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## MECHANICAL ENGINEERING | RESEARCH ARTICLE

# Evaluation of a concrete–graphite hybrid mixture for low-cost thermal energy storage material

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**Abstract:** The intermittent nature of solar energy is a drawback to its wide use in the absence of solar radiation. Therefore, there is the need for some forms of thermal storage. The objective of this study is to develop a hybrid mixture of a thermal storage material, which can be employed in medium-temperature-concentrated solar power plants. A concrete-graphite mixture sensible thermal storage material for applications up to 400°C for use with solar collectors was evaluated. Comparisons were made to determine the charging and discharging characteristics, thermal storage capabilities as well as costs between concrete only and a mixture of concrete and graphite. A mixture of expanded graphite and concrete was prepared and tested. The hybrid material exhibited fast charging and slow discharging for the same volume of thermal storage. The hybrid material showed an improved thermal storage capacity in a ratio of 1.625:1 to concrete and thus reduces the space requirements. Also, results from the study revealed that when the costs of space requirements and the costs of using a hybrid material are compared, the hybrid material is expensive and only desirable in cases where there are space limitations.

**Subjects:** Mechanical Engineering; Power & Energy; Clean Tech

**Keywords:** cost analysis; evaluation; hybrid mixture; solar energy; thermal storage

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### PUBLIC INTEREST STATEMENT

Solar energy from the sun is utilized for power generation, space and water heating. However, the intermittent nature of solar energy creates an energy gap between demand and supply. It is therefore economically justifiable to develop new ways of storing solar energy to reduce rate mismatch between supply and demand. Developing efficient and inexpensive energy storage devices is as important as developing new sources of energy. In the past few years, a great number of new developments have occurred and the experience gained from this has shown that sensible energy storage is inexpensive and less complicated. The major drawbacks, however, is the bulky materials, which have low heat capacities and occupy large volumes. Hence, this study attempts to reduce space requirements, cost and improve the heat capacity of concrete, a material whose aggregates are widely available, by mixing it with graphite, a material of moderate cost and higher thermal conductivity.

## 1. Introduction

Increase in industrial development and population growth has continued to place a high demand on energy. This demand is largely met by utilizing fossil fuels. The energy produced from these fossil fuels leads to depletion of these resources and environmental pollution from carbon dioxide emission and other pollutants. Therefore, if the current drive to decarbonize the world is to be achieved, alternative sources of energy need to be harnessed (Li, Lukso, & Weijinen, 2015).

Among these alternative sources, solar energy has attracted great attention worldwide. Solar energy is regarded as the most effective and economic alternative energy resource. However, solar energy is intermittent in nature due to changes in daily, seasonal and weather-related insolation (Adeala, Huan, & Enweremadu, 2015; Chiteka & Enweremadu, 2016). Therefore, to balance the energy supply and demand, equipment powered by solar energy require some form of thermal energy storage (TES) for use at a later time during the absence of solar radiation (Singh, Saini, & Saini, 2009; Tiwari, Kumar, & Sarviya, 2013). It is therefore, becoming more economically viable to study and develop methods of storing the sun's energy so that it can be used when needed.

The methods of storing thermal energy that can be categorized into physical and chemical processes (Mehling & Cabeza, 2008). Irrespective of the type, every TES follows a reversible sequential process of charge, storage and discharge. The reversible nature of this sequence makes the recovery of the stored energy possible. The simplest most common and least expensive form of thermal storage is the physical process in which the energy is stored as sensible heat of a liquid or solid material (Cascetta, Cau, Puddu, & Serra, 2015). If an energy system stores thermal energy without any change in phase, it is regarded as sensible heat storage.

One of the most important characteristics of any storage system is the length of time during which the energy can be kept stored with minimal losses. Another important characteristic is the volumetric energy capacity of the storage system. The smaller the volume, the better is the storage system. Therefore, a good TES system is characterized by long storage time and small volume per unit of stored energy (Adeyanju & Manohar, 2015; Hahne, 2009).

Sensible heat storage devices store thermal energy by heating or cooling the temperature of the storage material through heat transfer. They take the advantage of the thermal conductivity (and consequently the heat capacity) and the temperature change of the material during the charging and discharging processes.

Several studies have shown that for the application of a solid as a TES media, properties such as density ( $\rho$ ), specific heat capacity ( $c_p$ ), thermal conductivity ( $k$ ), coefficient of thermal expansion (CTE) and cyclic stability as well as availability, cost and production methods should be taken into consideration (Dincer, 2002). In addition, it has been shown that thermal conductivity improves the dynamics of the system. A high cyclic stability is important for better durability of the storage unit, and the CTE is important for the integration of the material in the energy storage system (Navarro et al., 2012).

The specific costs of a solar TES system are characterized by the fact that only one complete charging and discharging is carried out per day. Therefore, TES materials require small volume, excellent heat transfer rate, good long-term durability and low construction cost (Hasnain, 1998; Sachin, Ashok, & Abhijit, 2016; Sun, Zhao, & Wang, 2017).

Sensible heat storage systems suffer from the disadvantage of being bigger in size. For this reason, an important criterion in selecting a material for sensible heat storage is its heat capacity ( $\rho C_p$ ) value. A second disadvantage is their inability to store or deliver energy at a constant temperature.

Naturally-occurring packed bed materials used for thermal storage, have excellent thermal conductivities and have good working temperatures. However, their heat capacities are rather very low making the storage unit unrealistically bulky. To overcome this, researchers have come up with several thermal enhancement methods (hybrid storage materials) aimed at improving both the TES material as well as the effective thermal conductivity between the heat transfer fluid and the TES material. The principle behind hybrid energy storage is to retain the favorable characteristics of a storage material while minimizing the unfavorable characteristics.

The subject of thermal storage and thermal enhancement using concrete has been widely studied in the past few decades. Energy storage in concrete is a physical process, which involves sensible heat as a result of temperature change of the material. Gasia, Miro, and Cabeza (2016), outlined several techniques, which include the use of extended surfaces and combination of the TES materials with a highly conductive material. Adeyanju and Manohar (2015) predicted the thermal behavior of a simultaneous charging, storage and discharging of a packed concrete bed energy storage system during a heating cycle. Boonsu, Sukchai, Hemavibool, and Somkun (2016) studied the performance analysis of concrete with embedded pipes as a solid media sensible heat material using water/steam as the heat transfer fluid.

Gil et al. (2010), studied concrete and castable ceramics and concluded that by virtue of their good thermal and mechanical properties and low construction cost, they show great promise as solid sensible heat storage materials. A cost analysis, which aimed at comparing concrete and other heat storage materials was carried out by Strasser and Selvam (2014) and similar conclusion was reached. The study by Khare, Dell'Amico, Knight, and McGarry (2013) identified some common materials, for solid-state sensible heat storage and found that high alumina concrete had the lowest cost.

Despite some shortcomings (Laing, Lehmann, Fiß, and Bahl (2009), Skinner, Strasser, Brown, and Selvam (2013), John, Hale, and Selvam (2013) and Wu, Pan, Zhong, and Jin (2016), concrete has been found to be a relatively good solid medium for energy storage for application in intermediate-temperature solar thermal plants (Laing et al., 2012). Prasad and Muthukumar (2013) noted that when concrete systems are used they have an advantage of low cost, easy handling and harmony between the heat exchanger and concrete.

Thermal enhancement has been studied by Fernandez, Martinez, Segarra, Martorell, and Cabeza (2010) and graphite was one such material because of its good thermal conductivity, low density and chemical resistance. Gasia et al. (2016) realized that effective thermal conductivity enhancement can be done by combining with highly conductive materials such as graphite composites and nanomaterials. Similar studies have been carried out by (Gasia et al., 2016; Guo, Zhu, Zhou, & Chen, 2010; Khare et al., 2013; Liu et al., 2016; Miro et al., 2014).

Most of the experimental work carried out has been on the use of expanded graphite with phase change materials (nitrates and chlorides) of magnesium, sodium, lithium and potassium. The focus was more on which method (impregnation, infiltration and compression) guaranteed better enhancement of thermal conductivity (Huang, Gao, Xu, Fang, & Zhang, 2014; Kim, France, Yu, Zhao, & Singh, 2014; Xiao, Zhang, & Li, 2013; Zhao, France, Yu, Kim, & Singh, 2014). Besides the studies carried out by Guo et al. (2010) and Salomoni et al. (2014) on the fabrication and thermal properties of concrete and graphite for the enhancement of the thermal conductivity, it appears that most of those reports were suggestive only and limited work has been carried out on the hybrid mixture of graphite and concrete for TES. Hence, the objective of this study is the evaluation of a hybrid mixture of a sensible heat storage material made from concrete and graphite, with the aim of enhancing the thermal storage capacity of the concrete with graphite. A further objective is to carry out the cost analysis in terms of space requirements since space limitations may hinder the use of the sensible heat energy storage.

## 2. Materials and methods

### 2.1. Materials selection

The topic of energy storage has been studied for the past three decades but the material to be used for thermal storage still require further research. The analysis on the selection of suitable materials sensible heat storage applications has previously been carried out by many researchers (Anderson, Bates, Johnson, & Morris, 2015; Fernandez et al., 2010; Khare et al., 2013; Salomoni et al., 2014). These studies show that for sensible heat storage in stable solid media, within the operating temperatures, the thermo-physical properties of the selected materials are important. These properties include specific heat capacity, density, thermal conductivity, mechanical stability and CTE. The importance of high energy density is to reduce the storage volume required while high thermal conductivity enhances effective heat transfer. Thermal properties alone are not sufficient for the selection of any material for use in sensible heat storage. This is because the solid sensible heat storage is not the best option in terms of energy density as the highest values are for thermochemical storage. Therefore, other parameters such as cost, embodied energy, production methods, durability at high temperatures, cyclic stability, availability, stability, low thermal losses, available space, reversibility in charging and discharging, degree of compatibility with its containment, recyclability and a low CO<sub>2</sub> footprint should be considered in the procedure of selecting solid selecting materials in order to have a feasible alternative. Even though no single material can meet all the afore-mentioned requirements, however, materials selection processes have identified a number of common materials, which are highly cost competitive and can be mixed together with various materials to achieve the desired properties for specific uses.

In this study, Granta Design's CES Selector package (2012) was used for selection of the potentially suitable materials for sensible heat storage. The selection is based on the bulk physico-chemical properties of the materials and on economics. The major inputs considered in the design methodology when using CES Selector package include mechanical and thermal properties and costing. The choices made based on these inputs are then optimized to arrive at the most suitable material (Fernandez et al., 2010; Khare et al., 2013).

Since this study is not aimed at detailed selection criteria based on the CES Selector package, but from the preliminary design, common concrete and graphite were found to have the desirable properties suitable for sensible heat storage for the duty considered ( $\leq 420^{\circ}\text{C}$ ). Studies have shown that due to its special molecular structure, graphite has a high thermal conductivity. Its chemical stability allows it to endure acid, alkaline, and organic solvent corrosion (Real, Bogas, Da Gloria Gomes, & Ferrer, 2016). Both concrete and graphite are compatible in terms of CTE and possession of high energy densities. Concrete is cheap, it is easy to cast and handle and, possesses no critical environmentally non-benign components. However, both concrete and graphite may be susceptible to failure on repeated thermal cycling. From the overall analysis, concrete-graphite appear to have acceptable combination of properties as sensible heat storage material.

The concrete material was made from a mixture of crushed granite rock with average diameter of 15 mm, sand, water and ordinary Portland cement (CEM 42.5 N) as a binder. Generally, the thermal conductivity of cement is about 0.25 W/m.K. The sand aggregate was silica sand with an average diameter of 0.5 mm. On the other hand, the graphite used was modified expanded graphite (MEG) powder purchased from a local supplier. This expanded graphite is a loose and porous vermicular material which, when exposed to rapid increase in temperature, results in a puffed-up material with a low density and a high temperature resistance. The properties of the graphite were not measured but obtained from the manufacturer's specifications. The purity of the graphite exceeded 99% and the particle size was between 25 and 75  $\mu\text{m}$ . The properties are presented on Table 1.

### 2.2. Material preparation and testing

The material preparation and mix design procedure is modified from Liu, Alengaram, Jumaat, and Mo (2014) and Real et al. (2016) for graphite concretes in building structures. A normal

**Table 1. Properties of concrete and graphite used in the study**

Material	$T, ^\circ C$	$\rho, kg/m^3$	$c_p, kJ/kgK$	$k, W/mK$	$CTE(10^{-6}.K^{-1})$
Concrete	350	2250	1.01	1.23	11.6
Graphite	20	2200	0.61	155	23.7

concrete with mixture of cement, sand, aggregate material and water was prepared. The materials were mixed with volumetric ratios: the ratios of water (1): cement (2.3): sand (2.6): aggregates (3.9). The mixture of cement, aggregate, sand and water was stirred for 7 min using a horizontal forced mixer resulting in the binding of the materials together. For the hybrid material, graphite concrete was mixed using cement, sand, water, aggregate material, and 5% volumetric content of powdered graphite. According to Guo et al. (2010), this percentage composition is enough for use in energy storage. Cylindrical specimens 100 mm in diameter and 200 mm in height were produced. For the tests,  $50 \times 50 \times 50 \text{ mm}^3$  concrete mortars formed in the molds were used as test specimens. The normal and graphite concrete blocks prepared were cured for 28 days before and then subjected to drying treatment 2 h under heat ( $500^\circ C$ ) in a drying cabinet.

The test samples casted were measured for apparent density in accordance with ASTM C830. The samples which were cured in ambient water were removed from the water and oven dried in the oven at a temperature of  $105^\circ C$  until a constant weight was reached. The dried samples were saturated by moistening by a vacuum saturation process. Suspended weight and saturated weight of the specimen were determined by using a digital balance. The apparent density of the test specimen was expressed as:

$$\rho_a = \rho_w \left( \frac{m_d}{m_s} - m_h \right) \tag{1}$$

Where:

- $\rho_w$  = water density in  $kg/m^3$
- $m_h$  = saturated specimen mass in water
- $m_d$  = dry specimen mass
- $m_s$  = standard specimen mass in air

The thermal conductivity was measured using a DRE-2D coefficient of thermal conductivity tester with optional temperature sample controller. This instrument is based on transient plane heat source method, with a hot disk as the thermal detector probe. The measuring probe is made of metallic nickel with  $10 \Omega$  resistance, and its thickness is  $0.16 \pm 0.02 \text{ mm}$ .

The specific heat was measured by high temperature adiabatic calorimeter also known as the HTCP system. The sample to be measured was heated/cooled to the required measurement temperature. Once a stable temperature was attained, a known amount of energy was supplied to the sample and the resultant change in temperature recorded. The specific heat capacity was determined by using the equation:

$$c_p = \frac{1}{m} \frac{dQ}{dT} \tag{2}$$

Where:  $m$  = mass,  $dQ$  = supplied energy, and  $dT$  = change in sample temperature. The measurement of the CTE, which is based on the linear variable differential transformers (LVDTs) technique was carried out using an Autoscan CTE for concrete, AASHTO T336-11. All height measurements were accomplished by high precision LVDT. The height measurements of the sample were taken and averaged over a range of the specified temperature. The CTE values were automatically

calculated and displayed at the completion of the test cycle. The measured properties are shown on Table 1.

### 2.3. Experimental set up

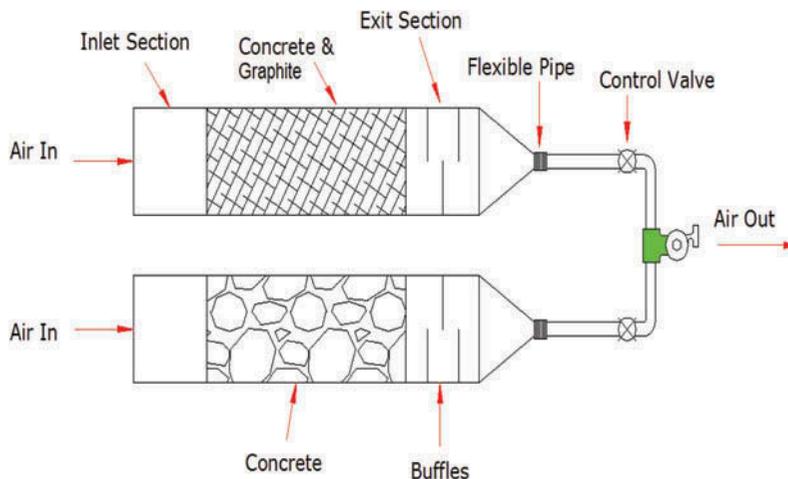
Two packed-bed laboratory-scale ducts were developed as shown in Figure 1. The schematic diagram of the experimental set-up was designed and tested according to American Society of Heating Refrigeration Air-conditioning Engineers (ASHRAE) standards (1978) and Sukhatme (1987). The ducts were inclined at an angle of 15° to allow hot air to rise through the duct. The standard documents the methods that are used in solar thermal collector testing in the determination of solar thermal collector parameters. Furthermore, it gives a guideline to avoid ducts, which are either too small or too large because too small a duct would not carry enough air and too large a duct will have high energy losses. This standard also stipulates that charging should be done from the bottom for vertical ducts and efficiency is tested under the conditions of steady state air flow. Based on this standard, the ducts' dimensions and general layout was determined.

The set-up of the thermal storage units consists of two identical packed-bed ducts of length of 1 m, width of 0.5 m, and height of 0.25 m and was made of wood and well insulated using 50 mm polystyrene foam. This was done to prevent heat transfer between the packed bed and the outside environment and the two ducts were designed to enable comparison. The TES units were packed with the thermal storage materials; one contained concrete and the other one was a mixture of concrete and graphite powder.

The two ducts were coupled to a 2 kW electric air heater at a temperature of 420°C. This air heater supplied hot air to the two ducts i.e. concrete duct and packed bed duct of concrete mixed with graphite. Calibrated copper-constantan type based digital thermometers were placed on different parts of the storage units and temperature measurements were taken and recorded periodically at 10-minute intervals. This was used to determine the temperature rise in the ducts as well as the temperature drop during discharging. There were a total of 3 thermocouples for each duct; one at the inlet, to measure inlet temperature, the other, inside the ducts to measure the bed temperature and the remaining at the outlet after mixing by the baffles. The ducts were charged using heated air at 420°C, i.e. at constant 420°C, air is coming out of the air heater during charging period, and air at constant temperature of 20°C was discharging the bed during the complete discharging operation. Air was circulated at a constant discharge of 0.01 kg/s both during charging and discharging, using a 0.05 kW centrifugal blower.

A set of observations involved monitoring the temperature attained in a given time interval for both ducts. The time to reach the 420°C temperature mark when charging and 20°C when

Figure 1. Schematic set up of packed bed ducts.



discharging was recorded for each of the ducts. Measurements were taken in both time intervals as well as temperature intervals. In one set of measurements, the time taken to attain a temperature of 420°C was noted in the temperature intervals of 20°C. On the other hand, temperature readings were taken to record the increase or decrease in temperature at 10 min intervals during charging and discharging, respectively.

The contribution of the hybrid material in space reduction was also evaluated. The packed bed duct with a mixture of graphite and concrete was reduced in size by 10% in stages from 0.125 to 0.013 m<sup>3</sup> (0.125, 0.113, 0.1, 0.089, 0.075, 0.063, 0.05, 0.038, 0.025 and 0.013) while the duct with concrete only had a constant volume of 0.125 m<sup>3</sup> (see Table 2). The ducts were charged to a temperature of 420°C and then discharged to a temperature of 20°C. The time taken to discharge to a temperature of 20°C was recorded for each volume. This was done in order to determine the volume at which the two ducts have similar discharge characteristics. The experiment was carried out in triplicate and the average values were taken for experimental set up taken.

In order to validate the experimental procedure, before collecting data from the packed bed duct with a mixture of graphite and concrete, data from the concrete duct was first collected to determine the charging and discharging time and consequently the thermal storage capability. Afterwards, the values from the concrete-graphite packed bed duct were compared with those from the concrete duct.

#### 2.4. TES process

A simple heat storage consists of the charging period, the storage period and discharging period. The charging time is assumed to be the time taken for the volume of the ducts' average temperature to reach a specified rise in temperature ΔT. The energy balance during these periods can be expressed according to Dincer & Rose (2011). For the charging period, the energy balance is:

$$\text{EnergyInput} - \text{EnergyLoss} = \text{EnergyAccumulation} \tag{3}$$

The storage system is regarded as the sensible heat, which is stored in solid storage medium. The energy balance is expressed as:

$$\text{Energy Input} - (\text{Energy Recovered} + \text{Energy Loss}) = \text{Energy Accumulation} \tag{4}$$

Generally, the performance of a thermal heat storage is characterized by storage capacity, heat input and output rates during charging and discharging operations. The amount of energy stored

**Table 2. Comparison of discharge characteristics of different volumes of hybrid material to a constant volume of concrete**

Percentage Volume	Volume (m <sup>3</sup> )	Discharge time (hybrid material)	Discharge time (concrete material) at 0.125m <sup>3</sup> volume
100%	0.125	195	120
90%	0.113	137	120
80%	0.100	99	120
70%	0.088	77	120
60%	0.075	59	120
50%	0.063	42	120
40%	0.050	26	120
30%	0.038	14	120
20%	0.025	7	120
10%	0.013	9	120

depends on the mass and specific heat of the solid storage medium and the temperature difference between its initial and final states.

$$Q = mc\Delta T = \rho c_p V \Delta T \quad (5)$$

where,  $\rho$  is the density of the storage material ( $\text{kg/m}^3$ ),  $\Delta T$  is the temperature range of operation ( $^\circ\text{C}$ ) and  $V$  is the volume of storage material used ( $\text{m}^3$ ).

During the discharging period, the storage bed attains a volume average temperature of the temperature at the inlet. The energy balance during this period is given by:

$$-(\text{Energy Input} + \text{Energy Loss}) = \text{Energy Accumulation} \quad (6)$$

The heat losses to the environment during the charging and discharging processes as well as between the end of discharging and the beginning of the charging periods, are neglected (Cascetta et al., 2016).

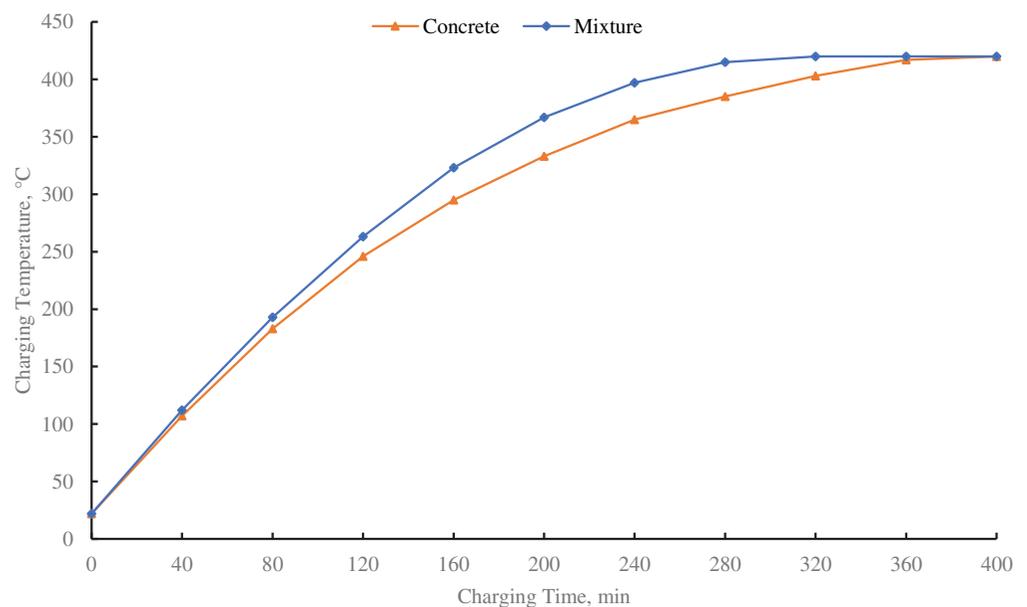
### 3. Results and discussion

#### 3.1. Charging time and discharging time

The charging began after the experimental set up. During the test, the air inlet mass flow rate was 0.01 kg/s. The average inlet temperature to the ducts was maintained at an almost constant level at about 420 $^\circ\text{C}$  for most of the charging process. The time to attain any particular temperature during charging for each of the thermal storage materials was recorded.

Figure 2 shows the time to attain any particular temperature during charging for each of the thermal storage materials. The storage temperature of the materials increased. Initially the volume average temperature of the storage bed rose rapidly and then rose slowly over the subsequent time up to 400 min. This might be due to the initial potential for heat conduction in the concrete. The figure shows that the concrete-graphite mixture charges faster than the plain concrete material. The hybrid graphite-concrete material gained heat at a faster rate compared to pure concrete material. This is may be attributed to the thermal enhancement characteristics of graphite mixed with concrete. The increased charging rate is probably due to the faster rate at which graphite absorbs heat energy and then transfers it to the concrete material. Graphite can

**Figure 2. Time vs targeted temperature.**



gain high temperatures in a short space of time compared to concrete material. This phenomenon can be attributed to the high apparent density associated with heated graphite-concrete mixture since graphite expands at high temperatures and fills the porous spaces in the concrete. Hence, high apparent density implies less porous spaces thus, thermal conductivity also increases.

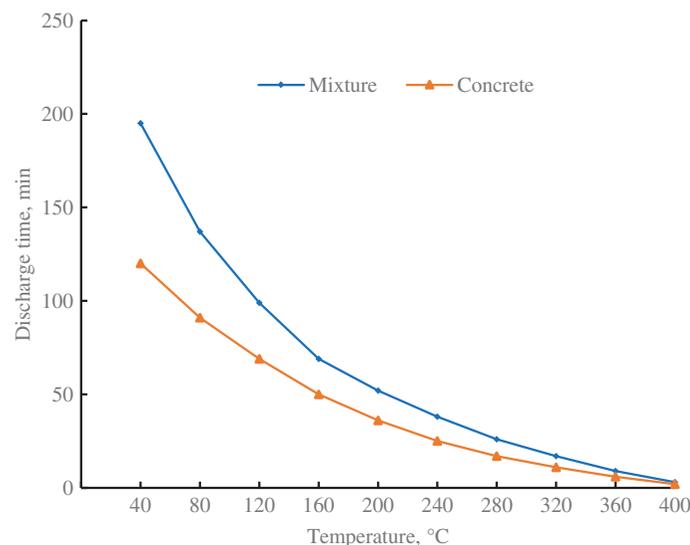
The average temperature attained by the concrete-graphite material was 304.7°C compared to 288.7°C for concrete. It can be observed that the average rate of charging for the concrete-graphite mixture to a temperature of 420°C was 1.06°C per minute whilst for concrete it was 0.95°C per minute. It took only 320 min to attain a temperature of 420°C for the hybrid concrete-graphite material while it took 400 min to attain the same temperature for concrete material. This is a time difference of 80 min. Initially the volume average temperature of the concrete material rose rapidly and then rose slowly over the subsequent time up to 320 min. This may be due to the initial potential for heat conduction in the concrete, which tends to decrease with time as it gains heat of the air heater.

The faster charging rate may be due to enhanced effective thermal conductivity, which might have arisen with use of graphite material. In all cases, the hybrid concrete-graphite mixture proved to be superior to concrete material.

During the discharging test, the mass flow rate of air at inlet was also 0.01 kg/s air at constant temperature of 20°C. The three thermocouples were fixed inside the ducts to measure the temperature distribution. The average temperature decreased over time.

The hybrid concrete-graphite material exhibited higher thermal storage capacity for the same volume of thermal storage material. This was evident during the discharge tests. It required 195 min to discharge the hybrid material packed bed from 420°C to 20°C (see Figure 3). On the other hand, it took the concrete material 120 min for the discharge in the same range as the hybrid material. Thus, the discharge capacity of the graphite mixture is 1.625 times or 62.5% superior compared to concrete. The hybrid material can be regarded as possessing higher thermal storage capacity compared to concrete material without any thermal enhancement. This is in agreement with the works of Guo et al. (2010) that thermal conductivity of concrete-graphite increases with increase in temperature and increases with increase in graphite content in a mixture.

**Figure 3. Temperature vs. discharge time.**



### 3.2. Thermal storage capabilities

Mixing concrete and graphite enhanced the thermal storage capacity of the mixture thus significantly reducing the space requirements for thermal storage. This may be explained from the point of the high density of the hybrid material which reduces the volume of the thermal unit required, thereby reducing the bulkiness and space requirements. In the view of Equation 5, it is evident that high density increases the heat capacity and hence the energy storage capacity. Also, when compared with the normal concrete there was an increase in the apparent density of the concrete-graphite hybrid. This increase in the apparent density of the graphite concrete can be advantageous to increase the TES. This is because high levels of high apparent density indicate low porosity.

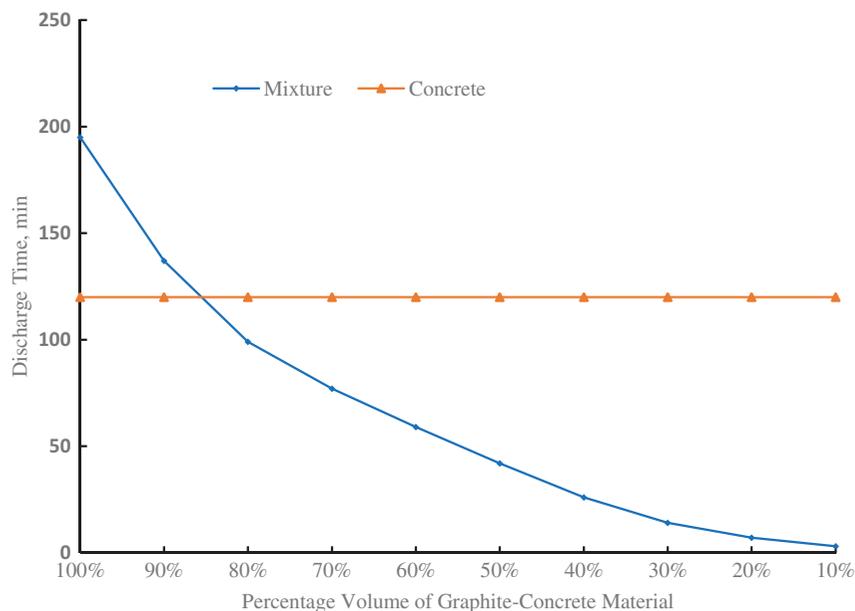
The thermal storage capacity was determined to be 1.625 times higher for the concrete-graphite hybrid material compared to the concrete material only. Experimental results (see Figure 4) shows that the volumetric reduction in space requirements when a hybrid material of graphite and concrete is used was 86.4%. This was realized by determining the percentage reduction in volume at which both ducts have a total time of discharge being 120 min.

It was clear that hybrid material had thermal enhancement induced in it by mixing with graphite. The thermal storage capacity also increased as proven by the longer discharge time. The space requirements for a hybrid material proved to be less when compared to concrete material for thermal storage.

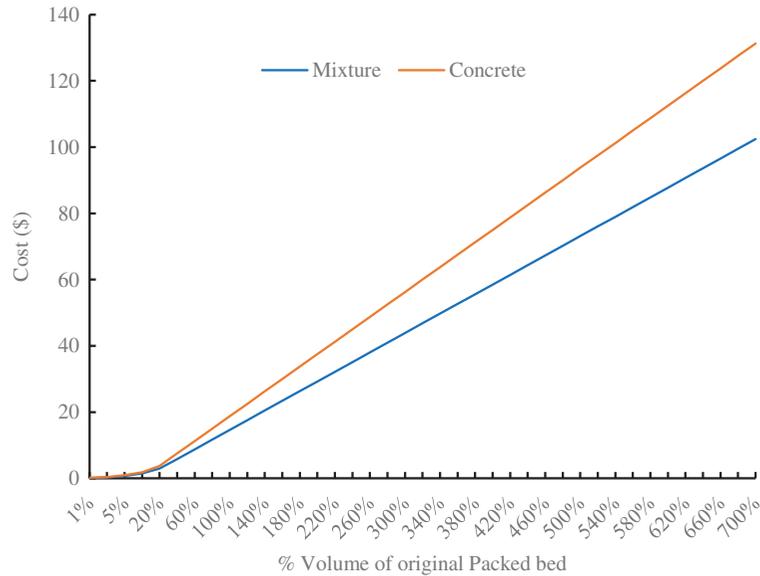
### 3.3. Cost analysis

According to studies carried out by Ataer (2006), denser materials will have smaller volumes and the advantage of larger energy capacity per unit volume when the mass specific heat capacity is not small. Also for transport and habitat applications, the available space is limited. Volume occupied by any storage system is an important factor that may limit the size of storage provided. Cost dictates the amount of storage provided and studies have shown that the cost of floor space or volumetric space should be one of the parameters considered when optimizing the size of a storage system. The average cost of land in the selected location is US\$150/m<sup>2</sup>, the cost of concrete is US\$40/m<sup>3</sup> and the required cost of graphite is US\$1.5 for material requirements to cover 25% of a total volume of 0.125 m<sup>3</sup>. To fill up a space of 1 m<sup>3</sup> would require US\$190 for space and material requirements using concrete material only. Using the hybrid graphite-concrete

Figure 4. Percentage volume vs discharge time.



**Figure 5. Thermal storage cost vs. percentage volume.**



material, 1m<sup>3</sup> of thermal storage facility would require a total of US\$166.5. If the cost of the 13.6% space reduction is taken into consideration this would translate to US\$131.844 for hybrid graphite-concrete material which is 69.4% lower compared to concrete material thermal storage. This would mean for any other big thermal storage the cost of storage using hybrid graphite-concrete will also be higher compared to the use of concrete material only.

When the cost of space requirements and the cost of using a hybrid material (concrete and graphite) were compared graphically, the threshold value in which the hybrid material is recommended was a very small fraction of the total volume considered in this study. The cost was only favorable for volumes of 0.031 m<sup>3</sup> and below. In places where space requirements are not a problem, it is therefore cost effective to use concrete only as a thermal storage material. However, in cases where there are restrictions in space requirements, using the hybrid material should be considered. Extrapolation of data showed that the costs, associated with the concrete-graphite mixture as a thermal storage material, are huge if used for large systems but can be used with reasonable investment on smaller systems as shown in Figure 5.

Since the cost of graphite is the major cost driver in the hybrid graphite-concrete mixture, using graphite in the form of nano-particles with concrete material may be less expensive since it would require less material.

#### 4. Conclusions

Thermal storage performance of concrete as a thermal storage media was compared to a hybrid concrete-graphite material. Results showed that mixing concrete and graphite produces a higher performance material compared to using concrete only. The average temperature attained by the hybrid material was 5.54% higher than using concrete only and the charging time for the hybrid material was 25% lower that when using concrete. The charging rate of the concrete-graphite mixture was higher by 0.11°C/min. The concrete-graphite material had 62.5% more thermal capacity than concrete and a volumetric space reduction of 86.4% was also recorded with a cost reduction of 69.4%. The good performance is due to the improved effective thermal conductivity and volume heat capacity brought about by the addition of graphite to the concrete. However, the hybrid material is more expensive to use compared to using concrete only. On the other hand, in cases of space limitations, the hybrid material becomes a material of choice. It is therefore, concluded that the concrete material can be used cost-effectively in cases where there are no

space limitations whilst the hybrid material would be chosen where there are space restrictions. However, further studies need to be carried out on the performance and cost effectiveness of the hybrid material with higher graphite content.

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#### Competing Interest

The authors declare no conflict of interest.

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