Measuring Thermal Mass of Sustainable Concrete Mixes

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ABSTRACT

One of the challenges in sustainable development is to optimize the energy efficiency of buildings during their lifespan. Modern concretes offer both low embodied CO_2 with the use of different types of cements and recycled aggregates and reduced operational CO_2 with the intrinsic property called "thermal mass" that reduces the risk of overheating in the summer and provides passive heating in the winter. Thermal mass is currently evaluated with "admittance" which is the ability of the element to exchange heat with the environment and is based on specific heat capacity, thermal conductivity and density. The aim of this study is to evaluate the effect of thermal properties namely, density, specific heat capacity and thermal conductivity on thermal mass. The objective of the study is to carry out laboratory experiments by measuring such thermal properties of concrete mixes with various percentages of GGBS (ground granulated blast furnace slag), PFA (pulverized fuel ash), and SF (silica fume) and RCA (recycled coarse aggregates). The results obtained from these tests would contribute to the evaluation of how such thermal properties influence the thermal admittance and hence the thermal mass performance of sustainable concrete elements in a building system.

INTRODUCTION

Sustainable construction is becoming more popular as this sector correspond the world changing needs. The purpose of those variations is to increase the life of the residence by lowering CO_2 emissions and to increase the use of natural resources. Examination of thermal mass can be used to prevent or minimize temperature swings in the building and can also be used to eliminate the need for energy consuming air conditioning systems. Thermal mass is related to the storage material. Storage material is the mass of the building including walls, partitions, ceilings and floors where all have high heat capacity. The most important factors associated to heat storage (i.e. thermal mass) are thermal conductivity (λ), specific heat capacity (c) and he density (ρ) of the concrete. Thermal mass can explain the ability of the concrete to store the transferred heat/cool. Thermal mass can be determined by thermal diffusivity (α) of the building material that can be expressed as;

$$\propto = \frac{\lambda}{c\rho} \quad (1)$$

As a conclusion, the usefulness of thermal storage depends on several parameters, such as materials' properties, the exposed surface area, the thickness of the storing elements and its location and orientation within the building (as an external or an internal partition). The storage capacity of the slab is determined by the thickness of the penetration depth. If a building has a natural ventilation system with a concrete of thin penetration depth (i.e. 50mm x 75mm), it is operationally efficient for heat transfer and storage. Daily temperature cycle which is called sinusoidal cycle has a period of 24 hours. The slab reacts to variations occurred in this daily cycle. According to CIBSE Guide (1999), exchange of heat and cool over the cycle is measured by thermal admittance that can be defined as;

$$\mathbf{Y}=\frac{Qswing}{Tswing} \quad (2)$$

From the above definition of thermal admittance, it can be resulted that for a given temperature variation, heat/cool load that can be absorbed by the slab has a direct relationship with the thermal admittance. Since heavy materials such as concrete, brick or stone have a large, internal exposed capacity, those materials were storing greater part of the daily energy cycle. High admittance of those materials results in small temperature swing in the room. The unit for admittance (Y) is W/ m^2 K. Admittance values for several constructions components are given in CIBSE Guide section A3. The aim of the admittance method described before is predicting indoor temperature and by this way, evaluating peak environmental temperature for any proposed building. Details about the technique of this method can be found from CIBSE guide, section A8. As a conclusion, application of heat on different materials will create different effect on each material. Efficient heat storage material should have high density, thermal capacity and moderate thermal conductivity.

RESEARCH METHODOLOGY AND EXPERIMENTAL

Research Methodology. By using each cement replacement material separately, such as SF (silica fume), PFA (pulverized fuel ash), and GGBS (Ground granulated blasted slag) will be illuminating the factor that how these cement replacement materials may affect the thermal properties of concrete.

Experimental Design

Preparation of Mixes. The mixes used in this study are described in Table 1. There are 16 different specimens that can be classified in into three sections, namely, natural aggregate (Group A), recycled coarse aggregate (Group B) and minimizing water cement ratio concretes (Group C).Table 1 is shown the mixes for applying thermal properties.

Table 1. The mixes prepared for the measurement of thermal properties

Mix No.	Description	Mix No.	Description
A1	100% NA +100% PC	C1	100% NA +100% PC
A2	100% NA+45% GGBS	C2	100% NA+45% GGBS
A6	100% NA + 20% PFA	C3	100% NA + 20% PFA
A10	100% NA+ 20%SF	C4	100% NA+ 20%SF
B1	30% RCA + 100% PC	C5	30% RCA + 100% PC
B2	30%RCA + 45% GGBS	C6	30%RCA + 45% GGBS
B6	30% RCA + 20% PFA	C7	30% RCA + 20% PFA
B10	30% RCA + 20% SF	C8	30% RCA + 20% SF

Materials. • PC (Portland cement): A single source of Class 52.5N PC confirming to BS EN 197-1 was applied;
• GGBS (ground granulated blast-furnace slag): A single source (Civil-Marine) of GGBS confirming to BS 6699/BS EN 197 -1 was applied;
• SF (silica fume): A single batch of silica fume confirming to EN 13263-1 was applied;
• PFA used in the UK is classified as CEM IV according to BS EN 197-1 (2011);
• Graded natural sand with a maximum particle size of 5 mm and complying with the requirements of BS EN 12620-1 (2009)
• Natural aggregate used was Thames Valley gravel with a size fraction between 20 mm and 5 mm. The used RCA was obtained from processing concrete debris from demolished concrete structures. The size of fraction of the RCA is between 20 mm and 5 mm (BS EN 2620:2002 Classifying Aggregates)

Mix Proportions. Table 2 gives the mix proportions for the test concrete mixes. All of the mixes applied in the study were designed to have a slump of 60-180 mm. which is the range of acceptable slumps according to EN 206-1. As well as this, the range of the compacting factor of fresh concrete mixes was determined. All the mixes applied in the study were designed to have a compacting factor of 0-3s.

Table 2. Mix proportions for concrete mixes (Group A, B and C).

Constituent Materials Kg/m^3										
Mix No.	Coarse Aggregate			Types of Cements				FA/CA	W	W/C
	FA	NA	RCA	SF	PFA	GGBS	PC			
A1	586	1240	-	-	-	-	345	0.47	195	0.57
A2	586	1240	-	-	-	155	190	0.47	195	0.57
A6	580	1222	-	-	60	-	295	0.47	185	0.49
A10	586	1240	-	70	-	-	275	0.47	195	0.57
B1	597	850	365	-	-	-	345	0.49	204	0.59
B2	597	850	365	-	-	155	190	0.49	204	0.59
B6	593	845	360	-	60	-	295	0.49	189	0.51
B10	597	850	365	70	-	-	275	0.49	204	0.59
C1	460	1150	-	-	-	-	557	0.40	195	0.35
C2	460	1150	-	-	-	306	251	0.40	195	0.35
C3	451	1132	-	-	120	-	478	0.40	180	0.30
C4	460	1150	-	111	-	-	501	0.40	195	0.35
C5	448	786	337	-	-	-	583	0.40	204	0.35
C6	448	786	337	-	-	262	321	0.40	204	0.35
C7	440	772	331		126	-	502	0.40	190	0.30
C8	448	786	337	117	-	-	466	0.40	204	0.35

SAMPLE OF TESTING CONCRETE MIXES

Thermal Conductivity. According to BS EN ISO 8990: 1996 and BS EN 1934: 1998, a method called "hot-box" is developed by Dundee University in order to measure steady-state thermal transmission properties. This equipment contains two sides: heating side and cooling side. By using the heating side of the equipment, total power input (Φp) is calculated by using the measurement obtained from thermostat of hot box and timer counting. Timer counting is used to determine the proportion of the time needed to maintain constant temperature with heat source generated by 40 W light bulbs and a fan that is used to circulate the air.

$$\Phi p = \frac{(40xCounter\ Reading)}{(Time\ between\ readings)} \quad (3)$$

The sample that will be used in this study is square shape slab with 300 mm length and 75 mm thickness. Hence, thermal conductivity values are calculated by using the equation below:

$$\lambda = \frac{Q1}{Ax\Delta T} xd \quad (4)$$

Where; Q1= Qp-Q3-Q4, therefore; Q4= (0.9763xQp)-6.2516
d is the thickness of the sample;
A= 0.004m^2 (exposed area);
ΔT is the temperature difference between the hot side of the equipment and cold side of the equipment and
d= 0.075m which is the thickness of the samples;
Qp is the total heat input;
Q_1 is the heat transferred from hot side of the equipment to cold side of the equipment through the specimen
Q3 is the heat loss from hot side of the equipment to the environment;
Q4 is the flanking loss that is the heat lost through the gap between the specimen and the equipment during the experiment.

3.2 Specific Heat Capacity

Thermal properties of building materials are examined in specific heat capacity, so that it can be determined how much mass is needed per unit for one unit increase in temperature of the sample. By this way, specific heat capacity can be used to explain association between heat and temperature variation. Specific heat capacity is found by performing an experimental procedure in an insulated box. This box consists one stainless steel bucket which is approximately about half of the bucket. This preheated sample of cube of concrete is placed in to the water which is inside the bucket, After that, the insulated box is closed and the temperature of the sample, water and air are recorded until the same temperature is observed on the sample, water and air. After that, observed values from three elements are used to evaluate the value for specific heat capacity by using the formula stated below;

$$Q=mc\Delta T \quad (5)$$

Table 3. Known specific heat capacities.

Known Specific Heat Capacities	
Material	Specific heat capacity (J/KgK)
Stainless Steel 18Cr/8Ni	502
Water at 20,30,40 & 50°C	4181.6, 4178.2, 4178.3, 4180.4
Air at 20 to 100 °C (Dry)	1006

$$C_C\ m_C\ \Delta T_C = C_S\ m_S\ \Delta T_S + C_W\ m_W\ \Delta T_W + C_A\ m_A\ \Delta T_A + [M_w\ \ell] \quad (6)$$

where, ɩ is specific latent heat of the water (226 ×10^4); Mw is mass of water in air (evaporated water). The values needed to calculate the specific heat capacity using the Eq. (6) can be found in Table 3

Density of Hardened Concrete. Hardened concrete density is determined either by simple dimensional checks, followed by weighing and calculation, or by weight in air/water buoyancy methods (BSEN 12390-7, 1097-6). The density of hardened concrete specimens such as cubes and cylinders can be quickly and accurately determined using a Buoyancy Balance.

EXPERIMENTAL RESULTS AND DISCUSSIONS

The thermal properties of concrete mixes were measured. The values of the measured properties are summarized in Table 4.

Table 4. Thermal Properties of Concrete Mixes

Mix No.	Density (Kg/m^3)	Thermal Conductivity (W/mK)	Specific Heat Capacity (J/KgK)	Thermal Diffusivity (m^2/sec) ×10^{-7}	Compressive Strength -28 day(N/mm^2)
A1	2270	0.921	785	5.2	45
A2	2255	0.880	836	4.7	42
A6	2220	0.820	847	4.4	41
A10	2250	0.84	850	4.4	43
B1	2150	0.720	882	3.8	39
B2	2135	0.670	940	3.3	42
B6	2120	0.610	950	3.0	41
B10	2135	0.65	958	3.2	38
C1	2345	0.990	686	6. 7	55
C2	2330	0.931	712	5.6	51
C3	2335	0.892	727	5.3	53
C4	2345	0.901	690	5.6	54
C5	2200	0.770	848	4.1	54
C6	2180	0.730	868	3.9	49
C7	2190	0.701	865	3.7	48
C8	2185	0.750	850	4.0	52

Group A and B concrete mixes were investigated. PC with natural coarse aggregate exhibits the highest value on both thermal conductivity and density. On the other hand, the lowest thermal conductivity and density of concrete occurred at 20% of PFA replacement for ordinary Portland cement. Additions of different types of cements material to the concrete affect the thermal conductivity and density. Comparing PFA, GGBS and PC, PC concrete is slightly greater than GBBS and SF concretes. On the other hand, recycled coarse aggregate decreased the thermal conductivity and density of the concrete. RCA concretes are the light weight aggregate concretes which have low density.. This means that SF and PFA are probably related to the higher air content and partly to the amorphous structure of SF and PFA. Types of cement materials increased with increasing specific heat capacity. It is observed that PC concrete is the highest density and the lowest specific heat capacity. On the other hand, the replacement of PFA for PC is the lowest density and the highest specific heat capacity in natural and RCA concrete mixes. In Group C, The water cement ratio is minimized with increasing the density of the concrete. Clearly, if the cement content increases with increasing thermal conductivity and density of the concrete mixes, this results in better dry density of concrete. The results explained that W/C ratio is minimized with increasing the thermal conductivity in all types of concrete mixes. The water cement ratio of concrete is minimized, the density of concrete increases with increasing thermal conductivity. As well as this, the investigation is carried out for the Recycled coarse aggregate concrete. The results showed that when RCA is used with minimizing water cement ratio; it is achieved to improve the thermal conductivity of concrete. When minimizing water – cement ratio is used in the concrete, the thermal diffusivity of the concrete is improved. For instance, when C4 concrete mix is used, nthe thermal diffusivity is increased by 27.3 % when compared against A10 concrete mix.

THERMAL DYNAMIC CALCULATION

The excel file is set up to calculate the thermal dynamic properties of concrete mixes by applying the thermal properties data (thermal conductivity, density and specific heat capacity) of the concrete mixes. Factors which affect the thermal storage are taken under examinations that include thermal admittance hence thermal mass, decrement factor, and thermal transmittance (U-value) of the concrete mixes. The main aim of this section is to understand the effects of different types of cements materials, recycled coarse aggregate and minimizing water-cement ratio of the concrete mixes on the thermal admittance, thermal transmittance and decrement factor of the concrete mixes. Before setting up the excel calculator, the thermal dynamic properties are calculated theoretically. BS EN ISO 13786:2007 standard is used to calculate those parameters. The thickness of the samples is 0.075m (constant). The results are provided in Table 5.

Table 5. Thermal Dynamic Results of concrete mixes.

Mix No.	R-Value ($m^2 \cdot K/W$)	U-Value ($W/m \cdot K$)	Thermal admittance ($W/m^2 \cdot K$)	Decrement factor
A1	0.081	3.98	4.19	0.87
A2	0.085	3.92	4.20	0.86
A6	0.091	3.82	4.14	0.86
A10	0.089	3.86	4.17	0.86
B1	0.104	3.65	4.03	0.86
B2	0.112	3.55	4.03	0.85
B6	0.123	3.41	3.96	0.84
B10	0.115	3.50	4.03	0.84
C1	0.076	4.07	4.18	0.88
C2	0.081	3.99	4.14	0.88
C3	0.084	3.94	4.12	0.88
C4	0.083	3.95	4.10	0.88
C5	0.097	3.74	4.07	0.86
C6	0.103	3.67	4.04	0.86
C7	0.107	3.61	4.01	0.86
C8	0.100	3.70	4.05	0.86

Group A and B concrete mixes were investigated. Especially PFA content in concrete mixes has the lowest U-value and However, GGBS content in concrete mixes have greater R-value than silica fume content in concretes. When recycled coarse aggregate content in concrete mixes is examined, it is concluded that RCA content in concrete decreased the U-value more than different types of cement materials of concrete mixes. When the results are examined that Natural aggregate concrete mixes are increased slightly if comparing with 30% RCA content concrete mixes at Group C. The laboratory results are provided that Water-cement ratio is more important for RCA content concrete. The reasons for this, firstly because minimizing Water-cement ratio is improved the density of RCA content concrete and secondly, this is directly affected on the thermal conductivity and U-value of the concrete. The laboratory results provided that when water-cement ratio, RCA content and different types of cement materials are considered, water/cement ratio is act as a main actor of affecting the thermal properties of the concrete. It can be concluded that since minimizing the water-cement ratio increases the thermal conductivity of the concrete. However, when the thermal conductivity increased, this decreases the R-Value and hence increases the U-Value which will then increase the decrement factor. Using GGBS in concrete mix, increase the thermal admittance of the concrete and at the same time, R-Value increase with increasing thermal admittance in GGBS concrete. When 20% silica fume is used in concrete mixes, a lower value of thermal admittance is obtained compared to Portland cement mixes. However, PFA concrete mixes, decrease thermal admittance with increasing R-Value of the PFA concrete mixes. Beside of this, PFA concrete mixes have the highest R-Value compared against all concrete mixes due to having less thermal conductivity in PFA concrete mixes that means observing improvements in R-Value of the concrete. PFA concrete mixes decrease the thermal admittance value more than others in group A. RCA content concrete decrease the thermal diffusivity in all mixes in group B. This is due to RCA material being lighter than normal concretes. PFA content concrete mixes have lower thermal admittance and reasons for this depend on thermal properties of concrete. The main reasons of group C having lowest thermal admittance and R-Value are; minimizing water/cement ratio improve thermal conductivity and density of the concrete. Therefore, in all groups, group C concrete mixes have the highest value of thermal conductivity and density. As well as this, most of the concrete mixes having lowest specific heat capacity values are present in group C. These factors are directly affecting the thermal diffusivity values are increased. However, these results are provided that higher thermal conductivity is not good for the thermal admittance of the concrete mix. The important thing is using less dense concrete such as lightweight concrete to achieve same or similar thermal admittance values in the concrete mix which is more sustainable concrete. In other words, achieving moderate thermal conductivity is more useful for the thermal admittance of the concrete. From the observations, C1 is heaviest concrete mix than all the mixes. However, C5 contains RCA content and it is lighter than some of the concrete mixes in group C. This results are lead to decide that the effect of materials and how these materials have to be used properly in concrete to achieve lightweight concrete with functional thermal properties and achieving optimum thermal mass in the concrete mix.

CONCLUSIONS

The laboratory tests results are shown that different types of cement materials are affected thermal properties of concrete mix. The results obtained proved that type of cements affected the density and thermal conductivity of the concrete. As well as this, all types of cement materials are increased with increasing the specific heat capacity of the concrete. The results also showed that different type of cements content is important in considering the effect of thermal properties of the concrete. On the other hand, RCA content increased with increasing of the specific heat capacity of concrete. The laboratory tests showed that RCA content decreased the density and thermal conductivity of concrete more than different type of cements content. When the water cement ratio is minimized, the density of concrete is increased with increasing the thermal conductivity of concrete. In the cases when RCA and different type of cements content in concrete mixes are used, this improved the density and thermal conductivity given that minimizing water cement ratio is applied. Specific heat capacity of concrete is decreased with minimized water cement ratio. This is due to water having greater specific heat capacity than cement and aggregate. When the value of thermal admittance is concerned, it is found that this value does not need to have high or low thermal conductivity of concrete mix. The importance is to have a moderate thermal conductivity. The results are provided that thermal admittance is increased with high specific heat capacity, high density and moderate thermal conductivity of the concrete mixes. Therefore, those factors are found to be vital for improving thermal admittance hence thermal mass of concrete mix. As an application of this research, results obtained from laboratory section and hence the calculations carried out afterwards can help in performing conceptual design of framed buildings including options such as floor, slabs and walls. Additionally, investigations of various materials used for concrete contribute in specifying which materials are more suitable to use than others in sustainable concretes.

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