Gummadivalli Shiva Kumar¹, Aparna Sharma¹, Durga Prasad Tripathi¹, and Arvind Kumar Nema¹

¹Department of Civil Engineering, Indian Institute of Technology

May 10, 2024

Abstract

Mining and refining of iron ore result in prodigious quantities of Iron Ore Tailings (IOTs), necessitating urgent adoption of sustainable management practices. Depleted iron ore reserves underscore the untapped value of IOTs’ iron content. To minimize waste generation and optimize resource utilization, efficient extraction of iron content from ores is imperative. Accurate identification of ore seams during or before mining mitigates gangue and waste accumulation, resulting in cost savings in material processing, refining, transportation, and disposal. Recycling IOTs from older processing lines into newer, more efficient ones presents a promising avenue for sustainable resource utilization. Available options for IOT reuse span various domains. IOTs serve as building materials (bricks, cement, concrete), providing cost-effective alternatives. Road construction, embankments, and structural fills utilize IOTs as construction materials. Additionally, IOTs demonstrate versatility in manufacturing processes, including ceramics, foam glass, and geopolymer-based materials. Applications in paints, pigments, slow-release fertilizers, and microcrystalline glass further expand the scope of IOT utilization. This study highlights the urgency of IOT reuse/recycling for environmental and economic reasons. It underscores the wealth of available reuse options, emphasizing recycling’s pivotal role in sustainable resource management. Examination of these potential applications charts the course toward environmentally conscious and economically viable management of IOTs. Article in AGU23 Website
Towards Sustainable Iron Ore Tailings Management: Exploiting Versatile Reuse Opportunities for Environmental and Economic Benefits

Gummadivalli Shiva Kumar*, Dr. Aparna Sharma, Durga Prasad Tripathi, and Dr. Arvind Kumar Nema

Department of Civil Engineering, Indian Institute of Technology Delhi, New Delhi, India - 110016

PRESENTED AT: AGU23
INTRODUCTION

Mined ore, generally, is sent for processing in ore refinement mills for extraction the valuable minerals or other geological materials, where large volumes of wastes (called tailings) are generated. Tailings are the materials left over after the process of separating the valuable fraction from the uneconomic fraction (gangue) of an ore.

Tailings are distinct from overburden, which is the waste rock or other material that overlies an ore or mineral body and is displaced during mining without being processed. Tailings are also called mine dumps, culm dumps, slimes, tails, refuse, leach residue, slickens, or terra-cone (terrikon).

Tailings management is often subject to regulatory scrutiny, as they can cause several risks (including major breaches or leaks from tailings dams) and environmental concerns such as metal leakage to ground- and surface-waters, effects to aquatic wildlife (due to increased suspension and pollutant/contaminant risk), toxic emissions, bird death (from tailings pond water), acid drainage from tailing piles and ponds, etc.

To vindicate sustainable material use, recover economic value, and mitigate the impacts from tailings, a wide range of methods/practices are being adopted worldwide, with ‘Global Industry Standard on Tailings Management (2020)’ (an UN-level initiative) as an established benchmark for the safe and environmental-friendly disposal of tailings.

Iron ore tailings (IOTs) are a form of solid waste produced during the beneficiation process of iron ore concentrate. Among all kinds of mining solid waste, IOTs are one of the most common solid wastes in the world due to their high output and low utilization ratio. The enormous amount of IOTs deposited as waste incurs a high economic cost for waste management; and creates serious environmental problems and security risks. With the passage of time, the earth’s iron ore resources continue to decline, and the residual unextracted iron content of the IOTs might become valuable resources in the future.

The current study presents various versatile reuse opportunities for sustainable Iron Ore Tailings (IOT) management while also exploiting different environmental and economic benefits from IOT stored in long-term storage facilities.

Five categories of utilization were presented:

1. Resource Recovery
2. Building Materials
3. Road construction and Structural fills
4. Paints and Ceramics
5. Other applications
The stockpiling of tailings will occupy land and potentially pollute the environment. Moreover, the producer has to pay for the land expropriation fee, transportation fee and landfill fee, which increase the production cost and cause the waste of resources. Therefore, there rises an urgent need to focus attention on the utilization of tailings.

Considering the vast abundance of IOT quantities and strict implementation of current environmental laws, exploring alternative utilization potential of IOT as a resource, and its adaptation in the replacement of different industrial raw materials must be thoroughly discussed.

The physico-chemical properties of IOT are one of the major factors responsible for its vast usability. Literature from eminent researchers suggested that IOT can be successfully used in the manufacturing of building blocks, replacement of fine aggregate, in powder technology, Brick manufacturing, synthesis of glass fiber, etc.

In precast concrete opportune properties with respect to Portland cement can be achieved with up to 50% IOT replacement along with mineral admixtures. In spray concrete, the IOT works very well in the replacement of fine aggregate and gives competitive results. The details of physical and chemical properties show that more profound applications can be researched in the future (Bharath et al., 2021).

The tailing waste from iron mining industries has been found suitable as materials for cement preparation, glass–ceramic plates, foam glass, and the manufacturing of building insulation material. It is mainly due to its lightweight, good thermal insulation, chemically inert and non-toxic, bacteria-resistant, water- and steam-resistant, and inexpensive to transport.

IOT is widely used in the fabrication of foam glass, which is used in construction and many other fields because of its unique combination of properties.

The use of iron ore tailings in mortars will improve its bulk density and reduced the quantity of incorporated air and similarly improve mechanical properties. The iron ore that is of extremely fins or slimes having a diameter much less than one hundred fifty is not useful and, as a result, discarded.

- Recovery of valuable minerals

The Asketoushan iron ore dressing plant in China adopts JHC type torque ring permanent magnetic separator and BX magnetic separator to recover about 65% iron concentrate powder of grade from tailings (Zhao, 2008). Yang et al. (2012) applied the combined process of strong magnetic separation and flotation to treat iron tailings of a vanadium titanium magnetite mine in Sichuan and obtained qualified titanium concentrate with a grade of 48.87%, with a recovery rate of 85.51%. In order to fully recover this resource, Maanshan mining research institute successfully studied the separation process of strong magnetic one-thick two-stage shaking table, and selected garnet concentrate with a grade of 97.4%, with a recovery rate of 41% (Chang, 2010).

Baotou steel concentrator adopts a combined flotation process to recover rare earth concentrate and niobium from strong magnetic tailings. The recovery rate is 57.34% of rare earth concentrate and 35.58% of niobium (Li, 1999).

In Tang et al. (2019), iron was recovered from IOTs through pre-concentration followed by direct reduction and magnetic separation processes. The effect of bituminous ratio, roasting time, roasting temperature, sodium carbonate ratio, lime ratio and grinding fineness on iron recovery was also studied. After the iron recovery, the
high-silica residues from the pre-concentration process were reused in slag-tailing concrete composite admixtures. Combining these recycling processes can ensure complete utilization of IOTs. Incorporating an extra pre-concentration step before the direct reduction circumvented the high costs of recovering small amounts of iron through direct reduction. Consequently, this innovative technology can be extended to other IOTs with low iron content, exhibiting high potential for many other applications.
The main chemical constituents of iron tailings are aluminum, silicon, calcium, and magnesium oxides. Generally, the content of aluminum and silicon is high, and most of them are non-metallic minerals, which are very similar to building materials, and this can also provide the precondition for the application of IOT in the building materials industry.

At present, alternate utilization of IOT in China has achieved remarkable results in the application of building materials, mainly in making bricks, and preparing cement and concrete (Bing et al., 2018).

Bharath et al. (2021) have studied the utilization potential of IOT as a resource and its adaptation in the replacement of different industrial raw materials. Figure 1 shows different aspects of IOT utilization.

- Brick manufacture

There have been a lot of research and application in the production of building bricks by iron tailings in China. According to different technologies, IOT can not only prepare building wall bricks such as sintered bricks, steam-pressed bricks, and non-fired bricks, but also prepare building decorative surface bricks. Ma'anshan mine research institute USES the high silicon iron tailings of Qidashan and Asketou mountains as the main raw materials, mixed with a small amount of aggregate, calcium cementing materials and additives, added a moderate amount of water, evenly stirred and extruded into the 60t pressure machine for forming, moulding and standard curing for 28 days, and successfully made the non-firing bricks (Guo, 2006).

Sun et al. (2010) prepared sintered porous bricks using Handan tailings of high calcium and magnesium by extrusion. Shi et al. (2011) added 20-30% Chengchao iron tailings on the basis of the formula of vitrified brick and obtained the vitrified brick whose main crystalline phase is calcium feldspar. The colored lawn tile, floor tile, wall tile and so on were successfully developed by the tailings in the Asketou mountain iron mine of bensteel (Xin, 2001).

Mendes et al. (2019) has aimed for an alternative to reuse high-silicon iron ore tailings in Brazil by applying them in the red clay ceramic industry. For this, a mixture design of experiments was developed, using three components - the iron ore tailings and two clayey materials (yellow clay and gray clay). The raw materials were characterized physically, chemically, mineralogically and morphologically. The addition of the IOT material contributed to reduce firing linear shrinkage and compressive strength, and increase in bulk density, water absorption and apparent porosity. Figure 2 shows the unfired bricks containing IOT content in them.

The environmental behavior has indicated that the Brick material with IOT content can be classified as non-hazardous and non-inert, and it is not aggressive to the environment or human health both during and after its useful life. Many studies have shown that the proposed brick presents advantages from environmental, economic, and technical points of view, contributing to sustainability in the industrial sector and civil construction.

- Cement and related products

The low-price IOT can be used as the raw materials of cement production which will bring great economic benefits. Li et al. (2010) made cementing materials from iron tailings, blast furnace slag, cement clinker and gypsum with a ratio of 30:34:30:6, whose strength can reach the standard of 42.5 grade silicate cement.
Consoli et al. (2022) has proposed a new trend for tailings disposal: stacking ‘compacted filtered ore tailings–Portland cement’ blends. Young and Yang (2019) has reported the use of high-magnesium and low-silicon IOTs as a raw material replacing clay to produce cement clinkers by conventional sintering process.

Almada et al. (2022) aimed to assess whether the heterogeneity of IOTs influences mechanical, durability, and microstructural properties when added to the cementitious composite. Four IOTs samples from different origins were collected and added to cementitious composite at 40% addition content. Huang et al. (2013) has utilized IOTs in powder form to partially replace cement to enhance the environmental sustainability of ECC.

The work done by Fontes et al. (2018) discloses the development of a sustainable cement tile (SCT) produced with Iron Ore Tailings from tailings dams (IOT). The feasibility of IOTs as a pigment was also investigated. Figure 3 shows IOT application in manufacture of sustainable cement tiles (SCT).

- Concrete and related products

Another alternate application of IOT is to make concrete. Wang et al. (2013) used the Dashehe iron tailings of Shougang to make the autoclaved aerated concrete with strength grade A3.5 and density grade B06 with 60% iron tailings, 25% lime, 10% cement and 5% gypsum. Ruidong et al. (2021) has prepared the Iron tailings powder and slag powder to prepare concrete composite admixture to investigate the impact of iron tailings powder on the workability and longterm mechanical properties of concrete.

In order to address the paucity of natural sand and make full use of industrial waste, Tian et al. (2016) assessed modified concrete performance with the addition of iron ore tailings.

Carvalho Eugénio et al. (2021) has investigated at how utilizing iron ore tailing (IOT) influenced the physical, mechanical, thermal, and durability characteristics of concrete roof tiles made by extrusion. When compared to typical concrete roof tiles, adding more IOT resulted in considerable improvements in transverse breaking strength and porosity values. Figure 4 shows concrete roof tiles produced using IOT.

Zhao et al. (2021) has utilized Iron tailing sand (TS) as an aggerate to create super high-performance concrete (UHPC). The experiments showed that when the amount of TS in the slurry increases, the workability of the slurry reduces while the amount of air in the slurry increases. With increasing TS concentration, compressive behavior and microporosity deteriorate, and compressive strength had a positive linear relationship with workability, indicating that the decline in compressive behavior is mostly attributable to a loss of flowability. Figure 5 shows the particle pattern of TS against river sand.
(3) ROAD CONSTRUCTION AND STRUCTURAL FILLS

- Road construction

Applying iron tailings to road engineering can consume a lot of iron tailings and reduce the cost of road engineering. China's iron tailings as road building materials are still in their infancy. Yang (2008) conducted an experimental study on the road performance of the inorganic binder to stabilize the iron tailings, and the research results showed that 11% cement, 31% lime, 2% cement and 12% lime stabilized iron tailings can meet the strength requirements of the low-grade road base.

Sun and Chen (2012) studied the performance of limestone fly ash to stabilize the crushing road of iron tailings and analyzed the influencing factors and mechanism of lime fly ash to stabilize the strength of iron tailings gravel. Bastos et al. (2016) has studied the utilization of iron ore tailing from tailing dams as an alternative material for road infrastructure. The chemical, mineralogical, environmental, and physical aspects of the iron ore tailings were studied. The study said the use of iron ore tailings from tailing dams as road infrastructure material is technically feasible, when appropriately stabilized.

- Embankments and structural fills

The study by Kuranchie (2015) suggests that ceramic floor and wall tiles, brick production, aggregate in concrete, geopolymer bricks, structural fills such as embankments, foundations, backfills, trenches and all other applications requiring filling in building and construction is a potential area where mine wastes could be applied in large volumes.

In another similar study, Kuranchie et al. (2015) has also looked into using iron ore mine tailings as a substitute for traditional aggregates in concrete. It was found that the iron ore tailings may be utilized for complete replacement for conventional aggregates in concrete (both the concretes shown in Figure 6).

Deng et al. (2021) conducted tests to determine the applicability of certain binders to iron ore tailing containing gypsum for use in backfilling.

- Backfilling the goaf area

Underground mining is the main method of mining in China, and the mining area left behind after mining ore from respective ore seams brings great hidden danger to mine safety. Water inrush in an underground mine occurs as the water from the aquifer (located beneath the mine) breaks through the aquiclude above it (also located beneath the mine) and proceeds into the goaf area.

He et al. (2018) proposed a system that facilitates realistic risk assessment of water inrush while also elucidating the water-inrush mechanism in underground mining. Bing et al. (2018) stated that using IOT to fill the goaf area can resolve the problems associated with mine safety, tailings stockpiling, filling aggregate cost, and so on. Figure 7 depicts goaf filling and its effect on water-inrush occurrence.

Zhou (2011) have presented a good effect on filling the goaf with dry tailings of an iron ore factory in the Chengde area, China. At Mazhuang Iron Mine, Laiwu Mining Co. LTD., after grouting, iron tailings, sediment and cementitious powder are mixed and stirred. The concentration of mixed slurry is controlled at about 55%-60% (Bian et al., 2008).
(4) PAINTS AND CERAMICS

- In manufacturing of ceramics

*Fontes et al. (2019)* collected materials from four tailings-dams, which are subjected to a dry separation procedure and characterized (particle size and morphology, chemical and mineralogical composition). Besides the recovered iron ore concentrate, two other powder fractions were produced ("clay" and "sand" fractions). The sands showed the greatest uniformity (particle size and shape, mineralogy and chemical composition) and may find use as aggregates in a variety of applications.

- Fabrication of foam glass

*Yin et al. (2016)* prepared foam glass using iron tailings and waste glass with SiC powders as foaming agent. The influence of the foam temperature on the bulk density, porosity, water absorption and compressive strength was studied. Foam glass (shown in Figure 9) is made with higher IOT content of 24.5 wt% could be prepared at about 830°C for 30 min.

- Microcrystalline glass

Microcrystalline glass with different properties can be prepared from iron tailings. On the basis of studying and analyzing the components of iron tailings in Tangshan area, used sintering technology to make microcrystalline glass with diophanite as the main crystal phase *(Zhang et al., 2005)*. *Li and Wang (2008)* prepared lightweight magnesium olivine thermal insulation materials that meet high-temperature fire resistance through different process comparison using Anshan high-silicon iron tailings.

- In making paints

*Galvão et al. (2018)* proposed the use of raw iron ore tailings from tailings dams (IOT) in the area of Minas Gerais as pigment in the production of a paint for buildings called as the Sustainable Paint. In addition to IOT and water, four types of binders were tested: polyvinyl acetate (PVA) resin (in the form of ordinary white glue), acrylic resin, hydrated lime for painting and high early strength Portland cement. The Sustainable Paint (Shown in Figure 10) presented reddish color.

- In the manufacture of pigments

*Gong et al. (2021)* have prepared a bright purple copper barium silicate (BaCuSi2O6) composite pigment from IOT, sodium silicate, Cu2+ and Ba2+ via a simple and mild one-step hydrothermal method.
Figure 1: Different aspects of IOT utilization (Source: adopted from Bharath et al., 2021)

Figure 2: Small-scale construction bricks (perforated) before firing (Source: adopted from Mendes et al., 2019)
**Figure 3:** IOT application in manufacture of sustainable cement tiles (SCT) — as, both, aggregate and pigment. (1) Various mixtures developed for the color layer, and (2) Surface design of SCT prototypes, based on the value analysis and color palette. *(Source: modified from Fontes et al., 2018)*

**Figure 4:** Concrete roof tiles produced using sand, cement, limestone powder (LP), and iron ore tailings (IOT), with IOT and LP at varying proportions. (A) control tile (0% IOT replacing LP), and (B) 100% IOT replacing LP. *(Source: adopted from Calvalho Eugênio et al., 2021)*

**Figure 5:** Pattern of particles packing model of two different types of aggregates — (a) river sand (RS), (b) Iron tailing sand (TS). *(Source: adopted from Zhao et al., 2021)*
**Figure 6:** (a) Tailings and (b) normal aggregates concrete (Source: adopted from Kuranchie et al., 2015)

**Figure 7:** Goaf filling and its effect on water-inrush occurrence.

(A) Water-pressure variation and water runoff in aquifer after coal seam exploitation. ① Areas with undisturbed water pressure. ② Area with disturbed water pressure. ③ Cavity caused by aquifuge deformation, situated between aquiclude and aquifer. Blue arrows: water seepage direction;

(B) Water inrush occurs if goaf has not been filled, and aquifer water pressure exceeds the critical pressure of aquifuge breaking;

(C) No water inrush occurs if goaf has been filled, as the material filled in goaf counteracts the aquifer water pressure

(Source: modified from He et al., 2018)

**Figure 8:** IOT can be used in several alternative and innovative applications, such as adsorption of dyes from industrial wastewater, reactive material in PRBs near any contaminated site, etc. (Source: modified from Piuatti et al., 2021)

1. Iron Ore Mining / Extraction
2. Iron Ore Processing / Beneficiation
3. Conventional Disposal of IOTs
4. Applications in Industrial Wastewater Treatment (like Textile Dye Removal)
5. Alternative Utilization of IOTs for various Applications and Reuse
6. Iron Ore Tailings Dam / Stacking
7. Porous Reactive Barrier (PRB) Created using of IOT
8. Applications in Environmental Remediation
Figure 9: Foam glass — macrostructure of IOT sample that is foamed at 830 °C for 30 min (Source: modified from Yin et al., 2016)

Figure 10: Hues of the sustainable paint (Source: adopted from Galvão et al., 2018)
(5) OTHER APPLICATIONS

- As an adsorbent to remove dyes from aqueous solution

*Puiatti et al. (2021)* collected iron ore tailings (IOT) samples from a tailings dam in Minas Gerais, Brazil and characterized it.

- Reclamation of vegetation with tailings pond

Reclamation of tailings pond can reduce tailings pollution, reduce land resource waste, and optimize mine environment. The local iron ore plants of Qianan and Zunhua county in Tangshan area have discharged the tailings on the waste beach of Luanhe river, covering a layer of 25-30cm on the surface for reclamation and land reclamation. Various crops have been planted successfully, and more than 10 million yuan of economic benefits have been obtained *(Huang, 2013)*. Anshan iron & steel mining co. ltd. has reclaimed the tailings pond of the Donganshan sintering plant and built a multi-functional ecological park on the tailings pond with an area of 200 km².

- In manufacturing slow-release fertilizers

*Hu et al. (2018)* have prepared slow-release silicon fertilizers from iron tailings by solid-phase sintering and characterized by X-ray diffraction (XRD) and scanning electron microscopy (SEM).

- Making of IOT based geopolymer

This work presented by *do Carmo e Silva Defáveri et al. (2019)* is an evaluation of the application of iron ore tailings as primary precursor material to geopolymer production. Glass wool residue (GWR) from the iron ore industry was also included as a blend material. Four mixtures of geopolymers were produced in the study: one mixture using only iron ore tailing; three mixtures where the iron ore tailing was replaced by the glass wool residue, with a substitution ratio of 10%, 20% and 30% (in mass).
REFERENCES


