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Experimental Determination of Thermophysical Properties of Concrete for Thermal Energy Storage

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Abstract: Experimental analysis of thermo-physical properties of concrete is necessary in order to determine a concrete composition suitable for thermal energy storage. This study carries out a laboratory experimentation in order to obtain the absolute thermal conductivity, resistivity and diffusivity of different composition of concretes with their strength test and it was discovered that concrete mix of ratio 1:2:0 (cement:sand:gravel) has the highest compressive strength of 74.5 N mm^{-2}, lowest thermal conductivity of 0.51 W/m°C thermal storage capacity of 2.74 J m^{-3}K while the mix of ratio 1:1.2:1.1 has the highest thermal storage capacity of 3.22 J m^{-3}K and that of ratio 1:1.9:1.7 has the highest thermal conductivity of 1.7 W/m°C.

Key words: Concrete, thermal conductivity, resistivity, diffusivity, compressive strength, thermal storage capacity

INTRODUCTION

The fundamental fact of thermal conductivity is that for steady flow, the quantity of heat flowing in a unit of time through a plate varies directly as the difference of temperature between the faces of the plate, directly as the cross section of the plate and inversely as the thickness of the plate. This law which was first stated clearly by Joseph Fourier is expressed as:

$$Q = k\frac{T_2 - T_1}{l}(At) \tag{1}$$

Q = The quantity of heat
$(T_2\text{-}T_1)$ = The difference of temperature at the two faces
A = The area of the cross section
t = The time of flow
l = The distance of flow or the thickness

The quantity k is a constant which is a property of the material of which the body is composed and is called the thermal conductivity of the material. The fraction:

$$\frac{T_2 - T_1}{l}$$

is the fall of temperature per unit distance and is called the temperature gradient. Thermal conductivity expressed above applies to the condition of steady flow that is the condition existing when the temperature at each point through the plate is not changing and the quantity of heat entering at one face is equal to the quantity emitted at opposite face. Thermal diffusivity (α) expresses the rate of flow of temperature for a material. This evidently depends not only on the thermal conductivity but also on the amount of heat required to raise the temperature of unit volume of the material one degree that is upon the density and the specific heat of the material:

$$\alpha = \frac{k}{\rho C_P} \tag{2}$$

P is the density of the material and C_p is the specific heat of the material. Thermal storage in concrete relies on sensible heat storage (Adeyanju and Manohar, 2009) where the stored thermal energy is defined by the heat capacity of the concrete and the temperature difference between the charged and discharged states. Concrete is a heterogeneous material essentially composed of cement, aggregate, water and air. The absolute values of the thermal properties will depend mainly on the thermal properties of the constituents of the mix i.e., of the aggregate, the un-hydrated cement, the amount of hydration products, the mixing water, the air volume, the temperature. This implies that for a given concrete mix, changes in the thermal properties can be described as a

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function of porosity, moisture content, amount of hydration products and temperature. The first three parameters are subjected to changes during the hardening phase and in turn, they can be expressed as a function of the degree of hydration, the temperature being a variable parameter that depends on the exchanges of heat with the environment and will affect the rate of hydration. As a matter of the fact, it will be possible to express the thermal properties as a function of the degree of hydration and evaluate separately the effects of the temperature on samples of concrete.

Very little data are given about the influence of the dry density on the thermal diffusivity. They seem to indicate a linear increase of the diffusivity of the order of 4% for an increase in dry density of 100 kg m^{-3}.

Since, both the conductivity and the specific heat increase with increasing moisture content, the net result on the coefficient of thermal diffusivity is only marginal. Data reported in literature do not seem to indicate a clear dependence of diffusivity on the moisture content. The influence of temperature on the thermal diffusivity depends upon the corresponding influence on both the thermal conductivity and the specific heat. Since with the increasing temperature the conductivity decreases and the specific heat increases, the thermal diffusivity will decrease at a greater rate (up to about 19% in the temperature range from 10-90°C) than thermal conductivity.

Thermal diffusivity is usually obtained from the relationship with the conductivity and specific heat. Since, it is not completely clear the dependency of the thermal conductivity on the degree of hydration, this prevents us from making final statements as regards the dependency of diffusivity on the degree of hydration. Even more difficult than for conductivity is the problem to measure the coefficient of thermal diffusivity of concrete. The main reason relies upon the fact that the heterogeneous nature of the material requires large samples to be tested. Currently testing methods, such as the laser flash method, research on little samples whose dimensions cannot be representative of a concrete.

So far, most of the testing methods to determine the thermal diffusivity consist in measuring the temperature variation in different points of large concrete sample samples or directly inside a structure, under dynamic thermal conditions. Through a careful data reduction which takes into account the phase shift of the thermal wave in the different points, thermal diffusivity can be estimated. Concrete is a substance designed to sustain large compressive forces. It is commonly known that concrete density is directly proportional to its compressive strength.

Concrete mixes are often exposed to extreme stress; the mixes require having a high level of durability. Scientists have attempted to manipulate concrete properties to make it more efficient at handling these loads. In order to accomplish this, researchers have created chemical admixtures that are added to a concrete mix to enhance its properties (Ramachandran, 1995). If these admixtures are not added to concrete, then there is a possibility that the concrete will experience deformation and mechanically fail. Consequently, it has become standard procedure to include chemical admixtures in concrete mixes.

Production and use of the three types of concrete mixes: Cement pastes are a mixture of cement, water and admixtures. It is one of the simplest concrete compounds that can be manufactured from cement. However, the lack of aggregates and sand results in weak cement paste. The lack of aggregate also allows extremely consistent mixes and samples; therefore, smaller sample sizes can be used in cocrete tests. The w/c in cements is relatively low. Bentz and Stutzman (2006) claim that if the w/c is >0.42, then there is theoretically enough water available for complete cement hydration. However, Ramachandran (1995) argues that cement pastes should have a w/c of 0.3-0.35. One possible reason for this difference is difference in cement type which can require different water/cement ratios for complete hydration.

Mortar is a mixture of cement, sand, water and admixtures. Mortars do not include aggregates but do include sand; consequently, its strength, permeability and workability levels is between the levels for concrete and cement pastes. By extension, its sample size is still small but significantly bigger than cement paste sample sizes. The major problem in using mortars is that the water absorbed by the sand must be taken into account when calculating the amount of water to put in the mortar.

Sarangapani *et al*. (2005) attempted to find the best recipe for mortars. Their result suggests that the best mortar recipe is 1 cement: 4 sand with 0.56 w/c. However, because the w/c was a variable in this experiment, the compressive strengths cannot be compared to each other. The difference in w/c is somewhat reasonable considering the sand content is directly related to the w/c but it is not perfect. Therefore, it is not possible to find the best proportion with the data given in the study.

Concrete mixes comprise cement, water, sand, aggregates and admixtures. Due to the inclusion of aggregates, concrete mixtures have a high compressive strength but low sample consistency. Therefore, concrete samples should be 6×12 inch cylinders or 6×6×6 $inch^3$. This causes difficulty when working with concrete because the material cost is extremely high. Bharatkumar *et al*. (2001) conducted a study to find a concrete recipe with optimum efficiency for strength and durability. The study suggested that the best recipe for concrete is 1 cement: 1.407 fine aggregate with a w/c of 0.35. However, if the concrete contains hydrated starch then the w/c should be approximately 0.39-0.46% (Glenn *et al*., 1999).

Theory: Thermal properties analyzer calculates its values for thermal conductivity, resistivity and diffusivity by monitoring the dissipation of heat from a line heat source given a known voltage. The equation for radial heat conduction in a homogeneous, isotropic medium is given by:

$$\frac{\partial T}{\partial t}=\alpha\frac{\partial^2 T}{\partial r^2}+r^{-1}\frac{\partial T}{\partial r} \tag{3}$$

Where:

T = Temperature (°C)
t = Time (s)
α = The thermal diffusivity ($m^2\ s^{-1}$)
r = Radial distance (m)

When a long, electrically heated probe is introduced into a medium, the rise in temperature from initial temperature, T_0 at some distance r, from the probe is:

$$T-T_0\cong\left(\frac{q}{4\pi K_h}\right)Ei\left(\frac{-r^2}{4\alpha t}\right) \tag{4}$$

Where q is the heat produced per unit length per unit time ($W\ m^{-1}\ K_h$) is the thermal conductivity of the medium (W/m °C) and Ei is the exponential integral function:

$$-Ei(-a)=\int_a^{\infty}\frac{1}{u}\exp(-u)du=-\gamma-In\left(\frac{r^2}{4\alpha t}\right)+\left(\frac{r^2}{4\alpha t}\right)-\left(\frac{r^2}{8\alpha t}\right)+\ldots\ldots \tag{5}$$

With:

$$a=\left(\frac{r^2}{4\alpha t}\right)$$

and γ is Euler's constant (0.5772), when t is large, the higher order terms can be ignored, so combining Eq. 4 and 5 yields:

$$T-T_0\cong\frac{q}{4\pi K_h}\left(In(t)-\gamma-In\left(\frac{-r^2}{4\alpha}\right)\right) \tag{6}$$

It is apparent from the relationship between thermal conductivity and $\Delta T = T\text{-}T_0$ shown in Eq. 8 that ΔT and In (t) are linearly related with a slope:

$$m=\frac{q}{4\pi K_h}$$

Linearly regressing ΔT on In (t) yields a slope that after re-arranging, gives the thermal conductivity as:

$$K_h=\frac{q}{4\pi m} \tag{7}$$

q is known from the power supplied to the heater. The diffusivity can also be obtained from Eq. 6. The intersection of the regression line with the t axis ($\Delta T = 0$) gives:

$$In(t_0)=\left(\gamma-In\left(\frac{-r^2}{4\alpha}\right)\right) \tag{8}$$

From the calculated t_0 {from the intercept of ΔT vs. In (t) and finite r}, Eq. 8 gives the diffusivity.

MATERIALS AND METHODS

Composition and preparation of the concrete cube: In making the concrete test cube, Portland cement, sand and gravel (granite) provided by the University of West Indies concrete laboratory were used.

After consideration of various mixtures of sand and gravel, the proportion of 55 and to 45% gravel by weight was chosen, though the proportioning was actually done by loose volumes. These proportions lie between the coarser mixtures that are frequently used and the mixtures that have larger percentages of sand which produced an easily worked mixture. The aggregate of this mixture had a weight of 3 kg per 0.001 m^3 of concrete cube.

One consistency was used in the concrete mixture which is referred to as 100% water content. This consistency was such that freshly moulded concrete in cubic form of size 0.1 × 0.1 m was made. Table 1 shows the proportions of different constituents for the mixtures tested.

The forms were removed from the mould after the concrete had set 24 h. The forms were then stored in damp sand for 14 days and later removed to a dry room. They were all thoroughly dry when tested. The appearance of the cubic shaped concrete is shown in Fig. 1.

Sample testing of concrete mixes: Concrete tests are administered to samples to learn about their properties. The most common concrete tests carried out in this study are the Conductivity Test, Diffusivity Test, Slump Test and the Compressive Strength Test.

Table 1: Composition of concrete mixtures used for the test

Samples	Ratios cement: sand: gravel	Aggregate /cement	Water/cement	Water (l)	Cement (l)	Sand (l)	Gravel (l)
A1	1:2:0	2.00	0.28	0.280	1.00	2.00	0.00
A2	1:1.2:1.1	2.33	0.31	0.280	0.90	1.10	1.00
A3	1:1.9:1.7	3.60	0.43	0.280	0.65	1.24	1.10
A4	1:2.4:2.3	4.08	0.37	0.196	0.53	1.26	0.90
A5	1:3.1:3.0	6.00	0.41	0.176	0.43	1.31	1.27
A6	1:4.3:4.0	8.38	0.53	0.171	0.32	1.39	1.29
A7	1:5.6:5.1	10.58	0.62	0.160	0.26	1.44	1.31

Table 2: Compressive strength of concerte specimens

Samples	Cast date	Date tested	Age (days)	Specimen Size and type (mm)	Weight (kg)	Density kg m^{-3}	Failure load (KN)	Compressive Strength(Nmm^{-3})
A1	5/3/10	1/4/10	28	100(Cube)	2.440	2440	745	74.5
A2	5/3/10	1/4/10	28	100(Cube)	2.850	2850	635	63.5
A3	5/3/10	1/4/10	28	100(Cube)	2.480	2480	540	54.0
A4	5/3/10	1/4/10	28	100(Cube)	2.490	2490	685	68.5
A5	5/3/10	1/4/10	28	100(Cube)	2.480	2480	565	56.5
A6	5/3/10	1/4/10	28	100(Cube)	2.440	2440	405	40.5
A7	5/3/10	1/4/10	28	100(Cube)	2.285	2285	260	26.0

Fig. 1: Cubic shaped concrete samples

Fig. 2: Compressive test machine

The slump test: The slump test measures the workability and consistency of a concrete sample. A slump cone (30.48 cm tall) or a mini slump cone (10.16 cm tall), a tamping rod (1.5875 cm diameter x 60.96 cm tall) and concrete mix is required to complete the slump test.To complete the slump test, the slump cone is filled with concrete mix that amounts to the height and rodded with the tamping rod 25 times.

This process is repeated 3 times until the cone is full. Then the excess cement is removed using the tamping rod. Immediately after the cement is removed, the slump cone is slowly lifted above the concrete mix which should be in the shape of a cone.

Within 2.5 min, the difference between the concrete mix height and the slump cone height should be measured. This value is known as the slump value.

While individually slump values do not relay a large amount of information, a set of slump values show the consistency of the workability of the concrete mix; all the slump values should have approximately the same slump in order to have consistent workability. The slump value for the samples tested in this study is zero.

The compressive strength test: The compressive strength test measures the compressive force a concrete sample is able to withstand. A concrete sample (cube), a compressive test machine and safety glasses are required to complete this test.

The seven concrete cube samples used for this test are all having dimension of 0.1×0.1 m. After the sample is cured, it is placed between two metal plates in the compressive test machine shown in Fig. 2. The machine applies force increasing at a constant rate upon the sample.

When the sample fails, the load applied is recorded in Table 2; this value is known as the peak load. By using the following equation, the compressive strength can be calculated: where P = peak load, A = minimum cross-sectional area and F_c = compressive strength.

The thermal conductivity, diffusivity and resistivity test: Description of test specimens and apparatus used; the

Linear Heat Source method is used to measure simultaneously the coefficients of conductivity and thermal diffusivity of the seven concrete samples. The storage capacity will be determined according to the relationship with conductivity and diffusivity.

In this test, a special thermal probe sensors needle coated with thermal grease (in order to maintain good contact with the concrete walls) is introduced into a drilled hole of 7 cm deep and 0.5 cm diameter in each of the seven concrete samples (samples A1-A7) and this is heated at constant power by the probe which also measures the temperature rise of the sample during the transient time through imbedded thermocouples.

The probe sensors needle contains both a heating element and a thermistor. Its controller module contains a battery, a 16-bit microcontroller/AD converter and power control circuitry. The thermal properties analyzer (probe) is as shown in Fig. 3.

To start measurement with the probe, the microcontroller waits for 90 sec for temperature stability and then applies a known amount of current for 30 sec to a heater in the probe that has an accurately known resistance. The microprocessor calculates the amount of power supplied to the heater.

The probe's thermistor measures the changing temperature for 30 sec while the microprocessor stores the data. At the end of the reading for each of the seven concrete samples the controller computes the thermal conductivity and diffusivity using the change in temperature (ΔT) versus time data. Thermal resistivity is computed as the reciprocal of thermal conductivity.

It is important to wait for about 5 min between readings in order to make the probe to be as close to equilibrium as possible. An ideal environment for equilibrium can be accomplished by placing the probe in an isothermal chamber or Styrofoam box.

Fig. 3: Thermal properties analyzer

RESULTS AND DISCUSSION

The results of the observations are shown in Fig. 4-11. Tests were made on seven concrete samples of cubic shape. Samples A1-A7 has thermal conductivity of 0.51, 1.42, 1.7, 1.46, 0.85, 0.66, 0.5 W/m°C, respectively and a thermal storage capacity of 2.74, 3.22, 2.8, 2.82, 2.81, 2.75, 2.57, respectively.

Sample A7 has the lowest thermal conductivity, density and thermal storage capacity of 0.5 W/m°C, 2285 kg m^{-3} and 2.57J m^{-3}K. Sample A3 has the highest thermal conductivity of 1.7 W/m°C which is in line with

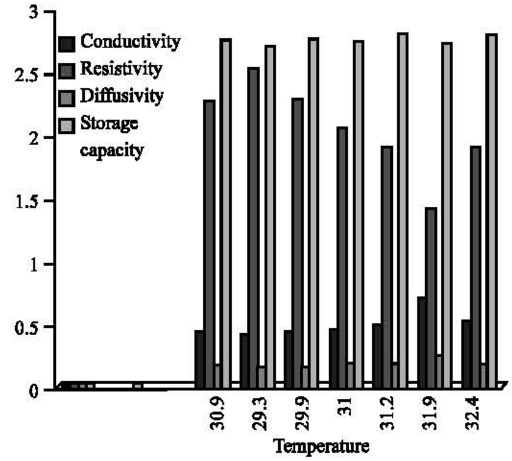

Fig. 4: Comparison of temprature with thermal conductivity, resistivity and diffusivity and storage capacity of concerete sample A1 (mixture 1:2:0)

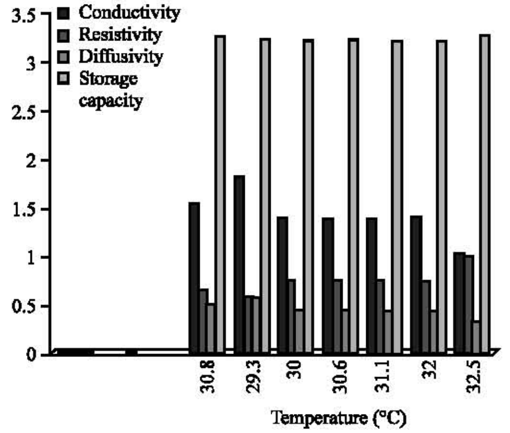

Fig. 5: Comparison of temprature with thermal conductivity, resistivity and diffusivity and storage capacity of concerete sample A2 (mixture 1:1.2:1.1)

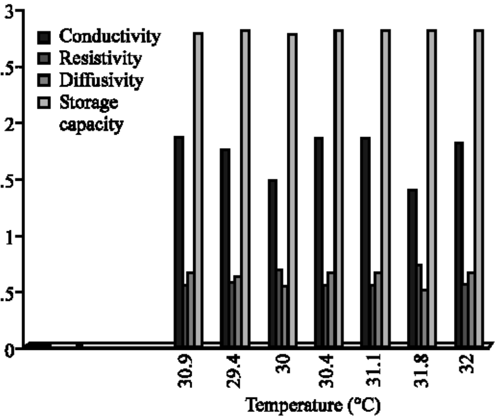

Fig. 6: Comparison of temprature with thermal conductivity, resistivity and diffusivity and storage capacity of concerete sample A3 (mixture 1:1.9:1.7)

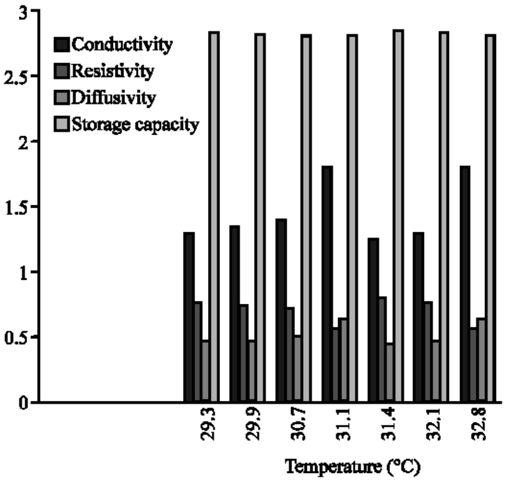

Fig. 7: Comparison of temprature with thermal conductivity, resistivity and diffusivity and storage capacity of concerete sample A4 (mixture 1:2.4:2.3)

thermal conductivity of 1.7 W/m°C which is in line with literature. This indicates that concrete mix of ratio 1:1.9:1.7 (cement: sand: gravel) is suitable when considering rate of heat transfer in a packed bed.

Sample A2 has the highest density of 2850 kg m^{-3} and storage capacity of 3.22 J m^{-3}K. This shows that concrete mix of ratio 1:1.2:1.1 (cement: sand: gravel) will be suitable for thermal energy storage in a packed bed.

The range of temperature for sample A1 is between 29.3 and 32.4; sample A2 is between 29.3 and 32.5; sample A3 is between 29.3 and 32; sample A4 is between 29.3 and 32.8; sample A5 is between 29.4 and 32.8; sample A6 is between 29.4 and 32.2; sample A7 is between 29.4 and 32.2.

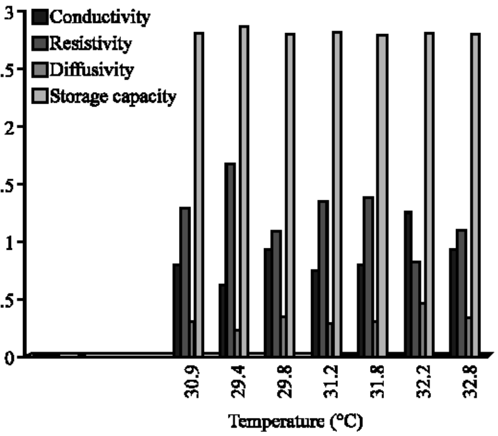

Fig. 8: Comparison of temprature with thermal conductivity, resistivity and diffusivity and storage capacity of concerete sample A5 (mixture 1:3.1:3.0)

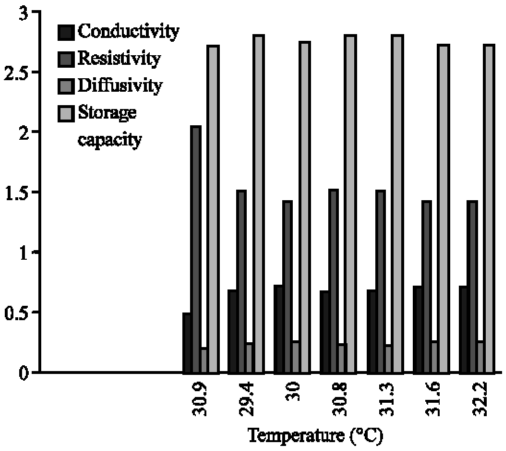

Fig. 9: Comparison of temprature with thermal conductivity, resistivity and diffusivity and storage capacity of concerete sample A6 (mixture 1:4.3:4.0)

It was discovered that for all the samples tested, the thermal conductivity increases as temperature increases and later the conductivity decreases as temperature increases.

The haphazard behavior of thermal conductivity with temperature is due to the low range of temperature in which the experimentation was performed. Experiment performed with higher range of temperature shows a decrease in thermal conductivity as temperature increases.

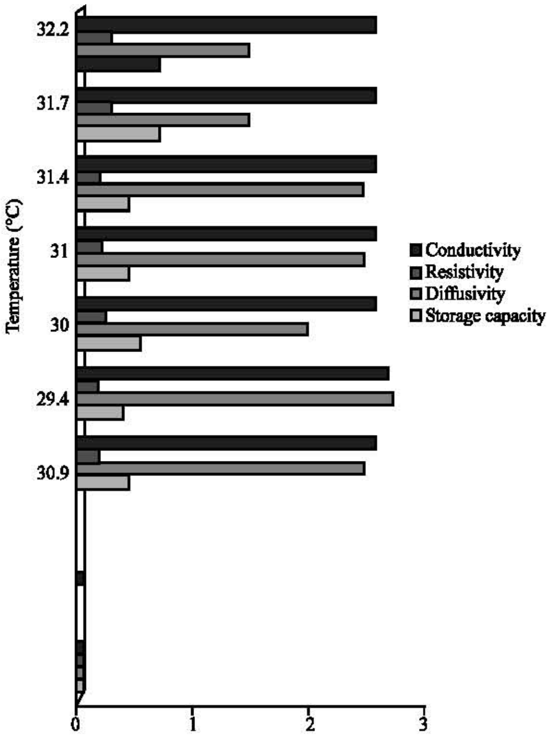

Fig. 10: Comparison of temprature with thermal conductivity, resistivity and diffusivity and storage capacity concerete sample A7 (mixture 1:5.6:5.0)

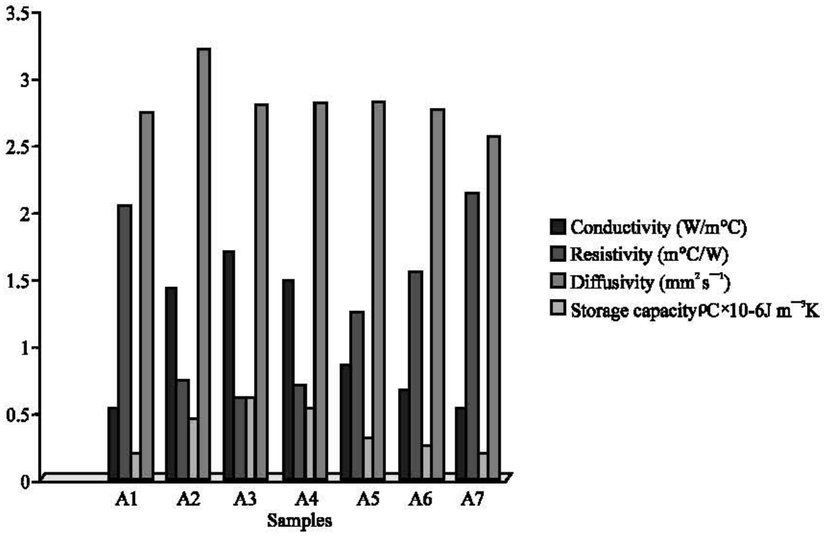

Fig. 11: Comparison of temprature with thermal conductivity, resistivity and diffusivity and storage capacity concerete sample A1-A7

CONCLUSION

From the analysis of the literature survey, it appears clear that many points are still to be studied. Numerical analysis of temperature distribution in actual concrete structures performed with differentvalues for the thermal conductivity have revealed that only marginal differences in the calculated temperatures have to be expected if moisture movements between the structure and the environment are prevented.

This condition is met only in massive structures for the greater part of the cross section. Similar analysis carried out with different values of specific heat have put in evidence that the differences on the temperature distribution, especially on the peak temperatures in hardening concrete are more pronounced.

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