Journal of Thermal Engineering
https://jten.yildiz.edu.tr/
https://doi.org/10.47481/jten.0014

REVIEW ARTICLE

# Application of industrial wastes material as energy storage: a comprehensive review

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## Abstract

Using industrial solid waste to generate energy is a viable approach that is attracting increasing attention as a business opportunity for environmentally friendly and cost-effective energy production. The research examines materials such as fly ash (FA), red mud (RM), steel slag (SS), calcium aluminate cement (CAC), and white cement (WC), focusing on their composition and synthesis, thermal storage properties — including thermal conductivity, specific heat capacity, and structural permanence under frequent thermal loading — and applicability in packed-bed and composite thermal energy storage (TES) structures. Thermal conductivities calculated at temperature as high 500 °C were verified by CAC composites that are stable at high temperatures, representing their appropriateness for high temperature applications. Whereas FA and RM were only moderately thermally conductive, SS demonstrated superior thermal performance. Although the WC looks better and has a smother surface, its heat resistance is disappeared. The review goes beyond what is usually known in the investigations. Through an energy-focused method, we determine that the materials can substitute energy rather than being treated as mere by-products. This types it thinkable to create goods that are good for the environment. This creates new opportunities for environmentally friendly design. For investigators and engineers looking to build bridges; in this work offers a new and important path.

**Keywords:** Thermal energy storage, industrial solid waste, high-temperature energy storage, phase change materials, composite heat storage systems, circular economy

**Cite this article as:** Madhuri, K. S., Panchal, M., Kalangi, C., & Rajak, U. (2026). Application of industrial wastes material as energy storage: A comprehensive review. Journal of Thermal Engineering, 12(3), 2–19. https://doi.org/10.47481/jten.0014

## 1. Introduction

Each year, increasing amounts of industrial solid wastes (ISWs) are generated as a result of rapid industrial expansion. Various materials, such as metallic slag, coal fly ash (CFA), factory gypsum, and steel slag, constitute ISWs. Much of the ISW remains inadequately managed owing to complex physicochemical properties, variable composition, and high treatment costs. Every year, billions of units of ISW are made around the world, and that number keeps going up [1]. If not properly disposed of, these wastes have disastrous effects on the Earth and human health. ISWs often contain heavy metals, acidic or alkaline compounds, and toxic organic chemicals. This contaminates stance health worries and seriously ill the ecosystem when they dissolve, seepage, or seep into the ground or water. Heavy metal effluence that piles up in the earth can constrain plants from emerging and seep into the food chain, where they force upset people's fitness over time [2-3]. Likewise, receiving free industrial solid wastes (ISW) occupies large areas, degrades soil, and reduces ground stability, thereby exacerbating environmental concerns. For of this, it is now extremely important to use and accomplish ISW well in the fields of technology, the economy, and the environment [4].

The use of ISW for TES impacts both the environmental and manufacturing sectors. Huge amount of materials such as FA, RM, and SS are produced in a diversity of businesses, including metallurgy, refining, and power producing. As already noted, positioning of them offerings a number of risks. Louts of these waste materials are appropriate for TES applications

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**Submitted:** 16 September 2025; **Accepted:** 15 October 2025

This paper was recommended for publication in revised form by Editorin-Chief Ahmet Selim Dalkılıç

Published by Yıldız Technical University, İstanbul, Türkiye

because they have constructive thermal parameters and stable mineral stages. By rerouting ISW into useful energy systems for industries or domestic purpose, thermally stable storage medium can be produced. Reusing the ISWs as thermal energy storage (TES) materials has recently attracted research interest. The TES technologies are broadly classified into two categories: sensible heat storage and composite heat storage systems [5-6]. To store energy as sensible heat, you increase the temperature of a substance. Therefore, this type of heat-storage device has a limited storage capacity because of its specific heat capacity and the attainable temperature range, although it is relatively simple and stable. Composite heat storage uses latent heat during phase change by absorbing or releasing heat, and thus offers higher energy density, better temperature control, and shape retention. This makes it an intriguing area of study for thermal storage.

Because they absorbed or release important amounts of energy during stage transitions, such as solid to liquid or liquid to gas, phase change materials (PCMs) are important for composite heat storage. PCM comes in several forms, counting fatty acids, paraffins, and salts [6-7]. Yet, PCM has a number of problems that limit its applicability. For example, they show instability, leakages during stage changes, and lesser thermal conductivity (k)<0.3 W/(m.k). The composite is strengthened and made more dimensionally stable thru Skelton materials (SMs), which also create conductive channels that aid in heat-transfer. The PCMs thermal conductivity (k) might be increased by SMs to 2.0W/(m.k). Also, SMs can stop molten PCMs from leaking via surface contact or their porous architectures. As result, the storage system continues longer of using ISW such as SMs for PCMs or composite PCM materials [8-9][10]. They want to find new ways to store heat and take advantage of the sole parameters and greasepaint of ISWs.

Elfeky et al. [11] made a packed-bed thermal energy storage (PBTES) gadget and looked into how well it worked. They identified the internal thermocline head and its effect on the HTF temperature at the device exit. This causes the actual released thermal energy to be lower than the ideal thermal energy. Wu et al. [12], did a computer study on cascaded PBTES devices with various PCM melting temperatures. They found that the internal thermocline created a cascading device. Li et al. [13] studied PBTES devices that were not cascaded and three-cascaded. They found that adjusting the PCM melting temperatures could reduce the thermocline thickness. The three-stage cascaded PBTES device produces the highest useful heat output. In their study [14], Wang et al. looked into how the PCM capsule width affects the performance of the PBTES devices. As the PCM capsule increased in size from 25 mm to 75 mm, its heat storage capacity decreased by 12%. Li et al. [15] developed a novel double-layer cascaded PBTES embedded with PCM capsules with varying diameters along the flow direction. Their research reported a 12.4% increase in heat storage capacity. Liang et al. [16] look at how the size of the tank affected the performance of the PBTES device. The results showed that the device performed best when the ratio of the tank diameter to the PCM capsule diameter exceeded 8 or the ratio of the tank height to its diameter exceeded 45. Yu et al. [17] log into how the speed of the heat transfer fluid affected the operation of the PBTES device. They found that the charging time decreased as the heat-transfer fluid velocity increased, whereas the heat storage capacity remained essentially unchanged. Based on the literature described above, thermocline properties have been incorporated into the PBTES device.. These results indicate that the use of multiple materials is preferable for energy efficiency; however, the melting process consumes more energy than it produces. The strength of this conclusion is largely due to the model used in that study, and further investigation is required. It was also found that the collector used to heat water collected more energy when more PCMs were used [18].

Aldoss et al. [19] experimented with PCM capsules of varied physical and thermal qualities. Spherical capsules containing paraffin 40, paraffin 50, and paraffin 60 were placed at different positions along the bed. This study found that increasing the number of steps in a PCM-based latent heat storage system improved the charging and discharging rates, the heat transfer rate, and the storage capacity. On the other hand, adding more than three stages did not substantially improve system performance. Watanabe et al. [20] designed and studied a heat storage module made up of horizontal cylindrical spheres that were filled with three different kinds of PCMs. The study shows that when the system is operated with a multi-stage PCM, the charge and discharge rates are higher than when it is operated as a latent heat storage system with a single PCM.

This is due to a more uniform distribution of temperatures between the heat transfer fluids to PCM. By authors Kousksou et al. [21] evaluated the solar system protects unused heat using the second criterion. They found that placing numerous PCMs in sequence inside the storage tank reduced damage. Gracia et al. [22] examined and discussed a number of numerical techniques used to evaluation the performance of a latent packed bed thermal storage system. Wang et al. [23] investigated the charging of three separate PCM types within a circular heat storage capsule. An increased charging rate was found in an experimental investigation. There is an important amount of recent study on bed storage, according to researchers. The temperature fluctuations and phase-change mechanisms inside PCM capsules in both single and three-stage system, but, are poorly understood. Some ISW kinds are more suited for TES applications than others because to differences in their physicochemical parameters. These consist of RM, SS and CFA. For example, CFA is ideally well-matched for TES applications because it includes a large amount of aluminosilicates, has great thermal permanence at higher temperatures, and can store an important amount of thermal energy [24-26][27-29]. The steel slide is an appropriate ISW for heat transmission and energy protection due to its higher thermal conduction and density. In this intelligence, it is better than many others. RMs thermal stability at higher temperatures is aided by the presence of many iron oxides. Additionally, it has the ability to store thermochemical energy, a feature that is less noticeable in other industrial wastes. These materials also vary in that they are affordable effortlessly reachable, and consistent with the circular economy's tenets. They might be a sustainable substitute for traditional TES materials..

ISW derives TES materials have a great deal of flexibility, which makes them suitable for a variety of uses. ISWs may be included into system that service sustainable energy sources, including concentrated solar power plants. Energy release and storage may be simplified by their higher stability and heat capacity [30]. The application of ISW based materials in electronic heat management systems may also be investigated. In this regards, they might be better than conservative materials due to their light weight and thermal conductivity. Separately from these applications, ISWs may also be used in cold chain transport and greenhouse farming [31-34].

TES materials have long been investigated using conventional materials including ceramics, phase-changes materials, and molten salts. Industrial solid waste as a TES medium is still a very new concept. These materials have been systematically investigated and may offer a long-terms solution for large-scale energy storage. Current research approached them as fillers rather than concentrating on their thermal of chemical properties. In order to assess their thermal behavior, counting heat capacity, thermal conductivity and stability, as well as their practical implementation in systems like packed-bed or composite TES topologies, a thorough review is required. In order to determine compositions that truly show promise for long term, high temperature energy storage, this review examines recent research on materials such as FA, RM, SS CAC and white cement. Innovative viewpoints that promote sustainable resource recovery and energy efficiency are presented in this paper. .

## 2. Characterization of ISW materials

### 2.1. Chemical and structural composition

A variety of ISW materials, including CAC (calcium aluminate cement), cement, CSCG (charred spent coffee grounds, CG (coal gangue), DK (dealuminated kaolin), FA, ITS (iron tailings slag), RM, SCT (sulfidic copper tailing), SS, and waste ceramics, have been utilised by researchers for TES, For the purpose of evaluating their potential as TES, their physicochemical parameters is important. The different materials utilised in TES and their chemical conformations are given in Table 1. Although their chemical configurations varies based on their production method and geographic location, the aforementioned solid wastes often consist of alumina, calcium oxide (CaO), magnesium oxide (MgO), and silica . These materials are particularly well suited for high temperature applications due to their favourable mineral compositions and high melting points, which make then, better material for TES and comparisons shown in Table 2. The primary components of DK are and as shown in Fig.8, FDK, on their other hand has an amorphous structure and a slightly lower content than DK. The characterization of various ISWs is presented in the following sections.

**Table 1.** Chemicals consist of different ISW materials

| Materials | $Al_2O_3$ ( wt. %) | $SiO_2$ ( wt. %) | $TiO_2$ ( wt. %) | CaO ( wt. %) | $Fe_2O_3$ ( wt. %) | MgO ( wt. %) | $K_2O$ ( wt. %) | Reference |
|---|---|---|---|---|---|---|---|---|
| FA | 26.73 | 41.55 | 1.66 | 10.32 | 6.92 | 1.96 | 0.7 | [35] |
| Cement | 8.11 | 24.56 | 0.39 | 53.39 | 3.41 | 1.96 | 0.7 | [35] |
| CSCG | 6.93 | 10.78 | - | 15.66 | 0.96 | 9.75 | 25 | [36] |
| SA | 2.81 | 3.88 | - | 76.4 | 6.17 | 5.31 | | [37-38] |
| Anthracite | 41.6 | 43.1 | - | 4.56 | 3.38 | - | - | [37] |
| CG | 21.62 | 45.26 | 0.72 | 2.69 | 2.839 | 0.608 | 1.65 | [39] |
| Phosphogypsum | 0.584 | 1.928 | 0.07 | 46.318 | 0.266 | 0.382 | 0.3 | [40] |
| RM | 28.7 | 15.55 | 5.9 | 1.87 | 34.7 | 0.09 | 0.28 | [40-42, 67] |
| SS | 2.8 | 15.22 | 1.77 | 41.74 | 25.25 | 4.29 | 0.1 | [42] |
| SCT | 5.63 | 36.07 | 2.22 | 17.74 | 19.45 | 6.16 | 0.88 | [43] |
| CAC | 55.67 | 7.26 | - | 30.85 | 1.6 | 0.58 | 2.34 | [43,47] |
| ITS | 7.84 | 66.19 | - | 4.77 | 9.4 | 6.7 | 2.7 | [44-45] |
| SS | 6.29 | 17.3 | 18.81 | 37-40.4 | 25.69 | 4.12-7.5 | 0.12 | [44-45] |
| DK | 10.2 | 70.2 | 10.1 | 0.19 | 0.61 | 0.62 | - | [46] |
| WC | 4.05 | 21.60 | - | 64.04 | 0.26 | 1.3 | 0.35 | [48] |

**Table 2.** Comparison of pore structure properties

| **Materials** | **Specific surface area ($m^2/g$)** | **Density (20 °C) ($g/cm^3$)** | **Particle size** | **pH** | **Heat value KJ/g** | **Ref.** |
|---|---|---|---|---|---|---|
| FA | 209.6 | 2.1-2.6 | 10 and 100 µm | 7 | | 49-54 |
| Cement | 0.389 | 1.66 | 1.5 µ | 11.5 | | 55, 61 |
| CSCG | 1.96 | 1.24 | 0.42mm | - | 26.0 | 36, 57, 58, 59 |
| SA | 18.88 | | 0.25–0.4 mm | | | 38, 56 |
| CG | - | 2-2.8 | - | - | 4.2–12.6 | 60, 62 |
| Phosphogypsum | - | 1.336-1.72 | 0.075-0.15 mm. | 4.56-9 | - | 63, 64 |
| RM | 9 | - | 3.372 nm | 6-8 | - | 65, 66 |
| SS | - | 2.6-2.9 | - | 8-10 | - | 68 |
| SCT | 0.339 | - | 63 µm | - | - | 43 |
| DK | 95 | - | - | - | - | 69 |

### 2.1.1. FA and cement

Fly ash is a major industrial waste generated by thermal power stations, pharmaceutical industries, refineries, and other industrial sources. The major constituents of fly ash include $Al_2O_3$, $SiO_2$, CaO, and $Fe_2O_3$. Some research has examined the potential of fly ash as TES, either alone or in combination with other materials such as cement. For example, Ho et al. [35] have synthesized fly ash cement composites to be used in net zero energy buildings. Various fly ash–cement composite samples were prepared, and their microstructural properties were characterized. Fig. 1 shows the XRD patterns, chemical composition, particle size distribution, and microstructures of cement and fly ash. The characterization of FA and cement is shown in Fig. 1a–d. The major compounds present in fly ash are mullite and quartz, while in the cement, they are gypsum and $C_3S$. The particles are uniform and micron-sized, as shown in Fig. 1.

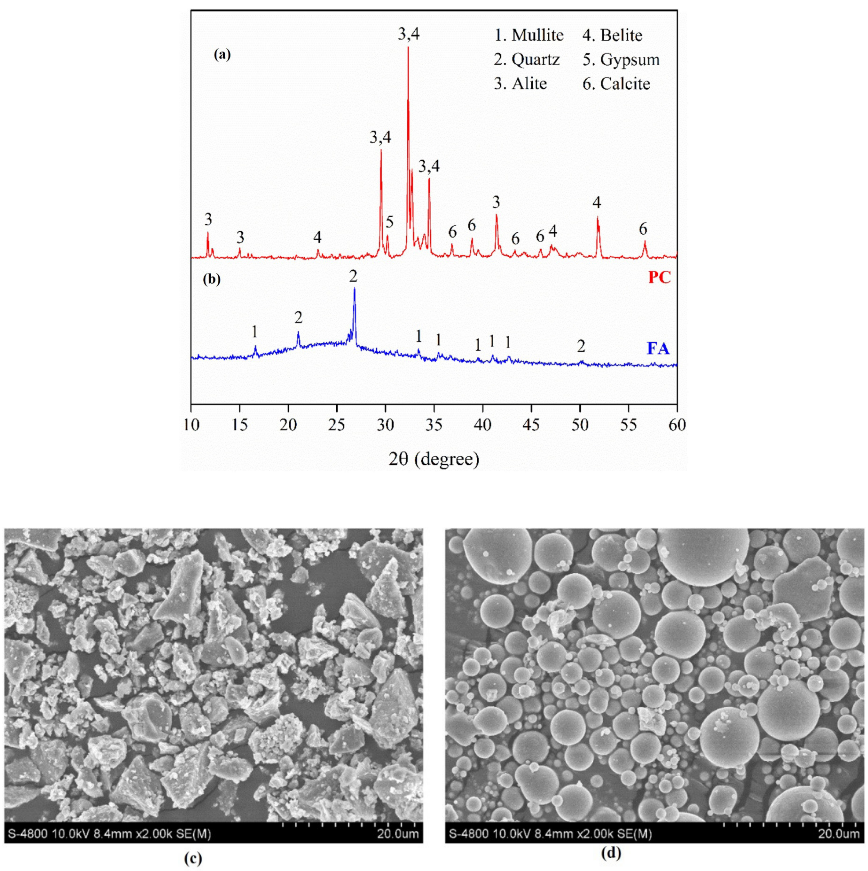


**Figure 1.** Microstructural analysis of fly ash and cement, **a)** XRD patterns for cement**, b)** fly ash, **c)** SEM image-Cement, **d)** SEM image-fly ash

In yet another research, Zuluaga et al. [36] have derived a modified version of fly ash that **is** charred spent coffee grounds(CSCG),a waste product of coffee processing. Its synthesis involves collecting coffee waste after consumption, followed by oven-drying the collected waste for an extended period. Further, the dried material is pyrolyzed at temperatures ranging from 200°C to 500°C for 2 hours. The principal elemental composition and structural attributes of the burnt waste coffee grounds are illustrated in Table 1 and Fig. 2, respectively. Fig. 2 shows that the CSCG is amorphous in nature; however, the presence of mineral compounds is clearly seen [36]. The appearance of a broad peak suggests the presence of an amorphous phase, indicating a lack of long-range atomic order. The tested material is dominated by an amorphous phase but also contains minor mineral residues.

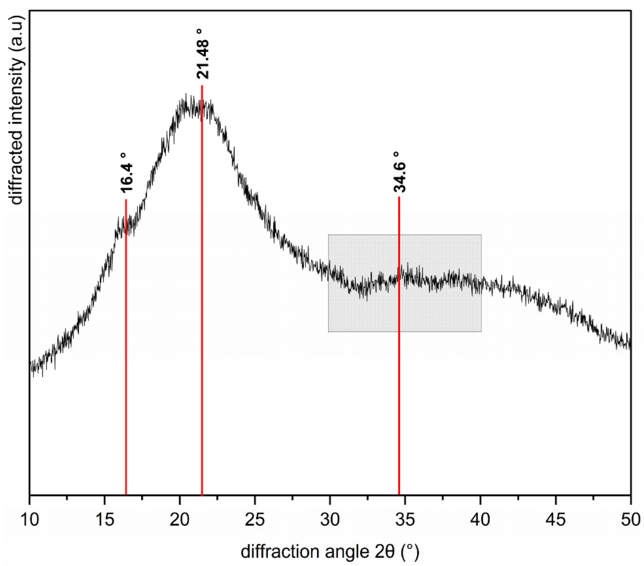


**Figure 2**. Characterization of CSCG XRD patterns

### 2.1.2. Semi coke ash

Semi-coke is another potential material that could be used, as TES has been characterized by Zhao et al. [37] in their research. The characterization involves proximate analysis, ultimate analysis, and the determination of heating value according to Chinese standards. In another study, ash derived from waste semi-coke was used to fabricate phase-change composites for heating and cooling applications in buildings. The chemical constituents of semi-coke ash are presented in Table 1 [38]. The SEM images are present in Figure 3 [37]. SEM images show that pure semi-coke exhibits numerous pores. Analysis of the CC1 sample confirms that a large number of PCMs caused cracking. However, the CC2 sample is dense, exhibits a pronounced structure, and displays numerous micropores in the SEM image.

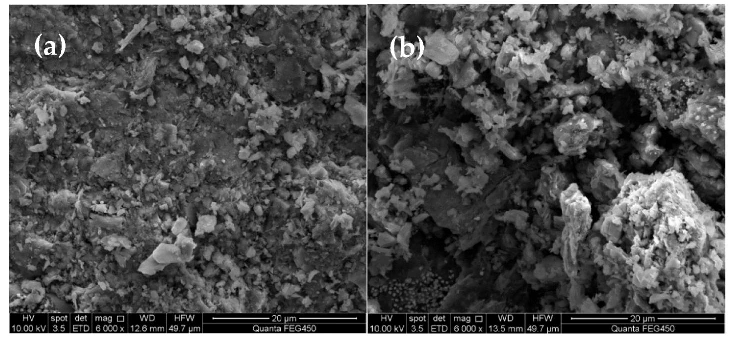


**Figure 3.** Transformation of the surface morphology of maceral group of semi coke and raw coal **a)** before combustion and **b)** after combustion

### 2.1.3. Coal gangue

Coal gangue (CG) is the waste generated during the mining and washing of coal. Figure 4 shows the visibility of coal gangue. Figure 4 shows coal gangue collected from a coal mine in mid-eastern China. The coal gangue could be segregated into two categories: fine aggregate(0.15-4.75 mm)and coarse aggregate(NCA),while rivers function as natural fine aggregate (NFA)[39].

(a) (b)

**Figure 4.** Apparent characteristics of coal gangue

### 2.1.4. Red mude

Alumina refining produces red mud as a byproduct. However, it is rich in iron oxide, aluminium oxide, and other heavy metals minerals [40]. The red mud (RM) samples used in this investigation were supplied by the Alumina Industry Company in Pungguo, Guangxi Province and analyzed by inductively coupled plasma optical emission spectroscopy (ICP-OES).The silicon content was ascertained via X-ray fluorescence(XRF)due to its inability to be fully dissolved [41]. The red mud also has been utilized as a catalyst for the extraction of platinum [42].

### 2.1.5. Sulfidic copper tailings (SCT)

SCT is a byproduct of the copper-mining process. They are rich in minerals, such as pyrite, and in other sulfides containing significant amounts of copper. They could serve as effective TES materials because of their high thermal conductivity. The chemical characterization of SCT was done elsewhere by using X-ray fluorescence spectrometry [43]. SCTs determined using a laser particle size analyzer are shown in Fig. 1(a).Its mineral composition was determined by the Rietveld method; the results are in Table 1. Figure 5 displays a picture and morphology of the SCT [43]. Figure 6 presents the particle size distribution and XRD pattern of SCT.

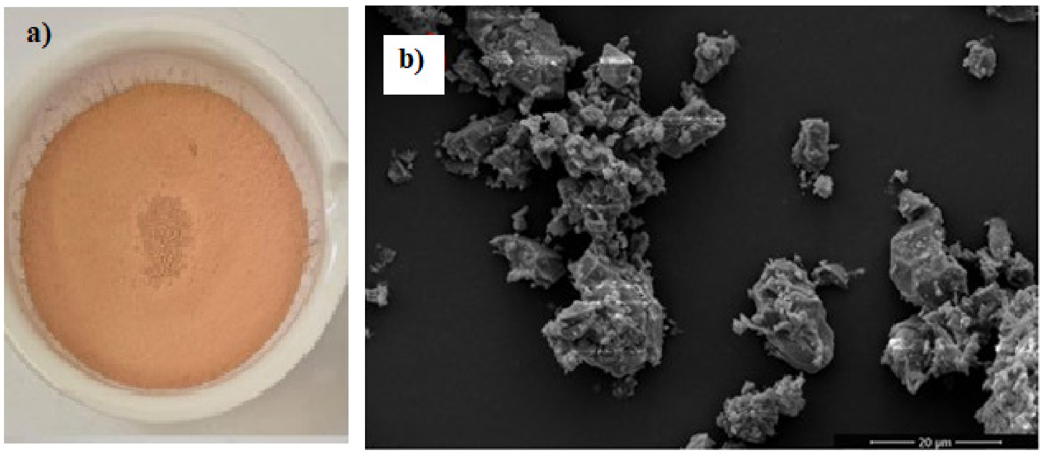


**Figure 5. a)** Photograph, **b)** Morphology of SCT

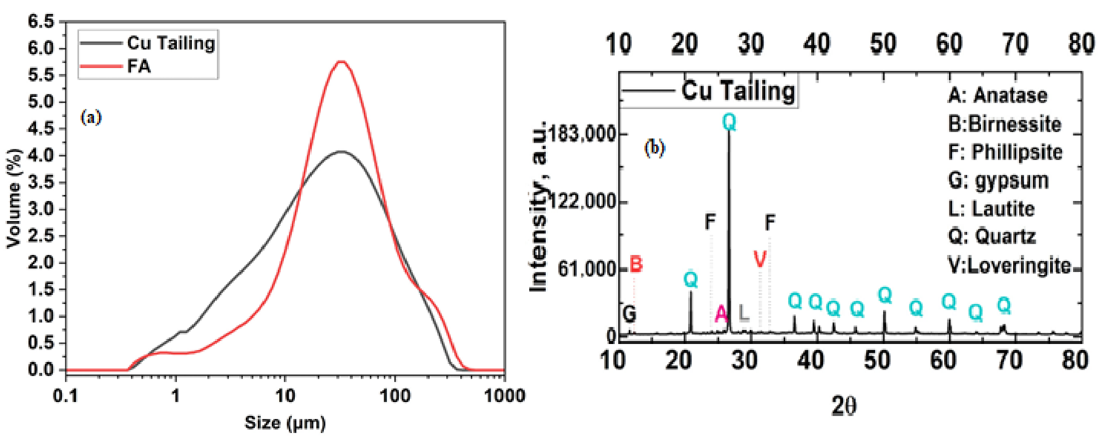


**Figure 6. a)** Size distributions, **b)** XRD pattern of SCT

### 2.1.6. ITS and SS

Iron ore tailings (IOTs), a by-product of iron refining, have recently been extensively investigated as potential materials for TES. Steel slag, a byproduct of steel production, is another similar material attracting considerable attention because it combines high thermal energy density with low cost. It has been found that it retains thermal stability comparable to CAC and Portland cement. Table 1 delineates the chemical compounds present in iron tailings and steel slag [44], whereas Figure 7 illustrates their corresponding XRD patterns. The main minerals detected in iron tailings are sekaninaite and quartz. The XRD image indicated a crystalline phase in steel slag, with the presence of this crystalline phase shown in Table 1 [45]. The slag used in this investigation was obtained from waste generated by an iron manufacturer.

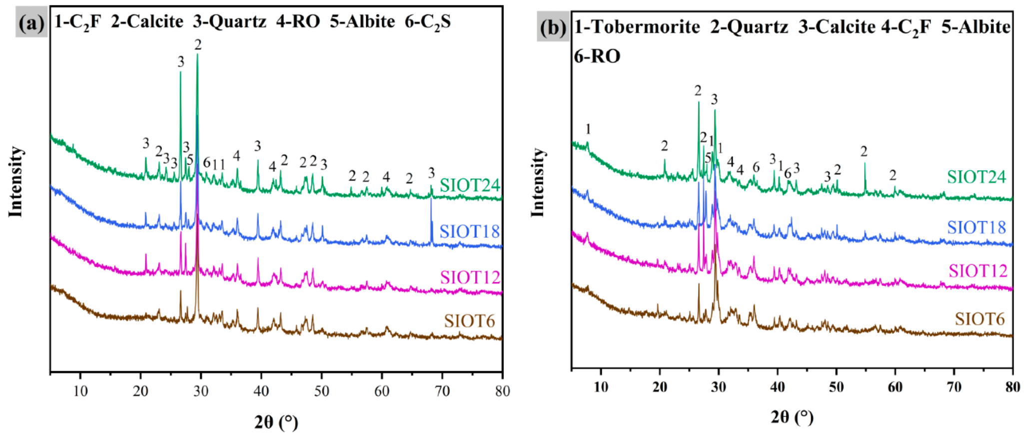


**Figure 7.** XRD pattern of SS and ITS

## 2.1.7. Dealuminated Kaolin (DK)

Dealuminated kaolin (DK) could be a suitable material for TES. It is prepared by removing aluminium from kaolin. It has high thermal conductivity and high heat capacity. It can be used for various applications, such as a PCM and a substrate for TES systems. In a study, a novel material that may have potential as a TES material was prepared by activating DK to remove the crystalline phase present in DK. It can be used as a sensible heat storage material. The synthesis of this material involves heating DK to 1000°C for 2 hours in the presence of 20 wt.% NaOH, producing a highly reactive silicate-rich substance. This substance was named FDK. Table 1 presents the chemical composition of DK and FDK. Fig. 8 shows that silica and alumina are the main constituents of DK; FDK, however, has a slightly lower silica content than DK and exhibits an amorphous structure. Figs. 8 and 9 show SEM and EDX analyses of DK and FDK at various magnifications. The SEM and EDX analyses of FDK indicate that the major elements are silicon, followed by aluminium (Figure 10a, b). Figure 9(c, d)shows the major constituents of FDK are silicon, followed by sodium oxide and aluminium [46].

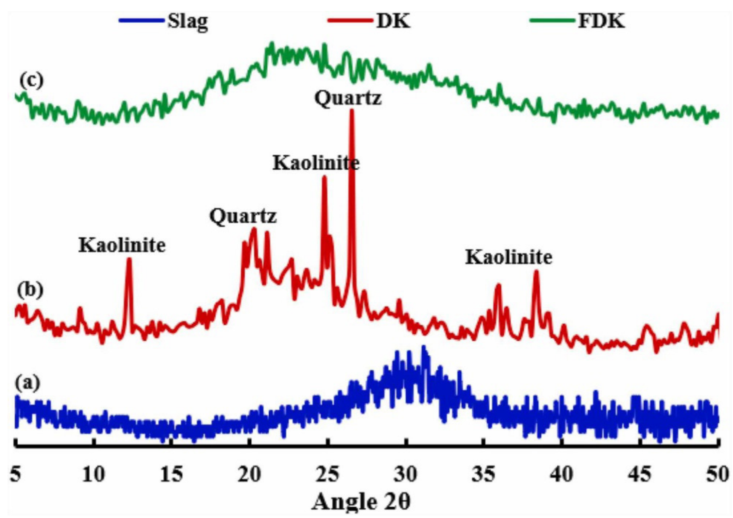


**Figure 8. a)** XRD pattern of slag, **b)** DK and **c)** FDK

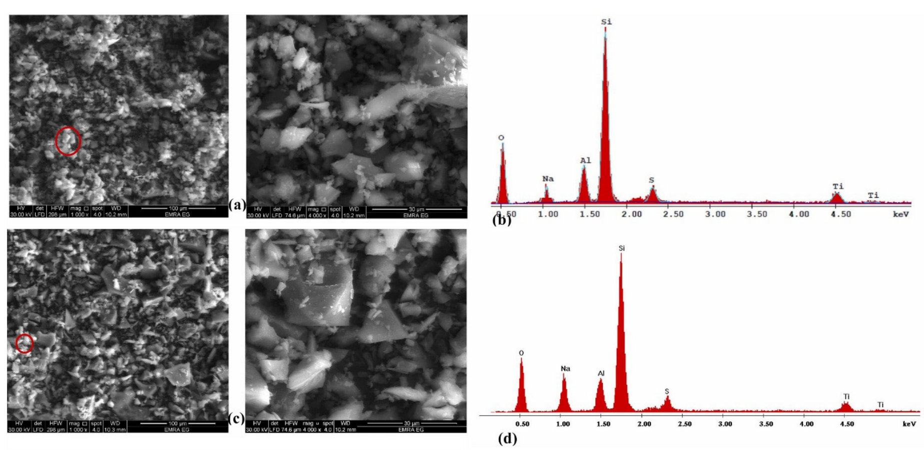


**Figure 9. a)** SEM images of DK **b)** EDS of DK, **c)** SEM of FDK, **d)** EDS of FDK

### 2.1.8. Calcium aluminate cement

Calcium Aluminate Cement(CAC)has emerged as a promising binder for high-temperature thermal energy storage systems due to its superior thermal conductivity and mechanical resilience under cyclic heating. CAC has potential as a TES because of its high heat capacity and thermal resistance. The chemical characterization of CAC was performed using XRD. Pore size analysis was also performed to assess the surface area, which was found to be 420 m²/kg. The chemical constituents identified in CAC are listed in Table 1. The XRD pattern could be seen in Fig. 10 [47]. Further studies reveal that when quartz filler is added to CAC composites, the thermal conductivity increases by up to 1.5 times compared with CAC in composite form, making them suitable for TES applications [100]. Furthermore, the curing conditions have a major impact on CAC's properties. Curing at elevated temperatures significantly enhances thermal conductivity and mechanical strength. This could be significant point for long-term thermal stability, which is required, as in solar power systems [101].

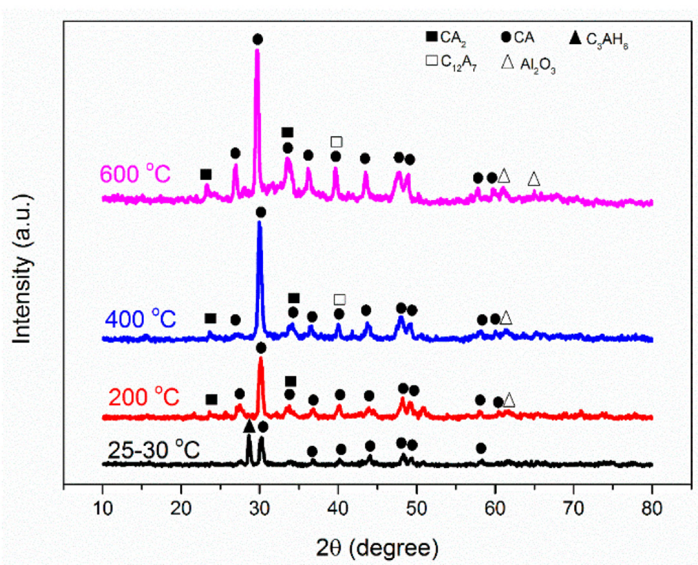


**Figure 10.** Shows as X-ray patterns

### 2.1.9. White cement

White cement could serve as a composite matrix into which nanoparticles or PCM could be incorporated to produce a TES material. The chemical compounds present in the white cements are listed in Table 1. While cement shows very high resistance even at elevated temperatures [48]. Although white cement offers a smooth and visually appealing surface, its thermal resistance is significantly lower than that of CAC. The white cement could be used as TES at a lower operating temperature range [102]

## 3. Thermo physical properties

The thermophysical properties of industrial waste materials are central to assessing their suitability for thermal energy storage (TES) applications (Table 3). Thermal characteristics such as thermal conductivity, specific heat capacity, density, and thermal diffusivity determine the performance of heat storage (TES). Literature findings show that a few materials show affirmative behaviour when it comes to thermophysical behaviour. Among those fly ash, red mud, and steel slag are quite promising due to presence of high concentration of metal oxides such as $SiO_2$, $Al_2O_3$, $Fe_2O_3$, and CaO. These oxides act as thermal performance enhancers [70-71].

fly ash in particular has quite high thermal conductivity and melting points(~1200°C),which makes it a promising material for sensible heat storage [72]. Furthermore, its mechanical strength and thermal resistance is considerably high due to presence of $SiO_2$ and $Al_2O_3$ making it an ideal candidate for TES applications. Another potential material could be Red mud, a by-product of the Bayer process, exhibits medium to high thermal diffusivity, however the the concentration of $Na_2O$ a pretreatment to enhance its durability under thermal cycling [73]. Metal slags, such as steel and copper slags, could also be utilized as potential TES due to their high thermal conductivity, which arises from dense microstructures and crystalline phases [74-75]. The thermal performance could be further enhanced by incorporating the aforementioned material as powder, as the matrix phase, and as PCMs. This improves the heat transfer rate without diminishing structural integrity. Surface modifications of these particles, such as coating or encapsulation, would improve their interfacial adhesion with PCMs. Literature findins shows potential of using industrial as TES as well as reinforcing agents in composites [76-77].

However, the variety of raw wastes, their sources, and their processing histories could affect the thermophysical properties. Therefore, their detailed characterization is essential and can be performed using thermogravimetric analysis(TGA),differential scanning calorimetry(DSC),and laser flash analysis. Further standardization and testing protocols for characterization of waste-derived materials is required and further establishing them as computation simulation for system integration could be taken up as future work [76-78].

**Table 3.** Thermal energy storage types of waste material

| Material | Melting Point (°C) | Phase Compatibility | PCM Integration | TES Type |
|---|---|---|---|---|
| Fly Ash | >1100 | High | Moderate | Sensible/ Composite |
| Red Mud | ~1000 | Moderate | High | Sensible/ Composite |
| Steel Slag | >1200 | High | Good | Sensible |
| Coal Gangue | ~900 | Moderate | Moderate | Sensible |
| CSCG (Charred Coffee Waste) | ~600 | Low | High | Composite |

### 3.1. Density

Density is a significant parameter that directly influences the volumetric energy storage capacity. Greater density results in higher energy density (TES). Industrial wastes have varied range of densities which depends of mineralogy, their source, and treatment [79]. For example, the bulk density of fly ash, which ranges from 1.1 to 1.5 g/cm³, is affected by particle size distribution and carbon content. The porous structure of fly ash improves the insulation properties of composite systems; however, it adversely affects thermal conductivity because of air entrapment [80]. Metals slags and steel slags shows have higher densities which varies from 2.6 to 3.5 g/cm³ when compared to fly ash, this could be attributed to presence of heavy oxides like $Fe_2O_3$ and CaO; making slags ideal candidates for concentrated solar power (CSP) systems which requires high volumetric energy storage [81].

The densities of red mud and coal gangue fall within a moderate range (typically 2.2–2.8 g/cm³), making them suitable PCM candidates. However, their density could be further improved by modifying the porosity of these materials for a specific application. Sintering could be used for densification purposes, which would improve packing density and reduce thermal resistance at the interfaces [82-83]. Moreover, changes in density due to thermal cycling require careful consideration. A few materials such as slag and coal gangue exhibits negligible changes in density undergoing through several heating and cooling cycles, exhibiting excellent dimensional and structural stability. Material such as lightweight ashes and bio waste like CSCG (charred spent coffee ground) loss their structural integrity due to residual organic matter [84]. Understanding density variation in waste-derived TES is key to optimizing volumetric energy-storage efficiency, as shown in Table 4. For practical deployment, a balance is required between density and weight. Future work could focus on compaction techniques and reinforcement strategies for TES systems.

**Table 4.** Bulk density of waste materials

| Material | Bulk Density (g/cm³) | Apparent Porosity (%) | Remarks |
|---|---|---|---|
| Fly Ash | 2.2–2.6 | 15–25 | Lightweight, good filler for composites |
| Red Mud | 2.9–3.3 | 10–20 | High density, suited for thermal bricks |
| Steel Slag | 3.2–3.6 | <10 | Heavy and dense, high-energy density |
| CSCG | 1.2–1.6 | 40–60 | Low density, highly porous structure |
| Sulfidic Copper Tailings | 2.5–2.9 | 20–30 | Moderate density, suitable for hybrid PCM |

### 3.2. Specific heat capacity

Specific heat capacity (Cp) is also an important criterion for evaluating a material's suitability for sensible heat storage applications, as illustrated in Table 5. Specific heat capacity quantifies the heat storage capacity of a material per unit mass per degree of temperature change. The specific heat capacity of industrial waste depends on mineralogy, density, crystal structure [85]. For example, fly ash and red mud exhibit Cp values ranging from 0.7 to 1.1 J/gK, owing to the presence of silicates and alumina. These values are in range that of ceramics showing a good fly ash and red mud could absorb and release moderate amounts of heat over a broad temperature range [86]. For metals slags such as steel slag and copper slag, have Cp values varies from 0.8 to 1.2 J/g.K, which may be due to presence of heavy metal oxides such as CaO and $Fe_2O_3$, making these system efficient for thermal storage for high-temperature storage systems [87-88]. For Charred biomass waste, such as charred spent coffee ground(CSCG)the Cp value varies from 0.9 to 1.4 J/g·K, which highly dependent on the pyrolysis temperature and carbon concentration. Although the heat capacity of CSCG is significantly higher, thermal degradation poses a risk during repeated thermal loading. pre-treatment and/or stabilizing agents are recommended to avoid thermal degradation [89-90]. Composite systems could also be developed using industrial waste and phase-change materials (PCMs). One way to fabricate composite systems is to encapsulate PCMs and use that encapsulation as a filler, while the porous red mud or coal gangue acts as the matrix material. This could result in effective enhancement in both $C_p$ and the thermal behaviour [8]the implementation of latent heat thermal energy storage (LHTES. The aforementioned material exhibits promising heat capacity values; however, its behavior during extended heating and cooling cycles remains to be evaluated. The repeated heating and cooling cycles may result in changes in phase structure that directly affect heat capacity. Therefore, calorimetric analysis along with thermal cycling tests should be done to assess reliability [85]. The Cp values of industrial waste ranged from moderate to high, indicating that they are suitable for medium-temperature energy storage. Their capacity could be enhanced by hybridization, a promising direction for future research. Moreover, different additives could be explored to increase heat capacity without compromising structural integrity.

**Table 5.** Specific heat capacity of industrial waste materials

| Material | Specific Heat (J/g·K) | Temperature Range (°C) | Suitability for TES |
|---|---|---|---|
| Fly Ash | 0.84–1.10 | 25–800 | Suitable for high-temp TES |
| Coal Gangue | 0.90–1.15 | 30–500 | Moderate SHS potential |
| Red Mud | 0.85–1.20 | 25–700 | Suitable for SHS/Composite |
| Iron Tailings | 0.78–0.96 | 50–800 | Stable, low heat capacity |
| CSCG | 1.20–1.40 | 25–300 | Better with PCMs |

### 3.3. Thermal conductivity

Thermal conductivity(K)is a critical parameter that affects the rate at which a material absorbs and releases heat. Thermal conductivities of various TES materials are given in Table 6. Generally, materials with higher thermal conductivity lead to rapid heat transfer, a critical parameter for dynamic thermal energy storage(TES)systems. TES materials from industrial waste shows wide range of thermal conductivity which depends on chemical composition, size of the particle, crystal structure and porosity [91]. For fly ash, thermal conductivity generally varies from 0.2 to 1.0 W/mK; the values depend on carbon content and particle size. Porosity reduces the thermal conductivity of fly ash because it traps air; consequently, fly ash has limited applicability in situations requiring rapid heat transfer unless combined with thermally conductive additives, such as graphite or metal particles. Thermal conductivity of fly ash also influence by presence of $SiO_2$ and $Al_2O_3$ [73, 86, 92]. Metal slags such as steel slag and copper slag exhibits significantly higher thermal conductivity values (1.5–3.5 W/m·K), due to their higher density and crystallinity due to presence of metal oxides such as MgO, $Fe_2O_3$, moreover higher density and compact structure leads to phonon transport thereby enhancing thermal conductivity. Furthermore, mineral such as FeO, gehlenite ($Ca_2Al_2SiO_7$), and merwinite ($Ca_3MgSi_2O_8$) contributes to high thermal conductivity and mechanical integrity. High k-value combined with high density makes slags suitable candidate for use in in packed-bed TES systems, [75, 82]. Red mud, on the other hand, exhibits significantly lower conductivity (~0.4–1.0 W/m·K), density, and moisture content. However, thermal conductivity can be improved through compaction techniques, such as sintering, or by adding conductive fillers as in composites [93]. Biomass-derived wastes, such as CSCG, exhibit poor thermal conductivity (0.1–0.5 W/m·K) owing to their highly porous structure and carbon residue. However, it could serve as an insulating medium for PCMs. The thermal conductivity of red mud could be enhanced via pyrolytic graphitization without significantly increasing mass or cost [86, 94]. Furthermore, these ISWs could be used in PCMs as a filler material, thereby enhancing their thermal conductivity. Studies show improvement in k-values when fly ash, red mud, or slag are used as composite fillers [74]. Overall, improving the thermal conductivity of waste-derived materials, either by sintering or by incorporation of additives, is crucial for the charge-discharge rate of TES systems. This modification, along with hybridization, is essential to both thermal and economic sustainability.

**Table 6.** Thermal conductivity of industrial waste materials

| Material | Thermal Conductivity (W/m·K) | Enhancement Potential | Use Case |
|---|---|---|---|
| Fly Ash | 0.5–1.2 | Yes (with CuO, $Al_2O_3$) | Matrix in composites |
| Red Mud | 0.6–1.5 | Yes | TES bricks/ composites |
| Steel Slag | 1.6–2.1 | Good natural value | Direct SHS media |
| CSCG | 0.2–0.5 | Needs enhancement | Organic PCM carrier |
| Sulfidic Tailings | 0.8–1.4 | Moderate | Hybrid filler/ aggregate |

### 3.4. Thermal stability

Thermal stability is a critical parameter that denotes the material's ability to withstand repeated thermal loads without losing its structural integrity. Thermal stability is a significant parameter for TES systems. Table 7 shows the thermal stability behaviour of different ISWs. Generally ISWs are by-production of combustion processes, which makes them inherently suitable for high-temperature applications [77]. For instance, fly ash, owing to the presence of aluminosilicates, exhibits high thermal stability and can withstand temperatures up to 1200°C without significant decomposition. Similar behaviour is observed for red mud, which has high concentration of oxides such as $Fe_2O_3$, $Al_2O_3$, $TiO_2$, and $Na_2O$, therefore exhibit stable behaviour up to 1000 °C, however presence of although volatility at elevated temperature causes chemical changes with extended usage [2, 72]. Moreover, the presence of hematite ($Fe_2O_3$), gibbsite (Al $(OH)_3$), and $TiO_2$ makes red mud quite suitable around 550 °C. However, fine particle sizecombined with a porous structure significantly reduces thermal conductivity. The thermal conductivity could be improved with sintering [27-29]. Metal slags, such as steel slag and iron tailings, exhibit high thermal stability even at elevated temperatures and under cyclic thermal loading. The crystalline phases such as $C_2S$, $C_3S$, and $C_{12}A_7$ maintain their lattice structures during heating and cooling cycles which in turn prevent thermal degradation. Previous studies involving thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) show that the degradation of metal slags is less than 5% up to 1000°C [95-96]. Other ISWs such as Coal gangue and sulfidic copper tailings are also quite stable at high temperatures however, presence of sulfur compounds in tailings results in $SO_2$ release under thermal loading. Pre-treatment, such as acid leaching or calcination are to be carried out to avoid such emissions [97-98], [99-100].

ISWs, such as CSCG, are unstable; however, they degrade at temperatures above 500 °C due to organic matter content. However, pyrolysis could improve its stability by reducing the volatile content, thereby enhancing thermal stability at elevated temperatures. [91,94]. Previous studies have observed that ISWs are suitable for long-term thermal cyclic loading and retain 85–90% of their thermal properties. However, repeated cyclic thermal stress causes microstructural which could affect thermal conductivity and specific heat capacity [79]. Overall, ISWs are thermally stable; however, application-specific testing is recommended. Furthermore, they could be incorporated into composites as fillers in thermally inert matrices to improve reliability.

**Table 7.** Thermal stability of industrial waste materials

| Material | Degradation Temperature (°C) | TGA Weight Loss (%) | Remarks |
|---|---|---|---|
| Fly Ash | >1000 | <2% | Excellent stability |
| Red Mud | ~950 | 3–5% | Slight mass loss at high temp |
| Steel Slag | >1200 | <1.5% | Stable under cycling |
| CSCG | ~550 | 8–10% | Limited thermal endurance |
| Iron Tailings | >1000 | <3% | Good high-temp retention |

### 3.5. Stability behaviour

Stability behaviour refers to the mechanical and chemical stability of ISWs during operation; both are crucial for their reliability in TES applications. Stability is presented in Table 8. Generally ISWs are by-production of combustion processes, which makes them inherently suitable for high-temperature applications which aligns well with the requirements of TES systems [79]. Fly ash is both thermally and mechanically stable under repeated thermal loading. The main constituents of fly ash are silica and alumina, which provide the necessary chemical and mechanical stability. Long-term cyclic tests (up to 300 cycles) demonstrated that fly ash shows minimal changes in specific heat and density [86-92]. Steel and copper slags exhibit excellent mechanical and thermal stability due to their high crystallinity and density. They are high resistant to erosion, thermal shock moreover, they shows very low reactivity towards thermal cyclic loading due to presence of $C_3S$, CaO, $Fe_2O_3$ leading minimal chemical degradation [71, 81]. Red mud exhibits reasonably stable behaviour; however, its high alkalinity and $Na_2O$ content may cause leaching at elevated temperatures. Surface treatment and sintering could improve its structural and chemical integrity. Furthermore, red mud could be incorporated into PCM matrices, which would improve the overall stability of TES [70, 73].

Coal gangue and sulfidic tailings, with chemical treatment such as acid bleaching, calcination are quite stable; however, mechanically they are weak and could be improved upon with proper reinforcement as in composites [83, 100]. Biomass-derived ISWs, such as CSCG, are susceptible to thermal degradation; however, they can be made thermally stable through high-temperature pyrolysis. The biochar produced by pyrolysis is stable up to 500–600°C but is mechanically weak. The mechanical integrity could be improved by using them in composites [84]. Overall, mechanical, chemical, and thermal stability depend on parameters such as processing conditions, operating environment, and chemical constituents. Most ISWs show stability for long-term use in packed beds, composites, or PCM systems. Reusing ISWs supports circular economy principles, sustainability, and energy efficiency.

**Table 8.** Stability during thermal cycling

| Material | No. of Thermal Cycles Tested | Change in Properties (%) | Stability Rating | Remarks |
|---|---|---|---|---|
| Fly Ash | 500 | <2% change in mass | High | Reliable across multiple cycles |
| Red Mud | 300 | Minor phase shift (<3%) | High | Good PCM encapsulation behavior |
| Steel Slag | 400 | <1.5% degradation | Very High | Ideal for long-term SHS |
| CSCG | 100 | 5–8% degradation | Moderate | Needs improvement with binders/ coatings |
| Sulfidic Tailings | 250 | <4% chemical loss | Moderate–High | Suitable with protective additives |

### 3.6. Comparative analysis of TES materials

Several studies on the thermal behaviour of individual ISWs and their potential have been conducted; however, direct comparison of these studies remains an open area of research. This review article focuses on not only discusses the thermal behaviour of various ISWs e.g. FA, RM, SS, CAC, and white cement and their potential to be used as TES but also present a comparative assessment of these materials. For instance, fly ash, a widely available ISW, exhibits moderate thermal conductivity and heat retention. It could effectively be used in low- to mid-temperature TES systems. Red mud, a by-product of bauxite refining, has a slightly higher density and greater heat retention than fly ash; however, it requires pretreatment to reduce its alkalinity before use. Metal slags, such as steel slag, are well-suited to high-temperature environments owing to their excellent thermal conductivity and mechanical stability and can be used in packed-bed TES configurations. Previous studies have primarily focused on chemical analysis, whereas our study provides insights into the practical applicability. Certain other ISWs, such as CAC, are effective binders that, when cured at high temperature, exhibit very high thermal conductivity (up to 1.5W/mK) and maintain mechanical integrity beyond 500C. CAC binders are superior to OPC and cement in thermal performance because CAC binders have higher thermal conductivity; however, cement offers superior surface quality and aesthetics. Additionally, cement degrades when exposed to heat for extended periods, making it unsuitable for cyclic TES applications. CAC could be blended with granite sand and quartz fillers to enhance its thermal conductivity [21]. These composites provide mechanical stability while offering effective heat-transfer capacity. Previous studies have focused on isolated materials; however, this review provides a detailed analysis of various performance metrics, sustainability, and applications. Table 9 presents the thermal characteristics and TES suitability of ISWs, while Table 10 compares the cost and thermal characteristics of ISWs and traditional TES materials.

**Table 9.** Comparative thermal characteristics and TES suitability of ISWs

| Material | Thermal Conductivity (W/m·K) | Stability (°C) | TES Suitability | Remarks |
|---|---|---|---|---|
| Fly Ash | ~0.6–0.8 | Up to 400 | Low–Mid Temp TES | Good retention, needs stabilization |
| Red Mud | ~0.7 | Up to 450 | Mid Temp TES | Dense, requires alkalinity treatment |
| Steel Slag | ~1.0–1.3 | >500 | High Temp Packed-Bed | Strong mechanical properties |
| CAC Composites | Up to 1.5 | >500 | High Temp Composite TES | Excellent conductivity and cycling stability |
| White Cement | ~0.6 | <400 | Limited TES use | Aesthetic, low thermal resilience |
| CAC + Quartz/Granite | 1.2–1.5 | >500 | Optimized Composite TES | Enhanced conductivity and stress resistance |

**Table 10.** Comparative thermal characteristics of ISWs and Traditional TES materials

| Material Type | Material | Thermal Conductivity (W/m·K) | Specific Heat Capacity (J/kg·K) | Stability (°C) | Approximate Cost (USD/kg) | Remarks |
|---|---|---|---|---|---|---|
| **ISW Materials** [103-105] | FA | 0.6–0.8 | 800–1000 | Up to 400 | ~0.02–0.05 | Abundant, low-cost, moderate thermal performance |
| | RM | ~0.7 | 700–900 | Up to 450 | ~0.03–0.06 | Requires pre-treatment due to alkalinity |
| | SS | 1.0–1.32 | 600–850 | >500 | ~0.05–0.10 | High strength and thermal stability |
| | CAC | Up to 1.5 | 800–1100 | >500 | ~0.10–0.15 | Excellent conductivity and cycling durability |
| | CAC Composites | 1.2–1.5 | 900–1100 | >500 | ~0.12–0.18 | Enhanced conductivity and mechanical integrity |
| **Traditional TES** [104-105] | Molten Salt | ~0.5–0.6 | ~1500 | ~300–600 | ~0.60–1.00 | Widely used, high heat capacity, corrosive and expensive |
| | Concrete | ~1.0 | ~880 | ~200–400 | ~0.10–0.20 | Inexpensive, moderate performance |
| | PCMs | ~0.2–0.4 | ~200–250 | ~30–150 | ~1.00–2.00 | High energy density, limited thermal conductivity |
| | Ceramics | 20–120 | ~800–1000 | >1000 | ~2.00–5.00 | Excellent stability, very high cost |

### 3.7. Environmental risk analysis of ISW materials

Industrial solid waste (ISW) materials show promise as low-cost, stable thermal energy storage media; however, the environmental risks they pose should be carefully assessed before large-scale deployment. Several ISW contain heavy metals such as lead, arsenic, and mercury, while exposure to moist or high-temperature environments can contribute to leaching into the environment [105-106]. The extent of leaching is influenced by pH, temperature, and the physical structure of the material. Sintering these materials could reduce leaching to certain levels; however, a lack of testing protocols inhibits proper assessment. Further studies aimed at ensuring the safety of ISW-extracted TES materials could include long-term leaching evaluations across their lifecycle. TCLP and EN 12457 standards could be used for material selection and treatment guidelines [106].

## 4. Conclusion

The present review bridges a gap in material-specific investigations by systematically discussing the thermophysical, microstructural, and ecological aspects of ISW materials for TES. This paper presents a comprehensive and rigorous analysis of the appropriateness of

ISW for TES applications. The following waste materials are promising as storage media for sensible heat and PCM: RM, FA, SS, gypsum, MS, WC, CG, SCA, CSCG, IT, and various slags.

These waste materials have significant potential for high-temperature storage(HTS)applications based on their thermophysical properties. High melting points, excellent thermal conductivity, and slight thermal deterioration over several cycles are characteristic of materials such as SS and FA. Some waste materials, such as RM and CSCG, have high surface areas and suitable porosities, which improve PCM encapsulation and heat absorption.

Based on density evaluations, ISM exhibit medium-to-high bulk densities (1.2–3.6), making them suitable for applications that require high energy density. The density can be improved by combining it with lightweight additives or by creating composites with organic or inorganic PCMs.

Materials such as gypsum and CG have moderate specific heat capacities, ranging from 0.8 to 1.4, which are adequate for practical heat storage. When paired with latent heat materials, the thermal buffering capability is greatly improved, increasing the system's total energy retention. IT, SS, and RM exhibit thermal conductivities ranging from 0.4 to 2.1, a range that is advantageous for TES applications, particularly those requiring rapid heat exchange.

Studies have also demonstrated improvements resulting from the use of metallic nanoparticles or carbon-based additives. According to thermal stability testing, most of these waste materials can withstand numerous heat cycles without appreciable chemical or physical deterioration.

At temperatures above 800 $^{0}$C, SS and FA, in particular, exhibit outstanding oxidation resistance and maintain their phase integrity. The stability under cyclic heating and cooling of several waste materials, a crucial requirement for long-term energy storage, was validated. Even after 300-500 thermal cycles, RM, DK/FDK slag, and SCT exhibited minimal weight loss, modest shifts in phase transitions, and stable microstructural properties, indicating their suitability for practical applications.

In conclusion, industrial solid-waste materials not only address environmental concerns by reducing the landfill burden but also serve as cost-effective, thermally stable, and sustainable components in thermal energy storage systems. However, to fully realize their benefits, further research into hybrid system design, PCM encapsulation techniques, material compatibility, and thermal fatigue resistance is essential. This work lays the groundwork for future industrial applications in which circular economy principles and energy efficiency converge to create a more sustainable energy landscape.

## Future work direction

One potential future direction is conducting focused research on thermal stability under cyclic thermal stress; another is investigating heat recovery. Research could be conducted on protocols for characterizing thermal conductivity, latent heat, and other related properties. environmental safety assessment could be done to understand decomposition and life cycle assessment. Moreover, hybrid systems could combine traditional TES with ISW TES material. This hybrid configuration could be explored for its experimental and economic feasibility.

## Abbreviations

| | |
|---|---|
| CAC | Calcium aluminate cement |
| CSCG | Charred spent coffee grounds |
| CFA | Coal fly ash |
| CG | Coal gangue |
| DK | Dealuminated kaolin |
| DSC | Differential scanning calorimetric |
| FA | Fly ash |
| ISW | Industrial solid waste |
| ITS | Iron tailing slag |
| PCM | Phase change material |
| RM | Red mud |
| SA | Semi coke ash |
| SMs | Skeleton materials |
| SS | Steel slag |
| SCT | Sulfidic copper tailings |
| TES | Thermal energy storage |
| TGA | Thermo gravimetric analysis |

## Conflict of interest

The authors declare that they have no potential conflicts of interest related to this review.

## Ethics

There are no ethical issues with this research.

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