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Research Article

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Thermal Energy Storage in Concrete for Domestic Heating

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Abstract The concrete composition influences significantly the total heat storage capacity of the systems using concrete as storage medium. In this work, we investigated the properties of concrete composition based on local materials in Syria in order to determine a suitable concrete composition for thermal energy storage. Eight concrete samples with various compositions were tested regarding their specific heat, density and volumetric storage capacity. The results showed that the optimum mixing ratio of concrete was 0.5 (water): 1(cement): 1.7 (sand): 3.9 (limestone). The volumetric heat capacity of this mixture was 2.2 J/cm^3.K. A heat storage unit has been manufactured using the above mentioned concrete mixture. The Charging and discharging behavior of this unit have been experimentally studied. The increase of the concrete temperature during the charging process slows down with increased temperature difference between the concrete and the ambient, whereas during the discharging process the concrete temperature decrease slows down with decreased temperature difference between the concrete and the ambient. Thus, the overall temperature working range of the unit shouldn't be more than 10 to 15 °C above the ambient temperature.

Keywords Thermal energy storage, Concrete

1. Introduction

The global energy consumption increases continuously, whereas the fossil resources are limited and their use has very negative impacts on the environment such as pollution and green house effect. On the other hand, solar energy is abundant, renewable and environment friendly, however its exploitation for room heating requires an effective storage material to store the solar induced heat during the sun shine hours within the day for the use later when the sun doesn't shine especially in the evening. Concrete, which is an essential building component, could be the material of choice because of its matching properties regarding this task such as high heat capacity, cheapness and availability.

Thermal energy storage in concrete is usually based on sensible heat transfer and thermal inertia [1, 2].

The relationship between the specific heat and the storage energy of concrete was studied by J. Pan et. al. [3]. They found that the specific heat increases when the storage temperature increases. This increase is linear in the range 300 to 600 °C.

S. Ünalan et. al. investigated the thermal stress distribution of a concrete column used as a sensible thermal energy storage medium and a heater [4]. The results of the calculations for sample flat showed that if a suitable concrete type is chosen in the construction stage according to the extra thermal load, the concrete columns can be used as a heater safety.

K. C. Gunasingh et. al. studied the impact of paraffin as Phase Change Material (PCM) on M20 grade concrete cubes [5]. They found that adding 1 weight percentage of paraffin to concrete improves the thermal energy storage within the concrete block significantly.

A two-step procedure to produce thermal energy storage concrete (TESC) is described by D. Zhang [6]. At the first step, thermal energy storage aggregates (TESAs) were made from porous aggregates absorbing phase changing materials (PCMs). At the second step, TESC was produced with a normal mixing method and using TESAs. An adequate amount of PCM can be incorporated into concrete by the two-step procedure. The thermal energy which can be stored using this method is markedly enhanced in comparison to normal concrete without PCM.

E. John et. al. developed economical concrete mixtures that resisted temperatures up to 600 °C [7]. Such mixtures are suitable to store solar thermal energy in concentrating solar power plants.

A new type of thermal energy storage concrete with high thermal conductivity is developed by P. G. Bergan [8]. The main component of the mixture is quartzite. This type of concrete is suitable for a wide range of applications between 100 and 550 °C.

H. Cui et. al. prepared structural-functional integrated cement-based materials by employing cement paste and a microencapsulated phase change material (MPCM) manufactured using urea-formaldehyde resin as the shell and paraffin as the core material [9]. The total energy storage capacity of the hardened cement specimens with MPCM increased by up to 3.9-times compared with that of the control cement paste. However, the compressive strength decreased with the increase in MPCM content linearly.

In this paper we investigated the properties of concrete composition based on local materials in Syria in order to determine a suitable concrete composition for thermal energy storage. Eight samples of concrete with different compositions were manufactured and tested to determine their specific heat, density and the volumetric heat capacity. In a second step, a heat energy storage unit has been manufactured using the composition with the largest heat storage capacity. The charging and discharging behavior of the unit have been experimentally studied.

2. Experimental Procedure

2.1 Characterization of the concrete samples

Eight concrete samples with different mixture are manufactured [6, 10]. The diameter of the cylindrical samples is 6.2 cm, whereas their axial length is 8.2 cm. The samples are undergone a wetting cure for 28 days. Table 1 shows the composition of the samples.

After the wetting cure the samples were dried for three days in room temperature and then they were weighted in order to determine the density of each one. The specific heat of the above mentioned mixtures is not given in the literature, therefore it is determined in this work using the conventional calorimetry method. The method was slightly modified as it will be seen in the following.

Table 1: Composition of the tested samples

Sample	Water	Sand	Limestone	Cement
S1	48	164.16	374.4	96
S2	95.47	261.63	171.36	153
S3	80.784	225.72	242.88	132
S4	74.24	218.88	261.12	128
S5	67	229.14	251.92	134
S6	64	218.88	270.08	128
S7	63.5	217.17	278.13	127
S8	57	179.55	334.02	114

An amount of water of the mass m1 is put in a well thermally isolated pot. Two temperature sensors T1 and T2 were mounted on the wall of the pot. The sensors are connected to a temperature data logger from Type Extech. The average value T_{ave} of T1 and T2 represents the water temperature. A third sensor T3 is connected to the logger. T3 measures the ambient temperature. The water in the pot is heated electrically until T_{ave} reaches 80 °C. The pot is then opened and the concrete sample, with the mass m2 and the initial temperature $T_{ini,con}$, is put in the water inside the pot. The pot is then tightly and quickly closed.

Thermal energy is transferred from water to the concrete sample inside the pot (ΔQ_1) and to the air outside the pot (ΔQ_2). The transfer rate towards the concrete sample is high because of the direct contact between water and the sample, whereas the transfer rate from water to the air is very low because of the thermal isolation.

Fig. 1 shows T_{ave} between 65 and 80 °C for the sample S_5. The decrease in the temperature is sharp at the beginning of the experiment (part ①) because the water loses thermal energy towards the concrete sample and the ambient air. In part ② the thermal balance is achieved between the sample and the water, therefore energy transfer occurs only towards the ambient air.

Fig. 2 shows the amount of decrease in the average water temperature ΔT_{ave} every 30 seconds during the measuring period. The decrease is approximately constant in part ② and equals 0.07 °C every 30 seconds. The decrease is maximum at the beginning of part ①, where it equals 1.6 °C every 30 seconds. This value becomes continuously smaller until it reaches the constant value of 0.07 °C when the thermal balance between the water and the concrete sample is reached.

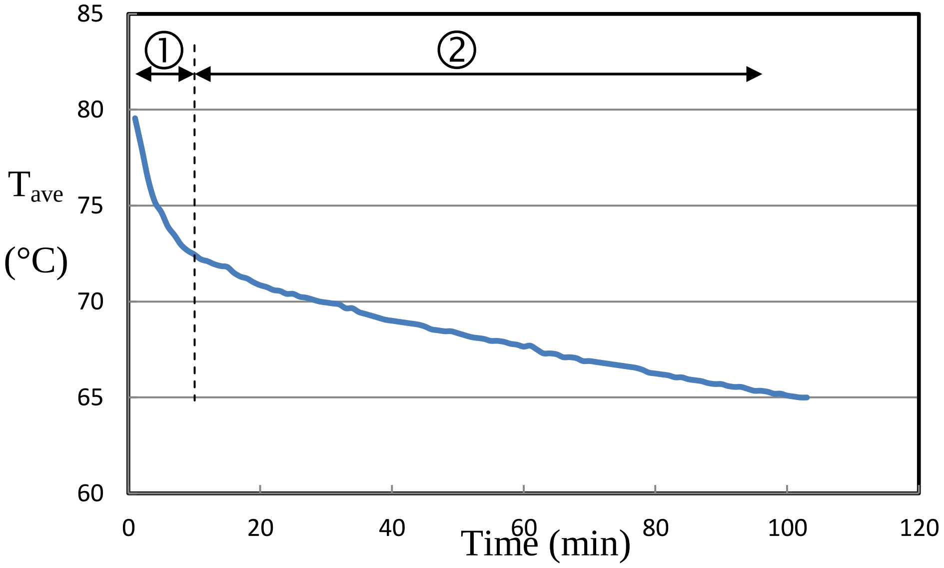

Figure 1: Average water temperature (T_{ave}) for the sample S_5

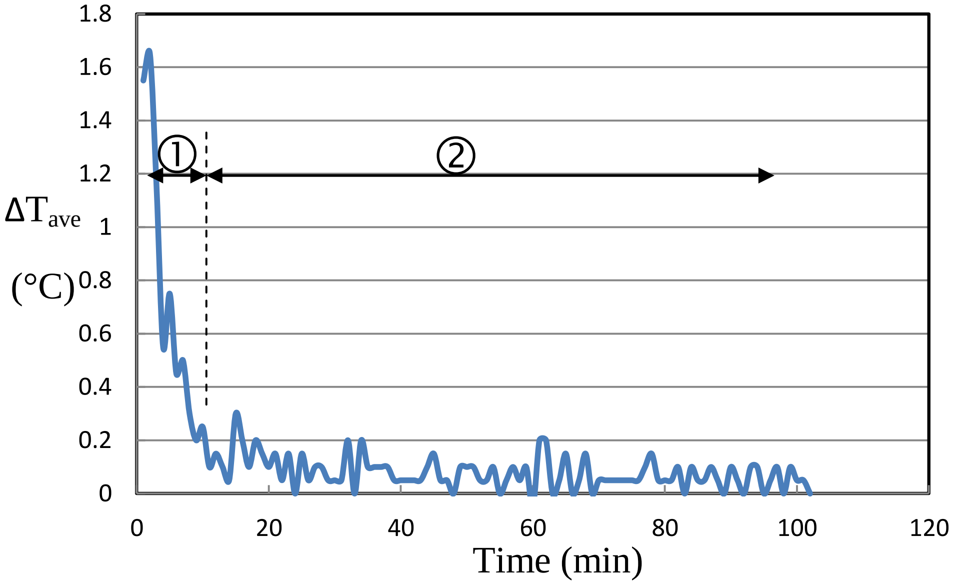

Figure 2: The amount of decrease in the average water temperature ΔTave every 30 seconds during the measuring period

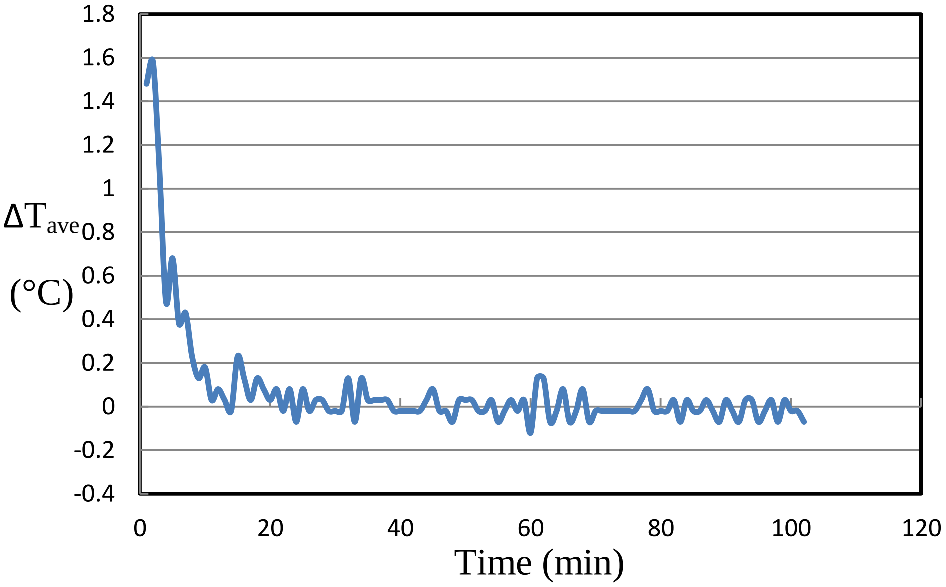

Figure 3: The amount of decrease in the average water temperature ΔT_{ave} every 30 seconds because of the heat exchange with the concrete sample

If we subtract the value 0.07 °C from the values presented in Fig. 2, then we obtain the amount of decrease in the average water temperature caused purely by the energy transfer from the water to the concrete sample (Fig. 3). The integration of ΔT_{ave} in fig. 3 results in the total water temperature decrease ΔT_{total} caused only by the energy transfer to the concrete sample.

$$\Delta T_{total} = \int_{0}^{t} \Delta T_{ave}.dt \tag{1}$$

The total thermal energy, which is transferred from the water to the concrete sample can be calculated using the following formula:

$$\Delta Q_1 = c_1.m_1.\Delta T_{total} \tag{2}$$

Where c1 represents the heat capacity of water. The temperature of the concrete sample when the thermal equilibrium is reached is:

$$T_{end,con} = 80°C - \Delta T_{total} \tag{3}$$

So the specific heat capacity c_2 of the concrete sample can be calculated:

$$c_2 = \frac{\Delta Q_1}{m_2.(T_{end,con} - T_{ini,con})} \tag{4}$$

Table 2 shows the determined values of the specific heat capacity of the eight concrete samples. Sample S1 has the highest specific heat capacity and therefore the mixture of this sample will be used to manufacture a thermal energy storage unit as described in the next section. For comparison the specific heat capacity given in the literature varies between 912 J/g.K for high strength concrete and 969 J/g.K for low strength concrete [11].

Table 2: Values of the density, specific heat and volumetric specific heat of the concrete samples

Sample	Density (g/cm^3)	Specific heat (J/g.K)	Volumetric specific heat ($J/cm^3.K$)
S1	2.18	1.01	2.2
S2	1.95	0.93	1.82
S3	2.02	0.9	1.81
S4	2.07	0.86	1.78
S5	2.11	0.96	2.03
S6	2.11	0.97	2.04
S7	2.15	0.9	1.92
S8	2.13	1	2.13

2.2 Charging and discharging behavior of the heat storage unit

The mixture of the sample S1 has been used to manufacture a thermal energy storage unit consisting of three modules. Each module is 100 cm long, whereas its width and height equal 10 cm. A water conducting tube, made of iron, is placed along the axis of the module (Fig. 4).

Figure 4: Schematic representation of the module

The modules are connected in series to each other using flexible well isolated plastic tubes (fig. 5). The inlet and outlet of the unit are connected to a water containing pot which can be heated electrically using a heating plate with nominal power of 1000 w. The amount of water inside the pot is 10 liter. A circulating pump circulates the water between the pot and the unit. Three temperature sensors are mounted on the inlet (T1), outlet (T3) and the middle of the unit (T2). The sensors are connected to a temperature data logger. A fourth sensor (T4) measures the ambient air temperature and is also connected to the data logger.

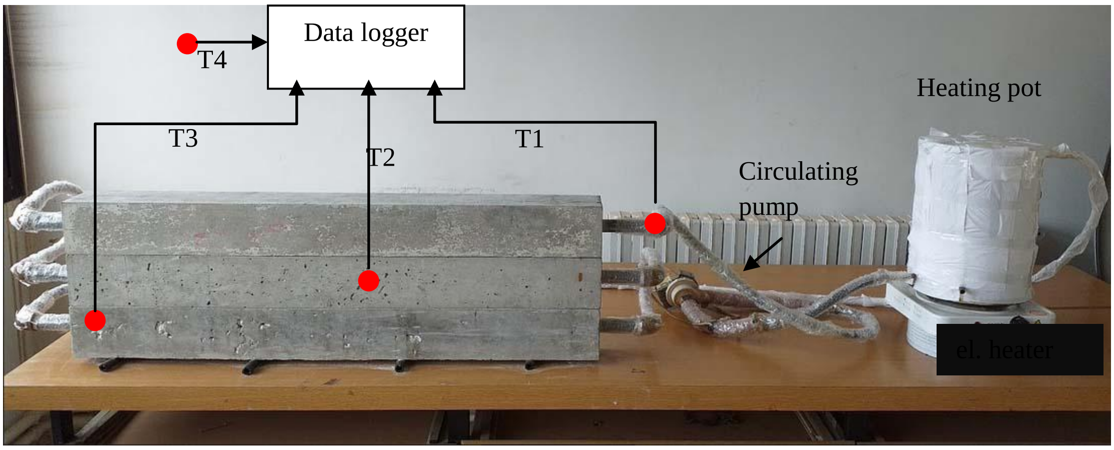

Figure 5: Setup for testing the heat storage unit

Several tests have been performed to study the influence of the circulating pump and the time of the heating on the charging and discharging behavior of the unit.

2.2.1 Circulating pump

Two tests have been done to investigate the influence of the circulating pump working time on the behavior of the storage unit. The first test was on 1 April 2019. In this test the heating plate has been turned on for 40 minutes, after that the circulating pump was turned on and the heating plate was turned off. The pump has been working for 26 minutes before it was turned off when the temperatures T1 and T3 have become equal. This equilibrium means that no energy transfer from the water to the concrete would occur after this point. The second test was done on 3 April 2019. In this experiment, the heating plate was turned on for 40 minutes, and then it was turned out. The circulating pump was turned on together with the plate, however it worked after the plate was turned out for 20 minutes until the temperatures T1 and T3 have become equal.

Fig. 6 shows the difference ΔT between the recorded temperatures T2 and T4. In the first test, ΔT remains equal zero for 40 minutes, because the pump was started 40 minutes after the heating plate. The temperature increase is sharp until the maximum is reached after 75 minutes of the test beginning.

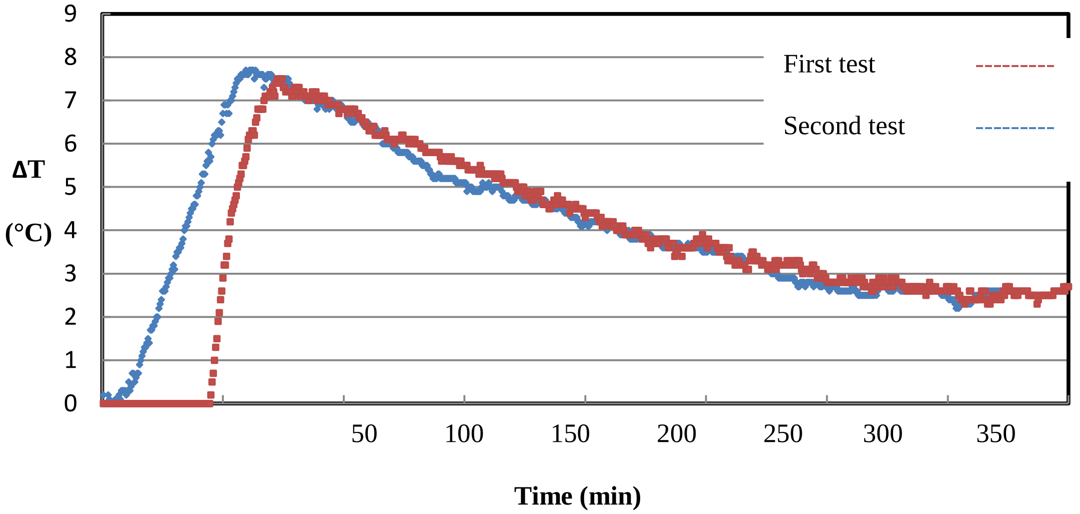

Figure 6: The difference between T2 and T4 during the first and second test

In the second test, the temperature difference increases continuously directly after the test beginning because the pump has been turned on together with the heating plate. In comparison, the charging in the second test begins much earlier than in the first test. Additionally, the achieved temperature maximum in the second test is higher than in the first test. Therefore, we conclude that the circulating pump should be turned on together with the heating plate.

2.2.2 Influence of the heating duration

The influence of the heating duration on the charging and discharging behavior has been investigated in four tests. The heating duration has been varied between 40 and 180 minutes. The circulating pump was turned on together with the heating plate and switched off when T1 equaled T3.

Fig. 7 shows the difference ΔT between the recorded temperatures T2 and T4 during the four performed tests. During the charging period, the curves are identical. They have also the same form during the discharging period, where they matched almost exactly if we perform a suitable shift of the curves with higher heating period from the right to the lift.

Table 3 shows the achieved maximum temperature difference ΔT_{max} and the required time for reaching this difference for each one of the four tests.

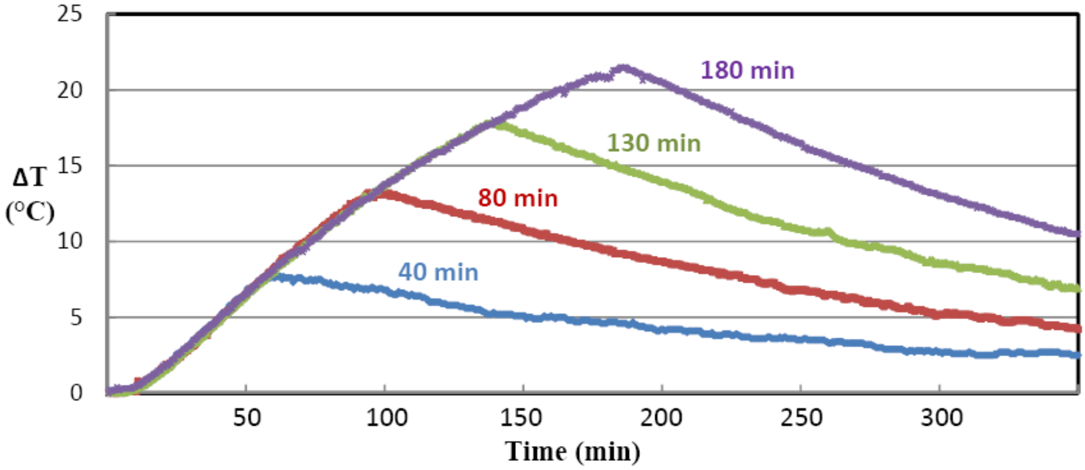

Figure 7: The difference between T2 and T4 during the four tests

Table 3: Influence of the heating time on ΔT_{max}

Heating time (min)	**Circulating pump working time (min)**	**ΔT_{max} (°C)**	**$t(\Delta T_{max})$ (min)**
40	60	7.7	60
80	92	13.2	94
130	132	17.8	135
180	180	21.5	185

Fig. 8 shows the increasing in ΔT every 10 minutes during the charging process for the test with 180 min heating time. The increasing in ΔT is maximal at the beginning of the charging process where the concrete temperature is close to the ambient air temperature. Continuously, the concrete temperature increases and the increasing in ΔT decreases which means that the charging efficiency is maximal at the beginning and decreases continuously.

Fig. 9 shows the decreasing in ΔT every 10 minutes during the discharging process for the test with 180 min heating time. The decreasing in ΔT is maximal at the beginning of the discharging process where the concrete temperature is high relative to the ambient air temperature. Continuously, the concrete temperature decreases and the decreasing in ΔT becomes slower.

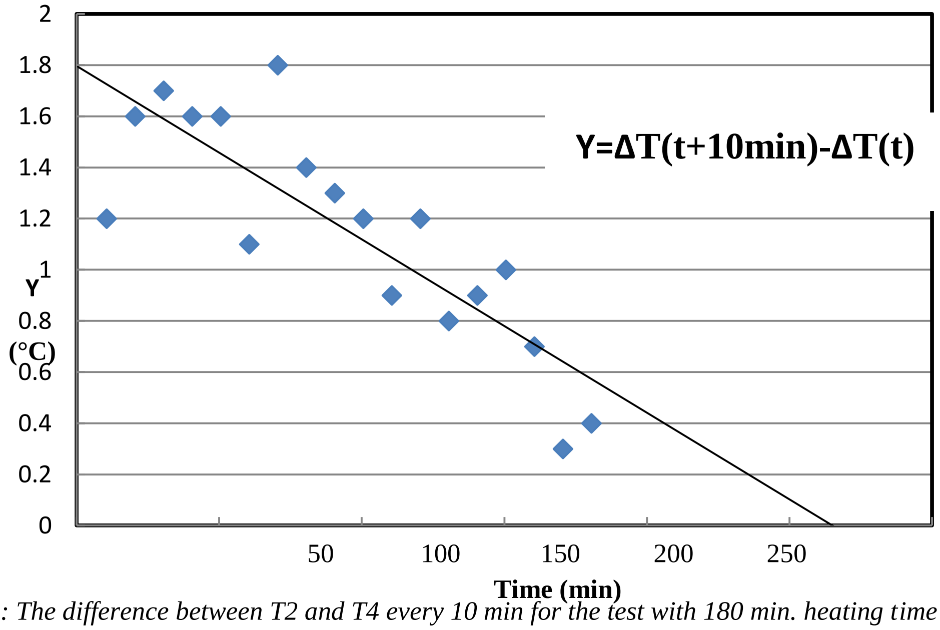

Figure 8: The difference between T2 and T4 every 10 min for the test with 180 min. heating time during the charging process

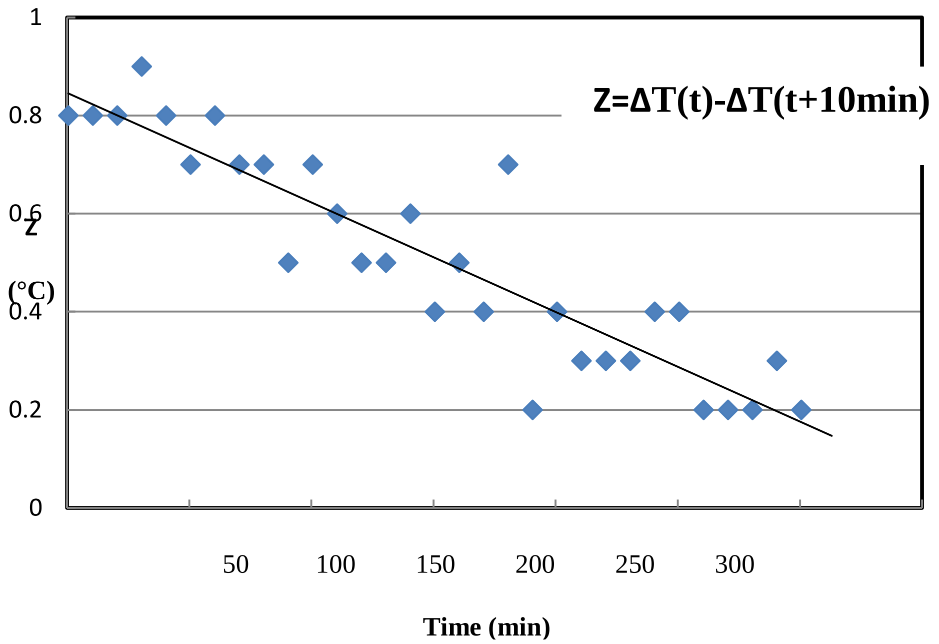

Figure 9: The difference between T2 and T4 every 10 min for the test with 180 min. heating time during the discharging process.

We conclude from Fig. 8 and Fig. 9 that the water temperature which is used to heat the concrete shouldn't be more than 10 to 15 °C above the ambient temperature. In this range, the charging rate is high, whereas the discharging rate is low. Additionally, the efficiency of the solar collectors, which should supply the storage unit with the heating water, is maximal at such low temperature ranges.

3. Conclusion

A concrete heat storage unit has been constructed and tested. The performance of the unit during the charging process is superior if the circulating pump is turned on together with the electrical heater rather than after the water has been heated. The increase of the concrete temperature during the charging process slows down with increased temperature difference between the concrete and the ambient, whereas during the discharging process the concrete temperature decrease slows down with decreased temperature difference between the concrete and the ambient. Thus, the overall temperature working range of the unit shouldn't be more than 10 to 15 °C above the ambient temperature.

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