource for crafting cement-free materials (Ranjbar et al., 2014). To effectively handle this waste and alleviate environmental concerns, numerous researchers have championed the concept of geopolymerization. Geopolymerization entails the interaction of waste materials with alumina-silica compounds and alkali activators. Diverse researchers employ a variety of waste products and varying proportions of alkali activators in this process. Geopolymer is synthesized from materials such as fly ash, bottom ash, rice slag, rice ash, palm oil ash, red mud, and other substances that are abundant in silica and alumina. It involves the use of alkaline solutions, specifically sodium and potassium hydroxide, in conjunction with soluble silicon salts. Geopolymer technology not only reduces carbon dioxide (CO2) emissions but also provides an environmentally friendly solution for the cement industry. Industrial wastes like fly ash and bottom ash can be utilized as partial replacements for cement, addressing both waste management and environmental concerns. The upcoming section will delve into the geopolymer reaction process and the crucial role played by alkaline activators in this context.

1.2.2 Effect of the Generated waste

(a) Inadequate management of this ash has the potential to result in heavy metal contamination through erosion and water infiltration, impacting the local ecosystem for extended periods. Furthermore, due to its relatively low density, fly ash can become airborne if not handled properly. The waste ash contains harmful metals capable of polluting surface and groundwater, as well as affecting soil and vegetation, as depicted in Fig 1.5

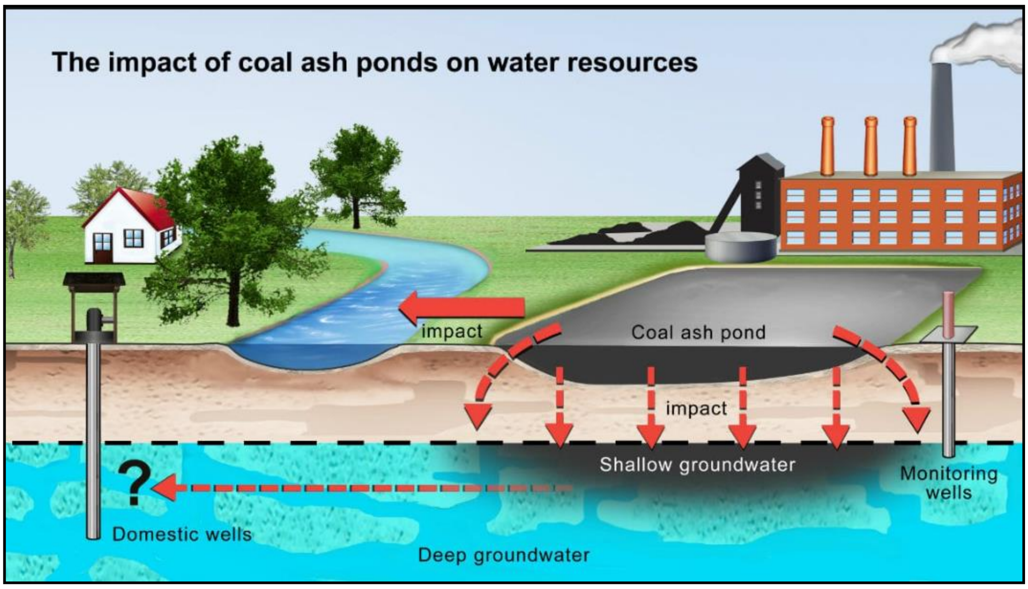


Fig: 1.5 The Impact of Coal Ash Pond on the environment (Evans et al., 2023)

According to the report of (An Ashen Legacy: India's thermal power ash mismanagement, Centre for Science and Environment, New Delhi), some case studies about the impact of fly/ pond ash failure has been discussed.

- In august 2020 at north Chennai thermal power plant, Tamil Nadu, toxic slurry from busted pipeline flooded the village which results in contamination of food, water and also affected the health.
- In July 2020, at Goindwal Sahib, Nabha Power and Hargovind thermal power plants, Punjab, a failure occurred in while scientifically disposing of fly ash.
- In April 2020, Sasan Ultra mega power project reliance, Singrauli, Madhya Pradesh, fly ash dam ruptured which flooded the populated village.
- In March 2020, at NTPC Talcher, Talcher Odisha, a pipeline carrying the fly ash slurry breached which flooded the houses, farms and roads.
- In October 2019, at NTPC Vindhyachal Power Plant, Madhya Pradesh, a fly ash reservoir Collapsed that damaged the agricultural land, groundwater and standing crop. Thirteen acres of land destroyed.

- In 2019 NTPC Aravali and CLP Jhajjar power plants, Haryana, there is a huge accumulation of fly ash which affects the nearby inhabitants.

In 2019, at several thermal power (Bokaro thermal power station (DVC plant), Bokaro Jharkhand, Essar power plant Madhya Pradesh & Khaparkheda thermal power plant Nagpur Maharashtra)), there is breach occurred in ash pond which affected the agricultural lands, groundwater

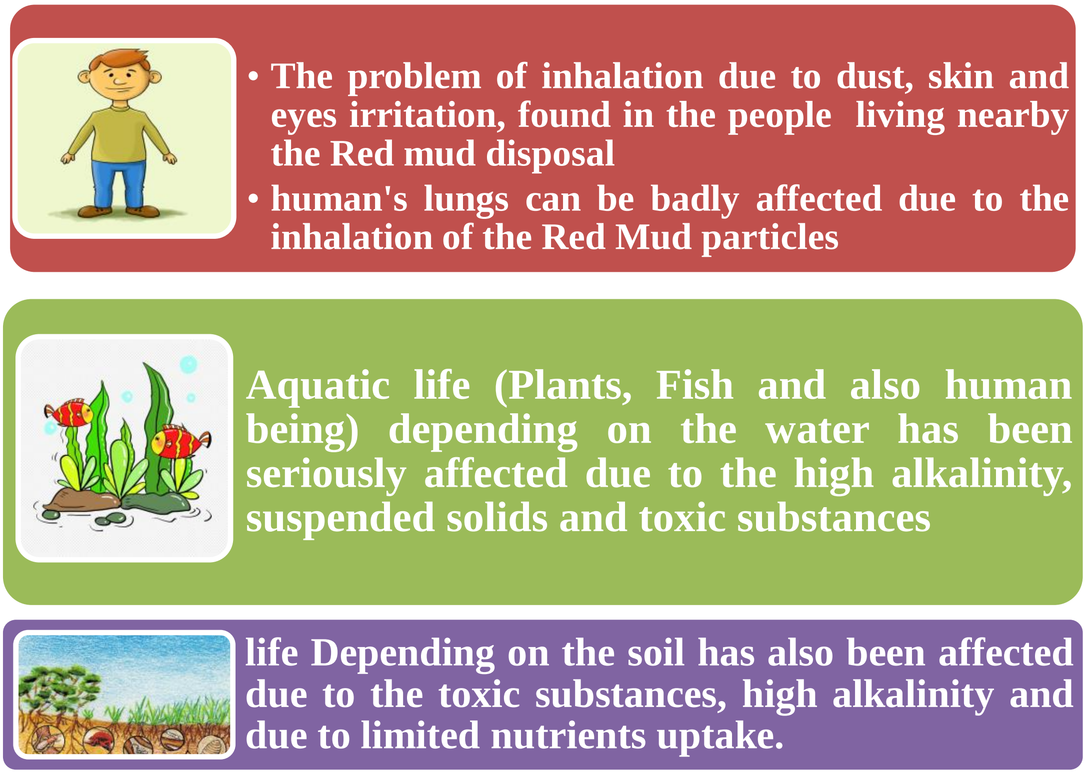
(a) Red mud is produced on land or in adjacent oceans worldwide, and its elevated alkalinity poses a threat to the surrounding water, soil, and air. Effectively treating and managing red sludge waste has perpetually presented a challenge to the alumina industry. India, in particular, has raised concerns about red sludge disposal due to its environmental implications (Samal et al., 2013). Fig 1.6 & Table 1.2 presented the negative results due to the Red Mud release in the environment.

(b) The disposal of bottom ash (BA) and rice husk ash (RHA) has evolved into a significant challenge, with substantial quantities of ash being frequently deposited into rivers, lakes, and open areas, causing harm to vulnerable ecosystems.

(c) The discharge of liquid industrial waste into the sea has reached a critically hazardous level for marine ecosystems.

(d) Industrial operations release numerous noxious gases into the atmosphere, including carbon dioxide (generated during cement production), sulphur dioxide, and nitrogen oxides, contributing to air pollution.

(e) The ambient air surrounding industrial facilities is often highly polluted, resulting in a range of health issues affecting the skin, eyes, throat, nose, and respiratory system.



- The problem of inhalation due to dust, skin and eyes irritation, found in the people living nearby the Red mud disposal
- human's lungs can be badly affected due to the inhalation of the Red Mud particles

Aquatic life (Plants, Fish and also human being) depending on the water has been seriously affected due to the high alkalinity, suspended solids and toxic substances

life Depending on the soil has also been affected due to the toxic substances, high alkalinity and due to limited nutrients uptake.

Fig: 1.6 Consequences of the release of Red Mud in the Surroundings (Guidelines for Handling and Management of Red Mud Generated from Alumina Refineries)

Table: 1.2 List of Accidents due to the Red Mud Pond failure in India and All over the world

Sr.no	**Location**	**Resaons**	**Effects**
01	Akja Hungary Red Mud Disaster (2010)	The foundation of the embankment was not appropriate	Structure failure
02	Red Mud Burst in India (2016)	Sudden break of waste containment wall	The irrigation area of village has been affected badly
03	Red Mud Over Spill at Alunorte, Barcarena, Brazil (2018)	Power failure of production system which results into overflowing of spent caustic liquor	The quality of municipal water supply in the town has been affected
04	Red Mud Pond Failure at Muri, India (2019)	Excessive overburden pressure on the base of the RMP	Weak portion of the gabion wires has been corroded by the Red Mud

(f) Industries consume substantial amounts of water and discharge vast volumes of wastewater containing harmful chemicals and heavy metals. This wastewater pollutes our natural water resources, posing threats to human health and the environment.

1.3 Essentials for Geopolymer Reaction

To address the challenges associated with waste disposal and environmental concerns, the conversion of these wastes into cementitious materials has been suggested as a solution. Geopolymer technology plays a pivotal role in transforming these industrial wastes into viable construction materials. The key factors influencing the geopolymer mechanism include.

1.3.1 Alumina-silica rich waste

The selection of industrial wastes rich in silica and alumina is crucial for effective geopolymer reactions. Researchers have utilized XRF (X-ray fluorescence) analysis techniques to identify suitable alumina-silica rich waste materials. It has been observed that industrial wastes like fly ash, pond ash, red mud, GGBFS, and silica fume exhibit a high content of alumina and silica, making them suitable candidates for geopolymerization.

1.3.2 Alkaline Activator

The alkaline activator is a crucial component in the geopolymer reaction. This solution plays a significant role by dissolving silica and alumina minerals from the raw waste material. The dissolution process results in the formation of a polymer structure that imparts strength to the geopolymer.

1.4 Geotechnical Concern

In contrast to other methodologies, this study adopts a distinctive approach in determining the requisite quantity of alkaline solution by evaluating the compaction characteristics, specifically the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD), for each formulated mixture. The selection of the alkaline solution amount is predicated on these compaction characteristics. Remarkably, the mixture exhibiting the highest MDD corresponded to the most elevated unconfined compressive strength. Moreover, the grain size distribution curve wields a profound influence on the kinetics of geopolymerization. An inherent correlation exists between the compressive strength and the granularity of the material, with finer-grained soils demonstrating superior performance. The permeability of the mixture is intricately linked to the results of the grain size analysis and the MDD. Conspicuously, the mixture achieving the highest dry density concurrently exhibited the lowest permeability values.

1.5 Organization of the Study

In this **Chapter One**, the meticulously examination of the voluminous waste generation and the myriad challenges associated with its disposal was discussed. To address these pressing issues, this work explores the in-depth filed of geopolymerization technology as a potential solution.

In **Chapter Two**, comprehensively elucidating the various research efforts related to status of waste in India, geopolymerization, sheds light on their mechanical characteristics and microstructural properties of various waste based geopolymers.

Chapter Three investigates into an in-depth examination of the materials opted in the current research, encompassing their chemical characterization, microstructural intricacies, and geotechnical properties. Additionally, a comprehensive description of the planned methodology in the synthesis of geopolymerization is presented.

Chapter Four centers on the exploration of geopolymer materials derived from Pond ash and GGBFS. It commences with a comprehensive analysis of the specific gravity and grain size distribution of the various mixes. Subsequently, the study scrutinizes the compaction characteristics of these compositions. Permeability analysis is conducted, and the determination of alkaline activator quantity is elucidated based on compaction characteristics. The chapter then embarks on unconfined compressive strength (UCS) analysis at varying curing intervals (1, 7, 28, and 56 days). UCS analysis on water cured, acid immersed pond ash-GGBFS mix samples. The rock triaxial tests and ultrasonic pulse wave velocities of mixes are also discussed. An examination into microstructural aspect using techniques like XRD, FTIR, and SEM is also documented.

Chapter Five delves into the realm of geopolymer formulations incorporating MSW Reject and GGBFS. The chapter starts discussion with specific gravity and grain size distribution profiles for the diverse mixes of MSW reject - GGBFS under consideration. Subsequently, a detailed scrutiny of the compaction characteristics exhibited by these mixtures is presented. The investigation proceeds to include permeability analysis, coupled with a delineation of the methodology employed to determine the requisite quantity of alkaline activator based on compaction properties. The chapter proceeds to perform a comprehensive analysis of unconfined compressive strength (UCS) at varying curing intervals (7, 28, and 56 days). Moreover, microstructural analysis utilizing XRD, FTIR, and SEM techniques adds depth to the understanding of the studied geopolymer systems.

Chapter Six delves into the intricacies of geopolymer formulations that harness the potential of Red Mud and GGBFS. The narrative commences with an insightful depiction of specific gravity and grain size distribution for the entire spectrum of devised mixes. A meticulous exploration of the compaction characteristics exhibited by the mixtures is reported. The analysis advances to encompass permeability, and the methodology underpinning the determination of the requisite amount of alkaline activator based on compaction characteristics is elaborated upon. A comprehensive investigation of unconfined compressive strength (UCS) at distinct curing intervals (7, 28, and 56 days) unfolds, enriching the understanding of these geopolymeric systems. The chapter culminates with the application of advanced microstructural analysis techniques such as XRD, FTIR, and SEM, further unraveling the intricate features of these materials.

Chapter Seven explores geopolymer compositions incorporating Pond Ash and Red Mud. It begins with an examination of compaction characteristics, followed by a permeability analysis to determine the optimal alkaline activator quantity based on compaction results. Unconfined compressive strength is studied at 7, 28, and 56 days of curing and reported. Shear strength parameters of the mixes using Tri-axial tests are discussed for mixes with or without NaOH. Advanced microstructural analysis (XRD and FTIR) unveils structural and compositional insights, enhancing understanding of geopolymer properties.

Chapter Eight serves as a comprehensive summary of the thesis, encapsulating the key discussions and findings from the preceding chapters.