International Journal of Civil and Structural Engineering– IJCSE
Volume 3 : Issue 1 [ISSN : 2372-3971]
Publication Date: 18 April, 2016

Experimental Study on Thermal Properties of Structural Lightweight Aggregate Concrete

M. Glória Gomes, J. Alexandre Bogas, Sofia Real, Beatriz Ferrer, A. Moret Rodrigues

Abstract—**This paper investigates the thermal properties of structural lightweight aggregate concrete. Different types of concretes with four types of lightweight aggregates and several water/cement ratios were prepared. The strength classes of the produced lightweight aggregate concretes ranged from LC 16/18 a LC60/66, whereas the density classes ranged from D1.6 to D2.0. A normal weight aggregate was also used as reference. The impact of the concrete constituents on thermal conductivity, thermal diffusivity and specific heat was assessed by a modified transient test method and relations between those thermal properties and both density and water content of concrete were established. A significant exponential correlation between thermal conductivity and density of concrete was achieved. On average, thermal conductivity decreased about 0.6% per each 1% increment in aggregate porosity, 8.3% per each 50 L/m^3 increment in coarse aggregate volume and 3-9% per each reduction of 1% by weight in water content. The specific heat decreased with density of concrete, whereas both thermal diffusivity and thermal inertia increased. Furthermore, it was found that the thermal conductivity of structural lightweight aggregate concrete can be half of that of normal weight concrete of similar composition, which can contribute to more energy efficient buildings.**

Keywords — lightweight aggregate concrete, normal weight concrete, thermal conductivity, thermal diffusity, specific heat

I. Introduction

The structural lightweight aggregate concrete (SLWAC) can have a relatively high strength while ensuring the reduction of both the permanent load and the thermal conductivity of construction elements [1,2]. The use of SLWAC with better thermal properties on building envelope reduces heat losses and thermal bridges effect which contributes to more energy efficient and environmentally sustainable buildings [3-5].

The thermal conductivity of concrete depends mainly on its density and water content, but it is also affected by other factors such as the pore size distribution, chemical composition, crystallinity of the solid components and temperature [5,6]. The thermal conductivity of a solid material tends to increase as its density, water content, temperature and percentage of crystalline phase increase and decrease with porosity [5,6]. However, the thermal conductivity is only slightly affected by temperature for current temperature variations [5].

The thermal conductivity of concrete is affected by the thermal characteristics of the paste and aggregates. Since aggregates usually compose about 70 to 80% of the concrete's volume, aggregates thermal conductivity might significantly contribute to the thermal insulation capability of concrete [7].

The low thermal conductivity of the air trapped in the porous structure of lightweight aggregates (LWA) is responsible for the higher thermal insulation of SLWA when compared to that of NWC of similar composition.

Several authors found that density is the property that best relates to thermal conductivity and exponential relations between these properties have been suggested [2,8]. According to Holm and Bremner [6], the thermal conductivity of SLWAC with an average density of about 1850 kg/m^3, typically ranges from 0.58 to 0.86 W/m.K, whereas in NWC of about 2400 kg/m^3, thermal conductivity can vary from 1.4 to 2.9 W/m.K. On the other hand, Santos and Matias [9] suggest that thermal conductivity may vary between 0.85 and 1.05 W/m.K in SLWA of 1400 to 1800 kg/m^3 and from 1.65 to 2.0 W/m.K in NWC of 2000 to 2600 kg/m^3 (equilibrium for 23ºC and 50% RH). This means a reduction of about 50-70% in the thermal conductivity of SLWA when compared to NWC. However, the knowledge of the thermal properties of SLWA is still limited, especially considering different compositions, strength levels, densities and water contents.

This paper investigates the most important thermophysical properties of SLWAC, such as thermal conductivity, thermal diffusivity, thermal inertia, density and specific heat. The analysed SLWAC were produced with different types of aggregate water/cement (w/c) ratios, comprising a wide range of strength and density classes, covering the most often used SLWAC for structural elements. The influence of the type of aggregate, w/c ratio and water content on thermal conductivity was analysed and relations between thermal conductivity and both density and water content of SLWAC were established.

II. Experimental procedure

A. *Materials*

In the present study, four types of coarse lightweight aggregate were selected for the production of LWAC specimens: two expanded clay aggregates from Portugal (commercial designations Leca and Argex, which was supplied in two different grain size classes, namely Argex 2-4 and Argex 3-8F); one sintered fly ash aggregate from the UK (commercial designation Lytag); one expanded slate aggregate from the USA (commercial designation Stalite). For the production of NWC reference specimens, two crushed limestone aggregates of different grain sizes were used, namely fine and coarse gravel. In order to obtain the same grading curve as Leca, for comparison purposes, a proportion was established between the two fractions of crushed limestone (34% fine and 66% coarse gravel) and the two fractions of Argex (70% Argex 2-4 and 30% Argex 3-8F). Fine aggregates consisted of 70% coarse and 30% fine normal weight sand for both SLWA and NWC specimens. The main properties of these aggregates, with very distinct porosities, are listed in Table I.

M. Glória Gomes, J.Alexandre Bogas, S. Real, B.Ferrer, A. Moret Rodrigues
DECivil /Ceris –ICIST, Instituto Superior Técnico, Universidade de Lisboa
Portugal

TABLE I. PROPERPIES OF AGGREGATES

Property		Dry density (kg/m^3)	Dry bulk density (kg/m^3)	Absorption at 24h (%)	Granulometric fraction (di/Di)	Total porosity (%)
Lightweight aggregates	Leca	1076	624	15.8	4/11.2	58.9
	Argex 2-4	669	377	21.4	4/8	73.1
	Argex 3-8F	597	330	19.3	4/11.2	76.1
	Lytag	1338	750	17.9	4/11.2	47
	Stalite	1483	760	3.6	8/16	43.1
Normal weight aggregates	Coarse Gravel	2646	1309	0.7	0/8	-
	Fine Gravel	2683	1346	0.4	4/11.2	-
	Fine Sand	2605	1569	0.2	0/1	-
	Coarse Sand	2617	1708	0.3	0/4	-

B. *Mixtures production*

Concrete mixtures were produced with five types of aggregate and four w/c ratios (0.35, 0.45, 0.55, 0.65), giving rise to 20 mixtures compositions. In addition, 6 types of paste, 3 mortars and 9 concrete mixtures with different volumes of coarse lightweight aggregate (250, 300 and 400 L/m^3) and the same composition of concrete made with CEM I were produced to better analyse the influence of each constituent phase on the thermal conductivity of concrete.

The different concrete mixtures were produced in a vertical shaft mixer with bottom discharge. The LWA were previously soaked for 24h to ensure a better control of the workability and the effective water content of concrete. The aggregates were then surface dried with absorbent towels and placed in the mixer with sand and 50% of the total water. After mixing for two minutes, the mixture was left to rest for one minute before adding the cement (CEM I) and the rest of the water. The total mixing time was 7 minutes. For concretes produced with Argex, the aggregates were initially dry before mixing. In this case, the absorption of LWA in the mix was estimated beforehand to take into account the correction of the total mix water, based on the method suggested by Bogas et al. [10].

C. *Specimen preparation and test methods*

For each mixture, there were produced the following concrete specimens: two 100 mm cubic specimens for determining the dry density of concrete at 28 days, according to EN 12390-7:2009; four 150 mm cubic specimens for compressive strength tests at 28 days, according to EN 12390-3:2009; three ϕ105x50 mm cylindrical specimens, sawn from a ϕ105x250 mm specimen, for determining the thermal properties by means of a modified transient pulse method (Fig. 1). After demoulding at 24 hours, the specimens were cured in water until 28 days of age.

The thermal tests were performed with ISOMET 2114 portable hand-held heat transfer analyser (Fig. 1), which is a measuring instrument equipped with a surface measurement probe for hard materials, which determines thermal properties by means of a modified transient pulse method (MTPS). A heat flow is generated by applying a heat impulse to the specimen in thermal equilibrium with the surrounding environment (ASTM D5334:2014; ASTM D5930:2009) and the thermal conductivity , λ, in W/mK,, the volume heat capacity, c_ρ, in J/m^{3}K and the average testing temperature, T_{mean}, in ºC are measured. The range and accuracy of the measured parameters are indicated in Table II.

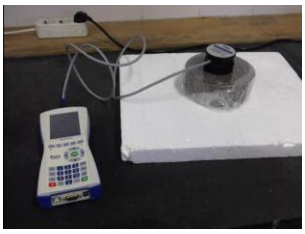

Figure 1. Measurement device (ISOMET 2114) used for determining the thermal properties of SLWA AND NWC

After 28 days of water curing, the thermal conductivity was measured in each cylindrical specimen for 4 different water contents, corresponding to saturated state, dry state and two in-between water contents. According to Santos and Matias [9], the thermal conductivity coefficient of CE-marked products is assessed at an average testing temperature of 10ºC. Thereby, the obtained test results were converted to a reference temperature of 10ºC, according to ISO/FDIS 10456:2007.

TABLE II. ISOMET 2114 RANGE AND ACCURANCY OF THE MEASURED PARAMETERS

Parameter	Measurement range	Measurement Accurancy
Thermal conductivity λ (W/mK)	0.015 - 0.7 W/m K	5% of reading + 0.001 W/m K
	0.7 - 6 W/m K	10% of reading
Volume heat capacity c_ρ (J/m^{3}K)	4.0×10^4-3.0×10^6 J/m^{3}K	15 % of reading+1×10^3 J/m^{3}K
Average temperature T_{mean} (ºC)	-20 to +70ºC	1ºC

III. Results and Discussion

Table III presents the main results obtained for each mixture composition, such as values of compressive strength, f_{cm} and of the most important thermophysical properties: dry density, ρ_d; dry thermal conductivity coefficient, λ_{dry}; dry specific heat, c_p; volume heat capacity, c_ρ; thermal diffusivity, α; and thermal inertia, I_T. The thermal diffusivity, α (eq. 1), is calculated directly by the equipment ISOMET 2114 whereas the thermal inertia, I_T, was determined in the present work by eq. 2.

$$\alpha = \frac{\lambda_{dry}}{\rho_d \; c_p} \; [\mathrm{m^2/s}] \qquad (1)$$

$$I_T = \sqrt{\lambda_{dry} \rho_d \; c_p} = \rho_d \; c_p \sqrt{\alpha} \; [\mathrm{J/m^2Ks^{1/2}}] \qquad (2)$$

The coefficient K_s, which represents the increment of thermal conductivity when the water content increases 1% by weight, is also provided in Table III.

The compressive strength of the tested SLWAC ranged from 19.8 to 66.8 MPa and the dry density from 1440 and

1890 kg/m3. It was thus possible to cover the most usual SLWAC with strength classes from LC 16/18 a LC60/66 and density classes from D1.6 to D2.0, according to EN 206-1 (2005). Depending on the type of LWA and the w/c ratio, the loss of compressive strength of SLWAC compared to NWC of the same composition, varied from 12 to 63%. The reduction was higher in SLWAC with lower w/c ratio and aggregates with greater porosity (Argex, Table I).

For the compressive strength and density ranges analysed, it was possible to produce concrete with a dry thermal conductivity of 0.87-1.36 W/mK (SLWAC) and 1.86-2 W/mK (NWC). The average reduction on the thermal conductivity coefficient in SLWAC, compared to NWC of the same composition, was 40, 44, 46 and 50% for SLWAC with Stalite, Lytag, Leca and Argex, respectively. The best performance, measured by the ratio between structural efficiency and thermal conductivity ($f_{cm}/(\rho_d.\lambda_{dry})$), was found in SLWAC with Stalite (2.2×10^{-2}), followed by SLWAC with Lytag and Leca (2.1×10^{-2}), SLWAC with Argex (1.7×10^{-2}) and NWC (1.4×10^{-2}).

Concerning the remaining thermal properties, Table III shows that the specific heat (c_p) decreased linearly with density of concrete, which is in accordance with previous studies [5,11]. The average specific heat, c_p, of dry concrete was of about 1010 J/kg.K in SLWAC with Argex, 965 J/kg.K in SLWAC with Leca, 924 J/kg.K in SLWAC with Lytag, 905 J/kg.K in SLWAC with Stalite and 740 J/kg.K in NWC. Table III also shows that both thermal diffusivity (α) and thermal inertia (I_T) are directly proportional to density, and hence inversely proportional to the aggregates porosity. Thermal inertia (which is associated with the ability to retain heat) and thermal diffusivity (which describes how quickly a material reacts to a change in temperature) are, respectively, 25-35% and 40-50% lower in SLWA than in NWA. The volume heat capacity, c_ρ, is, by its turn, very similar in the different concretes, with an average reduction of 2-6% in SLWA.

As mentioned, density is the property of concrete that best relates to thermal conductivity [2,8,12]. The results obtained for concrete of different compositions and aggregates confirm a high exponential correlation between thermal conductivity and dry density, with a correlation coefficient of about 0.9 (Fig. 2).

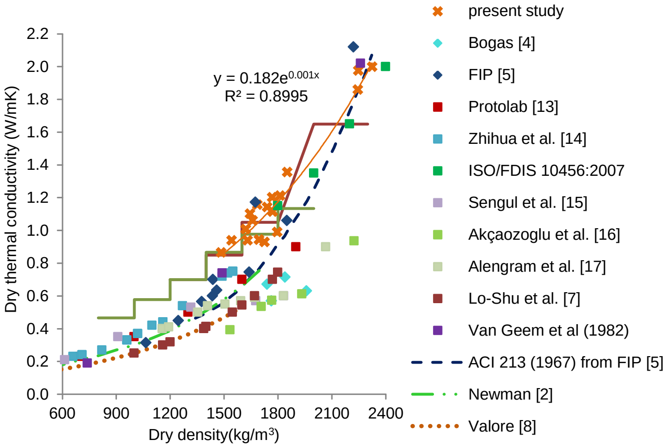

Figure 2. Relation between dry thermal conductivity and dry density. Comparison with results from other authors

Fig. 2 also shows that the results relating dry thermal conductivity and dry density obtained in this study generally follow the trends reported by ISO/FDIS 10456:2007 and other authors [5, 9, 11-17], for concretes with various types of aggregate, although the thermal conductivity coefficients obtained in this study were, on average, about 20% higher. Van Geem et al. [11] found a relevant variability in the thermal conductivity results determined by three different methods (guarded hot plate test, hot wire test, calibrated hot box test). This might partly explain the differences between the results obtained in this study and those reported in literature, as none of those published study applying the testing method adopted in this study.

TABLE III. MIXTURE COMPOSITIONS AND TEST RESULTS

Type of aggregate	w/c	CEM I (kg/m³)	V_{sand} (L/m³)	f_{cm} (MPa)	ρ_d (kg/m³)	λ_{dry} (W/mK)	K_s	c_p (J/kg.K)	$c_\rho=\rho.c_p$ ($x10^3$J/m³.K)	α ($x10^{-6}$m²/s)	I_T (J/m²Ks$^{1/2}$)
N.A.	0.35	450	314	76.3	2324	2	-	-	-	-	-
	0.45	400	310	57.7	2248	1.98	-	741	1665.8	1.19	1816.1
	0.55	350	315	47.8	2245	1.86	-	739	1659.1	1.12	1756.7
	0.65	300	328	37.0	-	-	-	-	-	-	-
Leca	0.35	450	314	43.3	1685	1.16	0.048	980	1651	0.7	1384
	0.45	400	310	37.6	1659	1.06	0.056	945	1568	0.68	1289.1
	0.55	350	315	32.6	1631	0.94	0.062	971	1584	0.59	1220.1
	0.65	300	328	28.4	1620	1.01	0.069	970	1571	0.64	1259.8
Stalite	0.35	450	314	66.8	1851	1.36	0.059	913	1690	0.8	1516
	0.45	400	310	49.9	1811	1.21	0.059	932	1688	0.72	1429.1
	0.55	350	315	41.5	1796	0.99	0.057	870	1563	0.63	1243.7
	0.65	300	328	31.9	1770	1.12	0.091	860	1522	0.74	1305.7
Lytag	0.35	450	314	47.8	1767	1.2	0.048	910	1608	0.75	1389.1
	0.45	400	310	41.2	1739	1.14	0.058	951	1654	0.69	1373.1
	0.55	350	315	37.3	1725	0.93	0.053	911	1571	0.59	1208.9
	0.65	300	328	30.6	1694	0.94	0.087	895	1516	0.62	1193.8
Argex	0.35	450	314	28.5	1644	1.1	0.049	958	1575	0.7	1316.2
	0.45	400	310	26.1	1541	0.94	0.057	1002	1544	0.61	1204.8
	0.55	350	315	22.5	1484	0.87	0.052	1069	1586	0.55	1174.8
	0.65	300	328	19.8	1486	0.89	0.068	1044	1551	0.57	1175

A. Impact of w/c ratio on thermal conductivity

Fig. 3 shows that, for each type of aggregate, thermal conductivity decreased as the w/c ratio increased, i.e. thermal conductivity was inversely proportional to paste porosity. Note that concretes with different w/c ratios also have small differences in the ratio of the volume of sand to the volume of paste (sand/paste ratio), which affects thermal conductivity. However, these differences were less significant since they were generally below 4%. Only for concretes with w/c ratio of 0.65, the sand/paste ratio variation was as high as 9%, which may explain the slightly different trends observed in the thermal conductivity values obtained for concretes with w/c ratio above 0.55 (Fig. 3).

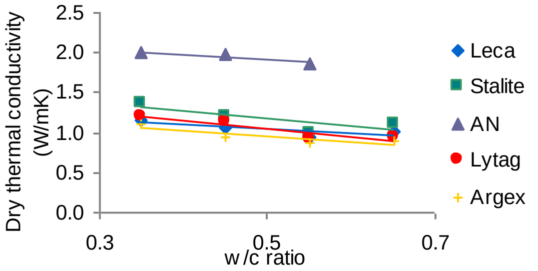

Figure 3. Relation between dry thermal conductivity and w/c ratio

B. Impact of type and volume of aggregate on thermal conductivity

The thermal conductivity of aggregates is essentially affected by their porosity and mineralogical composition [5,6]. As expected, and confirmed in Fig. 4, the thermal conductivity decreased as the porosity of the LWA increased. In general, a high correlation was found between these properties, suggesting that porosity might be the most relevant property affecting the thermal conductivity of LWA. On average, for concrete with 350 L/m^3 of coarse aggregate, an increment of 1% in the aggregate porosity corresponded to a reduction of about 0.6% in the thermal conductivity. These results allow a better prediction of the thermal conductivity variation when a different type of LWA is adopted, reinforcing the goal of establishing general relations between the thermal conductivity coefficient and the density of concrete.

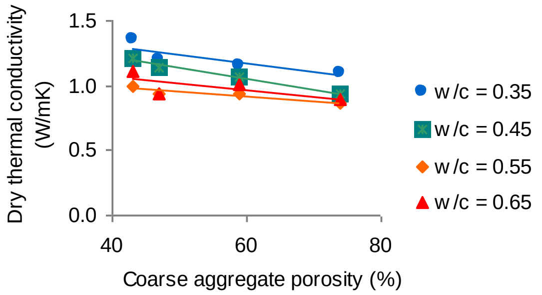

Figure 4. Relation between dry thermal conductivity and coarse aggregate porosity for different w/c ratios

Fig. 5 shows that, for a given type of aggregate and the same w/c and sand/paste ratios, the thermal conductivity decreased with the increment of the volume of coarse aggregate, since it represents a reduction in the density of concrete. On average, a reduction of 8.3% was obtained per 50 L/m^3 increment on the coarse aggregate content.

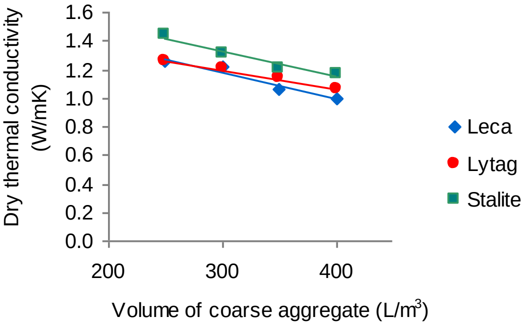

Figure 5. Relation between dry thermal conductivity and volume of coarse aggregate

C. Impact of water content on thermal conductivity

In general, a linear correlation was found between the thermal conductivity coefficient and the water content of concrete, regardless the concrete composition and type of aggregate (Fig. 6). Depending on the type of SLWAC, the thermal conductivity varied between 3 and 9% per each 1% variation of the water content, by weight. For low to moderate strength concrete (fc<40 MPa), ACI 213R [12] recommends a narrower range of 6 to 9% increase in thermal conductivity per 1% increase of water content, by weight.

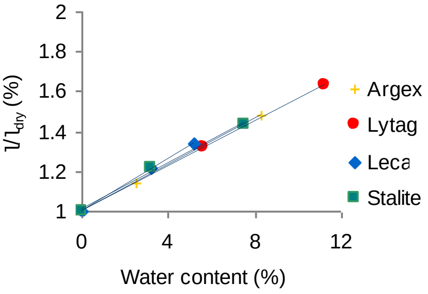

Figure 6. Relation between thermal conductivity normalised to the dry thermal conductivity and water content (w/c = 0.55)

The values of K_s, indicated in Table III, correspond to the linear regression slope between the thermal conductivity and water content. When SLWA starts to dry, the water loss first occurs in the aggregate and only afterwards in the paste [18] and, hence, a slight change in the relation between thermal conductivity and water content may occur for water contents near saturation (different slope between the 3rd and 4th point in Fig. 7).

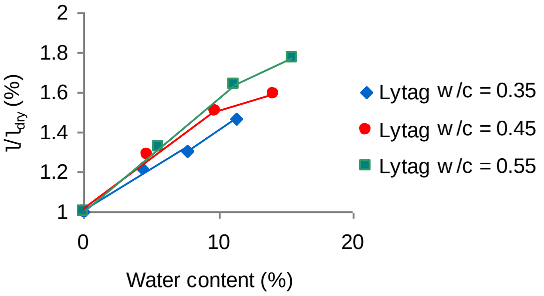

Figure 7 Relation between thermal conductivity normalised to the dry thermal conductivity and water content (Lytag)

Therefore, only the initial slope comprising the first three points in Fig.7 was considered in the determination of K_s. On average, the K_s coefficient was about 0.055, varying between 0.048 and 0.069 regardless the type of LWA and w/c ratio.

IV. Conclusions

LWAC offers a low density concrete solution which results in the reduction of both the permanent load and the thermal conductivity of construction elements. The better thermal insulation of SLWA when compared to NWA, contributes to the reduction of heat losses and also of the thermal bridge effect in building envelopes, leading to more energy efficient and environmentally sustainable buildings.

The present paper focused on the thermal properties of a large set of SLWA with different types of aggregates and w/c ratios. Twenty different concrete mixtures were produced and correspondent thermal properties (namely thermal conductivity, thermal diffusivity, thermal inertia and specific heat) were experimentally determined by a modified transient pulse method. Finally, the impact of the type and volume of aggregate, w/c ratio and water content on thermal properties were assessed. The main conclusions drawn were:

- A high exponential correlation of about 0.9 was obtained between thermal conductivity and dry density of SLWAC with strength classes ranging from LC 16/18 a LC60/66 and density classes from D1.6 to D2.0. This was valid for different types of aggregate and w/c ratios;
- Depending on the type of LWA, the thermal conductivity of SLWAC produced with 350 L/m3 of coarse aggregate was on average 40-50% lower than that of NWC of the same composition;
- The thermal conductivity tended to decrease as the density, the w/c ratio or the volume and porosity of LWA increased and as the sand/paste ratio or the water content of the concrete decreased;
- The specific heat decreased and both thermal diffusivity and thermal inertia increased with density of concrete;
- On average, there was a reduction of 0.6% and 8.3% in the thermal conductivity per 1% increment in the LWA porosity and in coarse aggregate volume, respectively;
- The thermal conductivity coefficient varied 3-9% per each variation of 1% in water content of concrete, by weight, regardless the type of LWA;
- A better compromise between structural efficiency and thermal conductivity was found in SLWAC with less porous LWA. LWAs with greater porosity were found to be more suitable for non-structural applications or the production of low-strength concrete where the reduction of density and thermal conductivity are relevant factors in building design.

Acknowledgment

This study was funded by the Portuguese Foundation for Science and Technology (FCT), through project PTDC/ECM-COM1734/2012. The authors wish to thank Ceris-ICIST/IST for funding the research and the companies Saint-Gobain Weber Portugal, Argex, Stalite, Lytag, SECIL and BASF for supplying the materials used in this study.

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