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Thermo-mechanical performance of concrete with alternative binder material.

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Thermo-mechanical performance of concrete with alternative binder material.

Abstract

Purpose – This paper investigates the effect of changes to fundamental components of concrete; cement type, water/cement ratio, aggregate size & age, on thermo-mechanical properties. Understanding the heat transfer properties of construction materials will enable a reduction in energy expenditure and associated CO_2 emissions, contributing to a more sustainable built environment.

Design/methodology/approach – Concrete specimens were subject to steady state heat transfer test methods to determine thermal conductivity and specific heat values. Pore volume of specimens was determined using water displacement method and compressive strength of specimens was tested according to procedures identified BS EN 12390 – 3 (2009).

Findings – Cement type CEM I produced the lowest thermal conductivity values by a maximum of 30%, with the cement type group CEM I corresponding to higher pore volumes and lower densities than cement type group CEM II. Specific heat was higher in cement types containing CEM II compared to cement type group CEM I, with cement type being the dominant factor determining specific heat out of cement type, w/c ratio and aggregate size. W/c ratio 0.55 provided the lowest thermal conductivity values of the w/c ratio specimens, however w/c ratio had no impact on the specific heat capacity of concrete. Cement type is found to be the most dominant component of concrete of the properties tested.

Originality/value – This paper presents knowledge of the thermal performance of concrete with easily achieved changes to concrete mix design, which can be used alone or combined for maximum effect, and their impact on compressive strength. Steady state heat transfer techniques in a low moisture environment, provides originality to the study of the behaviour of cement replacements as previous research has been based on transient techniques. The use of steady state heat transfer experimentation allows important thermal properties, thermal conductivity and specific heat to be calculated.

Keywords – Concrete Technology, Sustainable construction, Thermal conductivity, Specific heat, Steady state heat transfer, Pore Volume.

Paper type -Technical paper

Introduction

CO_2 emissions produced from the burning of fossil fuels are a leading contributor to global warming and climate change (Raupach & Fraser, 2011). As a large contributor of CO_2 emissions, the construction industry is responsible for 47% of total CO_2emissions when all stages in the construction process are taken into account (BIS, 2010). Energy saving in buildings is an area in which much can

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be done to reduce CO_2 emissions in the built environment (Lagüela et al, 2011). With 53% of household energy used for domestic heating (Yesilata & Turgut, 2007, MacMullen, 2011), it is important to develop more energy efficient building envelope materials to retain heat, and consequently keep energy wastage to a minimum (ACI 2002). In addition the UK Building Regulations require a dramatic improvement of building fabric by 2016, compared to that of the current standards (DeSaulles 2010, NBS 2010). Not only is there the damaging environmental impact from energy loss through poorly insulated buildings, there is the secondary effect of increased financial cost (Kaynakli, 2012). In the current economic climate with energy prices escalating this is an important consideration to both domestic and commercial energy users.

To reduce the impact of energy loss through buildings, our primary construction materials must be examined. Concrete is one of the most widely used construction materials in the world (ACI , 2002) and its use is fundamental to UK infrastructure, due to its durability, flexibility of use and availability (The Concrete Centre, 2010).

Although concrete can be utilised for its thermal properties in the form of thermal mass or light weight concrete (LWC); thermal mass retains heat in its thick walls which provide enhanced specific heat capacity (ACI 2002), and LWC provides a concrete of lower thermal conductivity, produced by aggregate with higher pore volume, or an aerated cement matrix (Kim, Jeon, & Lee, 2012), these applications are only suitable in certain applications to be of any benefit (Bennett, 2010). A concrete mix design providing reduced thermal conductive properties, appropriate for use in all general construction applications, could lower heat transfer through a building envelope, reducing energy loss, unlike other concepts which are fixed solutions to a specific set of circumstances and which rely on excess or specialised material, high in embodied energy (Bennett, 2010, Kim, Jeon, & Lee, 2012).

To fully understand the properties of concrete, we need to understand what is happening within its microstructure (Constantinides & Ulm, 2007), therefore this research focuses on the potential to reduce the thermal conductivity of concrete through alteration of its main components, to gain knowledge of their effect on thermo-mechanical properties.

This paper will examine the effect of; cement type, water/cement (w/c) ratio, aggregate size & age, on the thermo-mechanical properties of hardened concrete; thermal conductivity, specific heat, pore volume, and compressive strength.

Experimental study

Specimens

Concrete test specimens were batched to requirements as BS 1881-125 (1986). Cement type specimens included CEM I, CEM II B-V and CEM II A-V, in addition to cement replacements; fly

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ash (FA), ground granulated blast slag (GGBS) & silica fume (SF), added to CEM I and CEM II B-V in replacement percentages to CEM I as determined by BS 197-1 (2011). Cement type specimens were tested at age 28 and 56 days. W/c ratio specimens consisted of; 0.4, 0.55 and 0.75. Aggregate size specimens included two size ranges of 4.75 - 6.63mm, and 6.75 - 10mm.

Table 1 Specimen mixes

	Cement type	Age (days)		Aggregate size (mm)		w/c ratio		
		28	56	4.75-6.3	6.3-10	0.4	0.55	0.75
Cement type group CEM I	CEM I (100%)	Y	Y	Y	Y	Y	Y	Y
	CEM I + SF (15%)	Y	Y	Y	-	-	Y	-
	CEM I + FA (30%)	Y	Y	Y	-	-	Y	-
	CEM I + GGBS (50%)	Y	Y	Y	-	-	Y	-
Cement type group CEM II	CEM II B-V (100%)	Y	Y	Y	Y	-	Y	-
	CEM II B-V + SF (15%)	Y	Y	Y	-	-	Y	-
	CEM II B-V + FA (35%)	Y	Y	Y	-	-	-	-
	CEM II B-V + GGBS (50%)	Y	Y	Y	-	-	-	-
	CEM II A-V (100%)	Y	-	Y	Y	-	-	-

Thermal conductivity, pore volume and SEM specimens were cast in bespoke timber moulds 100 x 60 x 30mm; the largest size to eliminate aggregate size as a possible variation between samples, but small enough to achieve a stable temperature difference within the available time to perform thermal tests. A minimum sample size of six specimens were cast for each thermal conductivity and pore volume test, plus one additional specimen was cast per batch for SEM investigation. A sample size of three compressive strength test specimens were cast for each variable, in 150mm steel cube moulds and produced to BS EN 12390-3 (2009).

Thermal conductivity

Steady-state heat transfer test methods, based on the unguarded hot plate method (BS 874-2.2:1988), informed the design and calculations of the experimental test procedure. The test rig was arranged in a

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vertical alignment with a base heater block of solid copper, the test specimen, and another copper block. Heater cartridges were contained within the base block, connected in a parallel circuit to a power supply though an AC power supply with variable voltage. Each block had 2x 3mm holes positioned in vertical alignment, enabling type T thermocouples to be inserted to record temperature differences. The test rig was encapsulated by an insulating thermoplastic to minimise heat loss.

Specimens were tested for approximately 2hrs 45mins or until there is ≥0.2°C temperature difference over a period of 15 minutes. Specimens were measured and weighed to allow volume and bulk density to be calculated.

Current and power factor were recorded using an Electrocorder EC 164-A single phase current logger, voltage was recorded using a Voltech PM1000+ power analyser, and temperature differences were recorded using a Grant Squirrel 20/20 series data logger, enabling thermal conductivity calculations of the test specimen to be made. Equation 1 illustrates Ohms law, used to calculate power input.

$$W = Vx\,I \tag{1}$$

Where;

I	=	Amp
V	=	Volts
W	=	Watts

Power was then corrected using the power factor; the ratio of real power flowing through the circuit to the apparent power flowing through the circuit. With real circuit power known, values are known to input into Fourier's Law equation, to enable thermal conductivity to be calculated (Equation 2).

$$Q = -k\mathrm{A}\frac{\partial t}{\partial x} \tag{2}$$

Where;

A	=	Area (m^2)
∂x	=	Distance (m)
Q	=	Heat transfer (W)
∂t	=	Temperature difference (K)
k	=	Thermal conductivity (W/m·K)

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Thermal conductivity values were adjusted to take account any heat loss through the test rig by calculation in Equation 3.

$$Q = hA\partial t \tag{3}$$

Where;

A = Area (m^2)

h = Convective heat transfer coefficient ($W/m^2 \cdot K$)

Q = Heat transfer (W)

∂t = Temperature difference (K)

Specific heat

With voltage, current, power factor, temperature difference and mass already known, the specific heat of each test specimen is calculated using Equation 4.

$$Q = Cpm\Delta T \tag{4}$$

Where;

Q = Heat energy (J)

m = Mass of specimen (kg)

C_p = Specific heat (J/kgK)

ΔT = Temperature difference (K)

Pore Volume

The calculation of pore volume is achieved by fully saturating test specimens in a curing tank through water absorption by total immersion; BS EN 12390–7 (2009) determines specimens to be fully saturated at 72hrs or when specimen weight changes less than 1% by unit weight in 24hr period. Weight is recorded at fully saturated, surface dried state, then specimens are oven dried at 110°C, until weight change is less than 1% unit weight. The weight of each oven dried specimen is recorded and Equation 5 is applied to achieve pore volume percentage of the specimens.

$$Pv = \frac{(m_s - m_o)\rho w}{V} \tag{5}$$

Where;

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ρ_w = Density of water (0.998g/cm^3)

m_s = Mass of saturated specimen (g)

m_o = Mass of oven dried specimen (g)

Pv = Pore volume (%)

V = Volume of specimen (cm^3)

Compressive strength

Compressive strength testing was performed to determine the effect of each test variable on the compressive strength of hardened concrete. Specimens were placed in the test machine and subjected to constant loading until specimen failure, procedures were followed in accordance with those stated in BS EN 12390 – 3 (2009).

Results & Discussion

Table 1 shows the mean test result of each specimen for; thermal conductivity, specific heat, pore volume, density and compressive strength values, including the standard deviation for each group. Statistical analysis has been performed on each set of results using the analysis of variance (ANOVA) between group's test, to determine reliability and statistical significance of the test results. All results reported are the statistical test results unless otherwise stated.

Table 2 Mean test results with standard deviation (SD)

Cement type (28 day)	Thermal conductivity (W/m·K)	*SD*	Specific Heat Capacity (J/kg K)	*SD*	Pore Volume (%)	*SD*	Bulk density (kg/m^3)	*SD*	Comp strength (N/mm^2)	*SD*
CEM I	0.1977	*0.011*	18581	*1548*	15.89	*0.55*	2219	*31.64*	29.29	*2.41*
CEM I + FA	0.2018	*0.022*	20405	*1535*	16.48	*0.46*	2227	*25.53*	27.09	*0.78*
CEM I + GGBS	0.2261	*0.008*	17735	*1881*	15.27	*0.89*	2315	*49.00*	28.63	*1.43*
CEM I + SF	0.2284	*0.011*	18555	*2392*	16.82	*0.29*	2228	*41.63*	30.29	*5.61*
CEM II A-V	0.2393	*0.015*	20701	*2135*	16.71	*0.41*	2331	*97.95*	21.79	*0.20*
CEM II B-V	0.2612	*0.014*	21446	*2463*	14.27	*0.30*	2262	*47.93*	22.11	*1.20*
CEM II B-V + FA	0.2818	*0.017*	20943	*1841*	16.09	*0.43*	2185	*48.14*	16.93	*0.36*
CEM II B-V + GGBS	0.2608	*0.019*	19900	*1779*	12.99	*0.58*	2265	*73.24*	24.76	*0.08*
CEM II B-V + SF	0.2532	*0.022*	21037	*1530*	15.22	*0.29*	2274	*27.89*	20.02	*0.77*
Cement type (56 day)	**Thermal conductivity (W/m·K)**	***SD***	**Specific Heat Capacity (J/kg K)**	***SD***	**Pore Volume (%)**	***SD***	**Bulk density (kg/m^3)**	***SD***	**Comp strength (N/mm^2)**	***SD***
CEM I	0.2226	*0.010*	21325	*3598*	15.60	*0.73*	2288	*56.08*	34.09	*2.86*
CEM I +	0.2424	*0.019*	17649	*3308*	17.58	*1.02*	2317		30.89	*0.35*

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FA								*44.66*		
CEM I + GGBS	0.2251	*0.012*	17581	*1690*	13.86	*0.84*	2274	*68.54*	33.97	*2.11*
CEM I + SF	0.2342	*0.013*	16625	1790	12.98	*0.59*	2336	*92.02*	37.65	*5.50*
CEM II B-V	0.2260	*0.023*	17790	*2105*	16.95	*0.85*	2364	*123.6*	29.01	*0.94*
CEM II B-V + FA	0.2330	*0.015*	18313	*1495*	16.49	*0.81*	2125	*115.2*	22.53	*1.15*
CEM II B-V + GGBS	0.2059	*0.031*	16625	*2598*	15.27	*0.44*	2356	*26.37*	31.13	*1.15*
CEM II B-V + SF	0.2549	*0.013*	18816	*3859*	20.89	*0.61*	2256	*62.26*	25.31	*0.62*
w/c ratio (28 day)	**Thermal conductivity (W/m·K)**	***SD***	**Specific Heat Capacity (J/kg K)**	***SD***	**Pore Volume (%)**	***SD***	**Bulk density (kg/m^3)**	**SD**	**Comp strength (N/mm^2)**	***SD***
0.75	0.2207	*0.018*	23775	*6744*	19.89	*0.88*	2129	*119.3*	23.45	*1.08*
0.55	0.1977	*0.011*	18581	*1548*	15.89	*0.55*	2219	*31.64*	29.29	*2.41*
0.4	0.2278	*0.024*	20609	*1789*	18.35	*0.63*	2279	*37.18*	25.76	*3.98*
Aggregate size (28 days)	**Thermal conductivity (W/m·K)**	***SD***	**Specific Heat Capacity (J/kg K)**	***SD***	**Pore Volume (%)**	***SD***	**Bulk density (kg/m^3)**	***SD***	**Comp strength (N/mm^2)**	***SD***
CEM II A-V (6.3-10mm)	0.2331	*0.014*	24069	*1805*	15.13	*0.43*	2261	*36.14*	27.82	*0.08*
CEM II A-V (4.75-6.3mm)	0.2393	*0.015*	20701	*2135*	16.48	*0.70*	2331	*97.95*	21.79	*0.20*
CEM II B-V (6.3-10mm)	0.288	*0.022*	19164	*2730*	15.92	*0.34*	2215	*55.37*	25.83	*0.57*
CEM II B-V (4.75-6.3mm)	0.2612	*0.015*	21446	*2463*	14.27	*0.30*	2262	*47.93*	21.64	*1.37*
CEM I (6.3-10mm)	0.2318	*0.012*	18415	*1382*	16.56	*0.49*	2392	*30.84*	39.91	*1.99*
CEM I (4.75-6.3mm)	0.1977	*0.011*	18581	*1548*	15.89	*0.55*	2219	*31.64*	29.29	*2.41*

Thermal Conductivity

Cement type

Thermal conductivity test results show that cement type has a statistically significant effect on the thermal conductivity of concrete at 28 days. The lowest thermal conductivity value was achieved by cement type specimen CEM I, with mean values 30% lower than the highest conductivity specimen type CEM II B-V+ FA. In addition all specimens containing cement type CEM I produced lower conductivities than specimens containing CEM II. Mean values show that in comparison to CEM I; CEM I + FA was higher by only 2%, CEM I + GGBS was higher by 13% & CEM I+ SF was higher by 14% as shown in Figure 1. CEM II A-V had the lowest thermal conductivity out of CEM II specimens, however still 17% higher than CEM I, followed by CEM II B-V + SF 22% higher, CEM II B-V + GGBS and CEM II B-V at 24% higher, and CEM II B-V + FA 30% higher as shown in Figure 2.

Figure 1 Relationship between thermal conductivity and cement type group CEM I

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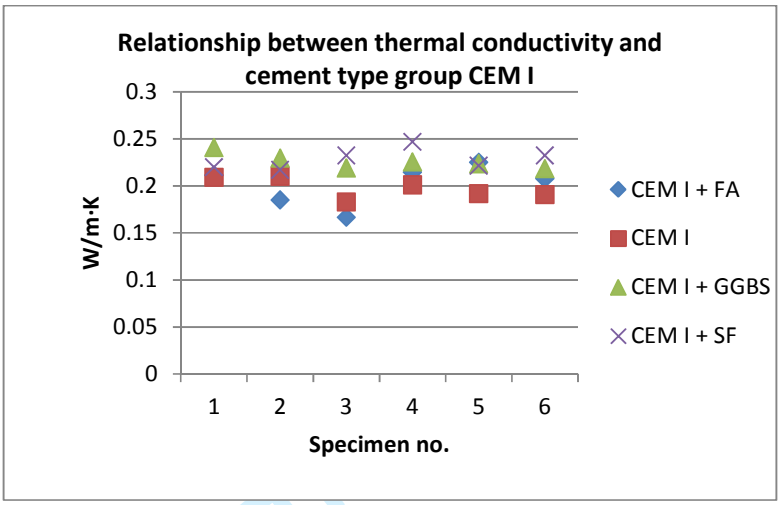
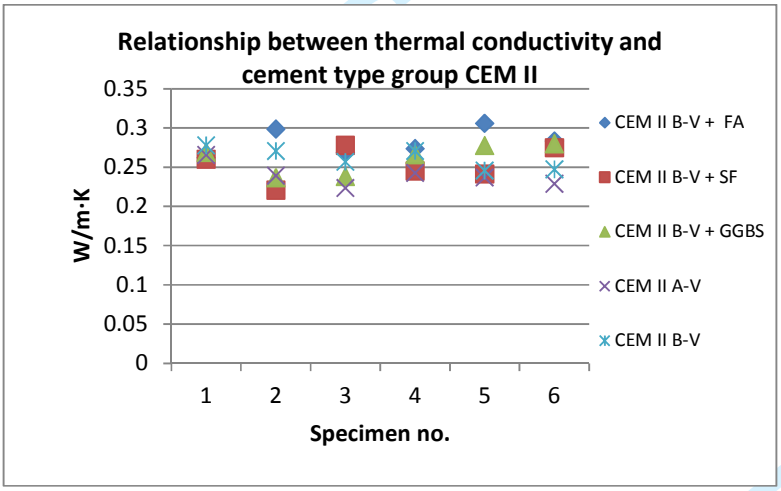


Figure 2 Relationship between thermal conductivity and cement type group CEM II



The reason CEM I specimens produced the lowest thermal conductivity is attributed to the fact that CEM II cements produce denser concrete pore structures (Oner & Akyuz, 2007), therefore facilitating a higher conductive path through the material. Although studies have shown cement replacements to reduce the conductivity of mortar using transient heat transfer test methods (Fu & Chung 1997, Demirboga, 2003), research using steady state heat transfer test methods involving oven dried specimens has provided knowledge on the effect of the behaviour of cement replacements in concrete when moisture content is controlled, as cement replacements are well known for their decreased permeability properties (Demirboga 2003, Nazari & Riahi, 2011). CEM II B-V + FA achieved the highest conductivity at 28 days, which is explained due to the high volume fly ash content (over 60%) which inhibits the hydration of fly ash, with un-reacted particles acting as filler between pore spaces (Lam, Wong & Poon 2000, Nazari & Riahi, 2011).

Age

Results show CEM I achieved the lowest thermal conductivity value for age 28 and 56 days. In the CEM I specimen group, thermal conductivity values either stayed the same or increased from age 28 days to 56 days, as shown in Figure 3. Specimens CEM I + SF & CEM I + GGBS showed no difference in thermal conductivity values, where CEM I & CEM I + FA increase in thermal conductivity by 11% and 17% respectively.

Figure 3 Relationship between thermal conductivity and age: CEM I

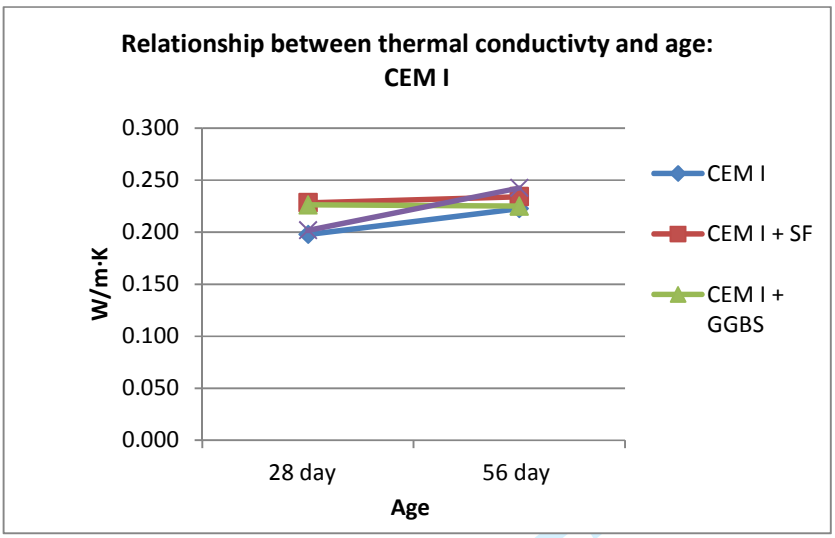


Figure 4 Relationship between thermal conductivity and age: CEM II B-V

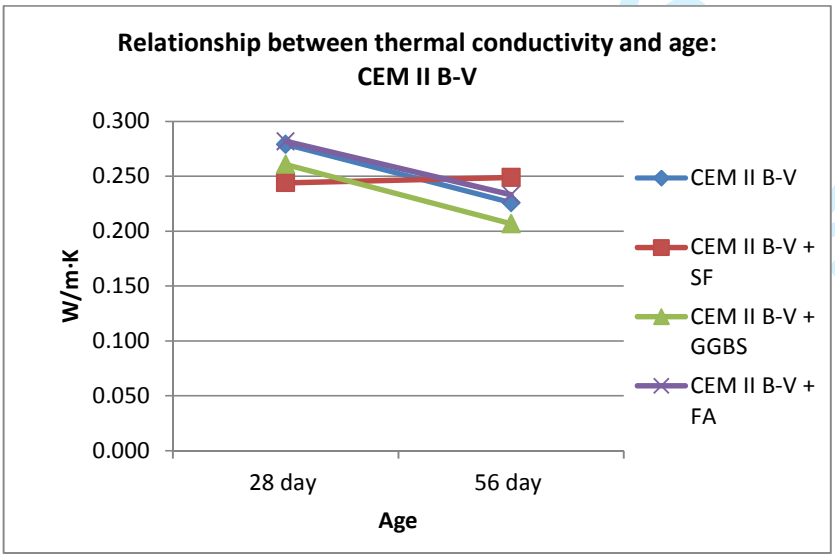


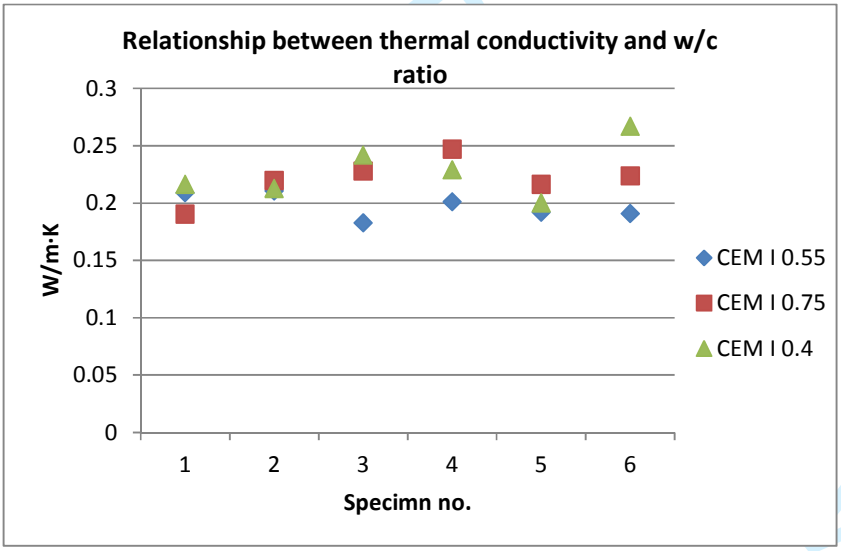
Figure 4 shows the relationship between 28 and 56 day CEM II B-V specimens. CEM II B-V, CEM II B-V + GGBS & CEM II B-V + FA all decreased in thermal conductivity with age by; 21%, 21% & 13% respectively, where CEM II B-V + SF showed no difference in thermal conductivity with age.

Although each cement type behaves differently, reduction in thermal conductivity with age could be explained with the continued hydration of cement replacements which require extended curing times. The additional curing time allows for the hydration of filler particles that block pores, allowing for air voids which provide a less conductive path.

W/c ratio

Results show from w/c ratio specimens 0.4, 0.55 & 0.75, a significant difference in thermal conductivity is observed with a w/c ratio of 0.55, however no statistical difference is observed in thermal conductivity between w/c ratios 0.4 and 0.75. A w/c ratio of 0.55 had the lowest thermal conductivity value by 13%, as shown in Figure 5. This finding is consistent with the theory that lower w/c ratios provide unstable pore structures with a decrease in porosity (Zivica, 2009) and that higher w/c ratios increase connecting pore structure at detriment to thermal properties (Wang et al 2005).

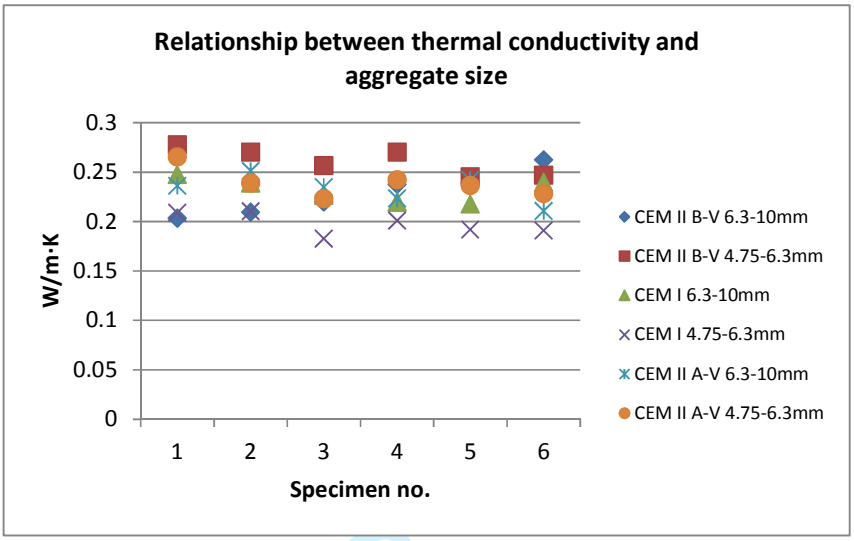
Figure 5 Relationship between thermal conductivity and w/c ratio



Effect of Aggregate Size

Figure 6 shows specimens containing CEM I produces the lowest thermal conductivity with smaller aggregate, however CEM II B-V specimen has higher conductivity with smaller aggregate. For specimens containing CEM II A-V no difference in thermal conductivity was observed between specimens containing smaller or larger aggregate. Results show the effect thermal conductivity has on concrete with different aggregate size changes with cement type, as aggregate size specimens follow the same trend as their respective cement types. This indicates that cement type has a more dominant effect on the thermal conductivity of concrete than aggregate size within the size range of 4.75-10mm.

Figure 6 Relationship between thermal conductivity and aggregate size



Specific heat

Cement type

Results show that there is no difference in the specific heat of specimens in the cement type CEM I group shown in Figure 7, in addition there is no difference observed between the specific heat of specimens in the cement type CEM II, as shown in Figure 8. However differences are observed in the specific heat between the two specimens groups, with specimens containing CEM I providing the lower specific heat mean values. As specific heat is directly related to the amount of substance it contains, this could explain why CEM II cement types provide higher specific heat, due to the denser pore structures compared to CEM I cements.

Figure 7 Relationship between specific heat capacity and cement type group CEM I

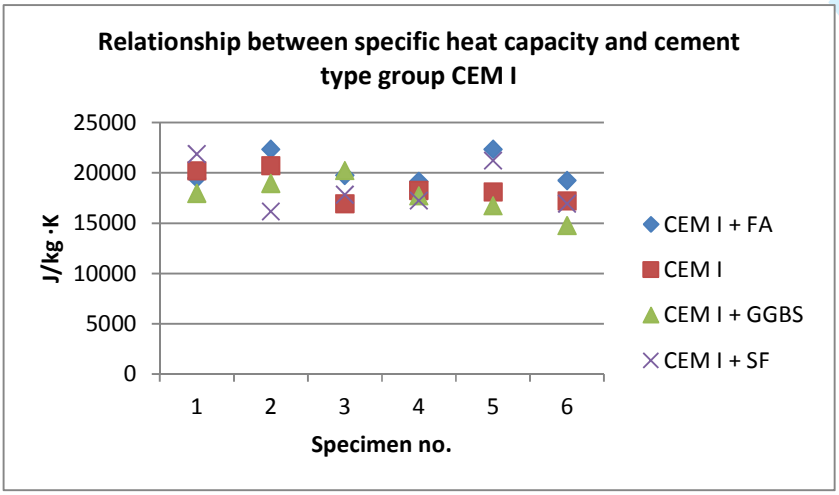


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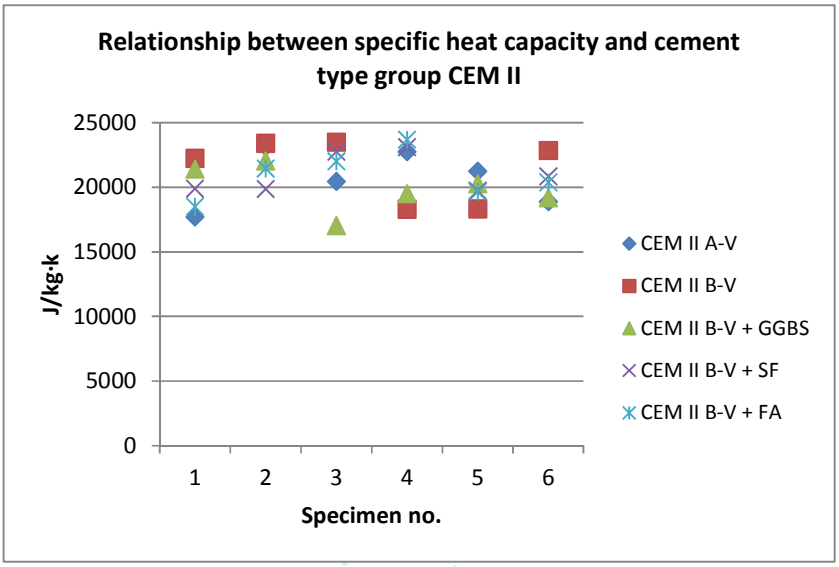
Figure 8 Relationship between specific heat capacity and cement type group CEM II



Age

Results show that specimens containing CEM I showed no statistical significant difference in specific heat capacity between 28 and 56 days (Figure 9).

Figure 9 Relationship between specific heat capacity and age: CEM I

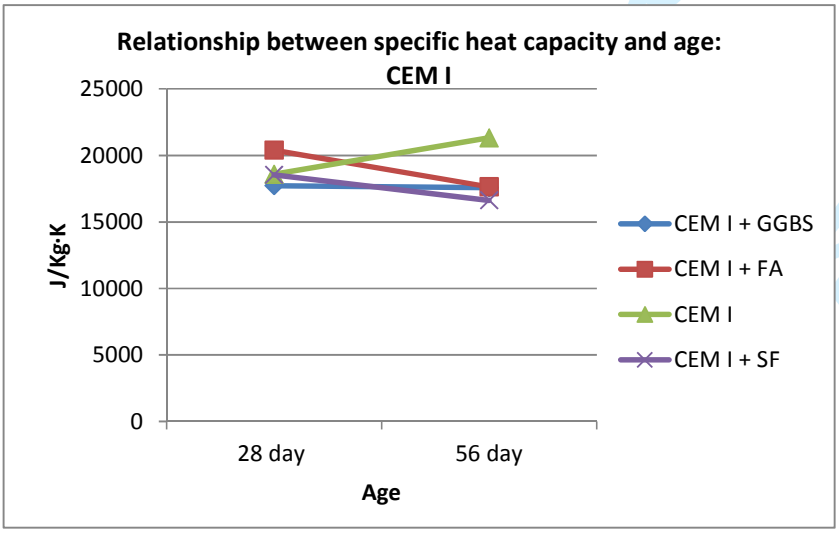
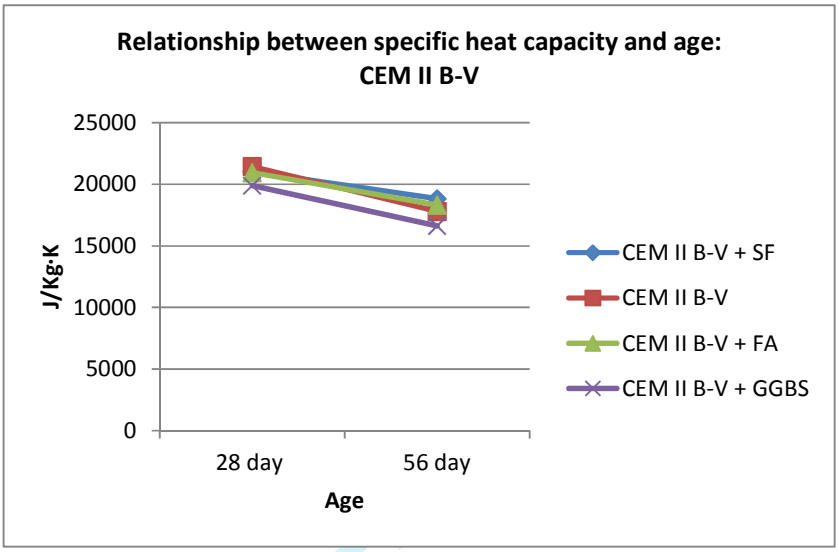


Figure 10 shows that specimens CEM II B-V, CEM II + GGBS, CEM II + FA decrease in specific heat capacity between 28 and 56 days age, however specimen CEM II + SF shows no difference in specific heat capacity with age. This finding shows important changes are still occurring from 28 - 56 days in CEM II B-V cement specimens, which can be related to their required extended curing time.

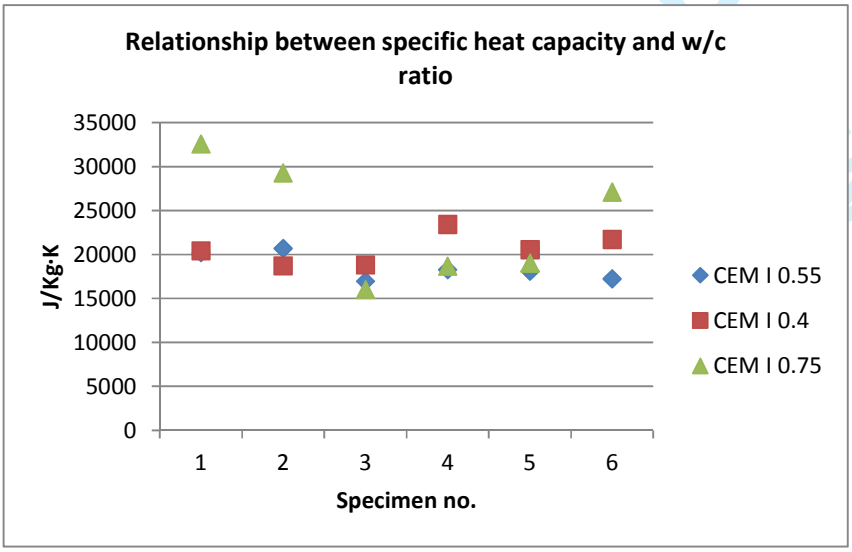
Figure 10 Relationship between specific heat capacity and age: CEM II B-V



W/c ratio

Results show there is no significant difference in specific heat between w/c ratios 0.4, 0.55 & 0.75 (Figure 11). This results supports the characteristics of specific heat, as the composition of the specimens are made with the same bulk materials therefore there is no additional material is available to enhance the specific heat of any one of the specimens.

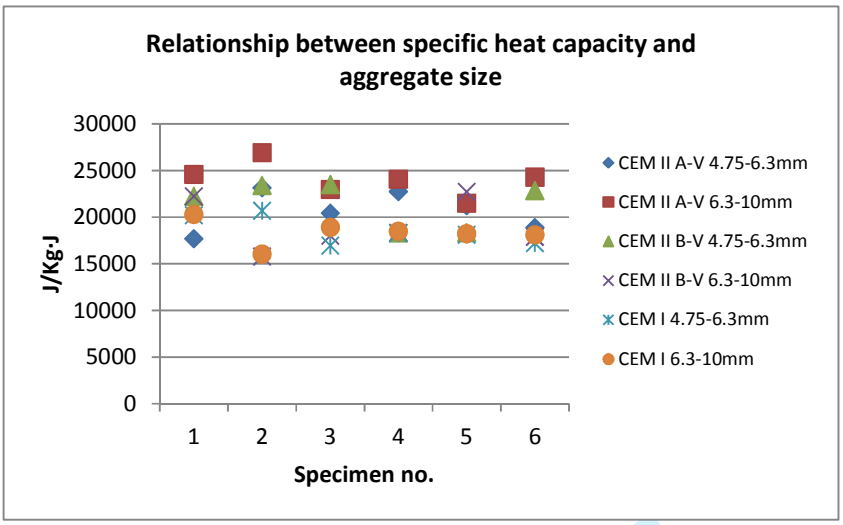
Figure11 Relationship between specific heat capacity and w/c ratio



Effect of Aggregate Size

Figure 12 shows that specimens containing cement type CEM II A-V with larger aggregate provide a higher specific heat than with smaller aggregate. Specimens CEM I & CEM II B-V shows no difference in specific heat with different aggregate size following the same trend as cement type specimens. The effect aggregate size has on specific heat changes with cement type, indicating cement type has a more dominant effect on specific heat than aggregate size. This is explained by the mass of the aggregate used in each specimen is a constant, with only the size changing.

Figure 12 Relationship between specific heat capacity and aggregate size



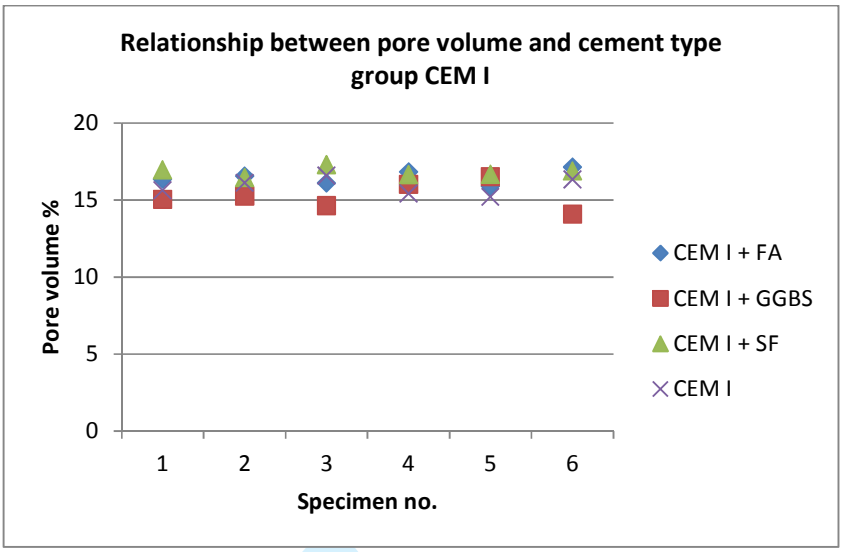
Review

Pore Volume

Cement type

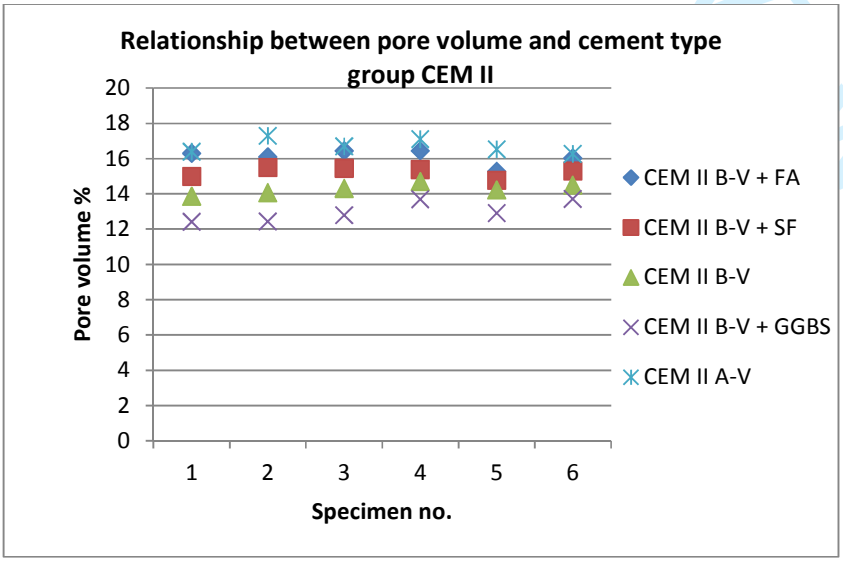
Results show that cement type has a significant effect on pore volume. CEM I specimen group has a higher average pore volume than CEM II specimens by 7%. CEM I + GGBS has the lowest pore volume, followed by CEM I which is 4% higher on average, CEM I + FA 7% higher and CEM I + SF 9% higher.

Figure 13 Relationship between pore volume and cement type group CEM I



Cement type group CEM II has a significant effect on the pore volume of concrete, as shown in Figure 14. CEM II B-V + GGBS has the lowest pore volume of the CEM II specimens, 15% lower than the lowest CEM I specimen. In comparison to the lowest CEM II specimen CEM II B-V had a 9% higher pore volume, CEM II B-V + SF 15% higher, CEM II B-V + FA 19% higher, and CEM II A-V 22% higher. The specimens with the lowest pore volume in both groups contain GGBS which is well known for a dense pore structure which contributes to higher strengths. However a lower pore volume does not necessarily correlate to the amount of replacement percentage contained, it is the cement type has a more dominant effect.

Figure 14 Relationship between pore volume and cement type group CEM II

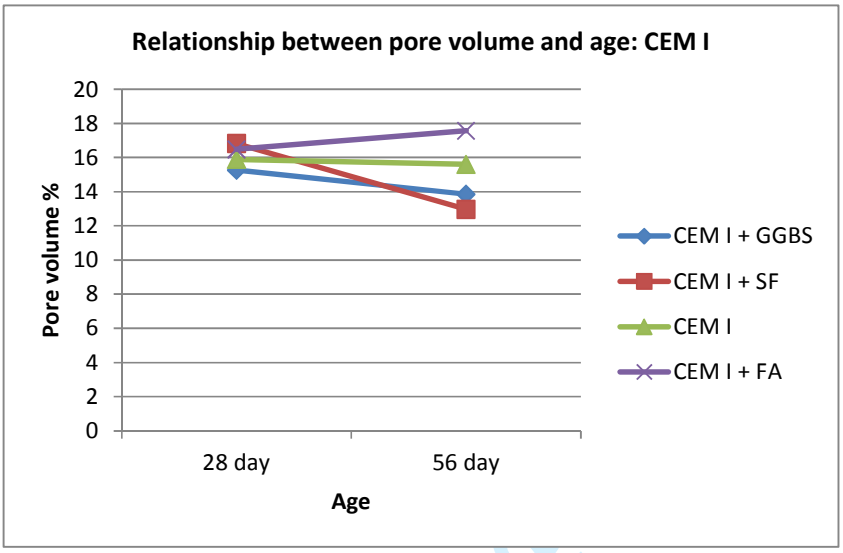


Age

For Peer Review

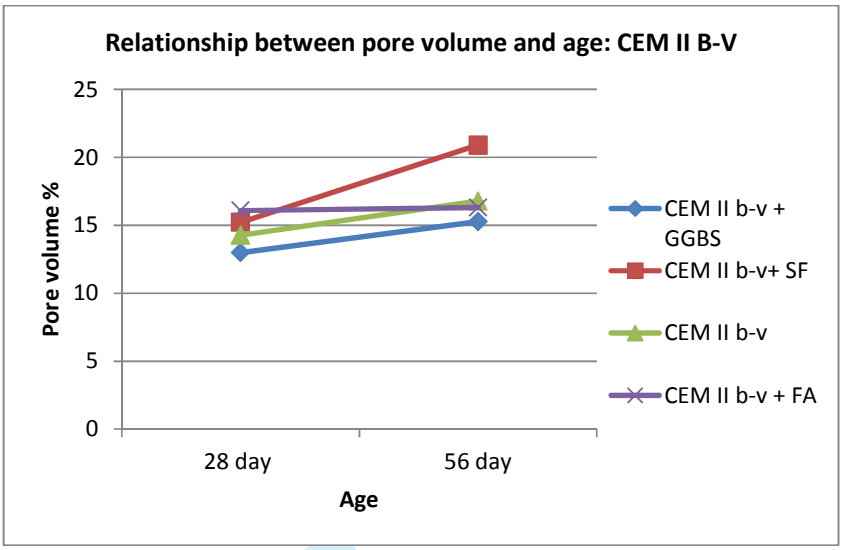
Results show that pore volume of specimens CEM I + GGBS & CEM I + SF decrease with age by 9% & 23% respectively. CEM I shows no difference in pore volume with age which is attributed to the fact that hydration of CEM I cement is largely complete by 28 days (Neville & Brooks, 2010, & Li, 2011). The pore volume of CEM I + FA 6 % is found to increase with age.

Figure 15 Relationship between pore volume and age: CEM I



No significant difference in pore volume is observed in specimen CEM II B-V+ FA with age. CEM II B-V + SF, CEM II B-V + GGBS & CEM II B-V, all increase in pore volume with age by 27%, 15% & 15% respectively. The increase in pore volume with age is thought to be due to the additional curing time allowing for the hydration of filler particles that block pores (Lam, Wong & Poon 2000, & Nazari & Riahi, 2011), which would provide additional pore volume. This result indicates each cement type has a different effect on pore volume, which can be linked to the differing hydration stages, required by different cement types (Li, 2011).

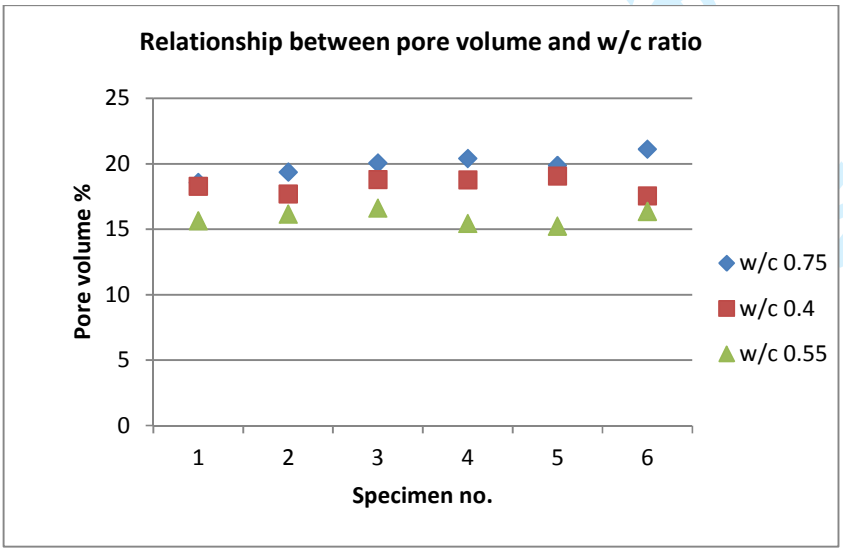
Figure 16 Relationship between pore volume and age: CEM II B-V



W/c ratio

Results show that w/c ratio has a significant effect on the pore volume of concrete specimens. The highest pore volume was produced by w/c ratio 0.75 with an average of 20%, followed by w/c ratio 0.4 with an average of 18% then 0.55 at 16%, as shown in Figure 17. This finding is attributed to the open pore network formed at higher w/c ratios, and the increased number of cracks and poorly formed structures with lower w/c ratios (Lagerbald, 2001).

Figure 17 Relationship between pore volume and w/c ratio

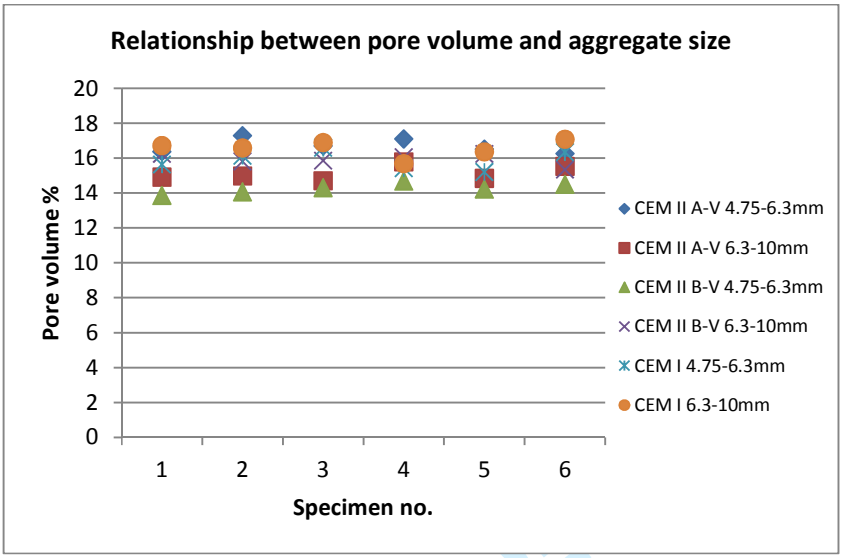


Effect of aggregate size

CEM I & CEM II B-V specimens with larger aggregate produced higher pore volumes by an average of 5% & 10%, however specimen CEM II A-V with smaller aggregate produced a higher pore volume

by 10% (figure 18). This finding indicates it is cement type which has a more dominant effect on pore volume than aggregate size, which is likely due to aggregate mass remaining the same between specimen groups and the differing cement types being responsible for the cement matrix composition which contains the gel and capillary pores (Neville & Brooks, 2010).

Figure 18 Relationship between pore volume and aggregate size

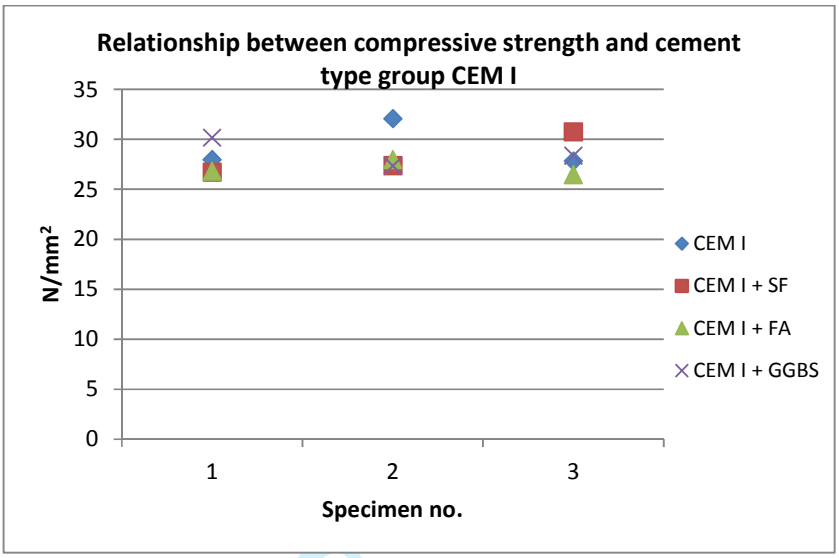


Compressive Strength

Cement type

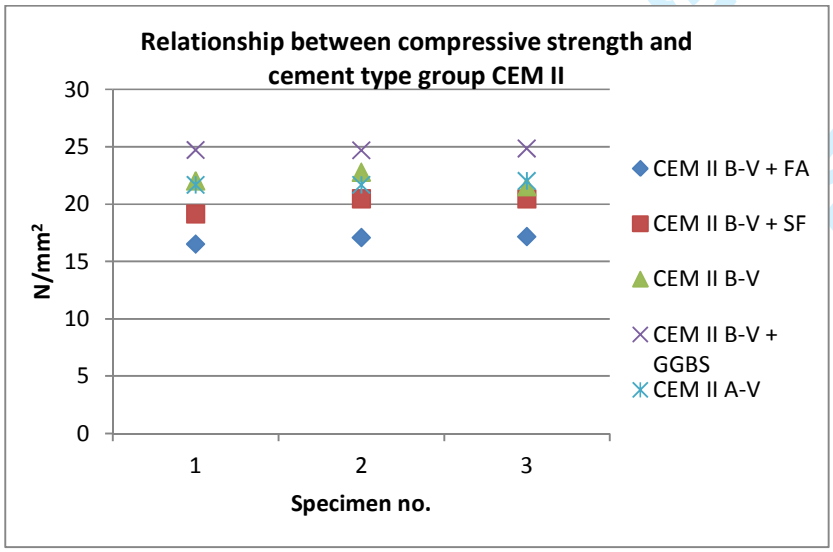
Results show that no statistical difference is observed in compressive strength between cement type CEM I specimens (Figure 19). This is expected as cement replacement percentages were applied as directed according to BS 197-1 (2011) to ensure appropriate strength gain.

Figure 19 Relationship between compressive strength and cement type group CEM I



Specimens containing cement type CEM II, show a lower mean compressive strength compared to specimens containing cement type CEM I. Figure 20 shows a difference in compressive strength is observed between the CEM II cement group specimens. CEM II B-V + FA produces lowest strength at a mean average of 16.92 N/mm^2, followed by CEM II B-V + SF 16% higher, CEM II A-V 22% higher, CEM II B-V 24% higher, with cement type CEM II B-V + GGBS 32% higher producing the highest compressive strength of CEM II specimens. These results are expected due to the slower and reduced strength gain properties of CEM II specimens.

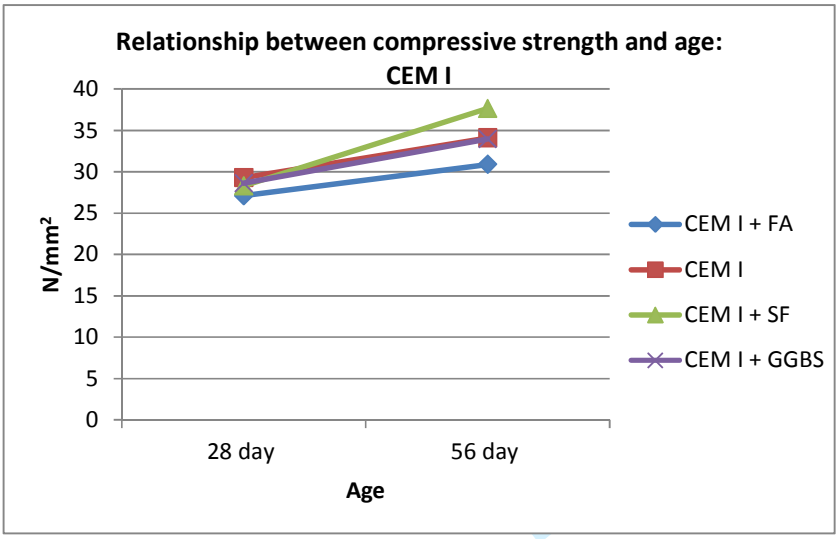
Figure 20 Relationship between compressive strength and cement type group CEM II



Age

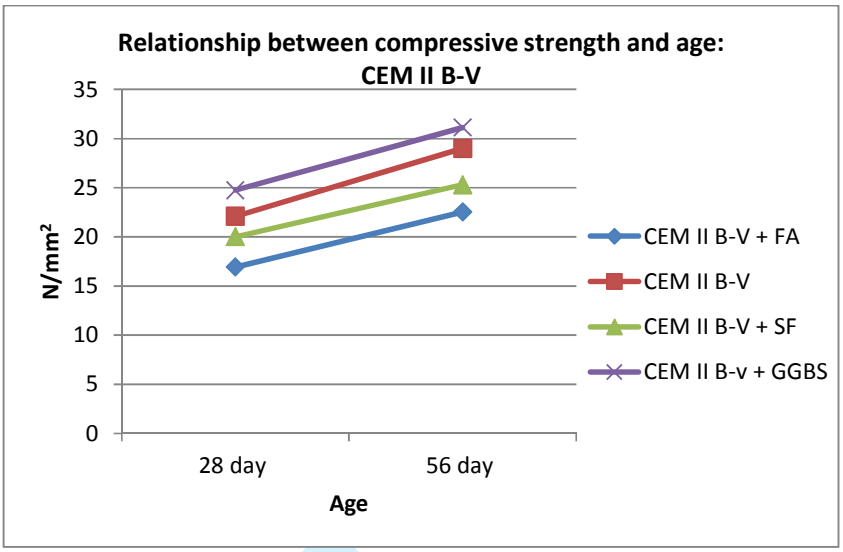
Figure 21 shows the relationship between the compressive strength of CEM I specimens between 28 – 56 days. CEM I + SF, CEM I + GGBS & CEM I + FA increase in compressive strength. CEM I + SF shows the highest increase in compressive strength at 25%, followed by CEM I + GGBS having a 16% increase, CEM I + FA increased by 12%. However 100% CEM I specimens shows no statistical significance in compressive strength from 28 – 56 days.

Figure 21 Relationship between compressive strength and age: CEM I



Compressive strength increases with age in all CEM II B-V specimens. Figure 22 shows that CEM II B-V increases by 15%, CEM II B-V + SF 21%, CEM II B-V + GGBS 21%, CEM II B-V 24 %. These results are expected due to cement replacements requiring extended curing time for strength gain; although porosity shows to increase due to hydration of filler particles blocking pores, while a large proportion of strength gain has occurred by 28 days in CEM I specimens.

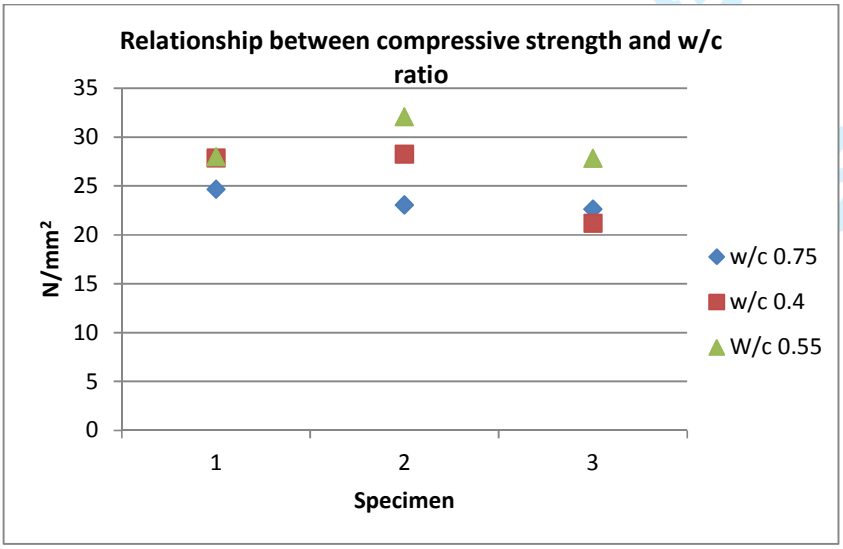
Figure 22 Relationship between compressive strength and age 28 – 56 day: CEM II B-V



W/c ratio

The compressive strength of w/c ratio specimens does not show a significant difference between specimens, although Figure 23 shows that the specimens do still follow a trend. W/c ratio 0.75 produced the lowest compressive strength, followed by w/c ratio 0.4, 9% higher, with w/c 0.55 achieving the highest compressive strength 20% higher. This result is likely to be due to the unstable effects of higher and lower w/c ratio, which forms irregularities in the structure of concrete (Lagerbald, 2001).

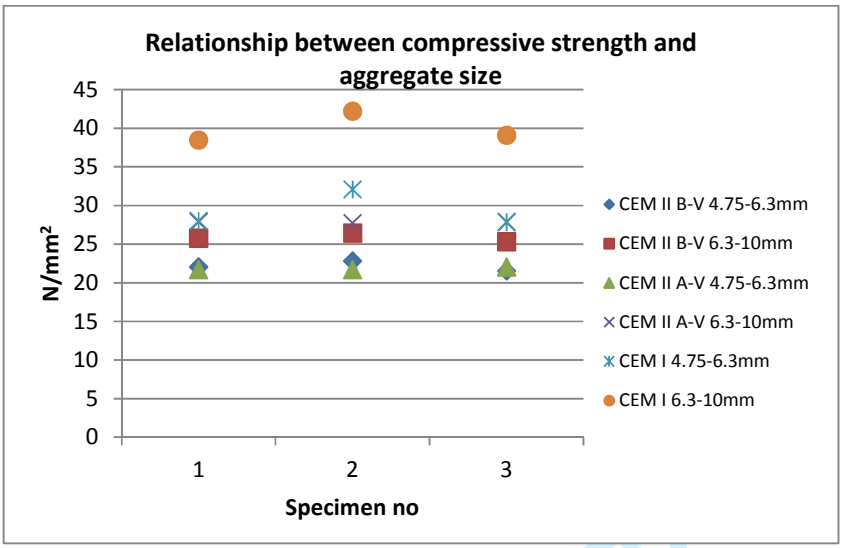
Figure 23 Relationship between compressive strength and w/c ratio



Effect of Aggregate size

Compressive strength increases in each specimen with larger aggregate size. Figure 24 shows that CEM I has the highest strength at 28 days, followed by CEM II A-V with CEM II B-V providing the lowest compressive strength. However, aggregate size is not the only factor effecting compressive strength, as aggregate size specimens CEM II B-V and CEM II A-V with larger aggregate produces lower strengths than the CEM I with smaller aggregate (Table 2), indicating some cement types with smaller aggregate can provide higher strengths than other cement types with larger aggregate.

Figure 24 Relationship between compressive strength and aggregate size



Density

Cement type

A similar variation in density is observed between cement types (Figure 25 & 26). Within the CEM I cement type group, CEM I + GGBS produces highest density, CEM I + SF was 4% lower, with CEM I + FA and CEM I producing the lowest density 6% lower, shown in Figure 25.

Figure 25 Relationship between density and cement type group CEM I

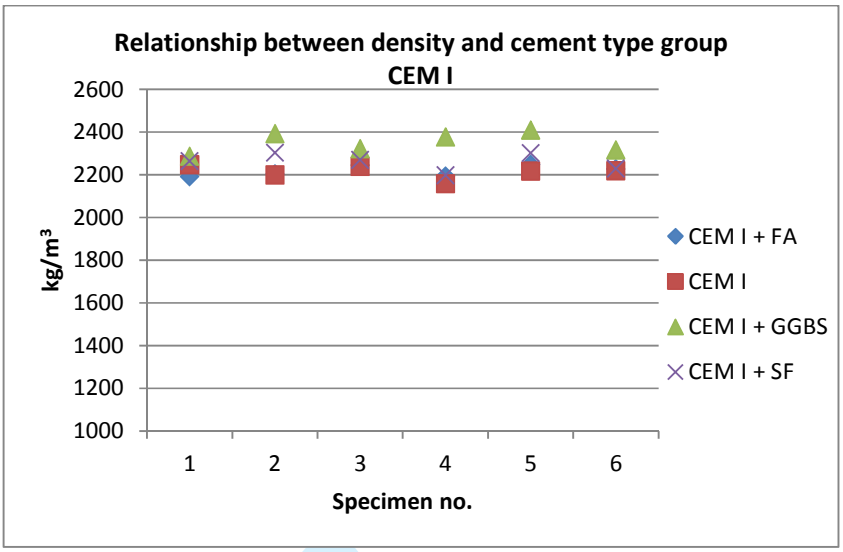
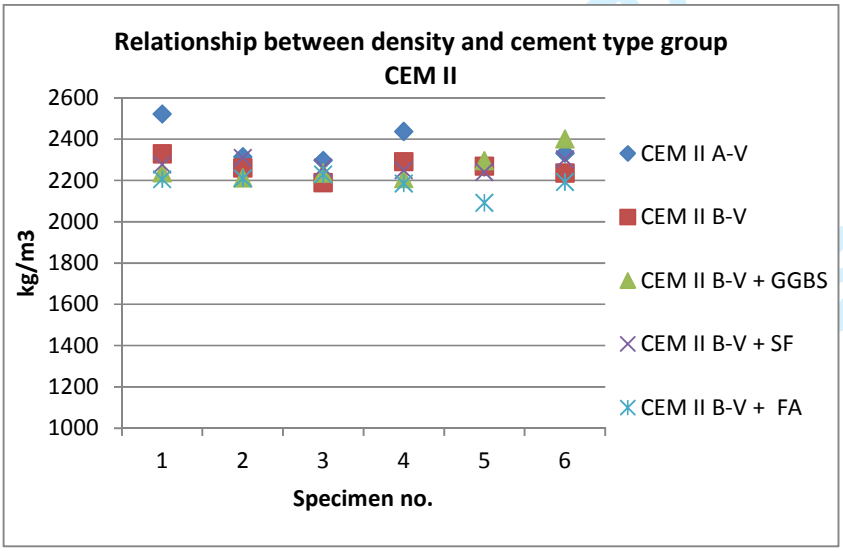


Figure 26 shows that CEM II A-V produces the highest density, followed by CEM II B-V +SF 4% lower, CEM II B-V + GGBS & CEM II B-V 5% lower, followed by CEM II B-V + FA 8 % lower. Specimen CEM I + GGBS & CEM II B-V + GGBS produced the highest density in each group which also corresponds to the lowest pore volume in each group. However, overall differences in the densities between the specimens are minimal.

Figure 26 Relationship between density and cement type group CEM II

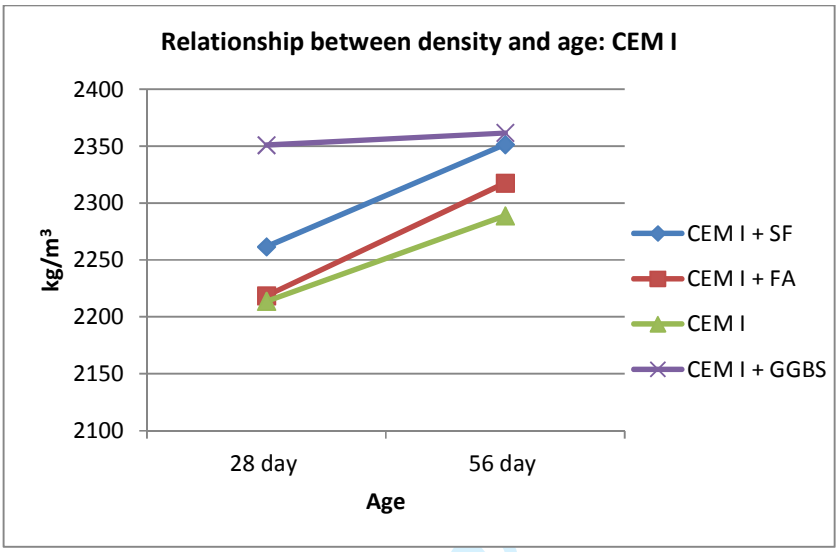


Age

A minimal difference in density is observed in CEM I specimens between 28 and 56 days. Figure 27 shows that specimens CEM I, CEM I + SF, & CEM I + FA increase in density from 28 to 56 days by 3%, 4% & 4% respectively. Specimen CEM I + GGBS shows no difference in density with age. This

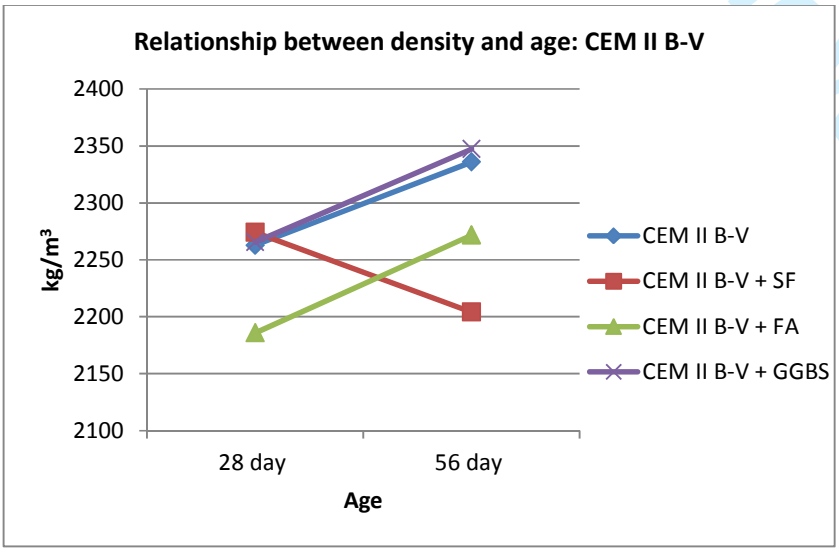
is attributed to the hydration process of CEM I being nearly complete at 28 days, however small hydration processes are still occurring, which changes the pore structure of the concrete.

Figure 27 Relationship between density and age: CEM I



Results show that specimens CEM II B-V & CEM II B-V + FA show no statistical significant difference in density between 28 and 56 days. Specimen CEM II B-V + SF shows a 3% decrease in density from age 28 – 56 day and CEM II B-V + GGBS shows a 3% increases in density from age 28 – 56 day. Although statistical significant differences between the groups are observed, as with cement type specimens the differences are minimal.

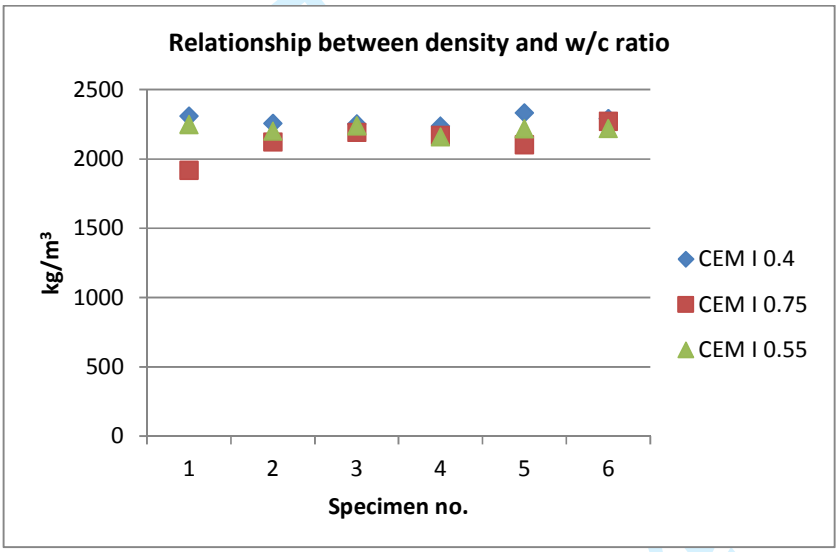
Figure 28 Relationship between density and age: CEM II B-V



W/c ratio

Results show that density is effected by different w/c ratios of concrete specimens, however only by a minimal amount. W/c 0.4 has the highest density, although this does not correspond to lowest pore volume. This could be attributed to the fact that although low w/c ratios are reported to provide denser pore structures, they are also reported to be at risk of developing more coarse open cracks during heat treatment, which occurred during the pore volume testing (Tolentino et al, 2002). W/c 0.55 was only 3% less dense and w/c 0.75, 7% less dense than w/c 0.4 (Figure 29).

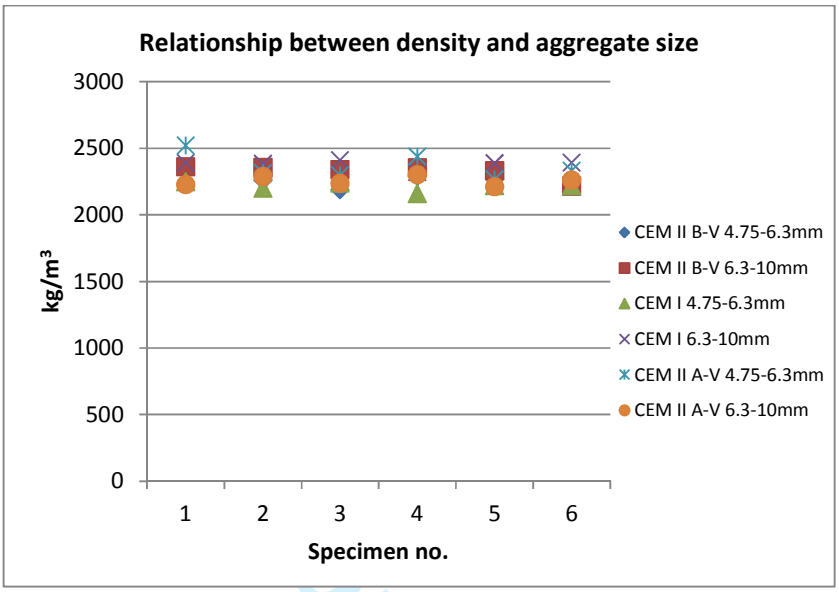
Figure 29 Relationship between density and w/c ratio



Effect of Aggregate size

Results show that CEM I specimens increase in density with a larger aggregate size however CEM II A-V increases in density with a smaller aggregate size. Aggregate size specimens containing CEM II B-V show no statistical difference in density with different aggregate sizes. This is attributed to the mass of aggregate remaining at a constant, with the only variation being size; therefore no trend with aggregate size is observed.

Figure 30 Relationship between density and aggregate size



Conclusion

Investigation into the thermal properties of concrete with alternative binder material has shown;

- Cement type specimen CEM I produced the lowest thermal conductivity by a maximum of 30%. Overall specimens from CEM I cement type group have lower thermal conductivity compared to the specimens from the CEM II cement type group, which also corresponds to higher pore volume and lower densities gained by CEM I group specimens. Specific heat is higher in cement types containing CEM II, with cement type being the dominant factor determining specific heat. CEM I specimens as a group have a higher compressive strength, compared to CEM II specimens, and have gained a large proportion of their strength by 28 days.
- W/c ratio 0.55 provides lowest thermal conductivity values, and the highest compressive strength. W/c ratio makes no difference to the specific heat capacity of concrete however a w/c ratio 0.55 has been found to provide the most beneficial properties with most consistent results, compared to w/c ratios 0.4 & 0.75 which tend to present more erratic results.
- Aggregate size effects the compressive strength of concrete, increasing compressive strength with increasing aggregate size, however cement type has a more dominant effect with smaller aggregate producing higher strengths in different cement types. In addition cement type has a more dominant effect than aggregate size on all the properties tested.
- Specimens with the lowest pore volumes correspond to the highest densities in both cement type specimen groups.
- Overall cement type has been found to have the most dominant effect on the properties tested.

For Peer Review

Steady state heat transfer experiment with controlled moisture content has provided an alternative insight on the thermal behaviour of cement types, which has implications for arid climates and certain environmental conditions.

Further work

Recommendations for further research are;

- Implementation of thermal results into an environmental computer simulation package to determine their effect on an integrated building system as a whole.
- Investigation into concrete microstructure using SEM and EDX analysis to link physical test results to pore structure formations.

References

American Concrete Institute, (2002), *Guide to Thermal Properties of Concrete and Masonry Systems ACI 122R-02*, Pennsylvania: American Society for Testing Materials.

Bennett. D., (2010), *Sustainable concrete architecture*, London: RIBA Publishing.

BIS, (2010), 'Estimating the amount of CO_2 emissions that the construction industry can influence', [Online], Available at; www.bis.gov.uk, (Accessed 27/11/2011).

British Standards Institute, (2011), BS EN 197-1:2011, Cement. Composition, specifications and conformity criteria for common cements, London: British Standards Institute.

British Standards Institute, (1986), BS 1881-125:1986, Testing concrete. Methods for mixing and sampling fresh concrete in the laboratory, London: British Standards Institute.

British Standards Institute, (2009), BS EN 12390-3, Testing hardened concrete, Part 3: Compressive strength of test specimens, London: British Standards Institute.

British Standards Institute, (1988), BS 874-2.2:1988, Methods for determining thermal insulating properties. Tests for thermal conductivity and related properties. Unguarded hot-plate method, London: British Standards Institute.

British Standards Institute, (2009), BS EN 12390-7, Testing fresh content, Part 7: Air content - Pressure methods, London: British Standards Institute.

Constantinides. G. & Ulm. F.J., (2007), 'The nanogranular nature of C–S–H', *Journal of the Mechanics and Physics of Solids*, Vol. 55, Issue 1, pg 64-90, Elsevier.

For Peer Review

Demirboga. R., (2003), 'Influence of mineral admixtures on thermal conductivity and compressive strength of mortar', *Energy and Buildings*, Vol. 35, pg189-192, Elsevier.

De Saulles. T., (2010), 'Changes to Part L and the implications for heavyweight buildings', *The Concrete Centre: Specifying Low Carbon Buildings*, Southbank Centre London 7th October, mpa The Concrete Centre, Available at: www.concretecentre.com, (Accessed:21/10/2010).

Fu. X., & Chung. D.D.L., (1997), 'Effects of silica fume, latex, methlcellulose, and carbon fibres on the thermal conductivity and specific heat of cement paste', *Cement and Concrete Research*, Vol. 27, No. 12. pp. 1799-1804. 1997, Pergamon.

Kim, K.H., Jeon. S.E., Kim. J.K. & Yang. S., (2002), 'An experimental study on thermal conductivity of concrete', *Cement and Concrete Research*, Vol. 33, pg 363 – 371, Pergamon.

Kaynakli. O., (2012), 'A review of the economical and optimum thermal insulation thickness for building applications', Renewable and Sustainable Energy Reviews, Vol.16, pg 415-425.

Kumar. R., & Bhattacharjee. B, (2003), 'Porosity, pore size distribution and in situ strength of concrete', Cement and Concrete Research, vol. 33, 155-164, Pergamon.

Lagerbald. B., (2001), '*Leaching performance of concrete based on studies of samples from old concrete constructions',* Technical report TR- 01-27, Swedish Cement and Concrete Research Institute.

Lagüela. S., Martínez. J., Armesto. J, &Arias. P, (2011),'Energy efficiency studies through 3D laser scanning and thermographic technologies', *Energy and Buildings,* Vol. 43, pg 1216-1221, Elsevier.

Lam. L., Wong. Y.L., & Poon. C.S., (2000), 'Degree of hydration and gel/space ratio of high-volume fly ash/cement systems', *Cement and Concrete Research*, Vol. 30, pg 747-756, Pergamon.

Li. Z., (2011), *Advanced Concrete Technology*, New Jersey: John Wiley and Sons Inc.

MacMullen. J, Zhang. Z., Rirsch. E., Dhakal. H. N. & Bennett. N., (2011), 'Brick and mortar treatment by cream emulsion for improved water repellence and thermal insulation', *Energy and Buildings*, Vol.43, pg1560–1565, Elsevier.

Nazari. A. & Riahi. S., (2011), 'TiO2 nanoparticles effects on physical, thermal and mechanical properties of self compacting concrete with ground granulated blast furnace slag as binder', *Energy and Buildings*, Vol.43, pg 995-1002, Elsevier.

NBS, (2010), '*Building Regulations Approved Document Part L 1a: Conservation of fuel and power in new dwellings'*, London: RIBA.

For Peer Review

Neville. A. M., & Brooks. J. J., (2010), *Concrete Technology,* 2nd ed., Edinburgh: Pearson.

Oner. A & Akyuz. B, (2007), 'An experimental study on optimum usage of GGBS for the compressive strength of concrete', *Cement and Concrete Composites*, Vol. 29, pg 505-514, Elsevier.

The Concrete Centre, (2010), *'Concrete Industry Sustainability Performance Report 2010'*, [Online], Available at: www.concretecentre.com/publications, (Accessed: 21/10/2010).

Tolentino. E., Lameiras. F. S., Gomes. A. M., Rigo da Silva. C. A., & Vasconcelos. W. L., (2002), 'Structural Evaluation and Performance of Portland Cement Concretes After Exposure to High Temperatures', *Materials Research*, Vol. 5, pg 27-36.

Raupach. M, & Fraser. P, (2011), Climate and greenhouse gases, Vol. 1, pg 15-34, CSIRO publishing

Wang. K.S., Tseng. C.J., Chiou. I.J. & Shih. M.H, (2005), 'The thermal conductivity mechanism of sewage sludge ash lightweight materials', *Cement and Concrete Research*, Vol.35, pg 803– 809, Pergamon

Yesilata. B.,& Turgut. P., (2007), 'A simple dynamic measurement technique for comparing thermal insulation performances of anisotropic building materials', *Energy and Buildings,* Vol. 39, pg 1027 – 1034, Elsevier.

Zivica. V., (2009), 'Effects of the very low water/cement ratio', *Construction and Building Materials,* Vol. 23, pg 3579 – 3582, Elsevier.

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Table 1 Mean test results with standard deviation (SD)

Cement type (28 day)	**Thermal conductivity (W/m·K)**	***SD***	**Specific Heat Capacity (J/kg K)**	***SD***	**Pore Volume (%)**	***SD***	**Bulk density (Kg/m^3)**	***SD***	**Comp strength (N/mm^2)**	***SD***
CEM I	0.1977	*0.011*	18581	*1548*	15.89	*0.55*	2219	*31.64*	29.29	*2.41*
CEM I + FA	0.2018	*0.022*	20405	*1535*	16.48	*0.46*	2227	*25.53*	27.09	*0.78*
CEM I + GGBS	0.2261	*0.008*	17735	*1881*	15.27	*0.89*	2315	*49.00*	28.63	*1.43*
CEM I + SF	0.2284	*0.011*	18555	*2392*	16.82	*0.29*	2228	*41.63*	30.29	*5.61*
CEM II A-V	0.2393	*0.015*	20701	*2135*	16.71	*0.41*	2331	*97.95*	21.79	*0.20*
CEM II B-V	0.2612	*0.014*	21446	*2463*	14.27	*0.30*	2262	*47.93*	22.11	*1.20*
CEM II B-V + FA	0.2818	*0.017*	20943	*1841*	16.09	*0.43*	2185	*48.14*	16.93	*0.36*
CEM II B-V + GGBS	0.2608	*0.019*	19900	*1779*	12.99	*0.58*	2265	*73.24*	24.76	*0.08*
CEM II B-V + SF	0.2532	*0.022*	21037	*1530*	15.22	*0.29*	2274	*27.89*	20.02	*0.77*
Cement type (56 day)	**Thermal conductivity (W/m·K)**	***SD***	**Specific Heat Capacity (J/kg K)**	***SD***	**Pore Volume (%)**	***SD***	**Bulk density (Kg/m^3)**	***SD***	**Comp strength (N/mm^2)**	***SD***
CEM I	0.2226	*0.010*	21325	*3598*	15.60	*0.73*	2288	*56.08*	34.09	*2.86*
CEM I + FA	0.2424	*0.019*	17649	*3308*	17.58	*1.02*	2317	*44.66*	30.89	*0.35*
CEM I + GGBS	0.2251	*0.012*	17581	*1690*	13.86	*0.84*	2274	*68.54*	33.97	*2.11*
CEM I + SF	0.2342	*0.013*	16625	1790	12.98	*0.59*	2336	*92.02*	37.65	*5.50*
CEM II B-V	0.2260	*0.023*	17790	*2105*	16.95	*0.85*	2364	*123.6*	29.01	*0.94*
CEM II B-V + FA	0.2330	*0.015*	18313	*1495*	16.49	*0.81*	2125	*115.2*	22.53	*1.15*
CEM II B-V + GGBS	0.2059	*0.031*	16625	*2598*	15.27	*0.44*	2356	*26.37*	31.13	*1.15*
CEM II B-V + SF	0.2549	*0.013*	18816	*3859*	20.89	*0.61*	2256	*62.26*	25.31	*0.62*
w/c ratio (28 day)	**Thermal conductivity (W/m·K)**	***SD***	**Specific Heat Capacity (J/kg K)**	***SD***	**Pore Volume (%)**	***SD***	**Bulk density (Kg/m^3)**	**SD**	**Comp strength (N/mm^2)**	***SD***
0.75	0.2207	*0.018*	23775	*6744*	19.89	*0.88*	2129	*119.3*	23.45	*1.08*
0.55	0.1977	*0.011*	18581	*1548*	15.89	*0.55*	2219	*31.64*	29.29	*2.41*
0.4	0.2278	*0.024*	20609	*1789*	18.35	*0.63*	2279	*37.18*	25.76	*3.98*
Aggregate size (28 days)	**Thermal conductivity (W/m·K)**	***SD***	**Specific Heat Capacity (J/kg K)**	***SD***	**Pore Volume (%)**	***SD***	**Bulk density (Kg/m^3)**	***SD***	**Comp strength (N/mm^2)**	***SD***
CEM II A-V (6.3-10mm)	0.2331	*0.014*	24069	*1805*	15.13	*0.43*	2261	*36.14*	27.82	*0.08*
CEM II A-V (4.75-6.3mm)	0.2393	*0.015*	20701	*2135*	16.48	*0.70*	2331	*97.95*	21.79	*0.20*
CEM II B-V (6.3-10mm)	0.288	*0.022*	19164	*2730*	15.92	*0.34*	2215	*55.37*	25.83	*0.57*
CEM II B-V (4.75-6.3mm)	0.2612	*0.015*	21446	*2463*	14.27	*0.30*	2262	*47.93*	21.64	*1.37*
CEM I (6.3-10mm)	0.2318	*0.012*	18415	*1382*	16.56	*0.49*	2392	*30.84*	39.91	*1.99*
CEM I (4.75-6.3mm)	0.1977	*0.011*	18581	*1548*	15.89	*0.55*	2219	*31.64*	29.29	*2.41*

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Figures

Figure 1 Relationship between thermal conductivity and cement type group CEM I

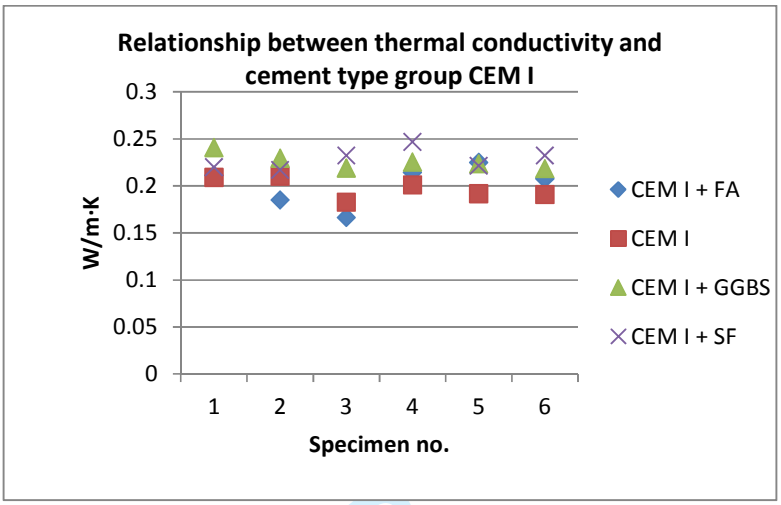


Figure 2 Relationship between thermal conductivity and cement type group CEM II

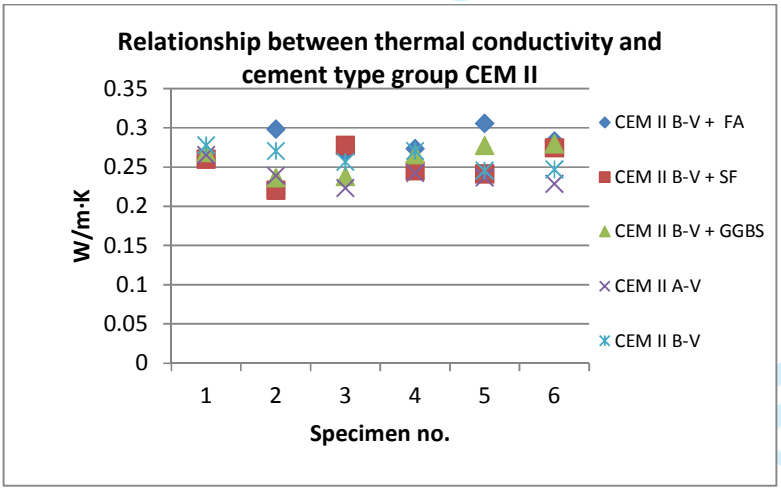


Figure 3 Relationship between thermal conductivity and age: CEM I

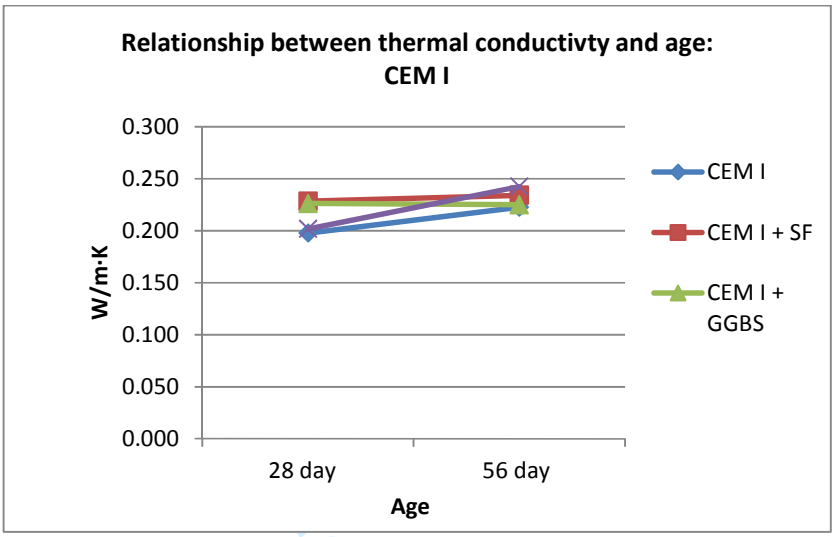


Figure 4 Relationship between thermal conductivity and age: CEM II B-V

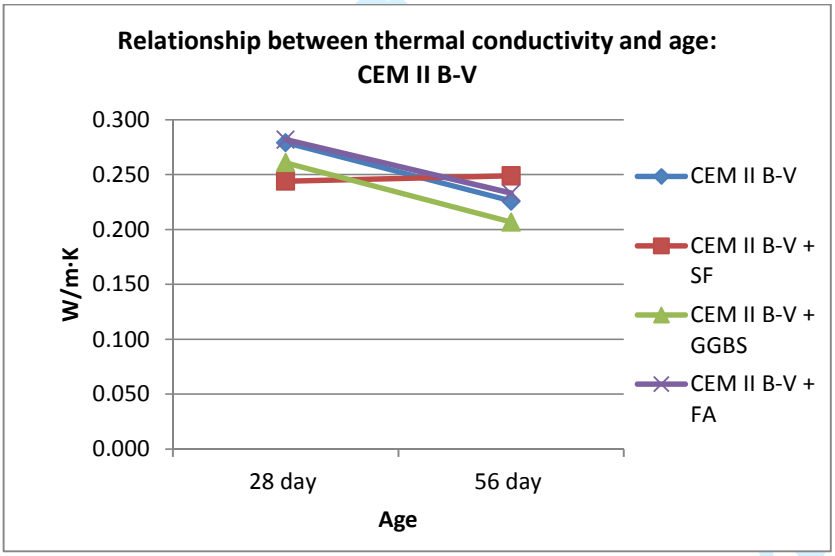


Figure 5 Relationship between thermal conductivity and w/c ratio

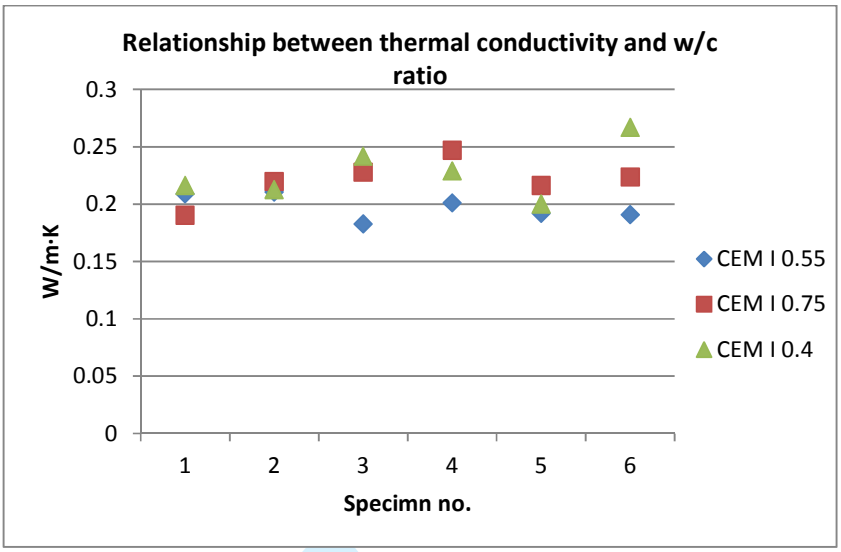


Figure 6 Relationship between thermal conductivity and aggregate size

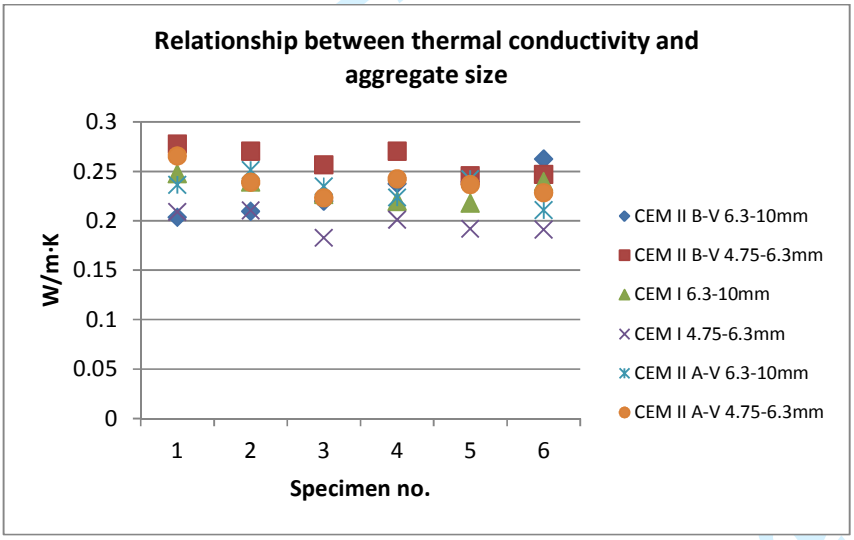


Figure 7 Relationship between specific heat capacity and cement type group CEM I

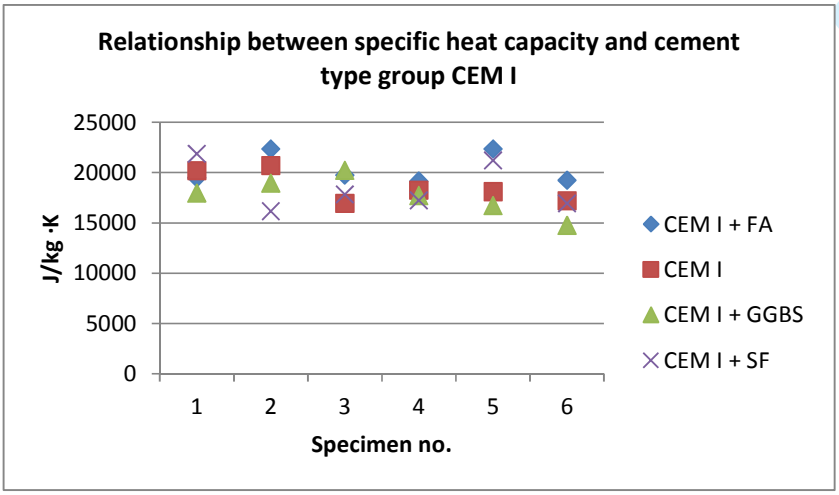


Figure 8 Relationship between specific heat capacity and cement type group CEM II

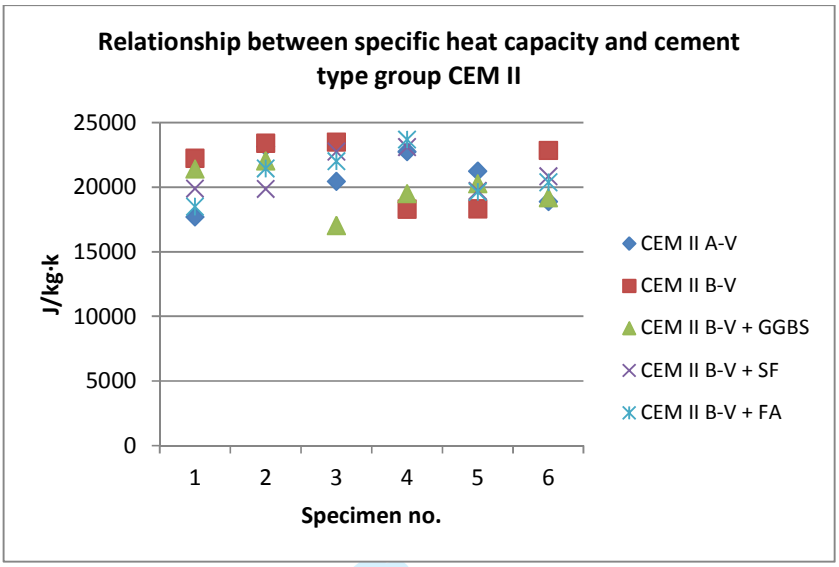


Figure 9 Relationship between specific heat capacity and age: CEM I

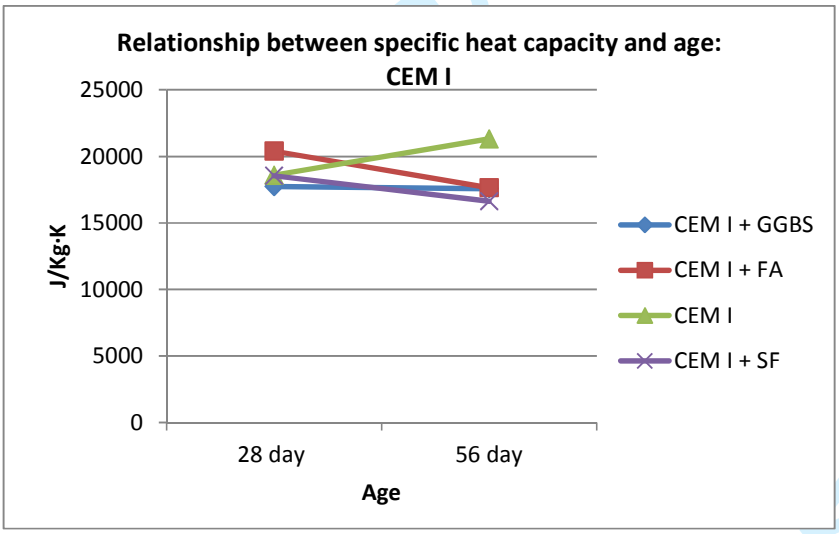


Figure 10 Relationship between specific heat capacity and age: CEM II B-V

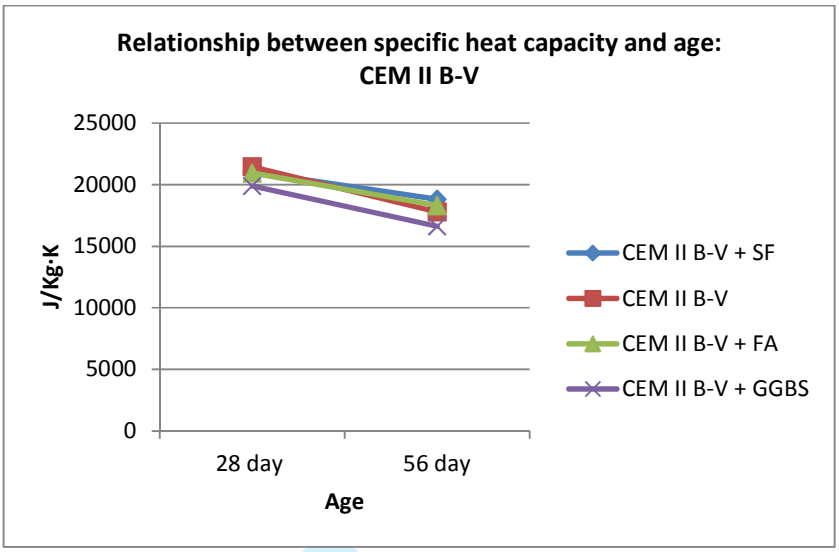


Figure11 Relationship between specific heat capacity and w/c ratio

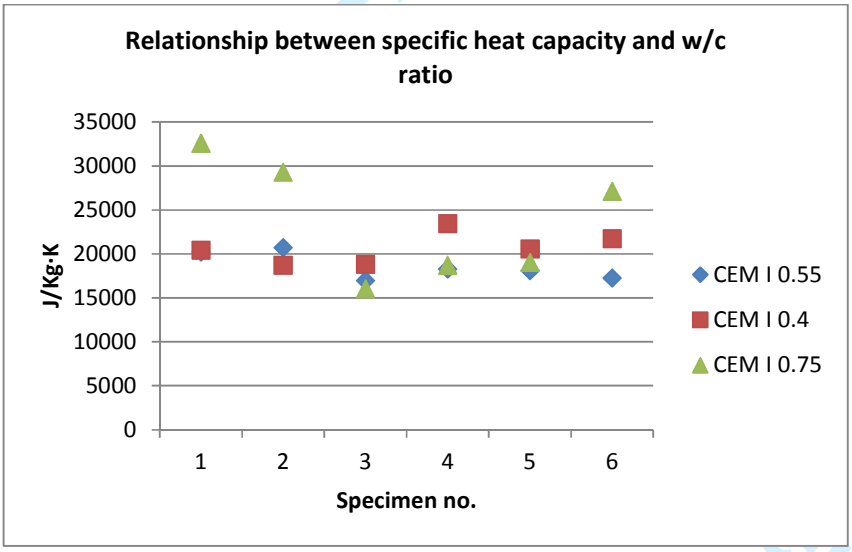


Figure 12 Relationship between specific heat capacity and aggregate size

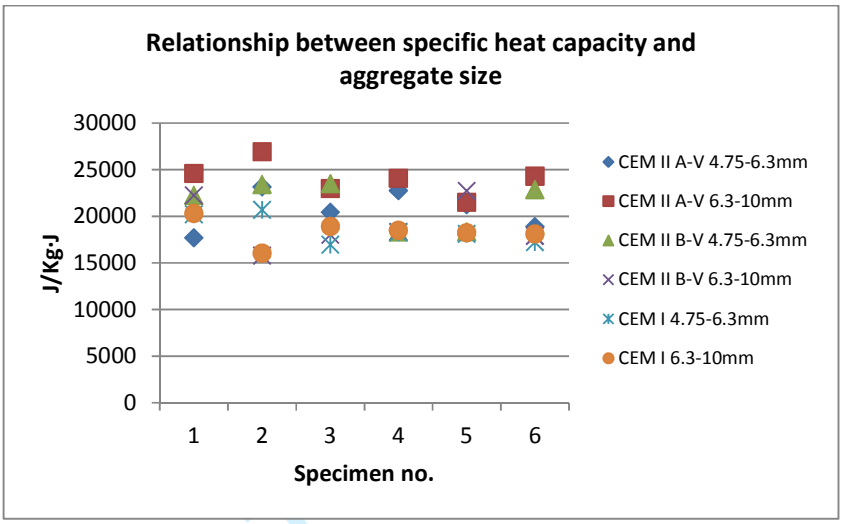


Figure 13 Relationship between pore volume and cement type group CEM I

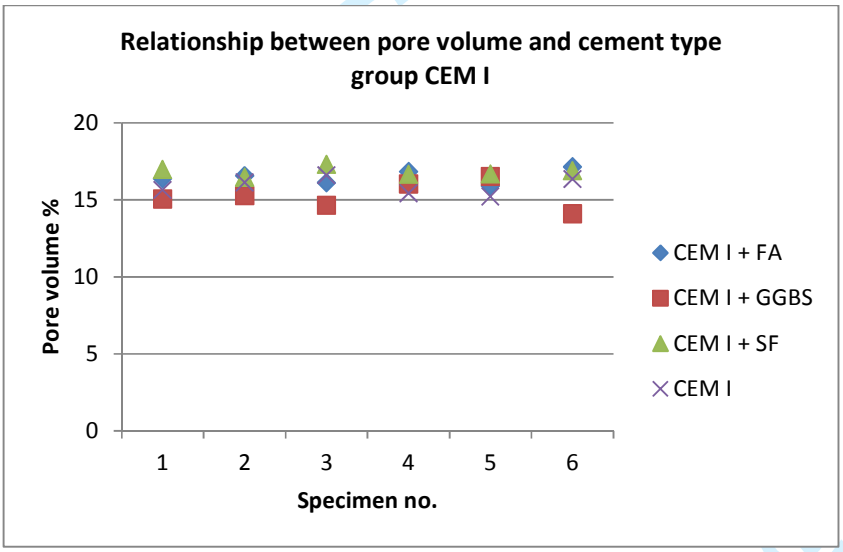


Figure 14 Relationship between pore volume and cement type group CEM II

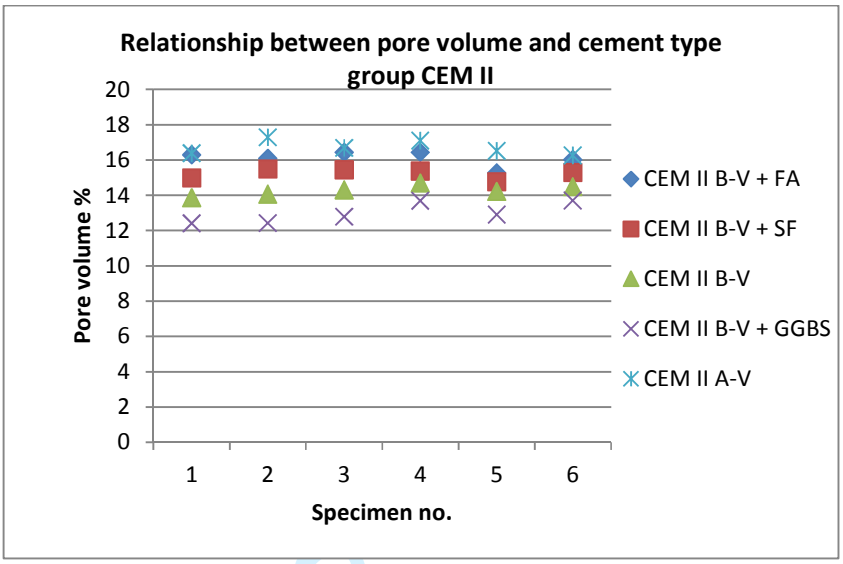


Figure 15 Relationship between pore volume and age: CEM I

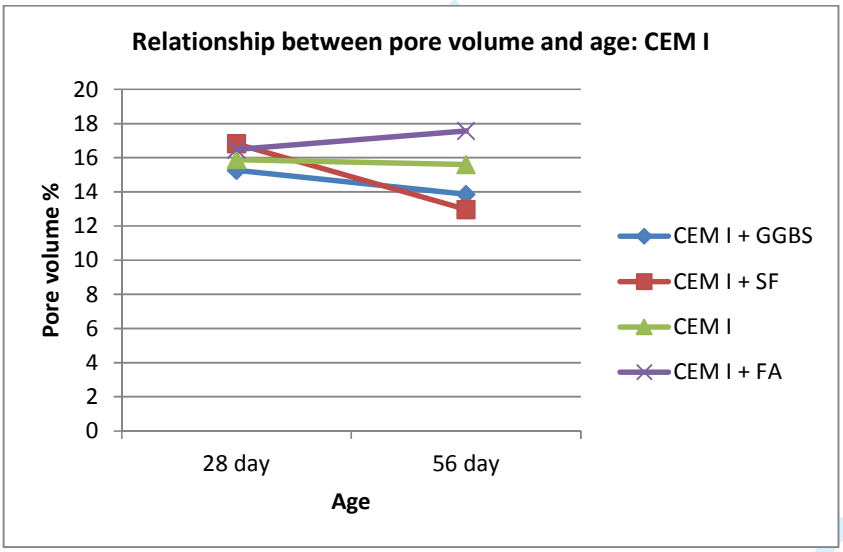


Figure 16 Relationship between pore volume and age: CEM II B-V

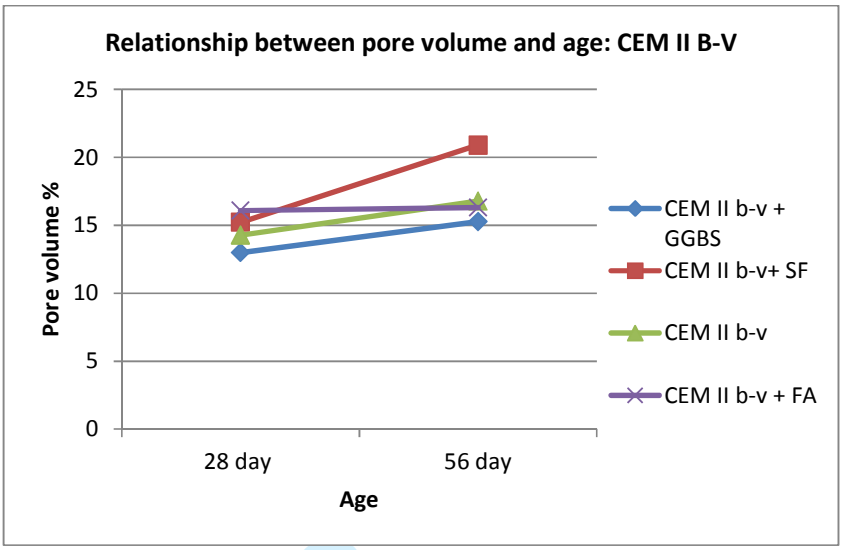


Figure 17 Relationship between pore volume and w/c ratio

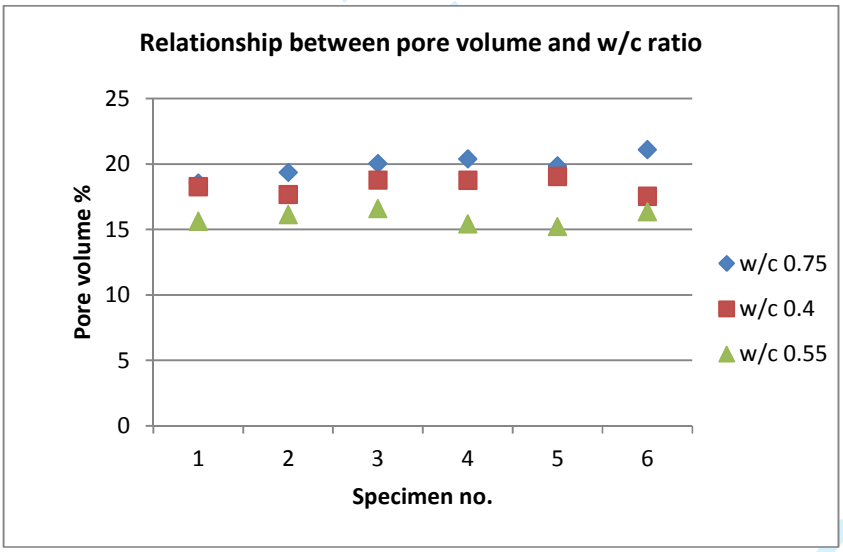


Figure 18 Relationship between pore volume and aggregate size

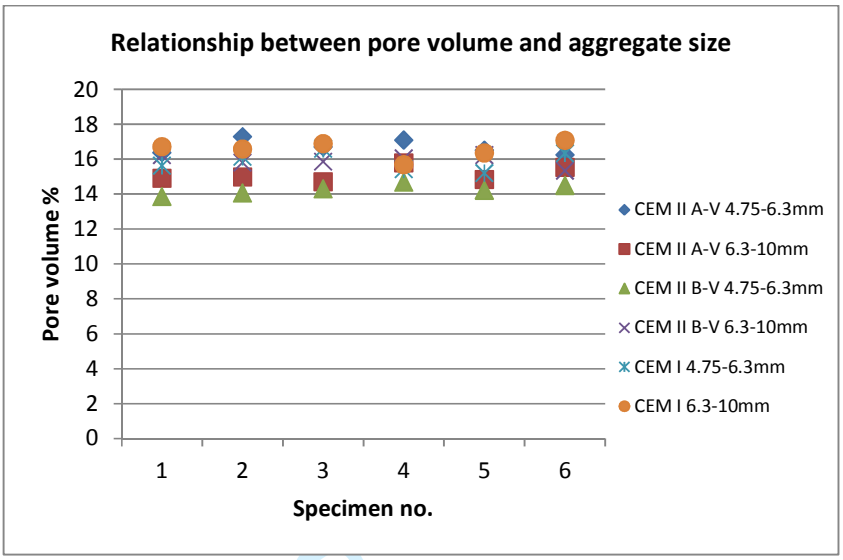


Figure 19 Relationship between compressive strength and cement type group CEM I

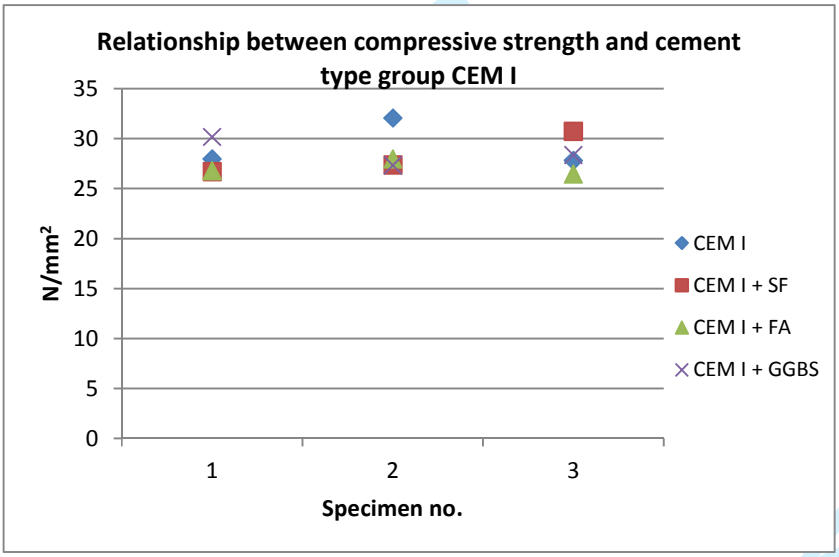


Figure 20 Relationship between compressive strength and cement type group CEM II

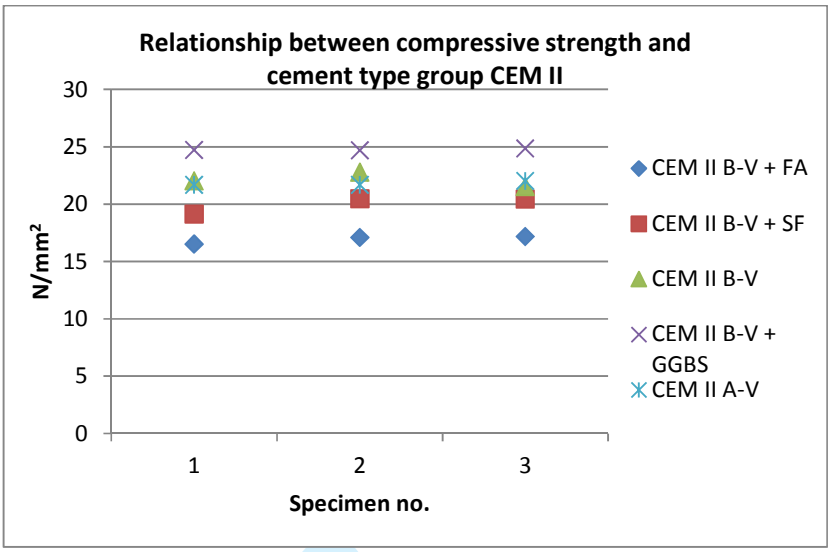


Figure 21 Relationship between compressive strength and age: CEM I

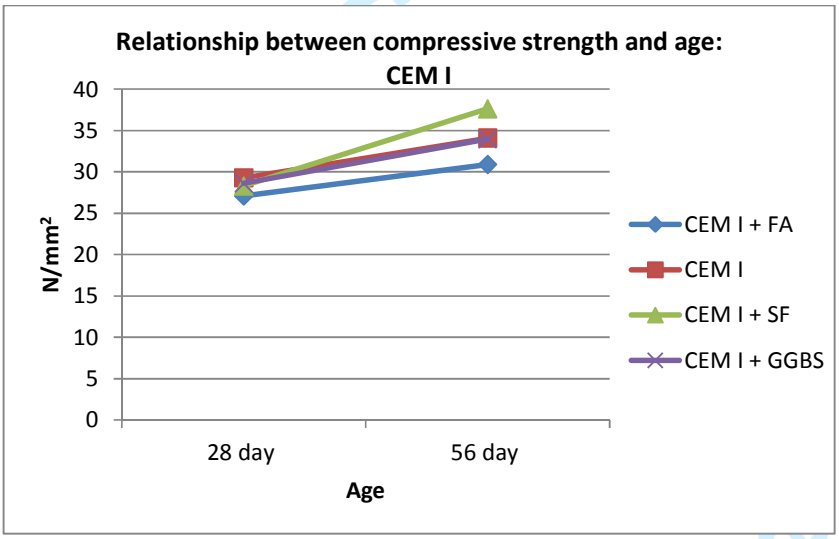


Figure 22 Relationship between compressive strength and age 28 – 56 day: CEM II B-V

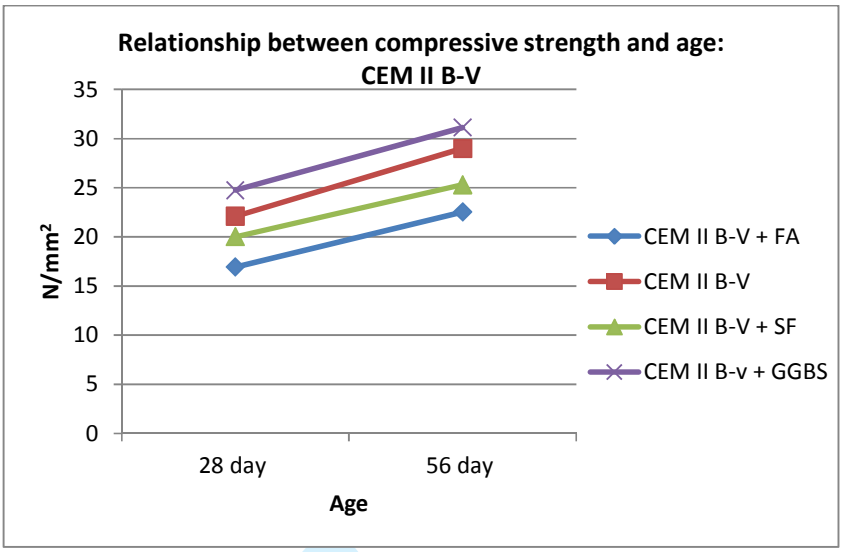


Figure 23 Relationship between compressive strength and w/c ratio

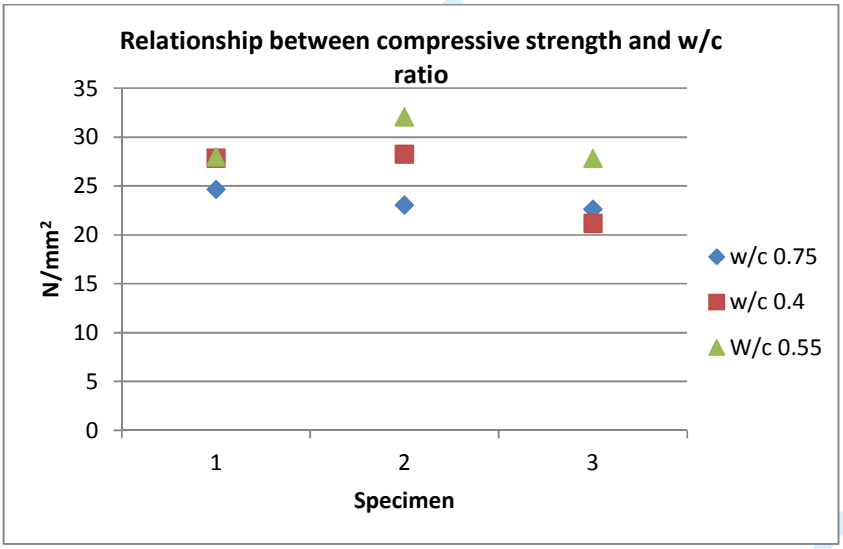


Figure 24 Relationship between compressive strength and aggregate size

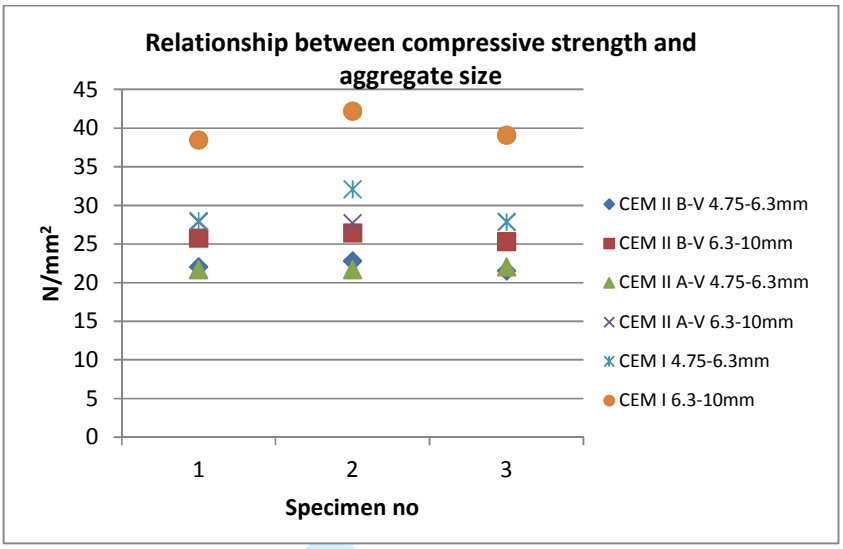


Figure 25 Relationship between density and cement type group CEM I

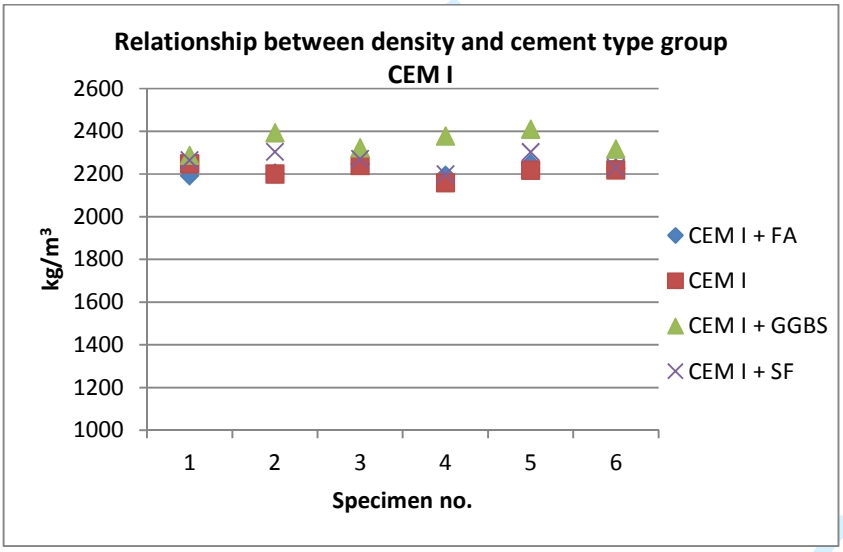


Figure 26 Relationship between density and cement type group CEM II

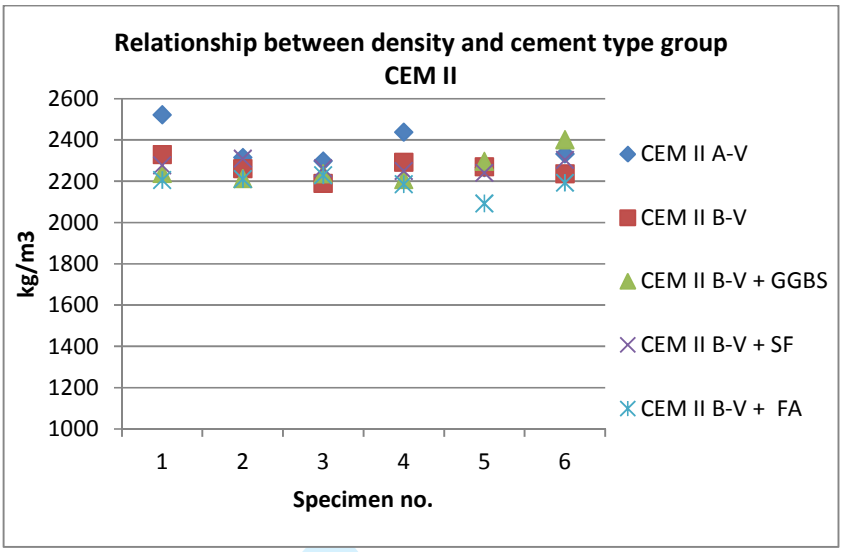


Figure 27 Relationship between density and age: CEM I

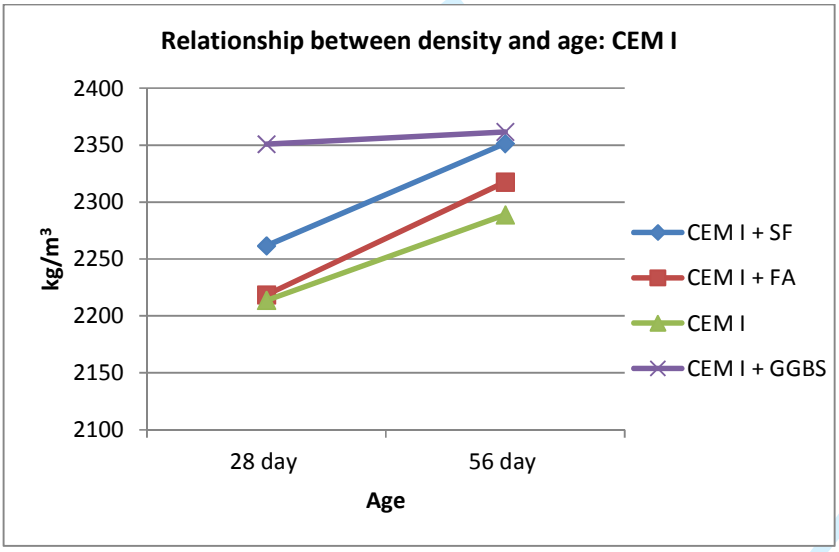


Figure 28 Relationship between density and age: CEM II B-V

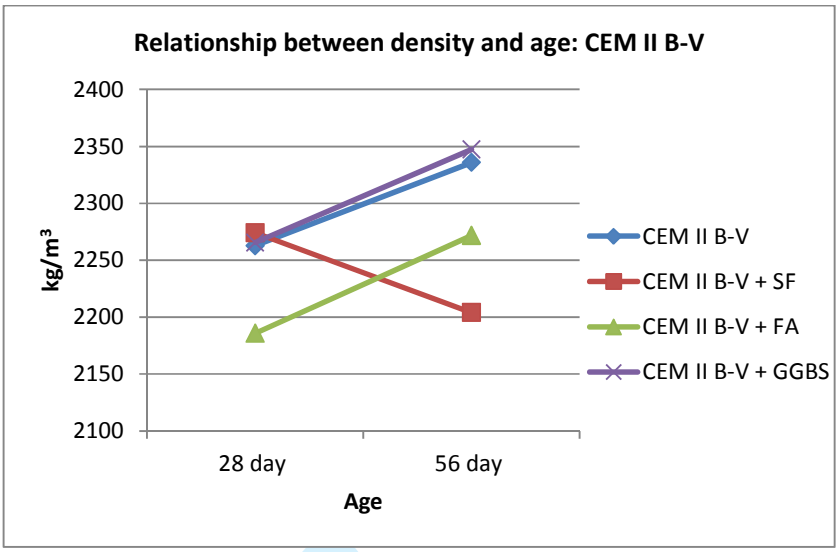


Figure 29 Relationship between density and w/c ratio

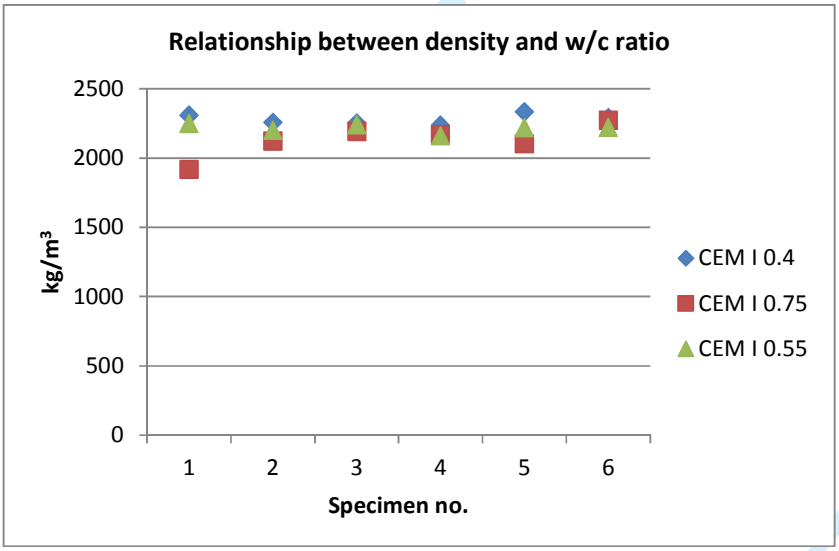
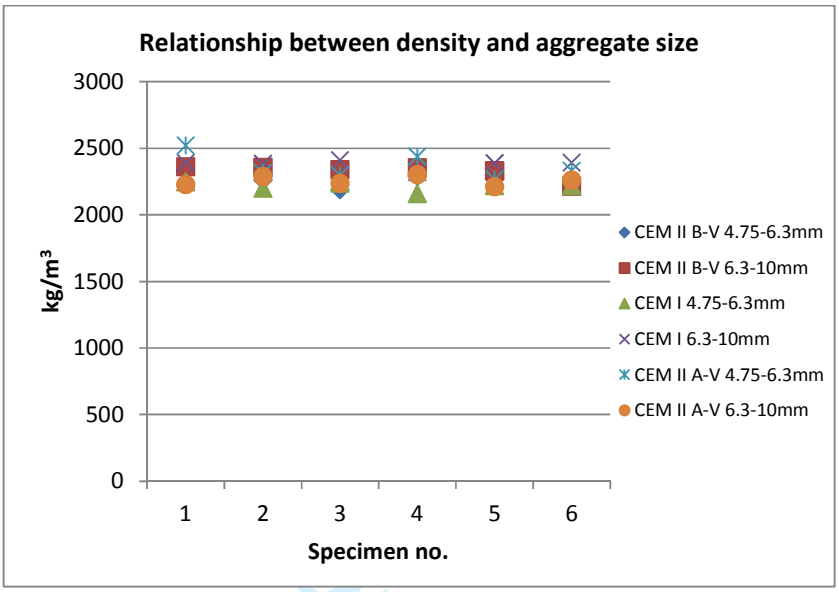


Figure 30 Relationship between density and aggregate size



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