UTILISATION OF GROUND THERMAL STORAGE CAPACITY FOR SUSTAINABLE BUILDING HEATING AND ENVIRONMENTAL IMPACT REDUCTION

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ABSTRACT
Space heating in northern countries accounts for a large share of total energy consumption and a significant portion of this heat is still produced by burning fossil fuels in individual heating systems or in district heating cogeneration plants. Therefore, greater attention is being paid to solutions that enable more efficient energy use and allow renewable heat produced in one season to be utilised in another. Seasonal ground thermal energy storage is one approach that can help balance the mismatch between heat production and demand while reducing environmental impacts associated with conventional heating. This study investigates the possibility of generating heat with solar collectors during the warm season and storing it in an underground seasonal thermal energy storage system for later use in building heating. The simulated and analysed case was a high-energy-efficiency single-family residential building representing a typical detached house. The building's annual space–heating demand was estimated using climatic data representative of Lithuanian conditions. An underground thermal energy storage volume beneath the building was considered for seasonal heat storage. To store sufficient thermal energy, the average soil temperature during the charging period was increased to approximately 40–45°C. Because large temperature gradients can occur near the heat exchangers' pipes, soil heat distribution is an important factor affecting storage performance. Laboratory experiments were conducted to examine whether heat dissipation in the soil could be improved using natural materials. Stones were added to the gravelly sand backfill at a concentration of 10–15% by mass. The results showed that this modification improved heat dissipation compared with gravelly sand alone, leading to a more uniform temperature distribution and more effective charging of the seasonal heat storage volume.
Keywords: seasonal energy storage, heat, building heating, soil thermal conductivity, dissipation.

1 INTRODUCTION

The temperature and humidity of indoor air in buildings are among the most important factors determining thermal comfort. The temperature inside a building must be maintained at a level acceptable to humans, usually within the range of 18–24°C, regardless of the weather outside. In countries with a northern climate, buildings need to be heated in winter when outdoor temperatures are low. In summer, when it is hot outside, buildings need to be cooled. During transitional periods, the demand for heating or cooling may be lower, and during certain short periods, it may not be needed at all. However, in general, a large share of energy in the building sector is consumed to maintain indoor air temperature. This makes it important to seek solutions that enable more efficient energy use and thus reduce dependence on fossil fuels [1].

The temperature of atmospheric air varies both during the day and with the season. In northern-region countries, intense solar radiation reaches the Earth's surface in summer, heat availability is high, and atmospheric temperatures are sufficiently high that building heating is not required. In winter, the situation is the opposite: demand for heat is high while solar energy availability is low. Thus, a clear mismatch arises between heat generation and heat demand over time [2]–[5]. One possible solution to this problem is seasonal heat storage, in which heat accumulated during the summer is retained and used during the cold season [2].

WIT Transactions on Ecology and the Environment, Vol 267

www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/EID260191

Our research focuses on a method of heat storage in which heat produced in an environmentally friendly way, namely by solar collectors, is stored in a thermal storage unit installed beneath a building [6]–[8]. Such a storage unit may be a specially formed chamber filled with natural granular materials, such as sand, sandy loam, gravel, or other soil-based fill materials, or, in some cases, an existing underground space, such as a basement, may be adapted. This solution is attractive because it allows the use of simple, natural and relatively inexpensive materials, while the system itself can operate without complex equipment such as a heat pump [6], [9]. Therefore, it is of interest not only from an energy perspective but also from economic and environmental perspectives [3], [6], [10].

However, previous studies show that one of the most important problems in such systems is the relatively slow heat propagation through the volume of the fill material [4], [7]–[9]. If the storage unit is filled with water, heat is distributed quite quickly because both thermal conduction and convection occur [5]. Meanwhile, in soil, sand, or another granular solid-phase material, heat is transferred mainly by conduction, and therefore the temperature distribution throughout the volume develops much more slowly [7]–[9], [11]. This means that simply accumulating heat is not enough; conditions must also be created to distribute heat as uniformly as possible throughout the storage medium [4], [8], [9]. Otherwise, part of the storage unit remains underutilized, and local overheating zones may form near the heat exchanger loop [8], [9].

For this reason, one of the most important research directions is increasing the thermal conductivity of the fill material [8]–[14]. This is important not only for the charging process itself, but also for discharging, when the accumulated heat must be returned to the building heating system [6], [8], [9]. The higher the thermal conductivity, the more uniformly the entire volume of the fill can be utilized, the more efficiently the heat exchange loop operates, and the smaller the required heat exchanger surface area may be [8]–[11]. In this way, the consumption of materials required for the heat exchange loop can be reduced, especially when metals with high thermal conductivity are used. On the other hand, when it comes to the fill material of the storage unit, not only are the properties of the material itself important, but also its moisture content, density, porosity, particle size distribution, and contact with the heat exchange elements [10]–[14]. A certain amount of moisture can improve heat transfer, but at the same time, the long-term stability of the system must also be assessed [8], [11], [13], [14].

The performance of a storage unit intended for seasonal heat storage is determined not only by the fill material but also by the chamber design and process management [2], [5], [10], [15]. Considerable heat losses may occur during long storage periods, so effective thermal insulation from the surroundings is necessary [2], [5], [15]. Installing the storage unit underground is advantageous in this respect because the influence of daily temperature fluctuations decreases with increasing depth, and the surrounding soil can also serve as an additional buffer medium [5], [9], [15]. However, long-term warming of the surrounding soil must also be evaluated, especially when the storage unit is installed close to building structures [6], [7], [10]. Therefore, in such systems, not only is energy efficiency important, but also control of the possible thermal impact on the surrounding soil and structures [15].

The heat storage system includes three main processes: charging, storage, and discharging [4], [6], [15]. During charging, the heat generated by solar collectors is transferred to the fill material through a circulation loop [6], [9]. During storage, the main task is to retain the accumulated energy for as long as possible while reducing heat losses to the surroundings [3], [5], [15]. During discharging, the heat is returned to the building heating system via an intermediate heat exchanger or a small-volume water tank, if necessary, to stabilize operating conditions. It is important that this concept is based on a system without a heat pump, which

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reduces equipment complexity, electricity consumption and operational dependence on additional technological units [7], [9].

From an environmental perspective, such a solution can be significant [1], [3]. If a gas boiler heats a building, the heat is generated by the direct combustion of a fossil fuel, which results in carbon dioxide emissions [10]. Meanwhile, storing the heat generated by solar collectors and later using it for building heating (Fig. 1) makes it possible to cover at least part of this demand without direct combustion of fuel [7], [8]. This means lower greenhouse gas emissions and lower dependence on fossil energy resources [1], [10]. An additional advantage is that natural materials such as sand, sandy loam, gravel, or clay are used [6]–[10] and installing solar collectors on a building's roof uses the existing building surface without requiring additional land and without creating additional shading of the ground surface. The urban aspect is also important. If a thermal storage unit is installed under a building, no additional land area is required. In this way, the space already occupied in the city is used, and the energy infrastructure can be expanded without encouraging horizontal urban expansion [10], [15].

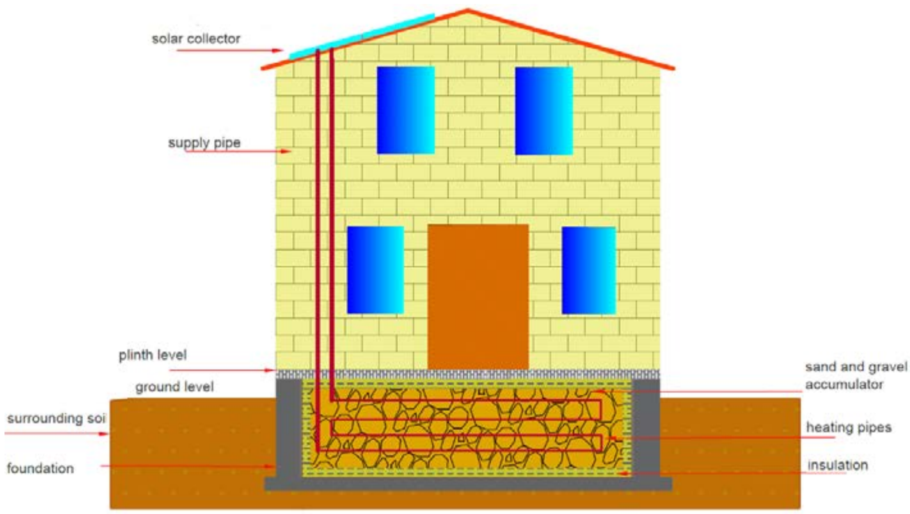

Figure 1: Heat storage system constructed below the building.

Thus, the scientific and practical problem is clearly defined: how to increase the effective thermal conductivity of the thermal storage fill material by natural means to achieve a more uniform heat distribution in the storage unit and more efficient operation of the heat exchange loop [6]–[14]. Such natural granular materials are attractive as low-cost, environmentally friendly storage media [6]–[9]. Therefore, this study focuses on the application of natural fill materials in thermal storage units installed under buildings, analysing their thermal properties, heat transfer characteristics, and the potential to improve system performance by increasing effective thermal conductivity [9]–[14]. At the same time, the benefits of such a solution from energy and environmental perspectives are assessed [1], [3], [10].

2 EXPERIMENTAL SETUP AND METHODOLOGY

The aim of the experimental study was to evaluate heat propagation in a loose ground-based filling material and to assess how changes in the filling composition influence temperature

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distribution, thermal charge propagation and heat storage behaviour. The study was carried out using a laboratory-scale test rig designed to simulate a ground thermal accumulator, in which heat was supplied to the filling material via a heated surface installed at the base. This configuration was selected because electric heating provides a more stable, uniform heat supply, enabling more reliable comparisons of filling materials with varying compositions.

The charging process was investigated under constant thermal power supplied by the heated surface, while temperature variations over time were recorded at different points of the filling material. This enabled us to directly observe heat propagation within the volume and to compare the thermal responses of different filling structures.

The laboratory test rig consisted of a 0.5×0.5×0.6 m container with thermally insulated walls and base (Fig. 2). A heating system was installed at the bottom: two 1 mm thick aluminium sheets were placed on a 24 mm thick plywood board, with a 3.2 m long heating element of 8.5 mm diameter arranged between them in a serpentine configuration. This setup provided a heated surface that ensured a uniform heat transfer into the filling material. The heating element was connected to the power supply via a transformer. The electrical current and voltage were measured at the heating element terminals, allowing heating power to be calculated. During each experiment, the heating power was kept constant. The walls and bottom of the apparatus were insulated with 5 cm thick EPS70 polystyrene. Pt1000 sensors were used to measure temperature, and the data were recorded with a PT104 data logger.

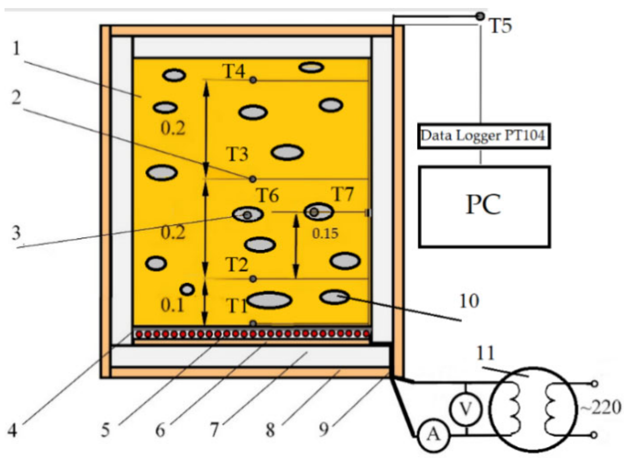

Figure 2: Scheme of laboratory experimental setup. 1–fine-fraction gravel filling, 2–temperature sensor (T1÷T5), 3–sensor installed into the stone (T6, T7), 4–heated plane surface, 5–heating tubes, 6–plane board, 7–thermal insulation, 8–housing of the setup, 9–connections of the heating cable, 10–stone, 11–transformer.

Temperature sensors were installed at four heights measured from the bottom of the box: 0, 10, 30, and 50 cm. Ambient air temperature was also recorded. This arrangement enabled monitoring of temperature changes near the heated surface and in the upper layers, as well as assessment of vertical heat propagation. In the rig with stone inclusions, additional sensors were installed inside the stones, making it possible to compare both the overall thermal response of the filling material and the local interaction between the stones and the fine fraction. Accordingly, sensors T1–T4 were used in the first case, while T6 and T7 were additionally installed in the stones in the second case.

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In the first experiment, the container was filled with dry, homogeneous fine-fraction gravel. The material was placed uniformly in layers to avoid disturbing sensor positions and to minimize the formation of larger air voids. Filling was carried out stepwise until the container was fully filled, ensuring a uniform particle distribution and improved repeatability.

According to the particle size distribution presented in the appendix, the material can be classified as a 0/4 fraction gravel. Granulometric analysis indicated that about 94.2% of the material passed through the 4 mm sieve, 77.4% through 2 mm, 61.3% through 1 mm, 33.6% through 0.5 mm, 17.8% through 0.25 mm, 4.0% through 0.125 mm, and approximately 1.0% through 0.063 mm. The bulk density of the loose filling was approximately 1607 kg/m³. The particle size distribution and loose structure directly influence porosity, the number of particle contacts, and consequently the effective thermal conductivity and heat capacity.

In the second experiment, the same test rig and procedure were used, with the filling composition as the only variable. The same fine-fraction gravel was supplemented with field stones with an average equivalent diameter of 8.5 cm. The filling was formed in layers: stones were placed on a layer of fine gravel so that they did not touch each other, the gaps were filled with gravel, and a new fine-fraction layer was then added above. This approach resulted in a heterogeneous filling material with coarse inclusions while maintaining identical geometrical and thermal boundary conditions to those in the first experiment.

During the experiments, the heating element operated until the sensor at the heated surface reached the predetermined limiting temperature. Heating was discontinuous, and heat propagation in the filling material continued to be recorded. This enabled analysis of both thermal charge accumulation and heat dissipation after heating. As identical experimental conditions, sensor configurations and procedures were maintained, the results can be directly compared, with observed differences attributed solely to variations in filling composition.

The comparative analysis focused on the rate of temperature increase, maximum temperatures at different heights, the time required to reach these values, and the subsequent cooling behaviour. The first experiment represents a homogeneous fine-fraction filling, whereas the second represents a heterogeneous filling in which heat propagation is influenced by stone inclusions with higher thermal inertia. This two-stage experimental design allows evaluation of how stone incorporation changes heat storage and transfer conditions and provides a basis for assessing the influence of filling composition on thermal energy storage properties.

3 RESULTS AND DISCUSSION

The experimental comparison between the homogeneous fine-fraction gravel filling and the heterogeneous gravel-stone filling showed that the addition of natural stones improved heat propagation within the storage volume. Since both experiments were carried out under the same heating power, using the same tank geometry, the same sensor positions, and the same operating sequence, the observed differences can be attributed mainly to the change in filling composition. The modified filling produced a faster temperature response at greater distances from the heated surface and promoted a more uniform temperature field during charging.

The temperature increase at the heating surface is shown in Fig. 3. In both experiments, the temperature increased rapidly after the beginning of heating and, after the power supply was switched off at 100°C, continued to rise slightly due to thermal inertia (Fig. 3). The difference between the two cases at the heated surface remained relatively small. At the 0.3 m level, the stone-modified filling showed an earlier and stronger thermal response (Fig. 4). In the reference case, the temperature rise at 0.3 m was slower, whereas in the modified case it started earlier and reached higher values during the 10 h experiment. According to the experimental data, the temperature of 23°C at 0.3 m was reached about 4287 s earlier, and

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24°C about 6416 s earlier, when stones were added to the filling. This corresponds to a reduction in response time of approximately 16–18% for the selected temperature levels. The results show a clear and practically relevant improvement in heat dissipation within the middle part of the storage volume (Fig. 4).

Figure 3: Temperature evolution at the heated surface in the soil for the reference (h = 0) and stone-modified (h_{st} = 0) cases.

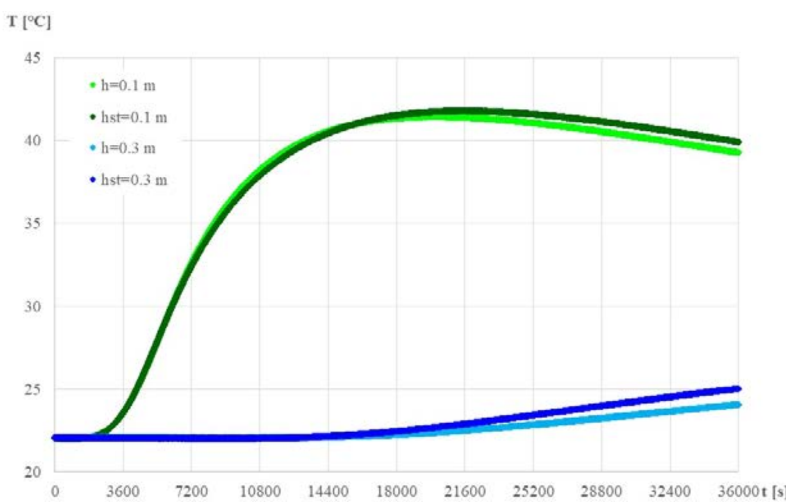

Figure 4: Temperature evolution in the filling at heights 0.1 and 0.3 m for the reference (h) and stone-modified (h_{st}) cases.

Additional information is provided by the temperatures measured inside the stones (Fig. 5). The temperature measured inside the stones was higher than that measured in the

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surrounding fine filling at a similar level (Fig. 5). By the end of the experiment, the temperature inside the stones reached about 28.0°C, while the temperature of the surrounding filling at 0.3 m was about 25.0°C. This indicates that the stones accumulated heat more intensively and acted as local conductive inclusions, assisting heat transfer from the heated bottom toward the upper part of the storage (Fig. 5).

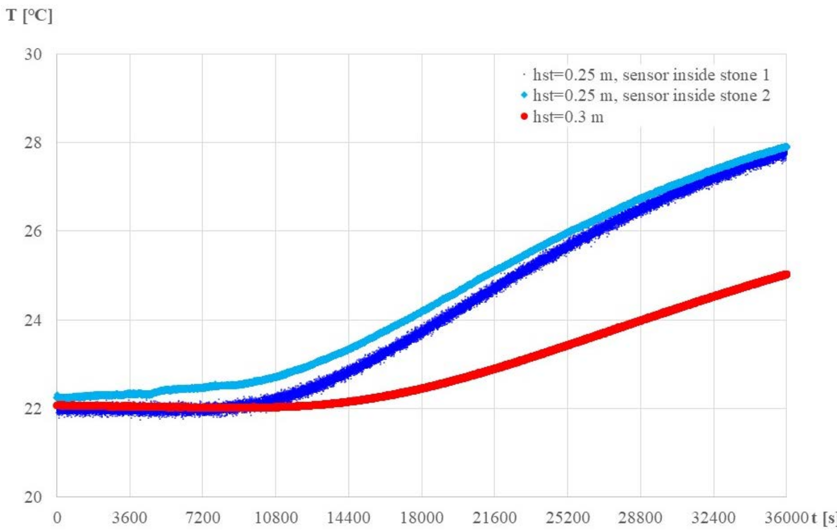

Figure 5: Temperature measured inside the stones at h_{st} = 0.25 m.

From the physical point of view, this behaviour should be interpreted mainly as an improvement in apparent effective heat dissipation rather than as a major change in heat capacity. The practical benefit is that a larger part of the storage volume becomes thermally active during charging. This leads to a more uniform temperature field, reduces local overheating near the heating zone, and improves the utilisation of the storage mass.

From an environmental point of view, this result is relevant because more effective seasonal thermal storage can increase the use of solar heat generated in the warm season for later building heating. This supports lower fossil fuel consumption, reduced greenhouse gas emissions, and more rational use of natural materials in building energy systems.

4 CONCLUSIONS

The addition of natural stones improved heat propagation within the storage volume and produced a faster thermal response, especially at 0.3 m above the experimental heating surface.

Under the present experimental conditions, the improvement is better described as increased apparent effective heat dissipation than as a twofold increase in thermal conductivity. At 0.3 m, selected temperature levels were reached approximately 16–18% earlier in the stone-modified filling.

The use of natural stone inclusions improved the practical utilisation of the storage volume and may contribute to lower environmental impact by supporting more efficient use of seasonal solar heat and reducing dependence on fossil-fuel-based building heating.

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