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Investigation of Different Types of Cement Material on Thermal Properties 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. Nowadays the applying of different types of cements in modern concretes provide low embodied 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 affected by thermal properties of concrete which it is the ability of the element to exchange heat with the environment and is based on thermal capacity, conductivity, and density. Laboratory experiments measured density, specific capacity and thermal conductivity of sustainable concrete mixes with various percentages of GGBS, PFA, SF. The results contribute to the investigation of the performance of thermal properties performance in sustainable concrete.
Key words: Thermal mass, different types of cements, thermal properties, sustainable concrete.

I. INTRODUCTION

Modern concretes offer both low embodied CO_2 with the use of different types of cement materials by reducing operational CO_2 with the intrinsic property called "thermal mass" which then reduces the risk of overheating in the summer and provides passive heating in the winter. Sustainable construction is becoming more popular as this sector corresponds to the world changing needs. Variations concerning global warming are the most important factors in which construction industry are exposed to.

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. Environmental problems created in construction industry can be overwhelmed by decreasing both embodied and total energy usage for the construction products. Energy consumption figures in European buildings are increasing every year due to increase in air-conditioning and heating usages as a result of greater standards of living. 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 for air conditioning systems.
Thermal mass which is also called thermal inertia 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 the 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;

$$\alpha=\lambda/c\rho \quad (1)$$

As a conclusion, the usefulness of thermal storage depends on several parameters, such as properties of materials, 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).
Materials having a high density will have a high thermal conductivity and therefore these materials are classified as good for heat storage.Therefore, high density in a building material indicates high thermal conductivity such as having a building with poor thermal resistance. On the other hand, insulation materials have a low thermal conductivity and high thermal resistance.

II. EXPERIMENTAL AND RESEARCH METHODOLOGY

Firstly, the effect of each cement material such as SF (silica fume), PFA (pulverized fuel ash), and GGBS (Ground granulated blasted slag) on thermal mass is investigated separately by keeping the other factors constant.

2.1 Experimental Design
2.1.1 Preparation of Mixes
The mixes used in this study are described in Table 1. There are eight different specimens that can be classified in into two sections, namely, coarse aggregate and recycled coarse aggregate concretes.

2.1.2 Materials
The following materials were applied to produce concrete mixes.

PC (ordinary Portland cement): A single source (Lafarge cement) of Class 52.5 N OPC 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 is used according to BS-EN 450-1 (2012). PFA used in the UK is classified as CEM IV according to BS EN 197-1 (2011);

Table1. The mixes preparation for this research

Mix No.	Definition
A1	100% coarse aggregatePC concrete
A2	100% coarse aggregate PC/GGBS (45%) concrete
A3	100% coarse aggregate PC/GGBS (55%) concrete
A4	100% coarse aggregate PC/GGBS (65%) concrete
A5	100% coarse aggregate PC/PFA (10%) concrete
A6	100% coarse aggregate PC/PFA (20%) concrete
A7	100% coarse aggregate PC/PFA (30%) concrete
A8	100% Coarse Aggregate OPC/SF (10%) concrete
A9	100% Coarse Aggregate OPC/SF (15%) concrete
A10	100% Coarse Aggregate OPC/SF (20%) concrete

Graded natural sand with a maximum particle size of 5 mm and complying with the requirements of BS EN 12620-1 (2009) was used as fine aggregate in the concrete mixes;Natural aggregate used was Thames Valley gravel with a size fraction between20 mm and 5mm. Company (BS EN 2620:2002 Classifying Aggregates) Table1. The mixes prepared for the measurement of thermal properties.

2.1.3 Mix Proportions

Tables 2 and 3 give 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 as 0-3s.

Table2 Mix proportions for concrete mixes.

Constituent proportions(kg/m^3)						
Mix No.		A1	A2	A3	A4	A5
FA		586	586	586	586	586
NA		1240	1240	1240	1240	1245
RCA		-	-	-	-	-
PC		345	190	155	120	315
CRM	GGBS	-	155	190	225	-
	PFA	-	-	-	-	32
	SF	-	-	-	-	-
FA/CA		0.47	0.47	0.47	0.47	0.47
W/C		0.57	0.57	0.49	0.57	0.53

Table 3Mix proportions for concrete mixes.

Constituent Proportions(kg/m^3)						
Mix No.		A6	A7	A8	A9	A10
FA		580	575	586	586	586
NA		1122	1190	12240	1240	1240
RCA		-	-	-	-	-
PC		295	272	310	293	275
CRM	GGBS	-	-	-	-	-
	PFA	60	82	-	-	-
	SF	-	-	35	52	70
FA/CA		0.47	0.47	0.47	0.47	0.47
W/C		0.49	0.45	0.51	0.57	0.57

III. SAMPLE OF TESTING CONCRETE MIXES

From this research, it is concluded that understanding the thermal properties by performing such concrete tests is vital. The most commonly used tests in this research are described as follows.

3.1 Specific Heat Capacity

Specific heat capacity is investigated as a thermal property of the concrete, so that it can be determined how much mass is needed per unit for one unit increase in temperature of the sample. In this way, specific heat capacity can be used to explain association between heat and temperature. Specific heat capacity is measured by performing an experimental procedure in an insulated box.

The following steps should be attained one day before carrying out the test.Oven is pre-heated at suitable temperature (i.e., 100oC±5ºC) and the sample is placed in this pre-heated oven in order to reach a constant temperature. Since the same stainless bucket is used for all specific heat capacity experiments, mass of the stainless steel bucket is constant and it is measured only once. Then, approximately half of the bucket is filled with water and the total mass of the stainless bucket with water is measured.

After that, the mass of water can be determined by subtracting the constant mass of stainless bucket from the total mass of bucket with water. Bucket with half-filled water is placed inside the insulated box. During the overnight stay, thefront of the insulated box is kept open in order to achieve constant temperature.

After this overnight stay, the thermometer is connected to the bucket with water to check the temperature. If the temperature is constant, this means that the bucket with water is now ready to be used for testing. However, before the start of testing, weight of the bucket with water should be re-measured to be aware of any variations in mass of water due to evaporation that might occur during overnight stay. Three different thermometers are

placed inside the insulated box to measure the temperature of the concrete, water and air respectively during the testing procedure.
Beside of this, relative humidity is measured to estimate the mass of the dry air. This apparatus is specifically observed values from the three different thermometers are used to evaluate the value for specific heat capacity by using the formula stated below:

$$Q=cm\Delta T \quad (2)$$

The specific heat capacity is found by using the following formula and known values for the specific heat capacity of water, the stainless steel bucket and air.

C_C x m_C x ΔT_C= [C_S x m_S x ΔT_S] +[C_Wx m_W x ΔT_W] + [C_Ax m_Ax ΔT_A] + [$M_W ɩ$] (3)

Where;

ɩ is specific latent heat of the water (226×104);
M_w is mass of water in air (evaporated water).

The values needed to calculate the specific heat capacity using the equation (4) can be found in table 4

Table 4Known specific heat capacities.

Material	Specific heat capacity ($Jkg^{-1}K^{-1}$)
Stainless steel 18Cr/8Ni	502
Water at 20ºC, 30ºC, 40ºC and 50ºC	4,181.6, 4,178.2, 4,178.3, 4,180.4
Air at 20 ºC to 100ºC(Dry)	1,006

3.2 Thermal Conductivity

According toBS 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. Heating side is achieved by using 40W light bulb and cooling side is achieved by using a fridge. Both cold box from cooling side and hot box from heating side needs to be insulated.
As well as this, the box which includes the sample is also insulated. This experiment with two sides are designed on a trolley where both fridge and cold box is kept fixed, while designing the hotbox and sample box in a way to move towards and away from the fixed part of the apparatus. The total power input is calculated by using the values obtained from this experiment. The formulae to calculate the total power input is;

$$\Phi_p = \frac{(40 \times counterreading\ \ )}{(timebetweenreadings\ \ )} \quad (4)$$

By using the heating side of the equipment, total power input (Φ_p) 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.

Insulated box is designed in a way to be open at both ends. At one open end, a fan is attached to the fridge whereas on the other open end the sample box is presented. This sample box is designed in a way that can be opened from the top to place the sample inside the sample box.After the sample is placed, thermocouples are sealed at both sides of the box. Same amount of thermocouples are placed on heating side and cooling side separately. The sample that will beused in this study is square shape slab with 300mm length and 75mm thickness. Temperature of the sample during the experiment is controlled by using a temperature controller at 240V/2A. The voltage and current used in the experiment is recorded by using 16 channel thermocouple data acquisition and a simple logger log system. Hence, thermal conductivity values are calculated by using the equation below:

$$\lambda = \frac{Q_1}{A \times \Delta T} \times d \quad (5)$$

Where,

$$Q_1 = Q_p - Q_3 - Q_4$$
$$Q_4 = \left(0.9763 \times Q_p\right) - 6.2516$$

$d$isthickness of the sample;
$A = 0.04m^2$(Exposed area);
ΔT isthe 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;
$Q_P$isthe total heat input;
Q_1 isthe heat transferred from hot side of the equipment to cold side of the equipment through the specimen;
Q_3isthe heat loss from hot side of the equipment to the environment;
Q_4isthe flanking loss that is the heat lost through the gap between the specimen and the equipment during the experiment.

3.3 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 specimenssuch as cubes and cylinders can be quickly and accurately determined using a Buoyancy Balance.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

The thermal properties of concrete mixes were measured. The thermal conductivity, density and water/cement ratio for each mix can be seen in Fig. 3.

The first concrete mix is formed from 100 % Portland cement (A1) and therefore set to be a control mix. PC was then replaced by GGBS, 45 (A2), 55 (A3), and 65 (A4) % in the concrete mixes to form the corresponding mixes.

PFA was replaced as a part of Portland cement by 10 (A5), 20 (A6), 30 (A7) % in the concrete content in the mixes from A5 to A7. SF was added in the cement content by 10 (A8), 15 (A9), and 20 (A10) % in the concrete mixes from A8 to A10.

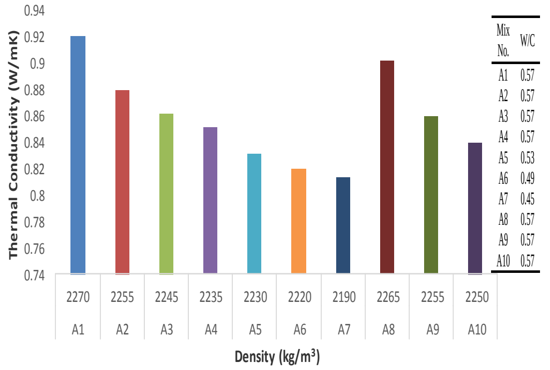


Fig 3.Thermal Conductivity of concrete varying density

In all of the concrete mixes, only natural coarse aggregate is used to make the concrete mixes. In this way, different types of cement materials can be compared with different percentages used in the concrete mixes where using various percentages of cement materials can be used to show the effect of different types of cement materials on the thermalproperties of concrete and hence on the thermal mass of the concrete.

Thermal conductivity, specific heat capacity and density of concrete are the three main tests used to measure this effect Since PFA, GGBS and SF have higher air-voided content than PC content concrete, concretes including PFA, GGBSand SF have lower density than concretes with PC. Reduction of density of the concrete causes a decline in thermal conductivity.

Such decrease is also reported by R. Gul, H. Uysal and R. Demirboga (1997), Akman and Tasdemir (1977) and Lu-shu et al. (1980), whose suggested that there is a relationship between density and thermal conductivity where the thermal conductivity increases as the density gets larger.Since, replacing cement by PFA or SF reduces the density of concrete content, when the Portland cement is replaced by PFA, GGBS or SF, an association of the higher the percentage of such materials (i.e. PFA, GGBS or SF), the lower the thermal conductivity is achieved. The results in this study showed that when SF, GGBS and PFA are used instead of PC, the thermal conductivity and density of the concrete are decreased.

When the percentage of PFA content in the concrete mix is increased to 10 (A5), 20 (A6) and 30 % (A7) by replacement of PC, this results in the reduction of the thermal conductivity value by 9.8, 10.9, 12 % respectively. When the PC is replaced by GGBS, 45 (A2), 55 (A3), 65 % (A4) replacement of PC decrease thermal conductivity by 4.5, 6.5, and 7.6 % respectively. On the other hand, when 10 (A8), 15 (A9) and 20 % (A10) of PC is substituted with SF, this interchange reduces the thermal conductivity by 2.2, 6.5 and 8.7 % correspondingly.

As a result of this, it can be concluded that the higher percentage of cement replaced, the lower thermal conductivity is achieved. However, it is the also vital to take account the chemical and physical properties of cement replacement. For instance, the percentage of GGBS content in concrete mix ishigher than SF concrete mix but the effect of SF is higher than the GGBS. As well as this, replacing cement by silica fume reduce the thermal conductivity of the concrete.

The main reason is silica fume and PFA are more reactive material than GGBS. Silica fume is mainly based on amorphous (non-crystalline) silicon dioxide (SiO_2). The individual particles in silica fume are very small in size such 1/100th amount of a mean cement size. This property of silica fume and in addition to this, having fine particles with large surface area and high SiO_2 content, enables silica fume to act as an extremely reactive pozolan when this material is used in the production of concrete.

When the different types of cement material is included in cement, the results obtained showed that increasing the amount of types of cement (such as GGBS, PFA and SF) results in raising the specific heat capacity of the concrete. The lowest specific heat capacity of the concrete is obtained when 100% PC is used. This is because the Portland cement has lower air-void contents than the other different types of cement materials. Whereas, the highest percentage of the specific heatcapacity of the concrete is obtained when GGBS is used instead of PC such as when the proportion of PC is replaced by GGBS, 45 (A2), 55 (A3), and 65 (A4) %.

When this replacement of PC is carried out, this results in increase in specific heat capacity of concrete by 6.5, 13.6, and 19.7 % correspondingly. This is due to GGBS having large interface area than Portland cement causing an increase in the specific heat capacity of theconcrete.

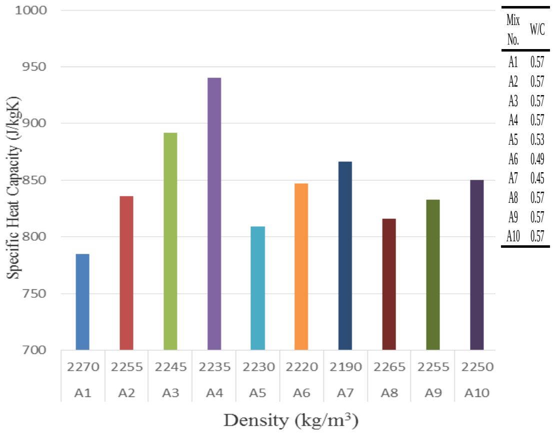


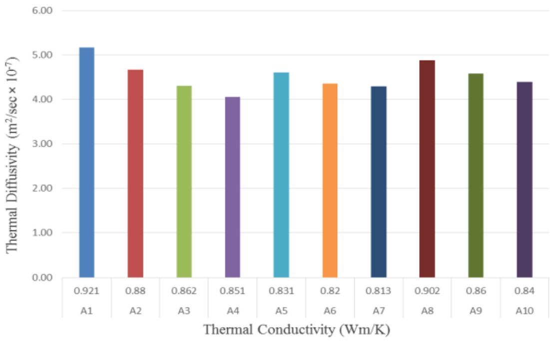
Fig 4. Specific heat capacity of concrete varying density

When silica fume is used as a replacement of part of the PC, the specific heat capacity of concrete is increased as well. For example, when the portland cement is replaced by Silica fume, 10 (A8), 15 (A9), and 20 % (A10) , this interchange of cement increased the specific heat capacity of conctere by 3.9, 6.1 and 8.3 % respectively.

Y.Xu, D.D.L. Chung (2002) state that when silica fume is added in cement, anincrease in specific heat capacity is achieved due to the reduction in thermal diffusivity caused by the effect of silica fume. Thereason for this reduction in thermal diffusivity caused by addition of silica fume is explained as the boarder among the silica fume and cement acting as a barrier relative to heat conduction. Hence,silica fume content in concrete decrease the thermal conductivity of the concrete.Increase in the specific heat capacity of the concrete is also achieved when PFA is added to the content of concrete.

For instance, if the portland cement is replaced by PFA, 10 (A5), 20 (A6) and 30% (A7) admixtures of cement results in an increase of thespecific heat capacity of concrete by 3.1, 7.9, and 10.3 % respectively. However, the results of the experiments concluded that Silica Fume concrete mixes are shown higher specific heat capacity than PFA concrete mixes.Particularly, the specific heat capacity of concrete is increased when thermal conductivity of the concrete is reduced. However, the thermal conductivity of concrete is increased when the thermal diffusivity of concrete is raised.

The results are explained that when PC is replaced by PFA, 10 (A5), 20 (A6) and 30% (A7) this alternate usage results in reduction of the thermal diffusivity 11.5, 15.4, and 17.3% respectively. This reduction is related to addition of PFA in the concrete mixes, decreasing the density with decreasing thermal conductivity and increasing specific heat capacity of the concrete.



	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
W/C Ratio	0.57	0.57	0.57	0.57	0.53	0.49	0.45	0.57	0.57	0.57
Density (kg/m^3)	2270	2255	2245	2235	2230	2220	2190	2265	2255	2250
Specific Heat Capacity (J/kgK)	785	836	892	940	809	847	866	816	833	850

Fig 5. Thermal Conductivity of concrete varying thermal diffusivity

On the other hand, when silica fume is used, the reduction in thermal conductivty more than GGBS is used in the concrete as an alternative to PC. For instance when reduction in the Silica fume and GGBS concrete are compared that Silica fume is used 20 % of cement content in the conrete has greater thermal diffusivity value than 45 % GGBS of cement content in the concrete.

From the results, it can be concluded that when 10 % of PC is replaced by PFA, this results decrease in the thermal diffusivity of concrete more than the same amount of the silica fume replacement. However, 20 % of PC is replaced by PFA in the concrete has the thermal diffusivty resulted to be less than the same amount of silica fume concrete.

This means that when the amount of PFA is increased in the concrete with decreasing in thermal diffusivity as well as increasing the specific heat capacity more than the same amount of SF concrete mix.In other words, Silica fume has greater density and thermal conductivity value than PFA. Beside of this, it is concluded that thermal diffusivity is indirectly proportional to thespecific heat capacity of concrete.

The laboratory results are observed that the density of concrete is slightly decreased with increasing the different types of cement material. The results are also identified that the density is directly proportional to thermal conductivity. In other words, the density of concrete is increased with increasing thermalconductivty of concrete.

V. CONCLUSION

The results obtained from laboratory tests are analyzed that PFA content concrete mixes are decreased the thermal conductivity more than other type of cements content mixes (such as SF and GGBS). 30% PFA content in concrete mix has greater reduction thermal conductivity of the concrete mix. On the other hand, 15 % SF is decreased the thermal conductivity equal percentage (6.5%) with 55% GGBS content concrete mix. Thermal conductivity of concrete is related about the types of material chemical properties. The laboratory results showed that 10 and 20% SF content concrete has greater specific heat capacity than 10 and 20% PFA content concrete. 65% GGBS content concrete mix has greatest specific heat capacity of the concrete mix than all of the mixes. However, GGBS content is greater than SF and PFA content in the concrete. Therefore, Silica Fume content concrete mixes show greater values of specific heat capacity than other types of cements content concrete mixes.

When the thermal diffusivity is taken into consideration, 20% SF content concrete mix has higher thermal diffusivity than 45% GGBS content concrete mix. It can be found that 10% PFA content concrete mix has decreased the thermal diffusivity more than 10% SF content concrete mix. However, 20% PFA content concrete mix has less thermal diffusivity than 20% SF content concrete mix.

Finally, the results explained that different types of cement materials affect the thermal properties of concrete. PFA is found to be more effective material than Silica Fume and GGBS in the concrete mix. When investigation is carried out between Silica Fume and GGBS, Silica fume has a greater effectthan GGBS. It is needed to highlight that the amount of material is important. However, the material affectivity (such as chemical reaction of the material) is more important than amount of the material in concrete mixes. The laboratory results are shown that all of the different types of cement materials are decreased the thermal conductivity and thermal diffusivity of the concrete comparing with Portland cement concrete mix. On the other hand, different types of cement materials increased the specific heat capacity of the concrete mixes.

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