CHARACTERIZATION OF DEMOLITION WASTE POWDER TO BE PROCESSED AS SENSIBLE THERMAL ENERGY STORAGE MATERIAL

Burcu Koçak [a,b] , A. Inés Fernández [a] , Halime Paksoy [b*]

[a] DIOPMA Centre, Department of Materials Science &Physical Chemistry, Universitat de Barcelona, Martí i Franquès, 1, 08028, Barcelona, Spain
[b] Chemistry Department, Faculty of Arts and Sciences, Çukurova University, Balcali Mah. Saricam, 01310 Adana Turkey
* Halime Paksoy, Balcali Mah. Saricam, 01310 Adana Turkey, Tel: +90 322 338 6084, Fax: +90 322 338 6945, hopaksoy@cu.edu.tr

ABSTRACT

Replacing fossil fuels with alternative energy resources to meet industrial heat demand necessitates using cost-effective thermal energy storage (TES) for efficient and secure operation. Waste-based materials such as industrial by-products, industrial furnace slags, municipal, demolition wastes (DW) offer alternative low cost sensible thermal energy storage materials (STESM) for solar heat industrial applications. The only drawback is their inhomogeneous nature requiring some pre-treatment steps. DW have a great potential as cheap and high performance STESM, if they can be conditioned with optimum properties. In this study, DW samples collected from an urban regeneration project were conditioned with some pre-treatment processes such as crushing, sieving, drying and mixing to produce rigid and homogeneous STESMs. DW powders obtained after processing were characterized to evaluate its suitability to produce STESMs. The results showed that DW powders could be converted to a durable STESM with high storage capacity for use in solar heat industrial applications up to 700°C.

Keywords: Demolition waste powder, sensible thermal energy storage materials, solar heat industrial applications, thermal energy storage

1. INTRODUCTION

Continuous growth in energy consumption leads to serious environmental problems mainly air pollution and global warming. 33 Gt CO_2 emissions were released to nature in 2019 due to fossil fuel combustion (IEA, 2019a). Industrial sector that mainly use unsustainable fossil fuels is responsible for one-fifth of this global CO_2 emissions (IEA, 2019b). Solar energy as renewable energy source is a promising alternative for industrial processes in terms of its abundance and eco-friendliness. Only drawback is intermittency of solar energy during nights and cloudy times. Therefore, it should be stored with a suitable thermal energy storage (TES) technology. TES systems provide alternative solutions to cover the mismatch between supply and demand of solar energy and provide longer and secure operation of the system. According to Palacios et al (2020), sensible thermal energy storage (STES) in packed-bed is the simplest and most cost effective method for high temperature applications. Especially, low cost sensible thermal energy storage materials (STESMs) provide cost effective systems for solar heat industrial processes. Packed-bed with low cost storage material is a promising TES method for high temperature solar applications (Khare et al., 2013).

The integration of packed-bed filled with low cost and effective storage materials can reduce dependency on fossil fuels, increase energy efficiency and sustainability and improve competitiveness of the industry. Studies on sensible heat storage materials have been carried out for the last 50 years, and there are more than 150000 commercial engineering materials (Fernandez et al., 2010; Gracia and Cabeza, 2015). Recent studies focus on reducing using mineral oil and molten salts as liquid STESMs in high temperature applications due to several problems such as cost, corrosion and stability. Solid STESMs such as silica sand, natural rock, desert sand, basalt, glass, steel, alumina, quartzite and concrete are suggested as alternative low cost STESMs instead of molten salt and mineral oil for high temperature applications (Molina et al., 2019, Emerson, 2013, Bruch et al., 2014; Diago et al., 2015; Tiskatine et al., 2017).

Solid STESMs are preferable options for industrial applications due to their high thermal and chemical stability, low cost and high storage capacity (Emerson et al., 2013; Khare et al., 2013; Alonso et al., 2016). While most of the natural solid STESMs can be used directly in large-scale TES system, some of them should need to be prepared by mortar formulations or additional processes to obtain STESM with desired properties. For instance, Li et al (2013) produced novel STESM called “green compact” from natural minerals such as clay, kaolin tailings and hematite by mixing, pressing, drying and sintering methods.

Although natural materials are alternative options for high temperature TES systems, thousands of tons of STES materials are needed that may require high investment cost and depletion of natural sources in large-scale applications. In recent studies, researchers focus on waste-based materials as STESMs mainly for high temperature TES applications up to 1000 °C. There are a number of waste-based materials that may be alternative as STESM such as demolition wastes, industrial furnace slags, asbestos containing wastes, industrial salts and industrial by products (Calvet et al., 2013; Miro et al. ,2014; Motte et al., 2015; Agalit et al., 2017; Grosu et al., 2018; Wang et al., 2018; Koçak and Paksoy, 2019)

Koçak et al (2021) performed a benchmarking study on several storage materials developed from waste materials. Due to the variation in physical properties, most of these materials need to be subjected to processes such as crushing, sieving, mixing, melting, molding, pressing, drying to prepare rigid and homogeneous STESMs or to enhance storage performance of STESMs.

Navarro et al. (2012) crushed by-products of potash industry into diameter range of 1 mm followed by sieving and compressing processes to provide shape stabilization. Miro et al. (2014) applied water treatment and molding processes to salt-based solid by-products coming from potash industry to increase thermal conductivity of STESMs from 0.33 $Wm^{-1}K^{-1}$ to 2.84 $Wm^{-1}K^{-1}$. Motte et al. (2015) crushed metallurgical furnace slags to below 10 μm diameter and compressed the powder samples to have heterogeneous structured STESMs with low porosity. In another study by Agalit et al. (2020), drying, milling and sieving processes were applied to coal fly ashes to obtain suitable samples.

Naimi et al. (2015) analyzed chemical and thermal properties of electric arc furnace (EAF) slag, ladle furnace (LF) slag, aluminum pot skimming (APS) and aluminum white dross (AWD) to investigate their potential as high-temperature STESMs. LF was already in powder form with particle size of 0-5 mm. But, crushing, grinding, mixing and sieving processes were applied to the others to obtain homogeneous material. Characterization results showed that the recycled samples were suitable for high temperature TES applications up to 1100 °C.

In previous study by Koçak and Paksoy (2019), DW were evaluated as low cost STESMs candidates for medium-high temperature industrial applications. Demolition and construction waste being one of the heaviest and the most voluminous waste material is a big burden for governments. 30-50 % of the total solid wastes worldwide are demolition and construction wastes (Maçin and Demir, 2018). This solid waste is also a problem in Turkey, where the amount of demolition and construction waste is not known exactly. Because of the Law No. 6306 on Transformation of Areas under Disaster Risk, urban regeneration projects have increased rapidly in the last 3 years. Thus, it is estimated that demolition and construction waste amount increased from 4-5 million tons/year to 10 million tons/year in Turkey (Fırat and Akbaş, 2015). In line with Turkish Waste Framework Directive (2008/98/EC), at least 70 % of non-hazardous DW need to be recycled. Therefore, valorization of DW will become an important key performance indicator for municipalities.

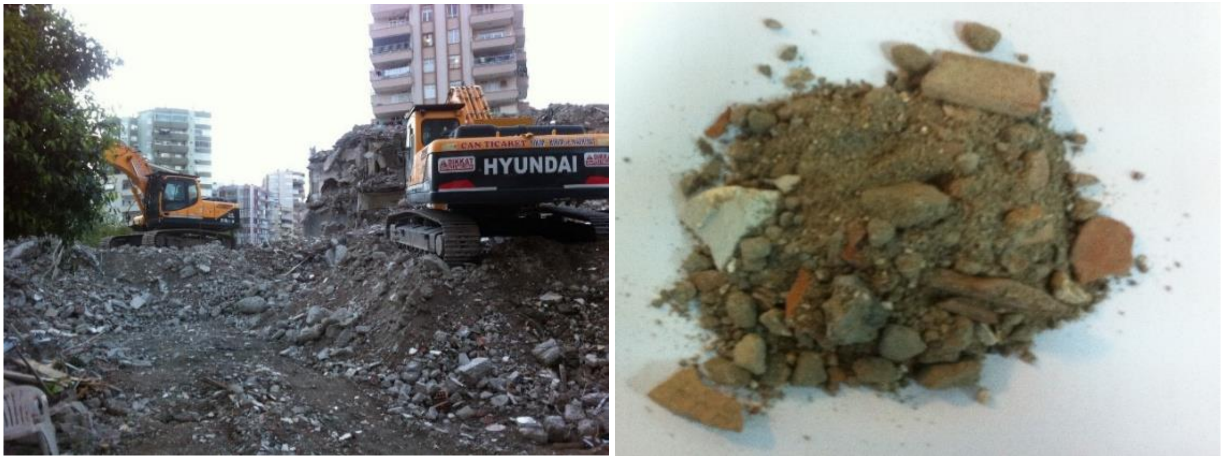
Main drawback of using DW as STESM is its inhomogeneous occurrence. Although DW mainly includes gypsum, wood (plywood, chip wood and sawdust), masonry (brick, concrete, rock), metals, plastic and cardboard (Demir, 2009), the composition varies according to the source of waste. In addition, physical and chemical properties such as size, shape, density, and humidity vary depending on location.

This study focuses on the convertibility of DW to a durable and homogeneous form as a novel STESM to be used in packed bed. DW samples were taken from an urban regeneration project in Adana, Turkey. The conditioning processes such as crushing, sieving, mixing and sun drying were applied to DW samples to obtain homogeneous powders. Then, DW powder samples were characterized to evaluate its suitability to produce STESMs.

2. MATERIALS AND METHOD

2.1 Materials

DW samples were collected from an urban regeneration project in Adana, Turkey. Figure 1 shows urban regeneration project (a) and waste samples taken from the project (b). As seen in Figure 1 (b), DW samples were not homogeneous. In addition to physical appearance, the properties such as size, shape, density, humidity and chemical content showed variations. DW is stored in open spaces in areas designated by municipalities. As a result of open storage, humidity may increase by over 20 % depending on climate conditions. Density of different components found in DW varies; for bricks it is 1600 kgm^{-3} and for concrete it is 2200 kgm^{-3}.



(a) (b)

Figure 1 Images of urban regeneration project (a) and demolition wastes sample (b)

2.2 Method

2.2.1 Preparation of Demolition Waste Powder

DW samples were first crushed below 1 mm by Jaw crusher machine. DW powders taken from the bottom of the crusher was sieved manually using 1 mm mesh size sieve. Larger particles over the sieve were re-crushed. All of the powder samples below 1 mm were mixed to get an even size distribution. Then, the powder samples were dried under sun for 8 hours.

2.2.2 Characterization of Demolition Waste Powder

Physical, chemical and thermal properties were investigated to characterize DW powder. Beckman Coulter LS 13 320 particle size analyzer was used to analyze particle size distribution in a range from 0.4 µm to 2000 µm using the Fraunhofer theory of light scattering. The specific surface area per unit mass of DW powder was measured based on "Brunauer–Emmett–Teller" (BET) theory. The test was performed by TriStar 3000 V6.04 A instrument and carried under pure Nitrogen flow at the boiling point of nitrogen (-196 °C). AccuPyc 1330 Pycnometer automatic density analyzer measured the average density of DW powder by using gas displacement technique. The measurements were repeated ten times under the same condition. The density of the DW powder was calculated as the mean value of ten measurements.

For investigating chemical properties, Fourier-transform infrared spectroscopy (FTIR) test was applied on DW powders by attenuated total reflection (FT-IR ATR) using Spectrum Two™

equipment from PerkinElmer. The test was done under the wavelength from 4000 to 450 cm^{-1}. Chemical composition of DW powder was studied further using X-Ray Fluorescence (XRF) and X-Ray Diffraction (XRD) techniques. XRF analysis was carried by PANalytical MiniPal 4 model XRF device. Pellet sample for XRF analyze was prepared by mixing 2 gram of starch powder and 10 grams of DW powder. Then, the mixture was pressed under 30 MPa. XRD analyze was performed using PANalytical EMPYREAN XRD analyzer (Cu-Kα) under the following conditions; voltage:20-50 kV, current: 5-60 mA, scan range from 10 to 90, and minimum step size of 0.00010 (θ/2θ).

Thermal conductivity of DW powder was measured with two different methods: with a KD2 Pro thermal properties analyzer, a TR1 type sensor with a size of 2.4 mm diameter and 10 cm long and accuracy of ±0.02 Wm^{-1}K^{-1} . Thermal conductivity measurement was also repeated with another method using pellet samples prepared by pressing DW powder. Measurements of these pellet samples were done by Hot Disk TPS 2500 S Thermal Conductivity Analyzer device.

SDT Q600 V20.9 Build 20 Thermogravimetric Analysis (TGA) device was used to determine thermal stability and decomposition characteristics of DW powder. Sample was heated up to 1000 °C at a heating rate of 10 °C/min under air atmosphere.

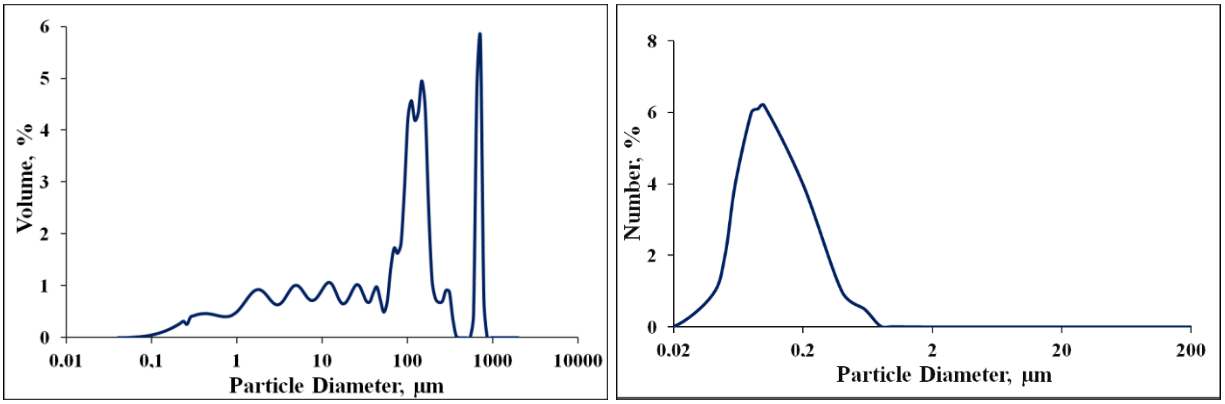
3. RESULTS AND DISCUSSION

3.1 Physical Characterization

The shape and size of the powder materials is a key issue to achieve TES materials with the desired stability, mechanical resistance, density and conductivity (Darkwa et al., 2015; Ndiaye et al. 2018). Distribution of particle size can be analyzed and reported by two different ways as volume and number. Although each method has its own advantage, particle size distribution by number provides more detailed and realistic values for smaller particle fractions (Luke and Silva, 2013; Calderon et al., 2019)

Figure 2 shows particle size distribution of DW powder based on volume (a) and number (b). In both methods, all particles are below 1000 µm by setting jaw crushers. This shows that homogeneity in particle size distribution was achieved successfully as a result of crushing and sieving processes. On the other hand, mean value and d90 range of particle size distribution vary significantly depending on the measurement method. Average particle diameter was measured as

154 μm by volume and 0.150 μm by number. In d90 range, particle size was measured 671 μm by volume, while it was 0.272 μm by number. This is because large particles have a greater contribution in the volumetric distribution. Particle size distribution range of DW powder measured here is compatible with the results on high strength concrete particles such as silica fume, metakaolin, finely ground mineral additives, fly ash and Portland cement which are in a range of 0.100 – 100 μm (Calderon et al. 2019).



(a) (b)

Figure 2. Particle size distribution of DW powder; a) Volume based, b) Number based

Particle size of powder materials affects the specific surface area of the material (Amador and Juan, 2016). Specific surface area of DW powders was determined by BET method from the nitrogen adsorption at -196 °C. As seen in Figure 3, the BET curve was plotted as an adsorption isotherm typically at a relative pressure (P/P0).

The surface area of a sample can be calculated by BET equation as a function of P/P_0, BET constant (C) and the volume of gas adsorbed at standard temperature and pressure (Q_m). The slope and y-intercept of adsorption isotherm curve gives Q_m and C. In this study, the BET curve and the calculations were provided by Tristar program. BET surface area of DW powder was found as 3.9520 ± 0.0459 m^2g^{-1} and molecular cross-sectional area as 0.1620 nm^2. Table 1 gives detailed report of BET analysis.

Surface area of concrete particle materials per unit mass was investigated by Calderon et al (2019). Comparison of the surface area results of DW powder with this study shows that they are nearly in the same range.

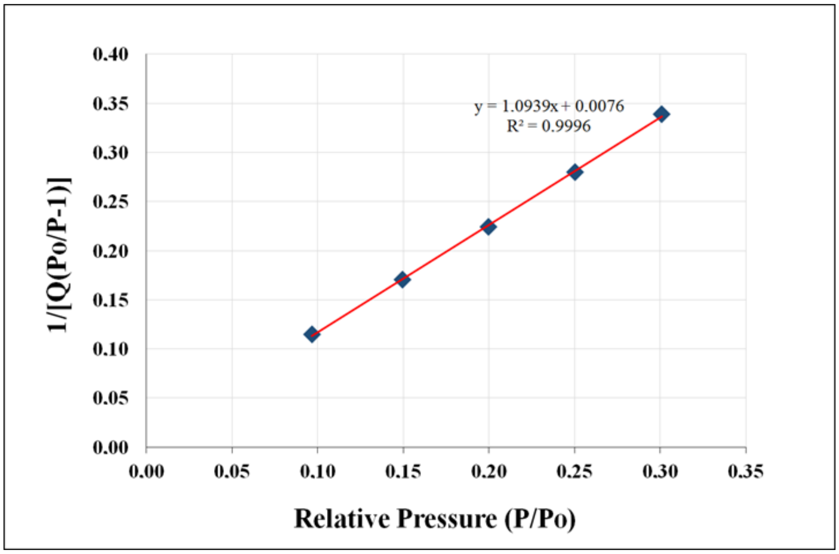


Figure 3. BET curve of DW powder

Table 1. BET surface area report of DW powder

Properties		**Values**
BET Surface Area	:	3.9520 ± 0.0459 m^2g^{-1}
Slope	:	1.093876 ± 0.012519 gcm^{-3} STP
Y-Intercept	:	0.007646 ± 0.002654 gcm^{-3} STP
C	:	144.067133
Qm	:	0.9078 cm^3g^{-1} STP
Correlation Coefficient	:	0.9998036

3.2 Chemical Characterization

Chemical content of STESM is also an important indicator to predict its performance in TES system. For instance, Diago et al (2015) collected natural sands from different desert regions and selected the one with less calcium carbonate content to prevent agglomeration in high temperature TES system. Also, specific heat of a STESM is mainly related to the chemical content. High specific heat components increase the specific heat of STESM (Lv et al., 2018), which is the most important thermal property to increase thermal energy storage capacity.

Material composition of a sample can be analyzed by different techniques. In the XRF analysis, the quantity of heavy elements in DW powder can be determined. With XRD analysis hints about the minerals and their species without quantity can be investigated. Using both techniques can provide an appreciation of the actual composition of the samples (Diago et al. 2015).

XRF results showing chemical composition of DW powder is given in Table 2. The results clearly indicate that DW powder is mainly composed of CaO (57.36%). The second most abundant composition is SiO_2 (17.50 %) that comes from clays and other silicates present in brick and vitrified materials. Higher SiO_2 content can increase thermal conductivity and thermo-mechanical strength of the material. Thus, TES packing material can have more strength and hardness during thermal cycling (Nahhas et al. 2019). The composition of Fe_2O_3 is 11.55 % and may come from the construction elements such as rebar in concrete. This component can also increase thermal conductivity of the samples.

Table 2. Chemical composition of demolition waste powder

Composition	Content, %	Composition	Content, %
CaO	57.36	**TiO_2**	1.23
SiO_2	17.50	**SrO**	0.44
Fe_2O_3	11.55	**MgO**	0,30
Al_2O_3	2.80	**BaO**	0.22
SO_3	2.58	**MnO**	0.20
Ag_2O	2.50	**Cr_2O_3**	0.10
K_2O	1.60	**LOI* and others**	0.32
In_2O_3	1.30		

*LOI: Loss on ignition

The XRD pattern of DW powder sample given in Figure 3 shows that crystalline phases with highest intensity are calcite ($CaCO_3$), quartz (SiO_2), iron (Fe), hematite (Fe_2O_3) and corundum (Al_2O_3). The diffractogram baseline also suggests the presence of non-crystalline phases. These results are compatible with the chemical composition determined by XRF.

Chemical composition of a STESM can vary significantly depending on its origin and nature. Higher amount of Ca and Si can be also seen in concrete, sand and rock (Diago et al., 2015; Becattini et al. 2017). Higher amounts of Ca, and Si in DW prove that major part of DW powder is coming from concrete and bricks in constructions. On the other hand, industrial by products or recycled materials may contain higher amount of Si, Al and Fe that increase thermal conductivity of STESMs (Navarro et al., 2012; Motte et al., 2015, Agalit et al., 2017)

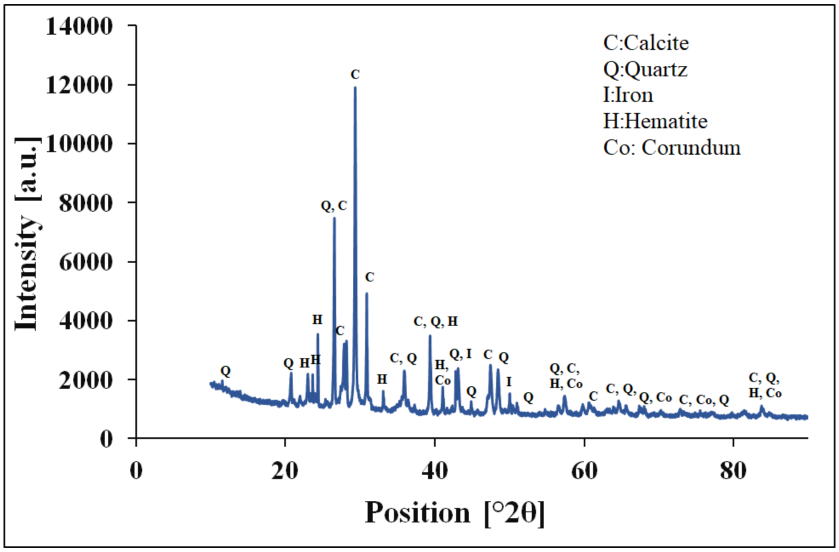


Figure 4. XRD patterns of DW powder sample

FTIR technique is used to identify chemical composition of materials by vibrational transition of molecular bonds (Ghosh, 2001). FTIR spectrum DW powder can be seen in Figure 4. Four different vibration bands were observed in FTIR spectrum. Some of these bands around 713, 876 and 1436 cm^{-1} can be related with the carbonate minerals. According to Ghosh (2001), carbonate minerals such as calcite, aragonite, dolomite and lime can be identified in 700, 876 and 1420 cm^{-1} vibration bands. In addition, the peak around 1008 cm^{-1} corresponds to Si-O vibration. This also confirms that DW powder is composed of carbonates and silicates, which was also indicated by XRF and XRD analysis.

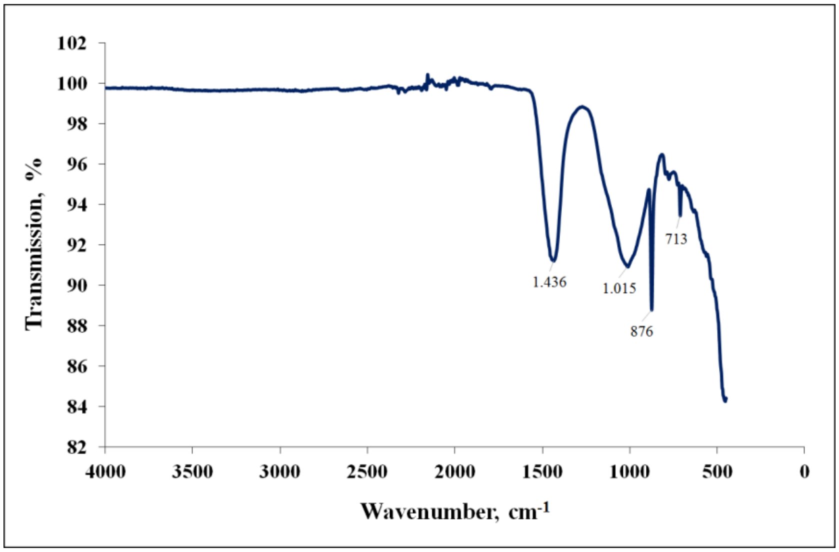


Figure 5. FTIR spectrum of DW powder

3.3 Thermophysical Characterization

Density is a significant property that affects the volumetric energy storage capacity of materials. The average density of DW powder was found as 2.7306 gcm^{-3} with a standard deviation of 0.0009 gcm^{-3}. It is quite high and close to density range of other solid and waste STESMs in literature (Jemmal et al., 2016; Motte et al., 2015; Navarro et al, 2012, Schlipf et al., 2015; Zavattoni et al., 2014).

Thermal conductivity measurements were performed on both powder form and pellet forms of DW powder. Thermal conductivity of DW powder was found as 0.1 WmK^{-1} for powder form and 0.53 WmK^{-1} for pellet form. Thermal conductivity of DW powder is comparable with other inorganic powders STESMs in literature. The pellet form had higher value due to the higher contact among particles, and less air contained within the pores (Lv et al., 2018). Extra processes may need to be applied to enhance thermal conductivity of powder samples (Navarro et al, 2012; Miro et al., 2014). Thermal conductivity of cementitious materials used in concrete production has similar thermal conductivity at around 1.0-1.2 WmK^{-1} with an average density of 2500 kgm^{-3} (Ndiaye et al., 2018)

In addition to porosity and density, chemical composition of storage materials is an important factor affecting thermal conductivity (Li et al., 2013; Motte et al., 2015). As indicated in previous section, waste samples from mining industries or samples that have more iron content can have higher thermal conductivities than DW pellet (Fernandez et al., 2015; Grosu et al., 2018;

Navarro et al., 2012; Py et al., 2011). Also high thermal conductivity materials can be added to mortar formulations to increase thermal conductivity of final product. For example, in the study of Li et al. (2013), thermal conductivity of green compact developed from natural minerals was increased to 1.1-1.6 $Wm^{-1}K^{-1}$ range by adding kaolin tailings.

Mass loss and thermal stability of DW powder was determined by TGA method up to 1000 °C. TGA analysis results are illustrated in Figure 5. Mass loss of 0.9 % was observed between 100 – 200 °C due to the evaporation of free water in the sample due to humidity. The initial humidity of DW samples taken from urban regeneration project was approximately 8% before any processes were applied. This shows that sun drying process is enough to decrease humidity of DW powder from 8% to 0.9%. According to Li et al. (2013) natural materials such as clay, kaolin tailings, and hematite show mass loss up to 400 °C due to the evaporation of free water and the dehydration of lattice water. Similarly, in this study, the second mass loss (0.8%) between 400-405 °C was due to the dehydration of lattice water.

The next mass loss was seen around 700 °C due to the decomposition of carbonates and 77.2 % of inorganic content remained after 1000 °C. There was no mass loss after 780 °C and the sample was thermally stable up to 1000 °C.

Natural materials such as sand, hematite, rock, limestones are also durable up to 800 °C (Li et al., 2013; Diago et al., 2015; Becattini et al., 2017). Amount of mass losses between 700-800 °C varies depending on amount of carbonates. Most of the industrial by-products, furnace slags, asbestos containing wastes are stable up to 1100 ºC (Py et al., 2011; Motte et al., 2015; Fernandez et al., 2015).

The results show that STESMs developed from DW powder are thermally stable for use in high temperature industrial applications up to 700 °C.

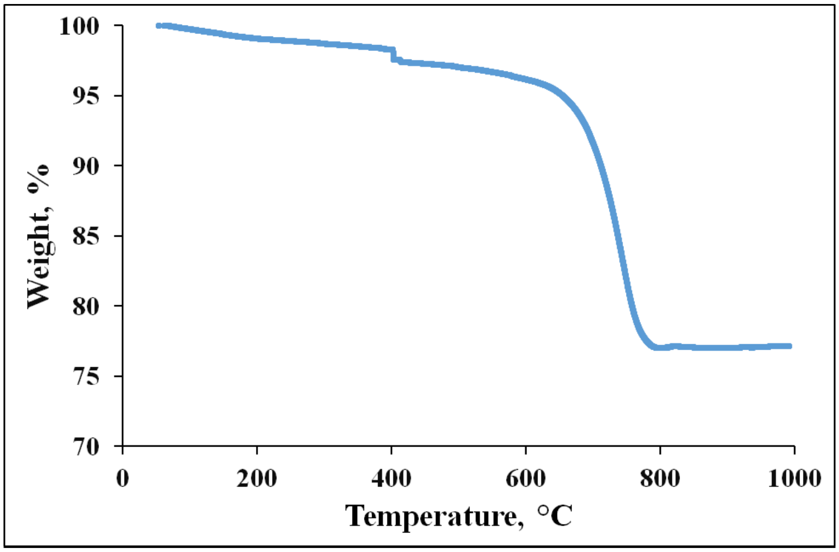


Figure 6.TGA analysis of demolition waste powder

3.4 Preparing STESM Candidate from DW Powder

DW powder samples can be shaped easily by preparing a mortar followed by molding and drying to be used as durable STESM in high temperature packed-bed TES systems. Different mortar formulations and molding methods were studied in our previous studies (Koçak and Paksoy, 2020; Koçak et al. 2021). Mortar formulation from 90% DW powder and 10% CEM I 52.5 White Portland Cement by mass was selected as the best mortar formulation with good thermophysical properties of the STESM candidate. DW powder and white cement were mixed to prepared mortar and tap water was added to the mortar until a doughy mass was obtained. Then, the mixture was shaped with the spherical molds of 1mm diameter. The spherical STESM samples were dried under the sun for 8 hours and in an oven at 150 °C for 1 hour. Figure 6 shows the DW powder sample (a) and the new spherical STESMs developed from DW powder (b).


(a) (b)

Figure 7. Images of DW powder (a) and STESM developed from DW powder (b)

The properties of the new STESMs given in Table 3 were evaluated and their performance was investigated in a lab-scale packed-bed TES system in our previous studies (Koçak and Paksoy, 2019; 2020; Koçak et al, 2021). The new STESMs were defined as candidate storage materials for high temperature industrial applications up to 700 °C with their high storage capacity (4160 kJ/m^{3}C) and mechanical durability. The new STESM has a significant potential compared with other alternatives for large-scale applications, especially in terms of cost. Properties of the STESM candidate developed from DW powder are listed in Table 3.

Table 3. Properties of STESM developed from DW powder (Koçak and Paksoy, 2020; Koçak et al., 2021)

Properties	**Value**
Density	2855 kg/m^3
Specific Heat Capacity	1457 J/kgC
Compressive Strength	5.4 Mpa
Thermal stability	Durable up to 750 °C
Cost	0.001 €/kg

4. CONCLUSIONS

In this study, DW samples were collected from an urban regeneration project and conditioning by crushing, sieving, mixing and drying were applied to obtain a macroscopic homogeneous powder sample. Then, DW powder was characterized to investigate their potential as STESM. Characterization techniques carried out in this study are important indicators to predict the quality and performance of the storage materials.

Processing is the key step that affects the mesh size, porosity, density, thermal conductivity of STESM. Fine grain, 0.150 μm average particle size, was ideal to obtain low porous, high thermal conductivity and high density STESMs by compressing and molding methods. DW powder has good physical and chemical properties to be used as high stability and performance STESM for solar heat industrial applications up to 700 °C. Using STESMs developed from DW powder offers more environmentally, economically and innovative approach for industrial scale TES systems. For further studies, sintering method is recommended to increase operating temperature range up to 1000 °C. Also, the materials of high thermal conductivity can be added to DW powder to increase thermal conductivity.

ACKNOWLEDGEMENTS

This study supported by Çukurova University Scientific Research Projects Unit, Project No: FDK-2018-9602 and Horizon 2020 research and innovation project INPATH TES, Grant agreement ID:657466. The research leading to these results is partially funded by the Spanish government RTI2018-093849-B-C32 MCIU/AEI/FEDER, UE. A.I. Fernández would like to thank the Catalan Government for the quality accreditation given to the research group DIOPMA (2017 SGR 188).

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