Nigerian Research Journal of Engineering and Environmental Sciences 7(1) 2022 pp. 203-210
p ISSN: 2635-3342; e ISSN: 2635-3350

Nigerian Research Journal of Engineering and Environmental Sciences
Journal homepage: www.rjees.com

Original Research Article

Characterization of Gravels for Solar Thermal Applications

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http://doi.org/10.5281/zenodo.6724813

ARTICLE INFORMATION

Article history:
Received 01 Jun, 2022
Revised 13 Jun, 2022
Accepted 14 Jun, 2022
Available online 30 Jun, 2022

Keywords:
Gravels
Solar thermal systems
Energy demand
Energy storage
Physico-thermal properties

ABSTRACT

Solar thermal energy storage can provide significant solutions for the sustenance of clean and affordable energy supply. Gravel physico-thermal measurements describes the gravels properties which govern the flow of heat through the gravels (density, porosity, thermal conductivity, and thermal capacity). This paper investigated the physico-thermal properties of gravels at transient state conditions. Seven different gravels of volcanic origin were tested for thermal conductivity, thermal effusivity, thermal diffusivity, specific heat capacity using the transient heat source method with the aid of KD2 thermal analyser, while density was determined through the gas jar method. Results indicate that Awulema gravels sourced from sourced from Ohimini local government area of Benue State, Nigeria State, Nigeria had the highest specific heat capacity, thermal conductivity and relatively good thermal effusivity (admittance) suitable for seasonal sensible heat storage application. The physico-thermal properties of the gravels (density, thermal conductivity, thermal effusivity, thermal diffusivity and specific heat capacity) gave results similar to the ones found in literature. The pertinence of laboratory investigation of sensible materials for solar thermal heat storage and transfer is vital for meeting solar thermal energy requirement during solar radiation off peak period. It is recommended that solar thermal heat storage applications such as gravel-water pit, gravels storage for district heating and solar drying be develop and verified using the materials.

1. INTRODUCTION

The availability of low-cost and sufficient supply of energy is imperative to a nation's economic growth as it is fundamental to the quality of life of the populace (Rapu et al., 2015). Nigeria is endowed with solar resources with variations from the coastal areas to the hinterlands in the far northern part of the country

(Emmanuel *et al.,* 2020). Notwithstanding, the harnessing and full potential of the solar resources has not be seen due to the inadequacy in the implementation of the country's renewable energy blue print (Johnson *et al.,* 2014). However, the current trend of energy supply in the world clearly shows that a substantial amount is obtained from the conventional energy sources which are disadvantaged by their finite nature as well as adverse effect on the environment (Gupta et *al.,* 2020). Reduction in the over dependence on power from conventional sources through the proper development and utilisation of solar energy devices will minimise the negative impact caused by the used of the conventional fuels (Gond et *al.,* 2016).

Prospective application of solar energy is found in air and water heating, process heat for industrial use, cooling system applications in refrigeration/air conditioning, electricity power generation among others (Decho, 2008). For instance, the air and water heating requirements for educational institutions and health centres in rural areas can readily be met by solar air and water collectors if properly designed (Emmanuel *et al.,* 2020). A major determining factor for all day operation and overall performance of solar devices is the amount of solar radiation received by these devices due to the intermittent nature of solar energy (Sreekumar, 2007). This has necessitated the search for means of solar energy storage in order to keep solar thermal systems actively running even during low or off solar radiation peak periods (Gond et *al.,* 2012).

The use of sensible heat materials is identified to be the simplest method adopted for the storage the storage and utilisation of solar energy by thermal means through charging and discharging a liquid or solid material (Decho, 2008). Sensible heat materials such as water, sand, molten salts, gravels, pebbles, or rocks are acknowledged to have some potentials for storing heat (Diago *et al*., 2015). Storage approaches could be in the form of underground, water tank and packed-bed storage. The use of sensible heat storage materials for storing heat is noted for its inexpensiveness as well as the safety associated with them (Chandravanshi, 2017). Charging and discharging processes of the storage media are achieved by the material heat capacity and the change in temperature during these processes. The measure of heat stored is determined by the specific heat capacity of the medium, the temperature elevation, and the quantity of the sensible storage material used (Hailu et al., 2017).

Various attempts have been made to investigate sensible heat materials mostly of gravels and soil for thermal energy storage technology. Indra and Barry (2010) investigated thermal conductivities of sands at steady state and cooling stage conditions. The tests gave different results between steady state condition and cooling stage condition. Determination of thermal conductivity of sands (dry coarse sand, saturated coarse sand, dry fine sand, and saturated fine sand) at cooling stage conditions gave similar results to the generic published values. The test confirmed that the thermal conductivity varies with material condition. Olukayode *et al.* (2012) investigated dry bulk density, saturated density, porosity and particle density of fifty rock samples in Ogun State, Nigeria. The results The results indicated that Ewekoro shale had had the lowest mean density, while Ibese, Yewa North local government local government limestone had had the highest mean density with the granite in Odeda local government having the highest porosity and the shale in Ewekoro local government having the lowest porosity. Hamdhan and Clarke (2010) studied the thermal conductivity of coarse and fine sand soils as sensible heat storage materials. Their findings show that the average thermal conductivity of dry fine sand at steady state condition and cooling stage condition were 1.76 W/m/^{o}C and 0.16 W/m/^{o}C respectively. However, the thermal effusivity, thermal diffusivity and specific heat capacity were not studied. Miguel *et al.* (2015) analysed thermal desert sand samples for their suitability for use as sensible heat thermal energy storage media. The average heat capacity for all the samples was found to be 926.1 J/kg.K. The work did not investigate the other thermal properties of desert sand material. Warkhade *et al.* (2016) designed and experimentally evaluated a sensible heat thermal energy storage system for a concrete material of high density having varying shapes for solar energy storage performance using air as a heat transfer fluid. Charging and discharging was affected by the shape of the material and void fraction. No study was carry out for various thermal properties of the material. Hailu *et al.* (2017) carried out experimental investigation into seasonal solar thermal energy storage using sand bed in a region with extended freezing periods. The results suggested that solar thermal storage systems are viable options in regions with long periods of freezing temperatures. The study is limited in terms of analytical approach for measuring thermal properties of the sand bed.

For short term applications for space heating in solar drying, several research works have been explored having thermal energy storage gravel materials either under the collector absorber plate of the solar collector and integrated to the drying chamber of the solar dryer for accelerated drying process (Okonkwo and Okoye, 2005; Shalaby 2012). Okonkwo and Okoye (2005) tested a developed passive solar crop dryer with imbedded pebble bed solar heat storage. However, no test for pebble material used for heat storage was carried out. Similarly, Shalaby (2012) studied the effect of using sand as a solar heat storage material under the back plate of an absorber. His work concentrated on dryer performance with no heat storage material property investigation. Clarke and Saunders (2012) in their work incorporated a slag bed heat storage absorber to a forced solar air kiln to dry timber. Though energy cost savings was achieved, no test on thermal properties of slag bed were investigated.

Based on reviewed literature, gravels are adequately available and well distributed in Nigeria. Thus, for the application of solar thermal energy storage, adaptation is desirable for the selection of affordable and efficient gravel material for solar thermal energy storage. Hence, this study aims to assess gravel for solar energy storage that will provide supplementary heat during solar radiation off peak periods for continuance operation of solar thermal systems.

2. MATERIALS AND METHODS

2.1. Materials

Volcanic gravels which are available in and around Benue State State, Nigeria were collected for the study. Seven gravels of volcanic origin were collected from various locations across the state namely Ikyuen in Gboko local government,Awulema, Ojano and Okete all in Ohimini local government area; while Ikowe and Ugba are found in Logo local government area of the state with Ushongu in Ushongu local government area (Figure 1).

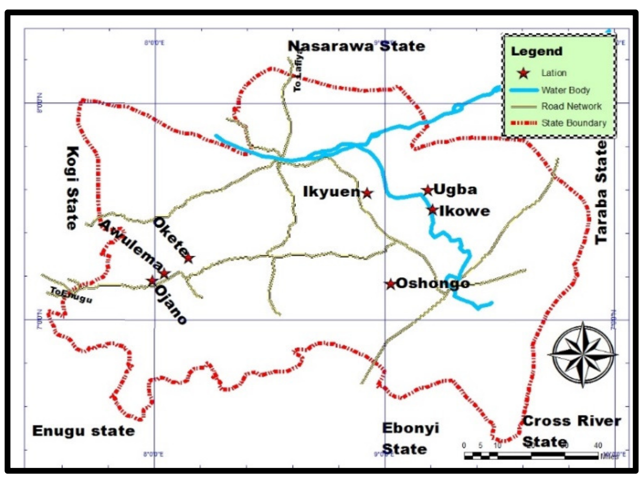

Figure 1: Map of Benue State showing gravel locations gravel locations (Source: Department of Urban and Regional Planning, ATBU Bauchi 2021)

2.2. Methods

2.2.1. Density determination

The density of the gravels was investigated by first determining the specific gravity of the gravels through the gas jar method. A representative sample of about 1 kg as prepared with each of the gravels specimen. The weight of the empty gas jar was determined in a dry condition to the nearest 0.2 g and taken as W_1. The prepared representative sample was then placed into the gas jar and its content weighed as W_2. Clean water of volume 500 ml was added to the gas jar and then left until the sample is fully saturated with the water and no air bubble was seen coming out. The weight of the gas jar, sample and water were weighed to the nearest 0.2 g as W_3. Lastly, the gas jar was then emptied, thoroughly cleaned and filled with clean water and its weight taken as W_4. The specific gravity(G_s) of the samples was then found from Equation 1.

$$G_s = \frac{w_1}{(w_4 - w_1) - (w_3 - w_2)} \tag{1}$$

Therefore, the densities of the samples are given as:

$$\rho_s = G_s \times \rho_w \tag{2}$$

where is the specific $\rho_s$is the density of the sample (kg/m^3) and $\rho_w$is the density of water (kg/m^3)

2.2.2. Determination of the thermal properties of the gravels

The KD2 Thermal Pro instrument, a portable handheld laboratory and field instrument was used for measurement of the thermal properties of the gravels. The KD2 thermal Pro instrument works on the principle of transient line heat source method meant for soils and gravels and made of a multi sensors usage (single needle sensors and dual sensors). The single needle sensor (TR-1) measures the thermal conductivity and resistivity, while the dual needle sensor (SH-1) measures the thermal diffusivity and volumetric specific heat capacity. Gravels samples were drilled to a depth of 30 mm and diameter of 3 mm each for proper insertion of the needle sensors. To eliminate the air gaps effects which act as thermal insulator from the interface area so as to maximize heat transfer between the thermal probe and gravel samples, thermal grease was used (Plate I). The SH-1 sensor was used in measuring the thermal effusivity and volumetric specific heat by inserting the sensor into the drilled hole of the samples and the end connected to the KD2 Thermal Pro and switched on. On display of the main menu by the KD2 Thermal Pro, the enter key was pressed to begin the process of measurement. Readings were then displayed and recorded (Plate 2). The instrument was then allowed to rest for a time duration of ten minutes before the next set of measurement was taken as recommended by the manufacturer (Decagon Devices Inc., 2011).However, the thermal diffusivity was calculated as the thermal conductivity (λ) of the material divided by the product of density and specific heat capacity (ρC) as given in Equation 3 (Michael and Oluseun, 2012).

$$\text{Thermal diffusivity} = \frac{\lambda}{\rho C} \tag{3}$$

Plate I: Filling the gravels drilled holes with thermal grease

Plate 2: Taking readings with KD2 thermal analyser

3. RESULTS AND DISCUSSION

3.1. Density

The thermal conductivity and heat capacity of rock tend to be independent of their density because rocks contain various mineral compositions (each mineral show difference in thermal properties). (Decho, 2008).

Rocks behave differently as compared to homogeneous materials, such as steels, ceramic and aluminums (Decho, 2008). For these homogeneous materials, the density has a relation with thermal conductivity and heat capacity. From Figure 2, it can be clearly seen that Ojano gravels exhibit the highest density value of 3370 kg/m^3 while Ugba the least value of 2160 kg/m^3. In energy storage applications, density relates the energy store to the volume of the storage facility. Hence, Ojano gravels will be most suitable for minimizing the heat storage volume at a reduced cost (Sarada et *al.,* 2013). Ojano will be most suitable for heat storage application considering density as a criterion. The discrepancy between Okete, Awulema, Ikowe gravels and Ojano is in the range of 500 kg/m^3 whereas that for Ushongo, Ikyuen and Ugba is more than 500 kg/m^3.

3.2. Specific Heat Capacity

The specific heat capacity of the samples of the samples ranged from 893.25 to 1322.93 J/kgK with a mean value of 1134 J/kgK. Substances with a high specific heat capacity absorb more energy before they change in temperature and hence could store much energy than substances with low specific heat capacity (Oyekan and Kamiyo, 2011). Figure 3 shows that Awulema gravels exhibited the highest specific heat capacity value of 1322.93 J/kgK and Ikowe had the least of 893.25 J/kgK. It means Awulema gravels which shows maximum value of specific heat has advantage for use as heat storage medium in comparison with other gravels under study. It means Awulema gravels can absorb and store more heat. However, there is not much variation in the specific heat capacity of the gravels in the study except for Ikyuen and Ikowe which have lower values. These values are similar to the ones reported in literature for volcanic gravels by Decho (2008).

3.3. Thermal Effusivity (Thermal Admittance)

Thermal effusivity which is sometimes called the heat penetration coefficient is the rate at which a material or substance can absorb heat. Figure 4 shows the variation of the thermal effusivities for each of the gravels samples. Thermal effusivity of the gravels in the study ranged from 2880.13 to 4213.06 W/m^{2}K with a mean value of 3489.72 W/m^{2}K. The effusivity of materials varies due to their differing ability to transfer heat. This is due to differences in heat transfer through and between particles, and could be a function of particle size, particle shape, density and moisture content (Michael and Oluseun, 2012). A material with high thermal effusivity cannot retain heat long enough because heat will quickly dissipate from its surface as soon as surrounding temperature drops while on the other hand, materials with low thermal effusivity will retain heat much longer (Diago et *al.,* 2015). Therefore, it can be said that gravels in the study such as Ikyuen, Ushongo, Ikowe and Ugba with low thermal effusivity will retain heat much longer while gravels found at Awulema and Okete will not retain heat for a long time following the conclusion of Diago et *al.* (2015).

3.4. Thermal Diffusivity

Materials with large thermal diffusivity will respond quickly to their their environment because they they conduct heat quickly and generally do not require much energy from their surroundings to reach thermal equilibrium (Evaldo *et al.,* 2012). The thermal diffusivity of the gravels ranged from 1.9288×10^{-7} to 1.0484×10^{-7} m^2/s with an average of 1.3649×10^{-7} m^2/s. Generally, high thermal diffusivity values implies faster heat transfer rate rate whereas low values results in low heat transfers. From Figure 5, it can be seen that Ikyuen gravels with thermal diffusivity value of $1.9288 \times 10^{-7}\ m^2/s$ will transfer thermal heat more rapidly than Ugba, Ikowa, Ushongo, Okete and Awulema while Ojano gravels with the least thermal diffusivity of $1.0484 \times 10^{-7}\ m^2/s$ will turn to release thermal heat at a slower rate (Sarada et *al.,* 2013). will tend to respond more than Ugba, Ikowe, Ushongo and Awulema. Whereas the response of Ojano and Okete gravels to thermal diffusivity is the least in the group. Low coefficient of permeability could be responsible for the differences in heat dispersion in the gravels according to Decho, (2008). Coefficient of permeability could be responsible for the differences in the heat dispersion in the gravels according to Decho, (2008).

3.5. Thermal Conductivity

The thermal conductivity of the gravels in the study ranged from 3.25 to 4.5 W/mK with an average of 3.92 W/mK.Ugba, Ikowe and Ushongo gravels had had thermal conductivity values less than 4.0 W/mK while Ikyuen, Awulema, Ojano and Okete gravels had had thermal conductivity ranging between 4.0 and 4.5 W/mK. The relatively low thermal conductivity values exhibited by some of the investigated gravels as against the investigated optimum value of 4.5 W/mK could be attributed to low porosity of the gravels (Diago et *al.,* 2015). This property of rocks affects the thermal conductivity of rocks (i.e., thermal conductivity tends to increase as the porosity increases but indifferent to density). The low conductivity of this category of gravels could be attributed to the presence of void spaces with either air or water (Decho, 2008).

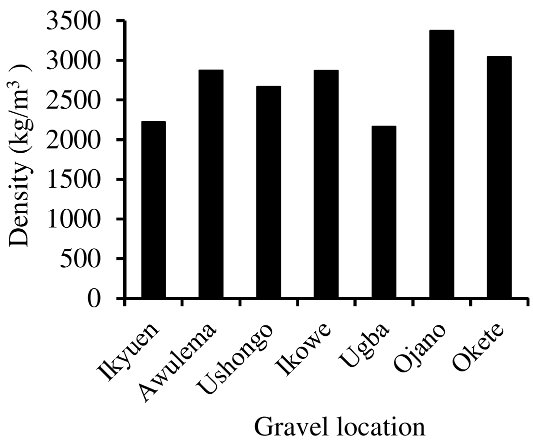

Figure 2: Variation of density

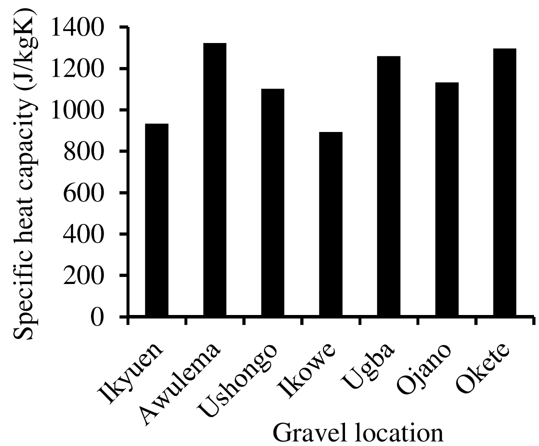

Figure 3: Variation of specific heat capacity of the gravels

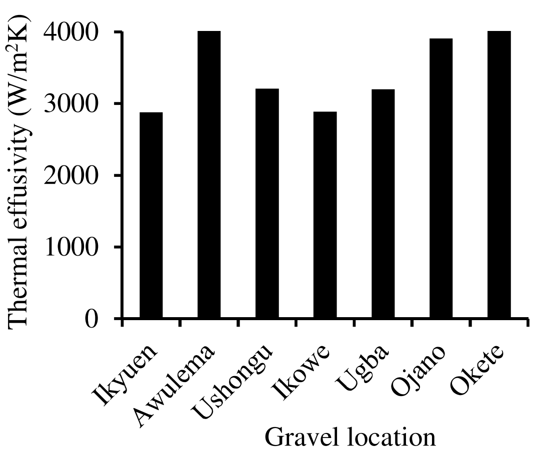

Figure 4: Variation of thermal effusivity

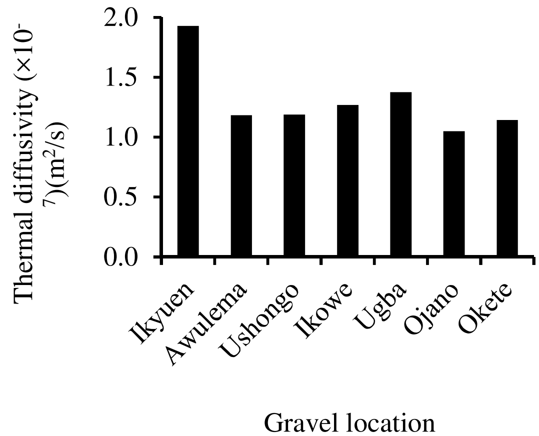

Figure 5: Variation of thermal diffusivity

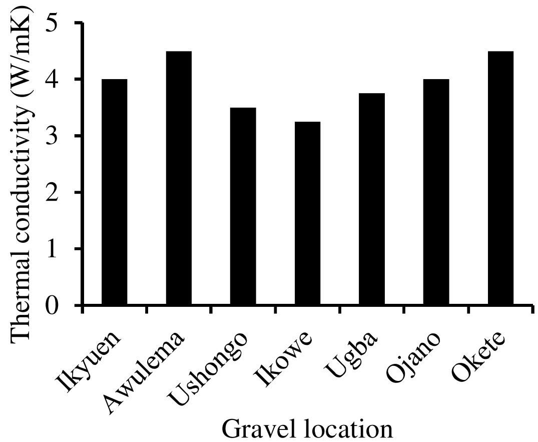

Figure 6: Variation of thermal conductivity

4. CONCLUSION

It has been observed that the thermal properties of the gravels in the study agreed with results reported in the literature with Awulema gravel exhibiting a better heat absorbing capability for seasonal heat storage. For applications where rapid discharging of absorbed solar thermal heat is needed, gravels situated at Ikyuen are preferred to those found at Ugba, Ikowa, Ushongo, Okete and Awulema due to higher thermal diffusivity. However, gravels situated at Ojano are good candidates where stored heat is to be release gradually. On the basis of solar thermal heat absorption capability, gravels situated at Awulema are better and preferred to the other gravels in the study as a result of their optimum value of specific heat capacity.

5. ACKNOWLEDGEMENT

The authors wish to acknowledge the assistance and contributions of staff of the Department of Physics, Federal University of Agriculture, Abeokuta, Nigeria where the tests were carried out.

6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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