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Experimental characterization of iron mining tailings as sustainable material for thermal energy storage

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Mine tailings are an unavoidable waste generated during iron ore mining operations, of which millions of tonnes are generated worldwide. Given the importance of steel, and therefore, iron ore mining, solutions are needed to recover this waste. Despite global efforts, the current proposed solutions struggle to reach the market due to cost-effectiveness issues. This study explores a potential solution, presenting iron tailings as a viable, economical, and sustainable material for thermal energy storage systems. Thermal characterization showed a specific heat capacity of 780–990 J/kg·K up to 590 °C. The material remained thermally stable without melting or decomposition up to 1000 °C, and the resulting storage density was estimated up to 450 kWh/m^3. The material stands up safety, minimal environmental impact, and favourable thermophysical properties at a low investment cost. This innovative application not only addresses energy challenges but also contributes to resolving the waste management crisis in the iron mining industry.

Keywords Iron tailings, Circular economy, Thermal energy storage, Mining industry

Steel is the main material used in construction, manufacturing, transportation, and many other sectors, making iron ore and iron mining a critical activity for economic, social and technological development and infrastructure projects worldwide. Iron ore accounted for 94% of the metals mined in 2023, with 2,500 million tonnes extracted (Fig. 1b)[1]. Furthermore, iron ore is produced worldwide. According to statistics, Australia constitutes the world's largest producer of iron ore[2] (Fig. 1a).

However, mining operations result in the production of massive volumes of waste materials, including mine tailings produced during ore beneficiation[3]. The accumulation of iron mine tailing is an environmental problem that has been widely discussed, mainly due to the vast quantities generated annually. The global production of iron ore tailings in mining industry was estimated at 1.4 billion tonnes of tailings per year[4–6] (Fig. 1c). Achieving sustainable growth while addressing environmental concerns is paramount.

Numerous studies have analysed the used of iron ore tailings in different applications[7,8]. Open literature suggest that iron ore tailings can be converted into different types of ceramics[9–11]: tiles, glass, bricks, etc., including structural or functional materials such as cement, concrete[12–15] or road materials[16–18]. Most studies focus on civil engineering, but despite the growing body of research, many proposed solutions fail to penetrate the market to limited low cost-effectiveness. Consequently, there is an increasing tendency to diversify and look for other environmental applications in different fields[19–22]. In this way, this paper proposes a novel application of iron mining tailings in the energy storage sector, to solve two major problems in two major industries.

Renewable energy sources, particularly solar and wind, face the challenge of intermittent generation, heavily reliant on resource availability[23]. Energy storage systems are thus pivotal for enabling the widespread adoption of renewable energy by mitigating supply-demand imbalances[24].

There are different types of energy storage solutions that can be classified into five main groups: electrochemical (batteries), electrical, thermal, chemical and mechanical energy storage systems[25]. High temperature thermal energy storage (TES) promising solution for large-scale energy storage, offering higher load capacity and longer storage duration compared to battery technologies[26].

TES technologies, categorized into sensible heat, latent heat or thermochemical reactions, find applications in seasonal and bulk energy storage[27]. The last two are not yet mature, compared to sensible heat storage

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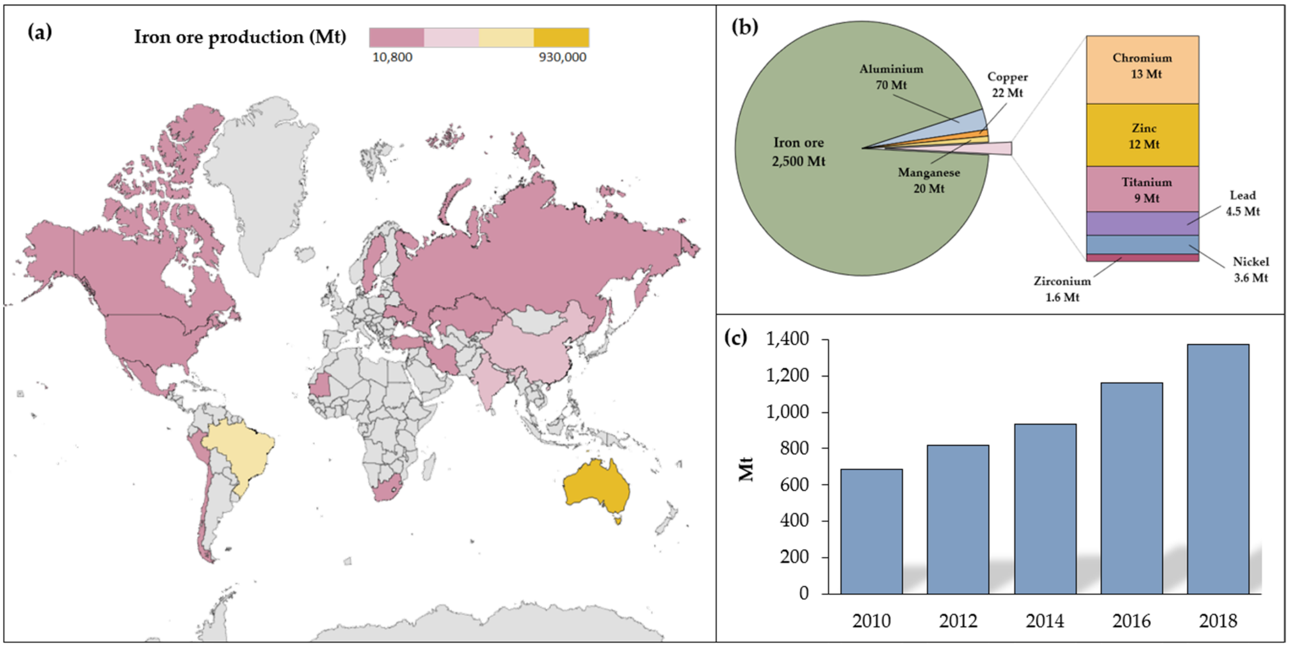

Fig. 1. (**a**) Iron ore main producers (Map generated using Microsoft Excel, version 16.0. Available at: https://www.microsoft.com/excel). (**b**) Metals production worldwide in 2023. (**c**) Iron tailings generation per year (Figure prepared by the authors using data from references[1,2,4]).

technology that is the most widely used system in large-scale concentrated solar power plants worldwide[28]. This technology is based on the ability of materials to heat up and cool down. The thermal energy is employed to increase the temperature of a material (liquid or solid, e.g., water, sand, molten salts, rocks…) that is later cooled down to recover the energy[29]. In comparison with the other two thermal storage technologies, sensible-thermal storage systems have relatively low capital costs[30].

The quantity of energy stored is mainly determined by the specific thermal capacity of the material. According to Khare et al.[31] appropriate material requires:

- Thermophysical properties: small density changes versus temperature, high heat capacity and heat transport properties.
- Chemical properties: chemical stability, non-toxic, non-flammable, low potential reactivity.
- Economic properties: abundant materials with low cost of manufacturing into suitable shapes.

The highest commercially viable materials for sensible heat storage applications are water and different mixtures of molten salts[32]. Nevertheless, this storage system has many drawbacks related to the use of molten salts, particularly the relatively high cost of the storage components.

As fossil fuel resources diminish and environmental policies evolve, the development of innovative, cost-effective, and efficient TES systems has become imperative for achieving global energy sustainability. Thus, the search for new low-cost storage materials is pivotal in attaining cost-effective thermal storage alternatives. Furthermore, the availability of storage material in sufficient quantity is a key factor. Lack of availability or even a conflict over the end use of the TES material can lead to price fluctuations and puts the development of storage systems at risk.

The characteristics of the materials to be used have been extensively studied, but environmental aspects are often given less consideration in the selection of a storage material. Leveraging various industrial by-products as heat storage materials presents a viable approach with a dual objective: obtaining a viable and cost-effective TES material while reducing mining environmental impact.

Several solutions have been proposed in this filed such as inert ceramics obtained from the treatment of the asbestos waste (Cofalit)[33], fly ashes from the incineration of municipal solid waste[34] or ashes from coal-fired thermal power plants[35].

This study proposes iron tailings, which is one of the main wastes of the mining industry, as a heat storage material. Introducing iron tailings into the energy recovery or production sectors opens new avenues for valorising this waste material while addressing pressing environmental and energy challenges.

Materials and methods

Approximately 20 kg of iron ore tailings were collected from an iron mine in Canada, where tailings are subjected to a crushing, grinding, magnetic separation and drying process as part of the operation. This desiccation step, commonly implemented to reduce water content, enhances storage safety, geotechnical stability, and facilitates subsequent handling. The resulting material consists of a fine, dry residue, which was used as the basis for the analyses carried out in this work. The material was homogenized and quartered to prepare representative samples.

An experimental design program for this research project was developed to achieve the presented objectives (Fig. 2). A full testing campaign was executed to provide an exhaustive physicochemical and thermal characterisation of the tailings.

Physicochemical analysis

Iron tailings were characterized in terms of chemical composition (X-ray fluorescence, XRF) and physical properties (permeability, particle size distribution and density).

XRF is an elemental, semi-quantitative analysis technique based on the ability of atoms to absorb energy from a source of X-ray radiation. As a consequence, secondary X-rays are emitted, which will have an intensity proportional to the concentration of each element. The equipment used in this case is the ARL-ADVANT-XP.

The permeability coefficient of iron tailings was determined using a constant load perimeter in which the vertical flow of water through a test tube is laminar according to ISO 17892-11:2019. Particle size distribution was obtained by sieving iron tailings (ISO 17892-4:2016) and density and porosity was determined according to ISO 17892-3:2015 as the ratio between the dry mass of the soil and the volume of solids, the latter being measured using a pycnometer with water.

Thermal properties

For thermal properties, thermogravimetric analysis (TGA), differential thermal analysis (DTA) and differential scanning calorimetry (DSC) were performed using a simultaneous TGA/DTA and TGA/DSC thermal analyser (SETARAM TG-DSC Setsys).

Thermogravimetry is based on the measurement of the change in mass of a sample when subjected to a change in temperature in a controlled atmosphere. In a DTA, both the sample and a reference material, which is thermally, physically and chemically inert, are subjected to a temperature variation.

Thermogravimetry and calorimetry analysis are thermal analytical techniques in which the difference in the amount of heat required to increase the temperature of a sample and a reference is measured as a function of temperature. TGA was performed from room temperature to 1000 °C at a heating rate of 10 °C/min, in an air atmosphere. DSC was conducted from room temperature up to 1000 °C, heating speed of 10 °C/min and in argon atmosphere to avoid reactive effects such as oxidation or combustion when using air. To ensure the representativeness of the results, 100 mg of material were used for the analysis.

Results and discussion

Physicochemical analysis

The iron tailings examined in this work are mainly composed of silica (SiO_2) along with significant iron oxides, primarily of Fe_2O_3, and alumina Al_2O_3. Minor quantities of calcium (CaO) and magnesium (MgO) can appear depending on the mineralogy of the source ore, but overall, the material is relatively inert chemically.

Figure 3 compares the tailings composition to those form other regions, confirming that while the SiO_2 ratio varies with ore type, iron tailings generally consist of silicate minerals similar to natural rock or ceramic materials. On the other hand, Fe_2O_3 proportion is relatively higher. It should be noted that XRF results are expressed as Fe_2O_3 equivalent, which reflects the total iron content in oxide form and does not directly identify the mineral phases. Nevertheless, considering the beneficiation route of the sampled ore (crushing, grinding, and magnetic separation), hematite (Fe_2O_3) and magnetite (Fe_3O_4) are the most likely Fe-bearing phases.

Tailings analysed in this study have very fine size (d_{50} in the silt range) with 44.9% of void content in the as-received dry state. The particle–size distribution curve of tailings as received is shown in Fig. 4.

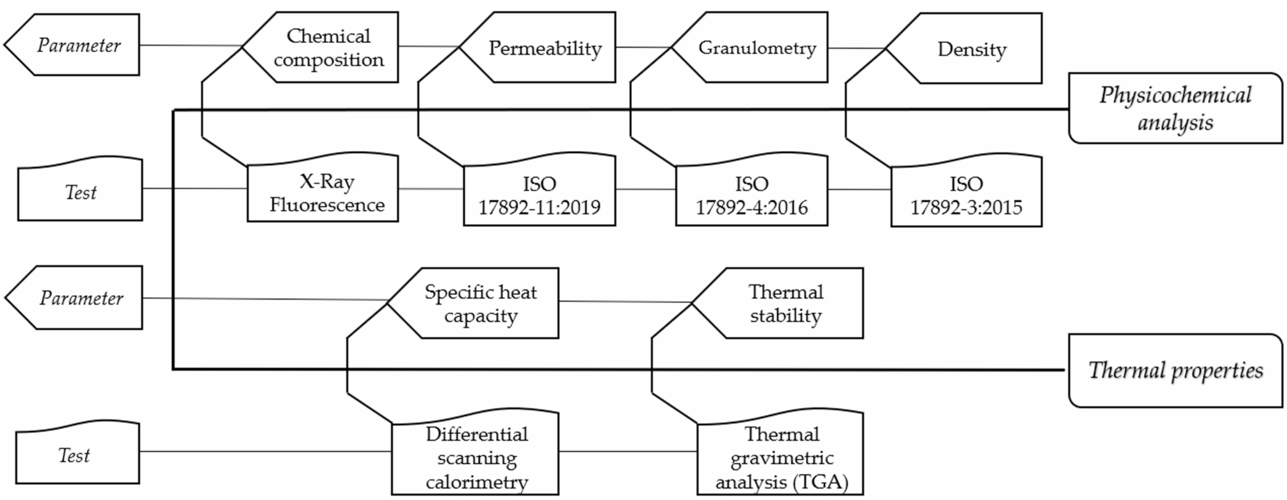

Fig. 2. Experimental design program.

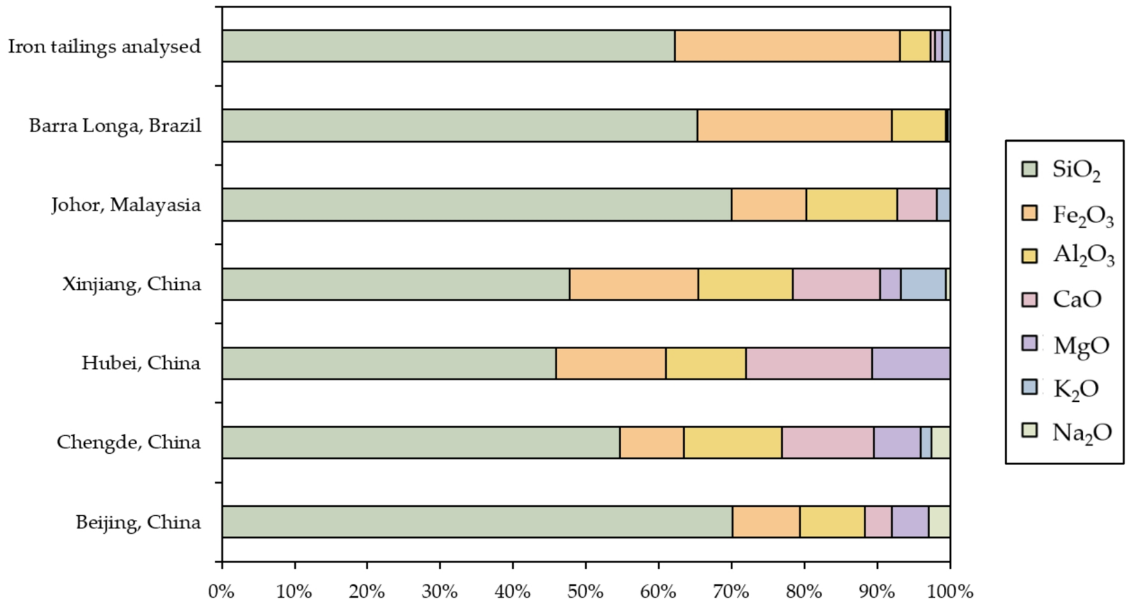

Fig. 3. Chemical composition of iron tailings analysed compared to other places.

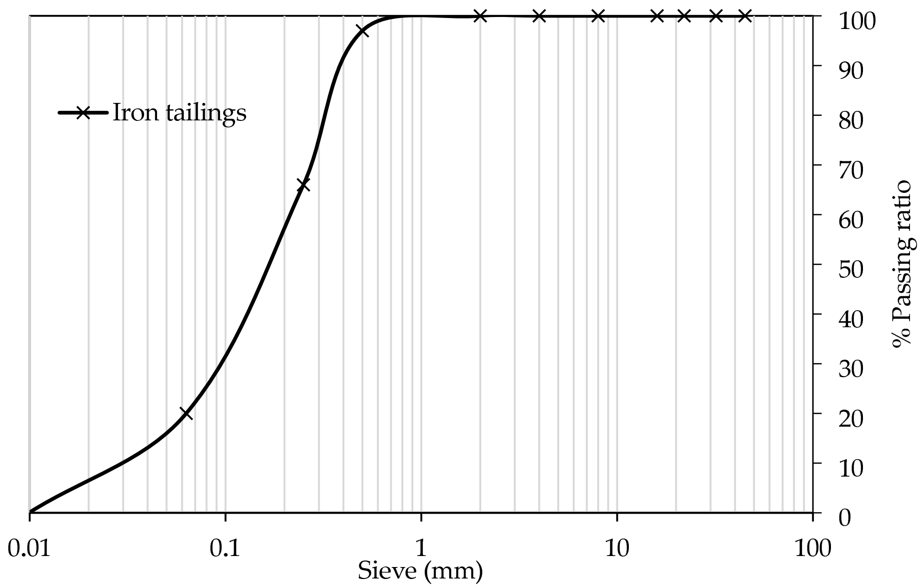

Fig. 4. Particle–size distribution curve of tailings as received.

This fine granulometry leads to a relatively low permeability (5.04×10^{-7} m/s), slightly lower than that of coarse packed-bed materials, which could influence heat transfer fluid flow in a thermal storage unit. Despite the fineness, the tailings exhibit a high bulk density of 2,948 kg/m^3. This high density is advantageous for volumetric energy storage since a cubic meter of iron tailings will weigh more and thus store more energy (for a given temperature rise) than a cubic meter of lighter material like concrete or rock[36]. Regarding the mean flow (0.0138 mL/s), hydraulic gradient (6.90 m/m) and permeability coefficient (5.04×10^{-7} m/s) obtained, they report slightly lower values than conventional materials.

Thermal properties

In order to determine the thermal stability of the iron tailings, thermogravimetric analysis (TGA) was performed from room temperature up to 1000 °C. Figure 5a shows the measured mass difference obtained from the experiments as a function of temperature. The TGA results are usually presented as 'mass loss' (TG%) since, at the beginning of the test, the balance is tared to 0 and the losses of mass are represented by negative values

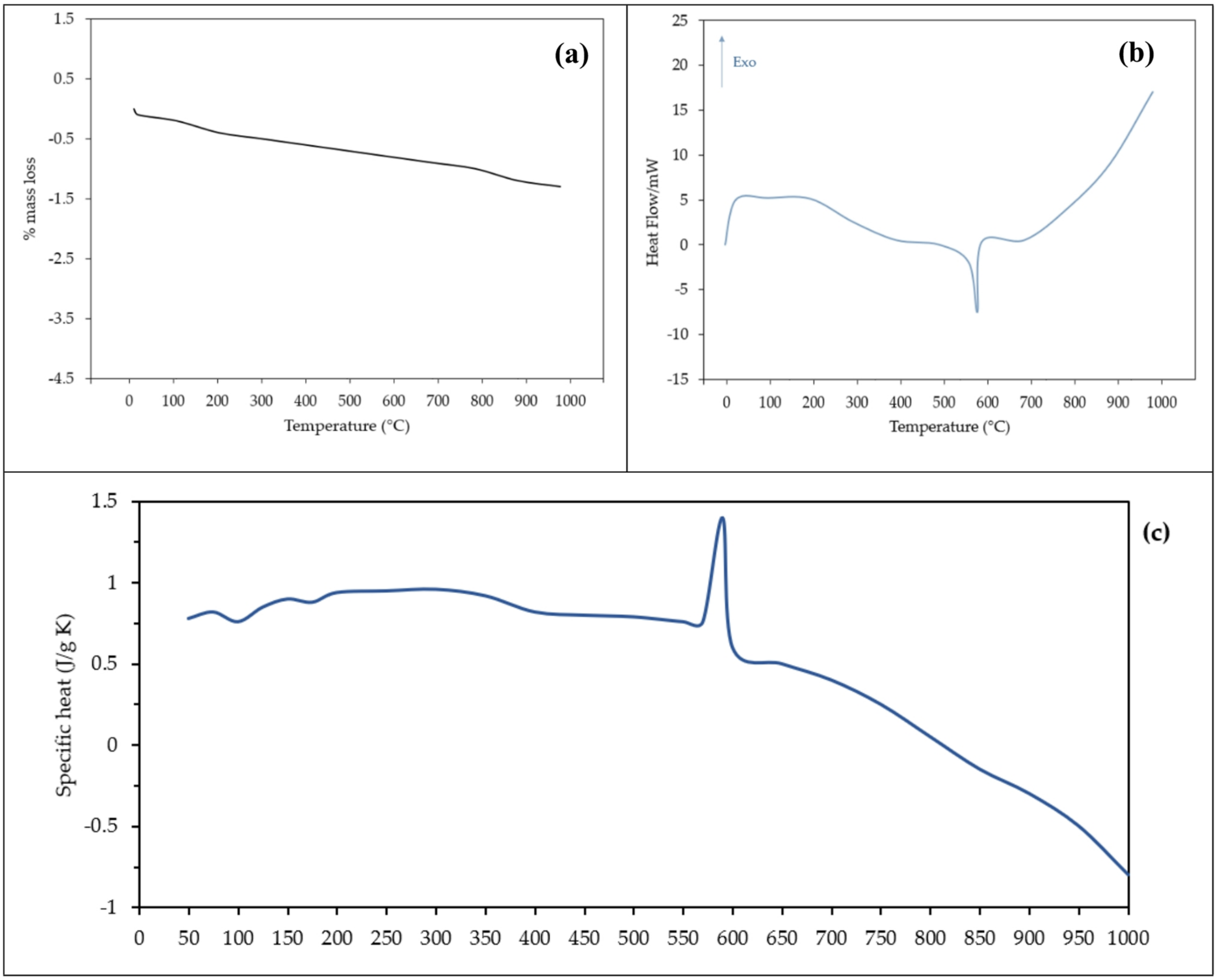

Fig. 5. (**a**) Thermal gravimetric analysis of iron tailings. (**b**) Records of the DSC analysis. (**c**) Specific heat capacity of the sample as a function of temperature.

from this initial point with a minimum value of −100% which would correspond to the total decomposition of the sample.

As can be seen, there is a slight mass loss of about 1.5% over the entire temperature range. An initial rapid mass loss occurs below 150 °C due to desorption of residual moisture, after which the mass remains nearly constant with only minor fluctuations up to 1000 °C. From this point onwards, the loss may be related to the oxidation-reduction reactions that take place when the material is heated. Many elements in the materials can potentially be oxidised, such as metal oxides (at higher oxidation rates), and/or may remain as trace metals in the tailings. However, no significant decomposition or reacting-away of the material was observed, even in an oxidative atmosphere, indicating that the tailings are thermally stable at least to 1000 °C with essentially no volatile content.

This thermal stability is a key requirement for sensible heat storage media, essential for long term durability in thermal cycling applications. Iron tailings behavior is on par with other inert solid TES materials stated in literature. For example, vitrified waste products like Cofalit® are reported to be stable even up to 1200°C[37] or natural basaltic rocks and glasses can also sustain high temperatures with minimal degradation[38].

Figure 5b shows the DSC curves representing the power-energy (mW) variation as a function of temperature. The curve reveals additional insight into phase transitions. An endothermic peak appears at around 590 °C. Nevertheless, this endotherm is not accompanied by any mass loss in the TGA, implying it is due to a solid-state phase transformation (solid-solid or solid-liquid (melting)) rather than decomposition.

A likely interpretation is the α–β quartz inversion. Quartz (SiO_2) is the major component of these tailings and undergoes a well-known crystalline transition at approximately 573 °C, wherein the low-temperature α-quartz shifts to a β-quartz structure[39]. This transition is reversible and entails a volume expansion on the order of 5–8%[39]. In materials like granite, the α→β quartz conversion around 573 °C can induce microcracking due to the sudden expansion. In the iron tailings DSC, the smooth endotherm at around 590 °C suggests the material absorbs heat for this internal reorganization.

Following this, a slight exothermic drift is observed above 600 °C which likely indicates that the new high-temperature phase is undergoing continuous structural adjustment (crystallization of a metastable amorphous fraction into a more stable crystalline phase), releasing some heat in the process. By 800 °C, the exothermic contribution becomes pronounced as evidenced by a net downturn in the apparent DSC curve. This phenomenon is essentially the material giving back heat (exothermic) as it further stabilizes its internal structure. Importantly, these thermal events cause no deleterious effects on the material's integrity since the sample remained physically intact, and the total mass change was negligible.

The quartz phase inversion is a reversible process, and the subsequent slow exothermic crystallization indicates the tailings develop a stable high-temperature phase without disintegration. No melting or irreversible phase decomposition was detected up to 1000 °C. This finding is positive, as some phase transitions (like certain polymorphic changes in ceramics[40] can lead to thermal shock or material damage, but the iron tailings display a robust tolerance to the internal changes at 590 °C.

The specific heat was derived from the DSC data and is showed in Fig. 5c. From room temperature up to 590 °C, the tailings exhibit a roughly constant heat capacity (790–990 J/kg K). From this temperature, a clear decrease is observed, directly tied to the exothermic structural change. The material is releasing heat in that regime, the DSC records a reduced net heat input required to raise its temperature, which mathematically manifests as a lower (even slightly negative) incremental heat capacity. However, the material continues to absorb energy as it heats further, but the exothermic contribution complicates its interpretation. Once the transformation is essentially complete (above 800 °C), the net heat capacity returns to a small positive value, although the exotherm still partially offsetting the sensible heat uptake. The maximum specific heat is recorded from 300 °C with values around 990 J/kg K.

This behavior means the material will undergo an internal exothermic event during initial heating in the 600–800 °C range, which could help the charging of the thermal store by releasing a bit of extra heat. Aside from this transient, the iron tailings show a stable and usable specific heat capacity across the relevant temperature window.

These values are consistent with the expected contributions of the main oxides identified by XRF. Magnetite (Fe_3O_4) generally exhibits higher c_p values, while hematite (Fe_2O_3) and other oxides contribute in the lower range. Since XRF reports total iron as Fe_2O_3 equivalent, it is not possible to distinguish directly between phases in this study. Nevertheless, the observed c_p behaviour can be reasonably explained by the combined effect of silicate phases (SiO_2, Al_2O_3, etc.) and Fe-oxides. A more precise quantification of the phase contributions would require mineralogical analysis (e.g., XRD) and the application of the Neumann–Kopp rule to calculate a theoretical bulk heat capacity as the weighted sum of the specific heats of the individual phases.

Regarding the thermal conductivity of iron tailings was measured from room temperature up to 450 °C (Fig. 6). From the density and specific heat data thermal diffusivity (α) values were obtained following the next Eq. (1):

$$\lambda = \alpha \cdot \rho \cdot C_s \tag{1}$$

Where λ is the thermal conductivity (W/mK), ρ is the density (g/cm^3) and C_s (J/g K) is the specific heat capacity.

An interval of maximum stability is observed between 100 and 275 °C, with minimal variation in conductivity. This trend is consistent with the thermograms. The endothermic event around 590 °C and the subsequent exothermic drift reflect internal rearrangements in the silicate framework that can subtly alter solid–solid contact networks within the granular matrix, reducing the effective heat-conduction pathways. The observed decrease

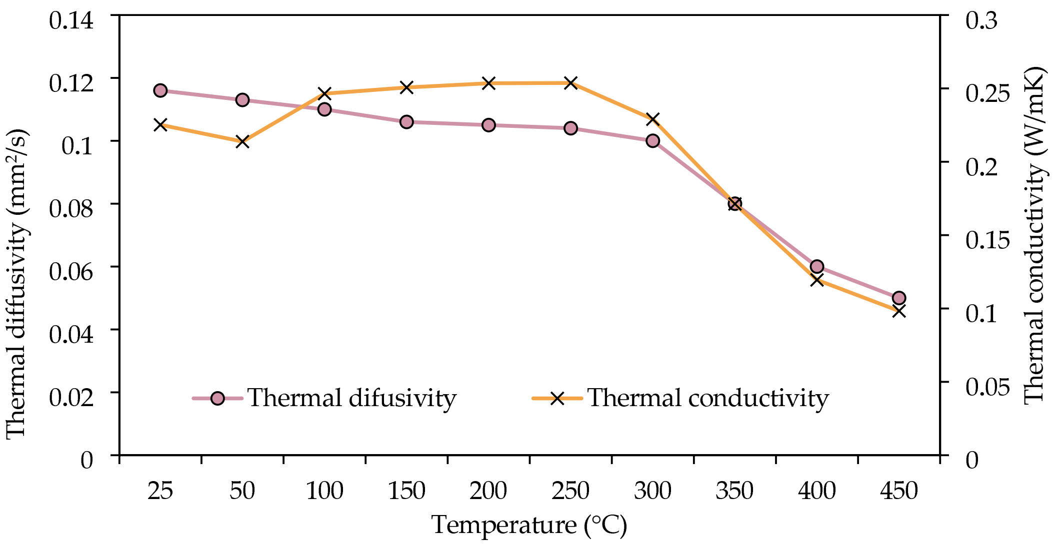

Fig. 6. Thermal conductivity and thermal diffusivity of iron tailings.

in λ and α beyond 300 °C implies slower transient heat penetration through individual grains and contacts. Quantitatively, the tailings exhibit low effective conductivity (0.10–0.25 W/mK in the studied range) which is attributable to the fine particle size and pore spaces in the tailings. While this could lead to steeper temperature gradients within a bulk bed of tailings during charging-discharging cycles, it is not necessarily a limitation.

Thermal diffusivity is a measure of how quickly a material reacts to temperature changes. Materials with a high thermal diffusivity will heat or cool quickly; conversely, substances with a low thermal diffusivity will heat or cool slowly. Thus, thermal diffusivity is an important property when considering unsteady-state heat transfer situations, that is, in the charge-discharge cycles. It can be seen in both cases that there is a noticeable decrease in conductivity and diffusivity from 300 °C onwards.

The results show very promising iron tailings properties for use as thermal energy storage material. Furthermore, the TGA analysis carried out demonstrated shows that there is hardly any mass variation, which ensures the thermal stability of iron tailings in a wide temperature range up to 1000 °C. The net effect is a high energy-per-volume with a conservative heat-transfer rate through the solid phase, indicating the high suitability of this mining waste for TES technologies.

Comparison of iron tailings with other TES materials

Once the technical feasibility of iron tailings has been discussed, a comparison with other TES materials commonly used is presented (Table 1). Molten salt, concrete, sand, cast steel, NaCl and crushed rock are the most common solid sensible thermal energy storage materials, but the table also shows other residues that have been analysed as TES material such as EAF slag or fly ashes.

The specific heat capacity of the iron tailings (780–990 J/kg·K in the tested range) is similar to those of common solid media currently in use. Silica sand typically offers 710–900 J/kg·K, and concrete around 850–920 J/kg·K, so the tailings fall comfortably within this band. They also match well with other waste-derived candidates, such as electric arc furnace (EAF) slag from the steel industry (900–950 J/kg·K) and Cofalit® (800–1030 J/kg·K). On a mass basis, therefore, iron tailings can store heat as effectively as these alternative materials. In terms of density, iron tailings (2948 kg/m^3) are denser than other common materials, such as natural rock (11500–2800 kg/m^3) or molten salts (1870–2600 kg/m^3), approaching that of processed ceramics Cofalit® (3120 kg/m^3) or fly ashes (2962 kg/m^3).

One area where iron tailings differ markedly from most other materials is in thermal conductivity. Because the tailings in this study are used in a dry, powdery form with significant porosity, their effective thermal conductivity is quite lower than other waste-based materials like EAF slag (1.3–1.5 W/m·K in the 200–600 °C range)[37]. Many packed-bed TES systems actually operate with filler materials (rocks, ceramics) that also have moderate thermal conductivity, relying on the heat transfer fluid to carry energy through the bed[54]. Although iron tailings have low thermal conductivity, they deliver high heat capacity and density, which can be advantageous if the storage system is designed to mitigate the conduction limits (for example, by ensuring good convective heat transfer with the fluid).

The specific heat and density properties enable the calculation of total energy stored (Q) as follows (2):

$$Q = \rho \ C_p \ \Delta T \tag{2}$$

Where ρ is the density (kg/cm^3), C_s (J/kg K) is the specific heat capacity and ΔT the temperature interval. Figure 7 presents a comparison between the energy stored (at 573 K) in each of the materials and the energy cost. Data for reference materials were obtained from Table 1 (literature values), while the values for iron tailings correspond to the experimental results of this work.

Material	Specific heat (J/kg K)	Temperature [°C]	Bulk density (kg/m^3)	Thermal conductivity (W/m K)	Price (€/t)	Reference
Rock	1000–1060	200–600	1500–2800	2.50–3.50	50–90	41–43
Alumina	800–1157	25–1000	3950–3960	11.98	315	31,44
Concrete	850–920	20–600	2200–2300	1.50–2.37	80	44,45
Cast steel	600–650	25–800	7800	40.00	5000	46,47
Cast iron	550–600	25–800	7200	37.00	1000	48
Silica sand	710–900	200–600	2200–2500	1.83–2.25	20	47,49
Magnetite	800–900	200–600	4962	-	135	42
NaCl	800–900	250–800	2160	0.51	150	47
Water	2400	100	1000	-	1.5	50
Molten salts	1500–1600	200–600	1870–2600	0.52–2.00.52.00	625–700	44,51,52
BOF slag	850–950	200–600	3807	-	-	42
Fly ashes	700–750	200–600	2962	1.16	-	53
Cofalit®	800–1034	200–600	3120	1.40–2.10	8	44,51
EAF slag	850–950	200–600	3770–3900	1.3–1.5	-	37,44
Iron tailings	780–990	*25–590*	*2948*	*0.10–0.25*	-	-

Table 1. Comparisons between iron tailings and common thermal storage materials.

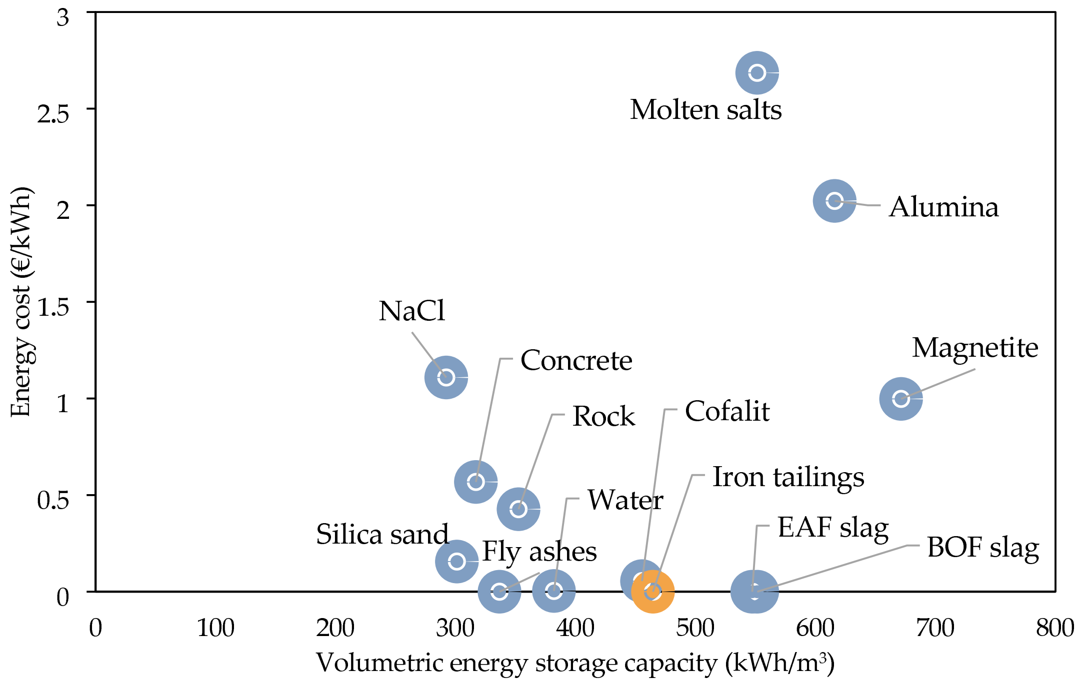

Fig. 7. Comparison between storage density and energy cost of iron tailings and different materials. (ΔT = 573 K).

The cost of the waste has been taken as 0, assuming only transport costs are necessary. For the calculation, the maximisation of stored energy along with the minimization of total material cost have been considered as criteria. These results represent the theoretical minimum value, as the calculation does not account for practical thermal storage issues such as charge/discharge conditions, heat losses, and other parameters.

As can be seen, iron tailings have a highly competitive performance. A preliminary estimate indicates the potential for a reduction of about 3 times the total cost of the current most used storage material (molten salts), which could lead to a significant cost reduction in the storage system and thus to a reduction of the LCOE (levelized cost of electricity). The performance of iron tailings is similar to Cofalit which is also cheap (8 €/t) although when it is treated by plasma torch, its price increases to (1200 €/t)[33].

Conclusions

Mine tailings are an unavoidable waste generated during iron ore mining operations, of which millions of tonnes are generated worldwide. Given the importance of steel, and therefore of iron ore mining, solutions are needed to recover this waste. On the other hand, research and development studies on thermal energy storage materials are a hot topic among the research community, particularly those focusing on sensible heat storage materials. Numerous scientists have worked on TES materials and their respective technologies. In this study, thermophysical and chemical characterization of iron tailings from the mining industry has been performed for its potential use as material for thermal storage systems.

Up to temperatures of 590 °C no change in the internal structure or phase transition of the material was noted, a temperature range within the normal working spectrum for other commonly used materials, such as molten salts. In cases requiring higher temperatures, more specific testing would be necessary, as the present analysis cannot ascertain whether the endothermic peak around 600 °C indicates a solid-solid or solid-liquid phase change.

Compared to materials currently in use, the heat capacity is medium (0.78–0.99 J/K-g) although the thermal conductivity is low (0.12–0.25 W/mK). According to the results obtained, each m^3 of iron tailing has a storage capacity up to 464.53 kWh (assuming the highest measured specific heat capacity is used in the calculations) at very low cost, involving only the transport of the material. Replacing molten salt with iron tailings would mean a reduction of approximately 2.5 €/kWh.

This study opens up a new potential market for the valorisation of the iron tailings produced linked to the field of renewable energies that no one had yet considered. This article sets out the first steps of the research, with future lines of development analysing the appropriate equipment for the incorporation of iron tailings and their viability on a pilot scale. In addition, future work should include a detailed mineralogical characterization to identify the specific phases (such as hematite or magnetite) and to better correlate the mineral composition with the measured thermophysical properties.

The implementation of this environmentally friendly alternative would reduce the need to exploit natural resources, which in turn would lead to environmental and economic savings. It would also give a second life to a waste that is produced in large quantities worldwide, in line with the principles of the circular economy. Finally, the recovery of iron tailings would avoid the disposal of a huge amount of this industrial waste, which also entails significant environmental risks depending on the conditions of deposition. In the face of new climate trends, production should be reduced to the minimum necessary, and the reuse and recycling of elements that cannot be returned to the environment due to their properties should be encouraged.

Data availability

No datasets were generated or analysed in this study.

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Declarations

Competing interests

The authors declare no competing interests.

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