THERMAL STORAGE CONCRETE

Hussein El-Sharkawy, Mohamed El Bably, Omar Ibrahim, Rafik Adel, Rafik Gendy, Minass Asaad, Amr Fathy, Mohamed N. Abou-Zeid, and Ezzat Fahmy
The Department of Construction and Architectural Engineering, the American University in Cairo, Egypt

Abstract: In recent years there has been a depletion of natural resources, consumption of fossil fuels and a dire need for conserving energy. Thermal storage concrete is a new type of concrete that is likely to store and conserve energy and thereby serving towards a greener environment. Concrete is considered a suitable media to store energy due to its ability to maintain its performance upon exposure to elevated temperatures, its relative-ease in preparation and widespread use worldwide.

This work aims at achieving better understanding of factors influencing thermal storage concrete. Twelve concrete mixtures were prepared using conventional, rubber and recycled aggregates and were made with various w/c ratios with and without silica fume. Mixtures were tested for fresh properties as well as compressive and flexural strength upon exposure to high temperatures for six hours. Using models and valid equations, concrete heat capacity, conductivity and other relevant heat storage properties were assessed. This study provides useful information regarding the foremost concrete mixtures that are likely to serve for thermal energy storage purposes. The role of various mix design factors in this regard are discussed and categorized.

Keywords: Thermal Storage, Concrete, Innovative Material

1. INTRODUCTION

In recent years there has been global depletion of natural resources while the population and demand has been markedly increasing. The persistence of such dilemma has only led to resource price increase, energy being one of them (Hassanein et al., 2013). This problem is even expected to escalate in the upcoming years (Intergovernmental Panel, 2007). Such concerns have led scientists to come up with other alternative sources as solar energy for its merits. Solar energy is abundant, renewable and cheap, making it one of the most attractive energy alternatives (John et al., 2013). Moreover, other profound studies have been assessing the process of storing such clean, cheap energy sources in reservoirs and then use it at time of need (skinner et al., 2011; John et al., 2011). Such new approach has been adopted by many scientists and trials have been made upon the optimum material for solar energy storage reservoirs (Kearney and Price, 2006). For a material to store energy and produce it at time of need, it requires to possess various characteristics for durability and long term thermal endurance. Concrete is one of the advocated materials for such purpose for many reasons (John and Selvam, 2011; John 2013; Ismail, 2014 and Laing et al., 2011,). The first reason is its ability to maintain performance under elevated temperatures. The second reason is its ability to be produced for mass productions with reasonable prices. Finally, but most importantly, is its environmental merits when produced green/sustainable. Recently, most of the concrete produced is meant to be sustainable with simple considerations as the use of recycled materials, by products and less Portland cement (Asaad, 2011; Green buildings, 2010).

The purpose of this research is to prepare and test various concrete mixtures, used as thermal energy medium/reservoirs. These mixtures should withstand elevated temperatures, above 600 degrees Celsius, and additionally at this elevated temperature should retain both their mechanical and physical properties. The 600 C was selected as the temperature prior to potential dissolution of most aggregates which is around 690 C depending on aggregate composition. However, this temperature is rarely reached except for the outer cover within 30 minutes of exposure.

2. EXPERMENTAL PROGRAM

The experimental program was designed mainly to investigate various properties of different PCC mixtures. These included tests of both mechanical and thermal properties such as: compressive strength test, spalling test, specific heat capacity test, energy transfer test, thermal conductivity test, and the thermal expansion test.

2.1 Materials Properties

Cement: Ordinary Portland cement, it has a specific gravity of 3.16. The cement is produced locally by a company called "Sinai Cement Company"

Water: Municipal tap water for all processes as curing and mixing.

Water Reducing Admixtures: Commercially-available plasticizer to produce concrete of high workability with lower water to cement ratios. It was applied as 0.2% of the cement weight. Super plasticizer was also used and applied as 2.5% of the cement weight. Both types of water reducing admixtures were purchased from "Sika" company

Silica Fume: SF is used to increase the strength of the cement mixture. It was purchased from "Sika" company,

Coarse & Fine aggregates: Obtained from 'Tashween Inventory'.

Polypropylene Fibers: Obtained from "Sika" company

Rubber: Styrene Butadiene Rubber (Outer Tire) from "Marso & Hoppec"

Recycled aggregates: Waste concrete cubes from "Demix" enterprise.

2.2 Mix Design

Twelve different mixtures are prepared in this study; they are illustrated in Figure 1. The concrete mixtures are classified into three different groups based on the water to cement ratios (w/c). The first group of mixtures had a water to cement ratio of 0.3 with the following admixtures: silica fume, super plasticizer and polypropylene fibers. Moreover, these mixtures also included a portion of their aggregates replaced as follows: one poured using conventional aggregates only, another poured with 8% & 10% rubber replacement of aggregates and the last with 15% recycled aggregates replacement. The second group of mixtures poured had a water to cement ratio of 0.45. Plasticizer was further added to these mixtures, and they were then also partially replaced with different aggregates, one mix was poured using conventional aggregates only, another poured with 8% & 10% rubber replacement of aggregates and the last with 15% recycled aggregates replacement. The third and final group of mixtures had a water to cement ratio of 0.5, these mixtures had no admixtures instead had the aggregates replacement.

2.3 Test Procedure

The following tests were used to examine the PCC mixtures:

Spalling

The first thermal test performed is the spalling test. The mixtures prepared were placed into the oven at a constant temperature of 600 degrees Celsius for a time of 6 hours. After that, the oven was turned off and the samples were left to cool. The samples were then examined for damage

Compressive strength

Compressive strength test was done before introducing the samples to the oven and after. The compressive strength test was conducted according to BS 1048 and tested on the 7th day.

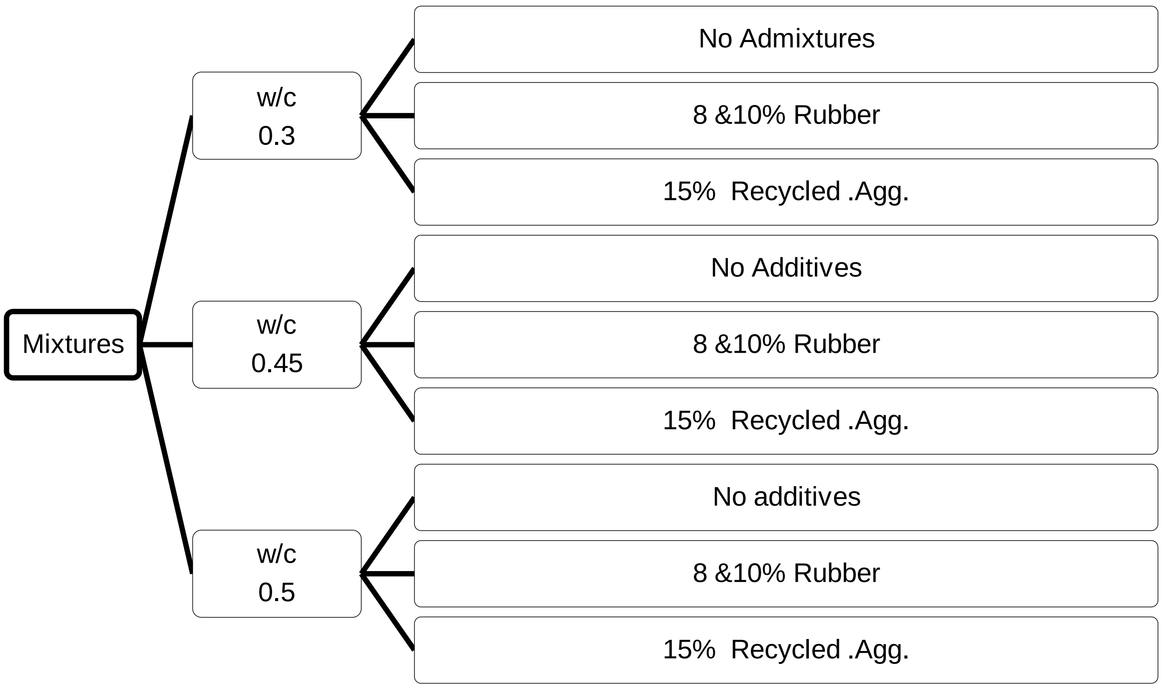

Figure 1: Summary of prepared mixtures with respect to water to cement ratio (w/c)

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Specific Heat Capacity

The specific heat capacity is the one of the most crucial tests. First a hole is drilled into the middle of a concrete block. The initial mass of the concrete is measured. Then it is placed into the oven at a temperature of 200 degrees Celsius, for a time span of 30 minutes. During this time, a container of water is set up, and the initial temperature of the water is measured. After the concrete block has been heated, it is taken out of the oven immediately and its initial temperature is measured at the same point where the initial temperature was measured using thermal couples. Afterwards, the block is placed into the container of water until both the water and the block reach thermal equilibrium; they both reach a point where their temperatures are equal. The final temperature is recorded, and the specific heat is calculated using Equation (1) (Serway et al., 1999)

[1] $$\mathrm{Cp_c} = \frac{\mathrm{m_w}\ \mathrm{Cp_w}\ \Delta\mathrm{T_w}}{\mathrm{m_c}\ \Delta\mathrm{T_c}}$$

Where C_p is specific heat capacity in j/kg ^{0}C, m is mass in kg and ΔT is change in temperature ^{0}C

Energy Transfer

The energy transfer test is used to measure how much energy can be stored within a sample. Using the specific heat capacity for the corresponding mixture, the energy stored can be calculated. Thermocouples were embedded within the concrete blocks in order to measure the initial and final temperatures. The mass of the concrete block is measured, along with the initial temperature. It is then placed into the oven for 4 hours at a temperature of 600 degrees Celsius, and the temperature is recorded immediately after being heated at the final temperature. The energy transfer is then calculated using Equation (2) (Serway et al., 1999).

[2] $$\mathrm{Q_c} = \mathrm{m_c}\ \mathrm{Cp_c}\ \Delta\mathrm{T_c}$$

Where Q is energy transfer in J, C_p is specific heat capacity in j/kg ^{0}C, m is mass of concrete in kg and ΔT is change of temperature in ^{0}C

Thermal Conductivity

Thermal conductivity test is done to measure the concrete ability to transfer heat from its warmer surface to its cooler surface. The test was conducted according to the law of thermal conduction, where two independent thermocouples were embedded within the sample in order to measure the difference between the core and surface temperatures. Using the thermal energy transfer result, the thermal conductivity was calculated using Equation (3) (Serway, 1996).

[3] $$K = \frac{Q\,L}{\Delta T\,A\,t} \rightarrow K_c = \frac{Q_c\,(L/2\,)_c}{\Delta T_c\,(6A)_c\,t_c}$$

Where K is thermal conductivity in w/m ^{0}c, Q is energy transfer in J, L is thickness in m, A is area in m^2, t is time in sec and Δt is the change of temperature in ^{0}C

Thermal Expansion

The thermal expansion test is done to measure the increase of the volume of the specimen due to heat exposure. Thermocouples were implanted inside the concrete sample, and its initial volume is measured. The sample is then placed into the oven at a temperature of 600 degrees Celsius for 4 hours. It is then removed and its dimensions are measured once more as well as its final temperature. The coefficient of thermal expansion was calculated using Equation (4) (Serway, 1996).

[4] $$a_c = \frac{\Delta V_c}{3\,V_{ic}\,\Delta T_c}$$

Where a is coefficient of thermal expansion and it is unite less, V_f is the final volume in m^3, V_i is the initial volume in m^3, and ΔTis the change of temperature in ^{0}C

3. RESULTS AND DISCUSSION

3.1 Criteria of selection (spalling, specific heat capacity and compressive strength)

After the mixtures shown in Figure (1) were casted, a criterion of selection was implemented. Three main criteria were the basis of elimination which are spalling, specific heat capacity and compressive strength, in order of importance. After conducting the spalling test, any specimen that was damaged physically was immediately eliminated.

Secondly a target value was set where any mix that showed a specific heat capacity lower than that of the control mixture (880J/kg^{0}C) would also be eliminated. Finally, a minimum7-day compressive strength of 20 MPa was required.

After comparing the specimens to the three required specifications, only 6 mixtures of the 12 have passed the selection which are shown in Figure 2 and further illustrated in Table 1. The six selected mixtures were subjected to further thermal testing that would be discussed below.

3.2 Spalling Test

All the rubber replacement 10% mixtures have shown spalling regardless of their w/c ratio. This could be incurred to the rubber high thermal expansion that causes the concrete to crack. Ultimately, these multiple cracks cause the breaking-up of layers of the concrete, which results in spalling of the cubes

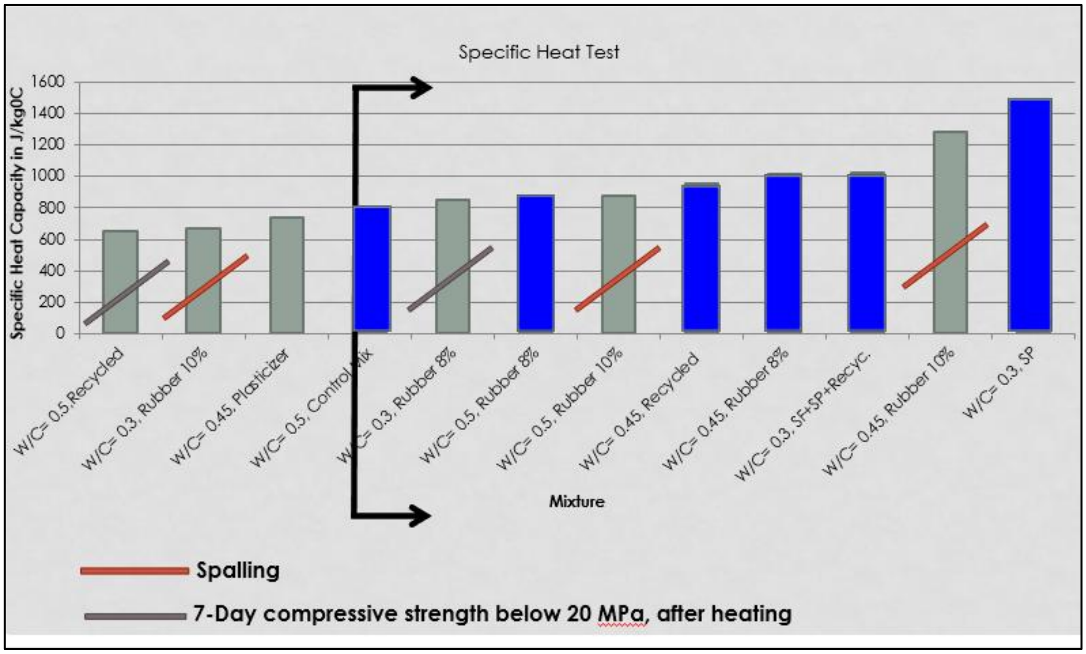

Figure 1: Elimination of samples based on criteria of selection

Table 1: Selected Mixtures

Mixture	w/c	Specific Heat ($J/kg\ ^0C$)	Compressive Strength (MPa)
Control Mix	0.50	809	20.1
Rubber Replacement 8%	0.50	861	19.5
Rubber Replacement 8%	0.45	1012	20.9
Recycled Agg (SP/SF/PPF**)**	0.45	957	20.8
SP+SF+PPF	0.30	1492	21.8
Recycled Agg (SP/SF/PPF)	0.30	1027	20.2

3.3 Compressive Strength

Regarding the compressive strength results, following the trend of the graph shown in Figure 3, it is clear that mixtures with w/c ratio of 0.30 have exhibited higher compressive strength compared to the 0.45 and 0.50 mixtures. This might be due to the binding power of the cement that is more effective with the lower w/c ratio. On the other hand, rubber seems to work the opposite way as rubber interacts better with the higher w/c ratio. Furthermore, mixtures that had silica fume, plasticizer, and superplasticizer or recycled aggregates have shown higher compressive strength trend. For the silica fume and plasticizers, they are known for interacting in a positive way with the chemical compounds produced from the pozzolanic reaction of the water, cement, and aggregate and produce other chemical compounds that enhance the compressive strength. Regarding the recycled aggregates, since they are one year old, they have already hardened; therefore, they induced the compressive strength of the concrete contributing to a higher strength.

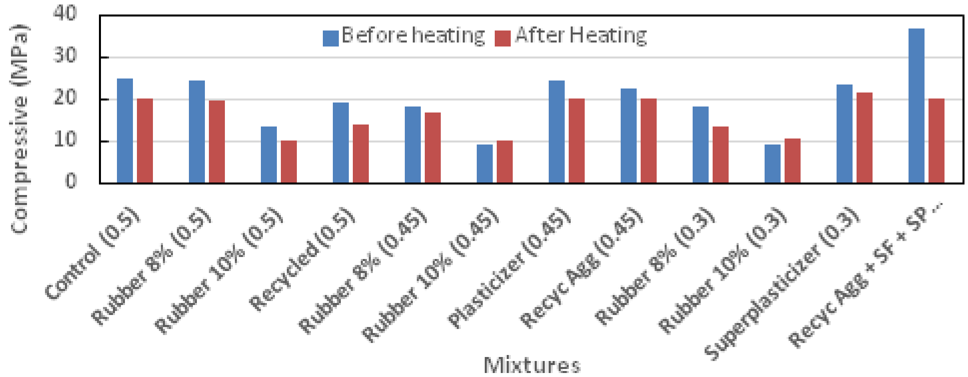

Figure 2: Results of Compressive Strength

3.4 Specific Heat Capacity Test

For the specific heat capacity test, the mixtures that showed higher specific heat capacity were those that included additives inside them, see Figure 4. For example, the mixtures that had polypropylene fibers and rubber had the highest values. This could be explained as those additives have a specific heat capacity above 1000 J/kg^{0}C while the concrete is barely above the 800 J/Kg ^{0}C. Therefore, those materials have induced the specific heat capacity of the whole concrete, resulting of a higher specific heat for those specific mixtures.

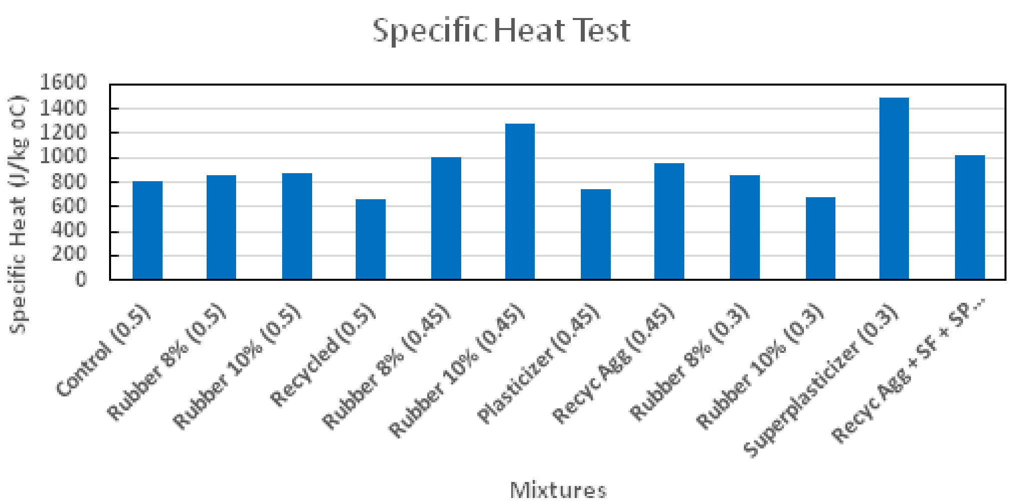

Figure 3: Results of Specific Heat Test

3.5 Heat Transfer Test

Following the above tests, the selected mixtures chosen through the criteria of selection were then subjected to an energy storage test expressed through heat transfer. This test was set for a time constraint of four hours, at 600 degrees Celsius. Mixtures that have tended to show higher energy storage are the same that have exhibited higher specific heat. This is because specific heat is directly proportional to the energy storage, therefore; it induces the amount of energy being transferred to the concrete. The results are shown in Figure 5.

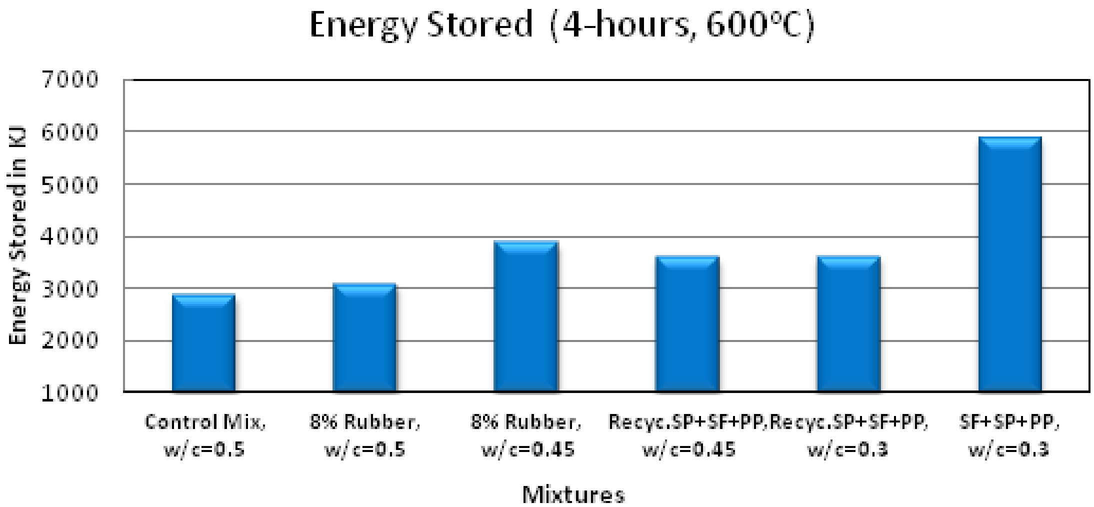

Figure 4: Results of heat transfer test

3.6 Thermal Conductivity

The mixtures were then subjected to a thermal conductivity test, which measures a material's ability to transfer heat from its warmer surface to its cooler surface. As shown in Figure 6, mixtures that have exhibited higher thermal conductivity are those with induced rubber. When rubber is subjected to heat inside the concrete, the polymers start to jiggle around and with more excitement it moves around the concrete. This phenomenon makes it lose electrostatic forces that are slow-moving to stationary charges. Therefore, it transmits the heat at a much higher rate from the surface to the core. The same for the polypropylene fibers, since the polymers inside it tend to react the same way upon heat exposure. The recycled aggregates have shown lower thermal conductivity as it takes longer time for the heat pass through already hardened concrete that has no additives to support the heat transfer.

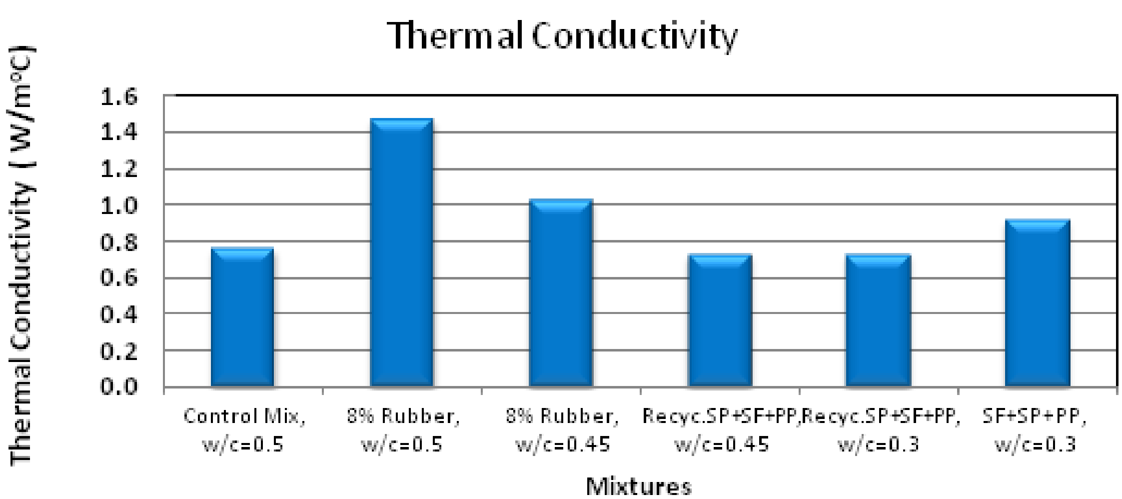

Figure 5 Thermal conductivity test results

3.7 Volumetric Thermal Expansion

For the volumetric thermal expansion test, the rubber mixtures had the highest volumetric thermal expansion as shown in Figure 7. This could be explained as the rubber material when exposed to heat, the polymers inside expand drastically. Moreover, this also applies to the mixtures with Polypropylene fibers, as the polymers inside those fibers also tend to expand upon heat exposure, causing the concrete cubes to expand. On the other hand, increasing the w/c ratio from 0.30 to 0.45, and with adding recycled aggregates to the fibers, the expansion seemed to decrease, as the recycled aggregates do not possess high thermal expansion. Fibers, oppositely, have tended to have less expansion compared to the rest of the mixtures, and lower to the conventional control mixture.

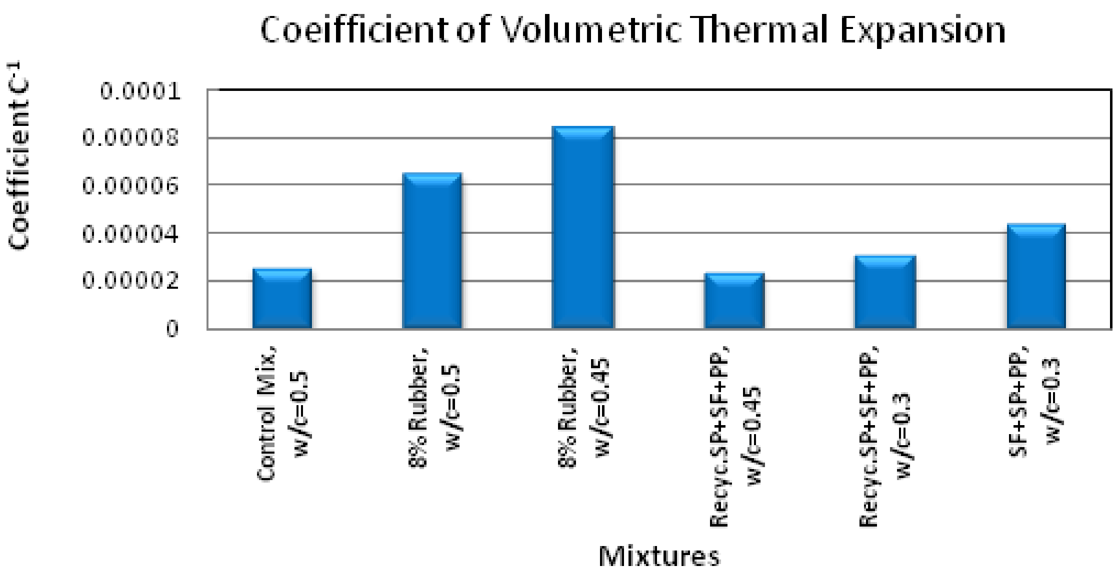

Figure 7: Results of volumetric thermal expansion

4. CONCLUSIONS

This research has attempted to study the most prominent concrete mixture design in terms of materials and proportions to be used for solar energy reservoirs. Selection should be based on thermal and mechanical properties performance. Based on the research conducted and results from the experimental work, one could conclude that there is no one mixture that is superior in all thermal properties as well as mechanical ones. However, one could be able to categorize the mixtures with respect to their performance. The mixtures with 0.30 w/c ratio have generally shown better performance in thermal tests specifically thermal energy storage. On the other hand, rubber aggregate replacement mixtures have shown the highest thermal conductivity. As for recycled aggregate replacements, they had the least thermal expansion properties.

Subsequently three conclusions were determined where each of three mixture designs has possessed a certain superior thermal property that is needed for the solar reservoir. Firstly, the mixture design that possessed the highest thermal energy storage is the mixture with a w/c ratio of 0.3 with silica fume and super plasticizer. Secondly, the mixture with the highest thermal conductivity is the one with w/c ratio of 0.45 with an aggregate rubber replacement of eight percent. Thirdly, the mixture that has the lowest thermal expansion is the recycled aggregate mixture. Finally, one can conclude that based on each project, and its location, decision makers should be able to perform a feasibility study, assess the situation and choose the optimum mixture design.

5. RECOMMENDATIONS AND FUTURE WORK

Stated below are some recommendations for future research related to this field of study:

1. Perform durability tests,
2. Decrease the percentage of rubber replacement of aggregates. Since based on results, one could notice that the 10% rubber replacement samples have poorly performed in thermal tests when compared to the 8% rubber replacement.
3. Perform more mixture trials. For example, mix both recycled aggregates and rubber aggregates together. Since both aggregates performed excellently in thermal tests individually, there may be a possibility that they will perform even better when mixed together.

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