Initial assessment of thermal and mechanical properties of fine-grained processing waste based materials for thermal energy storage applications

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Abstract. Growing demand for efficient and sustainable thermal energy storage (TES) has focused attention on mineral waste as an alternative to natural aggregates. This study investigates the potential use of fine waste fractions from hard coal mining (coal tailings), bottom slag from brown coal combustion, and stone-cutting residues (basalt and marble powders) for sensible heat storage materials. Mixtures were prepared using cement as a binder, alongside additives such as plasticizers and sealing agents. Mechanical (compressive strength) and thermal properties (conductivity, heat capacity, diffusivity) were evaluated, with particular attention to material stability under repeated heating cycles between 50°C and 600°C to simulate operational TES conditions. Results revealed that high carbon content significantly reduces mechanical strength and thermal cycling durability. The slag-based material was excluded from further thermal cycling tests due to its very low compressive strength (1.5 MPa). The coal tailings-based mixture showed the greatest strength reduction after heating (78%), while basalt and marble powder mixtures had a lower, comparable reduction (~55%). Overall, marble powder-based samples demonstrated the highest mechanical and thermal performance, suggesting that selected mineral wastes can be effectively utilized in TES applications, aligning with sustainability and circular economy objectives.

1 Introduction

The European Union (EU) has set ambitious clean energy goals under frameworks like the European Green Deal and subsequent policies. The Green Deal commits the EU to climate neutrality by 2050 and a 55% cut in greenhouse gas emissions by 2030 [1]. To achieve these aims, the EU has sharply raised its renewable energy targets – requiring 42.5% of overall energy consumption to come from renewables by 2030, up from the previous 32% goal. Meeting these targets entails a massive deployment of wind and solar capacity, necessitating equally ambitious expansion of energy storage to buffer the variability of these resources. EU lawmakers recognize that energy storage is integral for balancing power grids and saving

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surplus renewable energy, enhancing both energy security and flexibility as fossil fuels are phased out. Key policy initiatives explicitly highlight the role of storage in the energy transition. The European Green Deal and the "Fit for 55" package call for fostering innovative technologies including energy storage, by establishing a supportive regulatory framework [2]. Likewise, the REPowerEU plan – formulated in 2022 to reduce dependence on Russian fossil fuels – underscores that energy storage is the key to ensure security of supply and supports renewables integration, reducing the need for polluting gas power plants [3]. However, stakeholders note the lack of a dedicated EU storage strategy or targets; the European Association for Storage of Energy (EASE) warns that storage capacity must expand 14-fold by 2030 to meet decarbonization goals. In response, the EU is moving to bolster the entire storage ecosystem – for example, adopting its first unified Battery Regulation to ensure sustainable manufacturing, recycling, and supply of batteries in Europe. Overall, the EU's policy framework – from the Green Deal's climate neutrality vision to REPowerEU's urgent renewable push – is creating strong incentives and support for scaling up energy storage. These policies are actively shaping the energy storage landscape, driving innovation and large-scale projects to maintain grid stability in a high-renewables system.

Although the transition to renewable energy sources (RES) brings many undeniable benefits, it also presents numerous challenges, especially for electricity transmission system operators and power grids due to the intermittency and unpredictability of wind and solar energy. Furthermore, the integration of certain RES into the energy system is a significant challenge, as it impacts the voltage, frequency, and quality of power supply in electrical systems [4]. To mitigate these negative effects, energy storage systems have been developed. There are many solutions at various stages of development in energy storage systems. These can be categorized based on the method of energy storage, with a typical division into six categories (Fig. 1): mechanical, electrochemical, chemical, electrolytic/electromagnetic, thermochemical, and thermal [5,6]. There is also a division based on system scale: small-scale storage (<10 MW) and large-scale storage with capacities ranging from tens to hundreds of MW. Additionally, a division can be made based on the duration of energy storage: short-term (from minutes to hours) and long-term (from hours to days). Each type of storage includes different technologies at various levels of technological readiness, depending on the subcategory and the type of integration with the energy system. A detailed description of each type of energy storage can be found in the literature [7–11], and a comprehensive review of storage systems is not the aim of this paper.

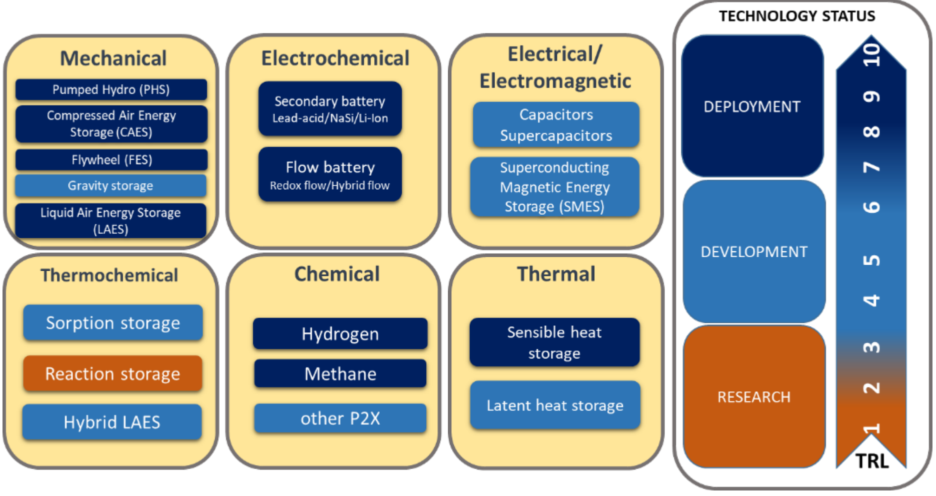

Fig. 1. Energy storage technologies with respective Technology Readiness Levels (TRL) [7–10,12]

Analyzing the current energy storage capacities in the EU and worldwide, the most commonly used large-scale energy storage technology is pumped hydro storage (PHS), a mechanical storage system. These facilities offer several advantages, including high storage capacity, flexibility, and rapid start-up times. However, the potential for constructing new plants is limited by the topography of the land, which makes it particularly unprofitable in lowland or densely populated areas. Another issue is the high capital cost and environmental concerns that may arise during the construction of new plants.

Electrochemical storage is the second most popular option, with off-the-shelf solutions and many recently developed facilities. However, the capacities of electrochemical systems are approximately three times lower than PHS. The largest battery energy storage system to date was commissioned at the end of 2022 in the Wallonia region of Belgium, with an installed capacity of 50 MW/100 MWh [13]. Other similar projects are underway, but achieving the EU's goal of 200 GW of storage capacity by 2030 may be challenging. Another solution for large-scale energy storage is Compressed Air Energy Storage (CAES), but to date, this solution has been limited to three locations: Huntorf (321 MW), McIntosh, USA (110 MW), and a smaller facility in Goderich, Canada (1.75 MW/7 MWh+) [14]. Other technologies, although some are at a much higher level of technological readiness (TRL), still do not provide network-scale storage capabilities.

Considering the above, there is a need to explore new locations for large-scale mechanical energy storage systems such as PHS or CAES. In particular, adiabatic CAES systems, where heat is stored in a separate reservoir, would be a good solution. These systems promise improved efficiency and scalability for integrating renewable energy sources at the grid level. Such systems, where a separate Thermal Energy Storage (TES) can reach up to approximately 70% round trip efficiency and can be installed in a mine shaft [15].

Thermal Energy Storage (TES) can be stored in the form of sensible, latent, or chemical heat. It can also be stored through a combination of sensible and latent heat storage. Sensible heat storage (SHS) systems store energy by heating a storage material without a phase change (the material does not change its state of matter). In contrast, latent heat storage (LHS) relies on phase transitions (melting and solidification - the material changes its state of matter) of phase change materials (PCM). Chemical heat storage is associated with a reversible chemical reaction. In solid-bed sensible heat storage systems filled with a solid material, the heating and cooling process, in its simplest form, follows the pattern shown in Figure 2.

Fig. 2. Idea of charging and discharging cycle of a solid-bed heat storage system.

In this study, it is assumed that the sensible heat storage system with a solid bed will be filled with either a granular solid material or a material that solidifies to form a strong, concrete-like structure. The filler material in the storage bed should have the following properties [16]:

- High thermal conductivity,
- High heat capacity,
- High density,
- Resistance to high temperatures during repeated heating/cooling cycles,
- Low cost.

This study aims to evaluate the thermal and mechanical properties of thermal storage materials for packed bed TES derived from mining by-products and waste. These are coal slurry (coal tailings), bottom slag processing waste from a lignite-fired boiler, basalt dust collector residue, marble dust collector residue, coal combustion residue from coal tailings combustion and fly ash from a hard coal-fired boiler.

Recent research has explored the use of various waste materials for packed-bed thermal energy storage. For instance, studies have investigated the use of Electric Arc Furnace Black Slag and Tundish from the steel industry as cost-effective and sustainable TES materials [17]. Other research has focused on natural rocks, sand, or ceramic industrial wastes as solid TES material candidates [18]. The potential of packed bed thermal energy storage systems for waste heat recovery in industrial processes has also been highlighted [19]. These studies underscore the growing interest in utilizing industrial by-products and waste materials to develop efficient and sustainable thermal energy storage solutions, aligning with circular economy principles.

2 Materials and methods

The selection of mine-derived products and waste materials for packed bed Thermal Energy Storage (TES) aligns with the principles of the circular economy, which focuses on resource efficiency, waste minimization, and sustainable material utilization. By integrating waste-derived materials into TES applications, this approach contributes to environmental and economic sustainability. Therefore, we have selected locally available materials:

1. coal slurry (coal tailings) (WS) from one of the settling ponds in the Upper Silesia Coal Basin, southern Poland.
2. bottom slag (SL) processing waste from a lignite-fired boiler from a large brown coal-fired plant in Poland, it was initially beneficiated using spiral separator LD4, (concentrate is used).
3. marble dust collector residue (powder) from stone cutting (MP).
4. basalt dust collector residue (powder) from stone cutting (BP).
5. coal combustion residue (CCR) from coal tailings combustion in toroidal boiler.
6. fly ash (FA) from a hard coal-fired boiler.

Materials 1 and 2 are coal-based, and have a high content of organic matter. Therefore, proximate analyses were performed on Materials 1 and 2. Additionally, the raw coal tailings proximate analysis of material 5 is presented, see Table 1, as this coal combustion residue (CCR) differs from conventional fly ash in particle size, composition, and reactivity due to its origin from toroidal combustion.

Table 1. Proximate analysis, LHV and sulphur content of materials used for the preparation of mixtures.

	Moisture, %		Ash, %		Volatiles, %		LHV, MJ/kg		Sulfur, %	
Materiał	*ADB*	*AR*	*ADB*	*AR*	*ADB*	*AR*	*ADB*	*AR*	*ADB*	*AR*
1 WS	0.99	1.93	74.49	73.77	13.50	13.37	4.86	4.81	0.27	0.27
2 SL	3.45	8.48	64.38	61.03	16.86	15.98	7.72	7.19	0.738	0.70
CCRraw slurry before combustion	17.47	21.32	63.31	49.78	1.35	1.06	13.37	10.51	1.35	1.06

ADB – air-dried basis; AR – as received

As shown in Table 1, Materials 1 and 2 exhibited a significant content of organic matter and volatile components, which could be attributed to an ineffective beneficiation process.

In contrast, fly ash from hard coal combustion (FA) was characterized by a Loss on Ignition (LOI) of 4.52% and a fineness of 38%. These tests were conducted according to PN-EN 450-1 and PN-EN 451-2 standards.

2.1 Preparation of experimental mixtures

The experimental mixtures were formulated using a combination of waste-derived materials, cementitious binders, and chemical additives. Mixtures based on materials 1-5 were prepared according to the following composition, where w/c stands for water-to-cement ratio:

- Selected waste material - 750 g (75% by mass);
- Fly ash cement (CEM II 32.5R) – 250 g (25% by mass)
- Sodium silicate (R145) – 4.35 g, equivalent to 3 ml per 200 g of water
- Plasticizer (Melment) – 3.0 g
- Mixing water (tap water):
    - 200 g (w/c = 0.20) for standard mixtures
    - 420 g (w/c = 0.42) for slag (SL)
    - 500 g (w/c = 0.50) for Coal Combustion Residue (CCR)

The prepared mixtures exhibited a plastic consistency with flowability. Cylindrical samples with a diameter of 43.5 mm and an aspect ratio of 1 were prepared (see Figure 4). The overall procedure for material preparation, experimental steps, and testing sequence is summarized in the flow chart in Figure 3.

Material FA was prepared in a different manner. In this case, a geopolymer (GP) was synthesized using the fly ash sample FA). For its production, an 8M sodium carbonate solution was prepared and then mixed at a 1:3 mass ratio with sodium silicate. The resulting activator was further combined with siliceous fly ash at a 0.38:1 mass ratio. The prepared geopolymer mass was used to form cylindrical samples.

The geopolymer samples were cured for 24 hours in a climate-controlled environment with a humidity of 90±5% and a temperature of 21±2 °C. The curing temperature was then increased to 75±5 °C for an additional 48 hours. After this period, the samples were brought back to 21±2 °C and stored under the same conditions as the other material samples until testing.

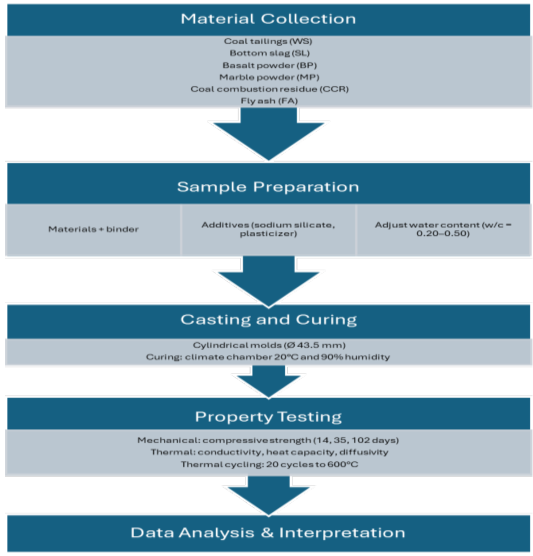

Fig. 3. Flow chart illustrating the preparation, experimental procedures, and testing methodology used in this study.

2.2 Experimental procedure and analysis

The experimental analysis focused on evaluating the mechanical and thermal properties of the prepared mixtures. The following parameters were assessed:

- Compressive strength
- Thermal conductivity
- Heat capacity
- Thermal diffusivity

Compressive strength tests were conducted after 14, 35, and 102 days of curing in a climate chamber maintained at 20°C and 90% humidity. After 80 days, a subset of samples was subjected to a heating process. An example of a thermal image of heated sample is shown in Figure 4.

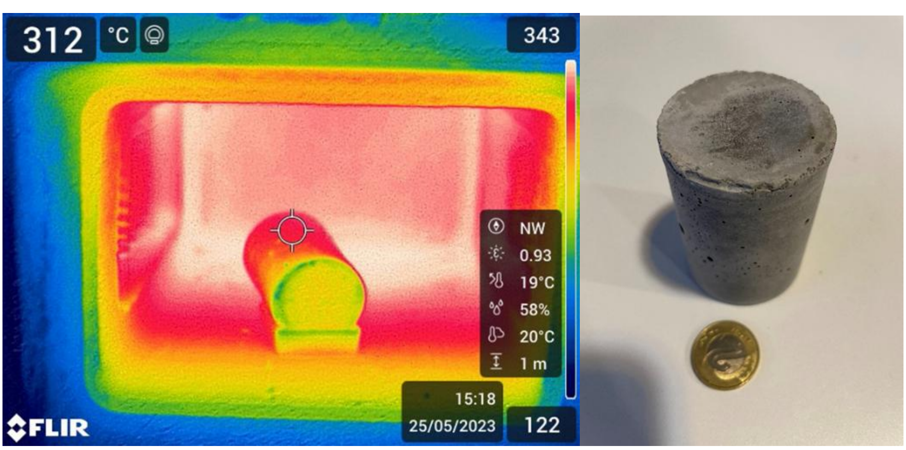

Fig. 4. Thermal image of heated sample inside the furnace (left) and view of the cylindrical sample after curing (right)

Following heating, the samples were tested for mechanical and thermal properties. The heating process was carried out by gradually increasing the temperature to 600 °C, followed by natural cooling to room temperature. This heating-cooling cycle was repeated 20 times to simulate thermal stress conditions.

The thermal conductivity, heat capacity, and thermal diffusivity of the materials were measured using the TEMPOS thermal properties analyzer (METER Group). The TEMPOS analyzer complies with ASTM D5334 and IEEE 442 standards and is manufactured under ISO 2008 quality requirements. It enables high-precision measurements of thermal conductivity, thermal resistance, thermal diffusivity, and specific heat across a wide range of materials, including soils, rocks, cement, polymers, lubricants (oils), and various industrial materials.

For these experiments, the SH-3 needle sensor was used, consisting of two parallel needles, each 3 cm in length. Before testing, the sensor calibration was verified by measuring the thermal properties of a Delrin (polyoxymethylene) reference material. A view of the device during calibration and measurement is presented in Figure 5.

Fig. 5. View of the TEMPOS thermal properties analyser. Sensor calibration on the reference material (left), measurement using the SH-3 probe (right).

This integrated procedure ensures the reliability and accuracy of the mechanical and thermal property assessments, providing valuable insights into the performance of the developed TES materials under varying thermal conditions.

3 Results and discussion

The following section presents the results of compressive strength and thermal property evaluations of the tested materials.

3.1 Mechanical properties

The mechanical performance was assessed over 102 days of curing, followed by thermal cycling to determine the resistance of the materials to high-temperature exposure. Additionally, thermal conductivity, heat capacity, and diffusivity were measured to evaluate the suitability of these materials for thermal energy storage (TES) applications. The compressive strength evolution over time is presented in Figure 6.

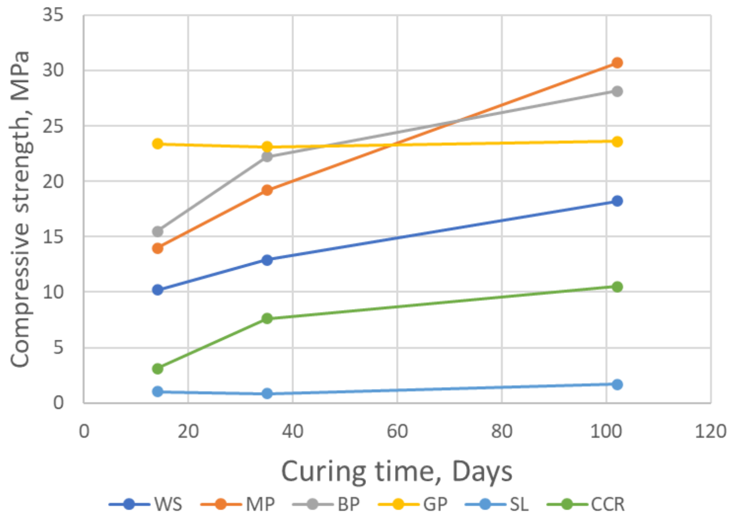

Fig. 6. Time-dependent compressive strength of the tested materials after 102 days of curing in a climate chamber (20°C, 90% humidity).

The compressive strength tests conducted after 102 days of curing in a climate chamber indicate that the material based on slag (SL) exhibited extremely low compressive strength, reaching only 1.5 MPa, rendering it unsuitable for any practical application. This might be attributed to the considerably high organic content and porous structure. The materials containing Coal Combustion Residue (CCR) and sedimentation pond coal tailings (WS) achieved compressive strengths of approximately 10 MPa and 18 MPa, respectively. The mixtures incorporating basalt powder (BP) and marble powder (MP) displayed higher strengths of 28 MPa and 31 MPa, respectively. The geopolymer (GP) maintained a constant strength of 23 MPa throughout the testing period.

The compressive strength results obtained after 102 days of curing are critical in assessing the structural integrity of materials intended for packed-bed TES systems. As indicated in Figure 6, the marble and basalt powder-based composites exceeded 28 MPa, which aligns with the minimum mechanical thresholds reported for stationary TES structures subjected to cyclical thermal loading [20,21] These values are comparable to or exceed those of traditional concrete-based TES materials, confirming their suitability for repeated heat storage and discharge operations. Conversely, the coal tailings (WS) and CCR-based samples, with strengths of 18 MPa and 10 MPa respectively, approach the lower bound of acceptable limits for TES infrastructure and may require reinforcement or hybridization with other binders for high-load applications. The geopolymer material, with consistent compressive strength of 23 MPa, demonstrates sufficient structural resilience and confirms previous reports on the thermal-mechanical reliability of alkali-activated binders in TES settings [22]. These findings reinforce the viability of selected waste-derived materials as sustainable candidates for TES systems while highlighting the importance of strength optimization in the design phase.

3.2 Thermal properties

The impact of thermal cycling on the compressive strength of the tested materials is illustrated in Figure 7.

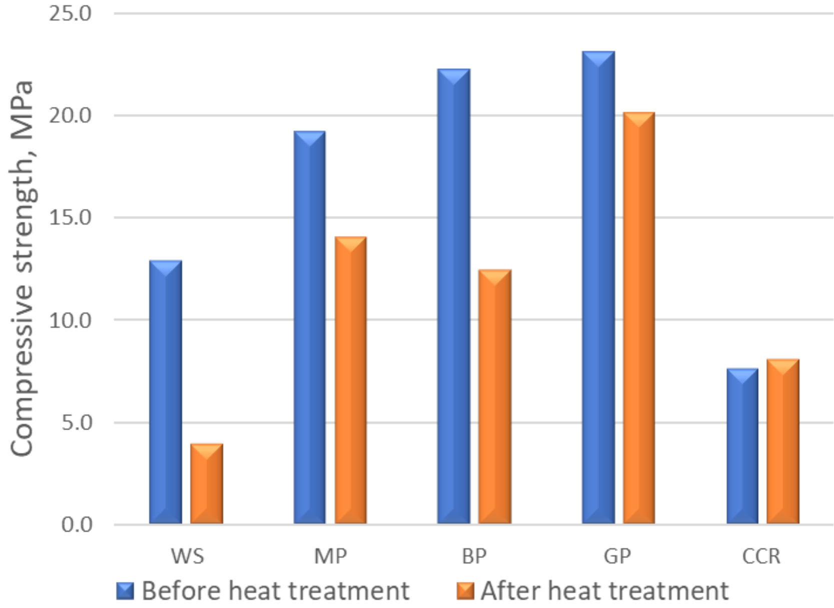

Fig. 7. Reduction in compressive strength due to thermal cycling (20 cycles) after 102 days of curing.

Due to its low initial strength (1.5 MPa), the slag-based material (SL) was excluded from the thermal cycling tests. Among the tested materials, the highest strength reduction (78%) was observed for the material containing sedimentation pond waste (WS). The mixtures incorporating basalt powder (BP) and marble powder (MP) exhibited a similar strength reduction of approximately 55%. In contrast, the Coal Combustion Residue (CCR) mixture demonstrated a relatively moderate decrease in strength (23%). The geopolymer (GP) displayed the highest thermal resistance, with only a 6% strength reduction after 20 thermal cycles.

The thermal properties of the developed materials significantly influence their applicability in thermal energy storage systems. Optimal thermal performance ensures effective heat storage and transfer, making material selection critical for practical applications. The detailed results of the thermal property measurements are presented in Table 2, while their average values are graphically represented in Figure 8.

Table 2. Thermal properties of the tested materials.

Material	Thermal Conductivity (K), W/(m·K)	Heat Capacity (C), MJ/m³K	Thermal Diffusivity (D), mm²/s
Coal tailings (WS)	0.476 – 0.509	1.637 – 1.707	0.289 – 0.298
Basalt Powder (BP)	0.637 – 0.666	1.797 – 1.833	0.354 – 0.363
Marble Powder (MP)	1.086 – 1.140	1.920 – 1.977	0.566 – 0.577
Geopolymer (GP)	0.356 – 0.384	1.121 – 1.395	0.256 – 0.451
Coal Combustion Residue (CCR)	0.625 – 0.658	1.411 – 1.469	0.432 – 0.461

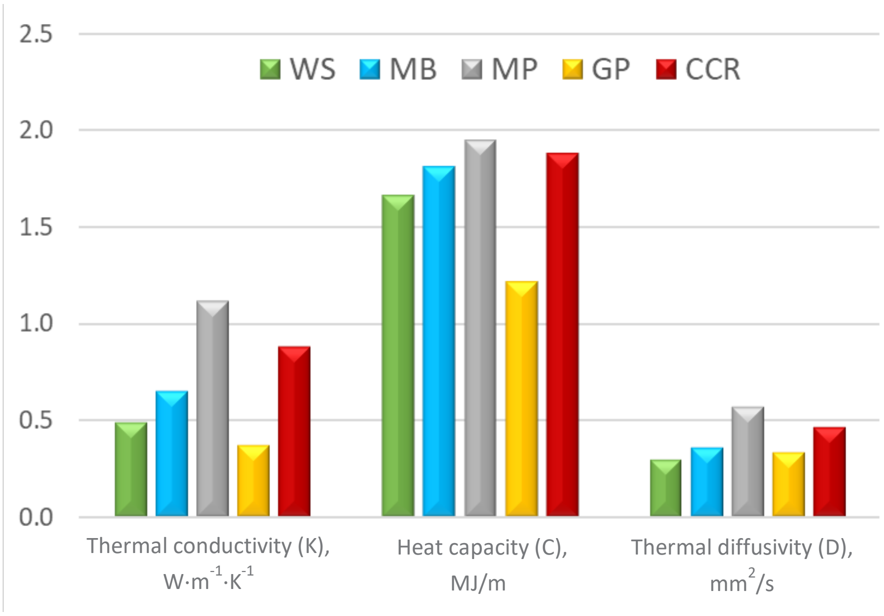

Figure 8. Averaged thermal property values of the tested materials.

The results indicate that the marble powder-based samples exhibited the highest thermal conductivity, heat capacity, and thermal diffusivity, followed by basalt powder and coal tailings-based material. The observed thermal characteristics directly influence the material's capacity to function as an effective TES filler, with high thermal conductivity and diffusivity translating to faster heat absorption and release cycles. When compared to values reported in the literature (Table 3), it is evident that the measured thermal properties of the tested materials are lower than those of the raw rock materials originally used but are within the range typically observed for concrete-based materials. Despite its high-temperature resistance [23], geopolymer (GP) demonstrated the lowest thermal performance among all tested materials.

Table 3. Thermal properties of selected rocks, construction, and waste-based materials [16].

Rock/Material	**Density (g/cm³)**	**Thermal conductivity at 20°C (W/m·K)**	**Specific heat at 20 °C (J/kg·K)**	**Heat capacity (J/m³·K)**	**Remarks**
Granite	2.6–2.7	2.6–3.1	600–950	1560–2517	—
Sandstone	2.2–2.6	1.7–2.9	694–950	1492–2508	—
Shale	2.8	1.1–2.1	820 (at 45°C)	2255 (at 45°C)	—
Dolomite	2.8	2.1	802	2205–2269	—
Slag	2.7	0.6	840	2268	—
Concrete	2.2–2.7	0.9–2.0	750–1130	1680–3005	Strength decreases above 400 °C
Ceramic brick	1.7–1.8	0.5–0.7	840	1419–1512	Low thermal conductivity
Silica brick	1.8	1.5	1000	1820	Low mechanical strength

Overall, the results obtained in this study demonstrate that mine-derived waste and by-product materials show considerable potential for sensible heat storage in packed-bed TES systems. Combining high mechanical durability with advantageous thermal properties, selected mixtures such as marble and basalt powder-based compositions present viable options for large-scale thermal storage applications. Further research should focus on optimizing geopolymer mixtures to improve their thermal characteristics and evaluating the long-term behavior of these materials under real-life operational conditions.

4 Conclusions

Based on the presented experimental studies and analyses, the following conclusions can be drawn:

1. Among the materials tested, marble powder-based mixtures (MP) exhibited the highest compressive strength (31 MPa) and superior thermal properties, including thermal conductivity ($K = 1.086–1.140$ W/m·K) and thermal diffusivity ($D = 0.566–0.577$ mm²/s), making them suitable candidates for sensible heat storage in thermal energy storage (TES) systems.
2. Basalt powder (BP) mixtures demonstrated favorable mechanical strength (28 MPa) and satisfactory thermal performance, making them a good alternative, especially considering their sustainable sourcing and cost-effectiveness.
3. Coal combustion residue (CCR) and coal tailings waste (WS) showed moderate compressive strength (10 MPa and 18 MPa respectively), accompanied by acceptable thermal properties, and thus could be considered for TES applications with moderate thermal and mechanical demands.
4. The geopolymer-based (GP) materials maintained consistent mechanical strength (approximately 23 MPa) throughout testing and exhibited the highest thermal resistance, with minimal strength reduction (6%) after thermal cycling. However, their low thermal conductivity and diffusivity restrict their immediate applicability in high-efficiency TES systems, indicating the need for further compositional optimization.
5. The material based on bottom slag processing waste (SL) demonstrated very low compressive strength (1.5 MPa), rendering it unsuitable for TES purposes. This low performance is likely related to its high organic matter content and porous structure.

Thermal cycling significantly impacted the compressive strength of the tested materials. The highest strength reduction (78%) occurred in coal tailings waste-based materials (WS), whereas geopolymer (GP) mixtures exhibited the greatest resilience. These findings underscore the importance of assessing mechanical durability under cyclic thermal loading when selecting materials for practical TES applications.

Compared to literature data, the thermal properties of the tested mixtures are generally lower than those of raw geological materials but are within the typical range observed for concrete-based materials, demonstrating their potential utility as TES fillers.

Overall, the study confirms the viability of integrating selected mine-derived by-products and wastes into packed-bed sensible TES systems, aligning well with circular economy principles and supporting EU energy storage and sustainability objectives. Future work should emphasize economic analysis, long-term performance monitoring, and optimization of geopolymer compositions to enhance their thermal efficiency.

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