THERMAL PERFORMANCE ANALYSIS OF THE BUILDING ENVELOPE IN LIGHTWEIGHT CONCRETE

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Extended Abstract

Masters in Civil Engineering

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1. Introduction

The buildings are responsible for a great part of energy needs, being therefore very important increase its energy efficiency. One of the following strategies for increase the energy efficiency of buildings involves improving of the thermal envelope of buildings. The present study intends to analyze the thermal performance of buildings with structural elements in lightweight concrete.

This study, in the first stage, seeks to characterize experimentally the mechanical and thermal behavior of the normal and lightweight concrete.

This program, it was observed that the lightweight concretes compared with normal concretes of similar composition, have low density and show a reduction of the mechanical resistance (axial compression and traction by diametrical compression). The lightweight concrete made of lower density aggregates has a lower thermal conductivity coefficient, making it a better solution for thermal isolation.

To assess the thermal benefits in the use of lightweight concrete in structural elements of the building envelope, it was conducted, in the second stage, a data of energy simulations. On these simulations was used the experimental results of thermal conductivity, specific heat and density obtained for 4 lightweight concrete and 3 normal concrete.

In the program EnergyPlus are introduced the characteristics of the apartment, as well as its geometry, the constituent materials and their properties, the location, the climate data and the program, in turn, it returns the various outcomes about thermal and energy behavior of buildings.

The thermal analysis of the case study, also aims to provide for a better understanding of the thermal performance and energy efficiency of lightweight concrete solutions in buildings, compared to traditional solutions.

2. Experimental program

This experimental program intends to characterize the properties of aggregates, as well as the mechanical and thermal properties of the concrete produced. In this work 4 types of lightweight concrete and 3 types of normal weight concrete were analyzed, these concretes are listed below:

- Normal weight concrete with water/cement ratio of 0,60 (BN 1);
- Normal weight concrete with water/cement ratio of 0,45 (BN 2);
- Normal weight concrete with water/cement ratio of 0,35 (BN 3);
- Concrete produced with lightweight coarse aggregates and natural sand with water/cement ratio of 0,60 (BL 1);
- Concrete produced with lightweight coarse aggregates and natural sand with water/cement ratio of 0,45 (BL 2);
- Concrete produced with lightweight coarse aggregates and natural sand with water/cement ratio of 0,35 (BL 3);
- Concrete produced with lightweight coarse aggregates and lightweight sand with water/cement ratio of 0,35 (BL 4);

The compositions have been defined in order to cover a wider range of structural lightweight aggregate concretes, taking into account solutions of moderate to high resistance for classes of density between D 1,6 e D 2,0. It was also produced a lightweight concrete with lightweight sand in order to achieve largest decreases of density and coefficient of thermal conductivity without large reductions of its mechanical characteristics. Finally, reference concreted were also produced with lime aggregates in order to gauge the relative performance of different types of lightweight concrete in relation to solutions of normal density.

In this study, specimens were tested in order to determine the main features of concrete behaviour. Table 1 presents the tests conducted during the experimental campaign, as well as the standards used.

Table 1 - Description of performed tests and standards

Aggregate tests	**Test standard**
Sieve analysis	NP EN 933-1/ NP EN 933-2
Particle density and water absorption	NP EN 1097-6
Water content	NP EN 933-4
Fresh concrete tests	**Test standard**
Slump	NP EN 12350-2
Fresh density	NP EN 12350-6
Hardened concrete tests	**Test standard**
Compressive strength	NP EN 12390-3
Splitting tensile strength	NP EN 12390-6
Modulus of elasticity	LNEC E 397
Thermal conductivity coefficient	

2.1. Properties of aggregates

In Table 2 are presented the results obtained with a bulk density test, particle densities (ρa, ρrdeρssd), water content (TH) and water absorption after 24 h of immersion ($W_{abs,24}$).

Table2 – Properties of aggregates

	Bulk density (kg/m^3)	**ρ_a (kg/m^3)**	**ρ_{rd}(kg/m^3)**	**ρ_{ssd} (kg/m^3)**	**$W_{abs,24}$ (%)**	**TH (%)**
Lightweight sand	578	944	865	949	9,68	0,16
Leca HD	633	1297	1161	1266	9,07	0,17
Fine sand	1450	2603	2590	2595	0,19	0,08
Corse sand	1589	2684	2614	2640	1,00	0,11
Fine lime	1353	2691	2651	2666	0,55	0,13
Coarse lime 1	1368	2699	2672	2682	0,38	0,04

As it was to be expected, the Leca HD and lightweight sand showed results of bulk density and particle densities within the limits established by European standards in the definition of the lightweight aggregates. In the standards EN 13055-1 (2002) and NP EN 206-1 (2205), the lightweight aggregates are defined as aggregates of mineral origin with density, after kiln-drying, less than or equal to 2000 kg/m^3 or bulk density less than 1200 kg/m^3. These results verified that aggregates of expanded clay can arise bulk density from300 to 800 kg/m^3 (Chandra and Berntsson 2003), (Newman 1993).

The lightweight aggregates present higher values of water absorption due to their higher porosity. The most commonly used lightweight aggregates present values of water absorption between 5 and 25% (EuroLightConR2 1998).

In lightweight sand, it was found that approximately 30% of water absorption after 24 hours occurs at the end of 60 minutes and for the Leca HD approximately 36%. These results show that great part of the absorption occurs in the first minutes, followed by a decrease in the absorption rate.

The absorption rate of lightweight aggregates shows similar values. Zhang and Gjorv (1991) characterized the absorption of different aggregates of expanded clay, it was verified that two aggregates analyzed, despite the difference of more or less 20 % between the particles density, the absorption at 30 minutes was identical.

2.2. Concrete design

Having in mind other studies realized in the Instituto Superior Técnico in order to obtain current lightweight concrete of moderate to high resistance with slump of 120±20 mm, the main data considered was:

- The dosage of coarse aggregate was 350 l/m^3 for all types of concrete. This dosage was defined based in the study of composition realized by Bogas (2011). The value was defined taking into consideration the Faury method, in order to attain mixtures with appropriate compactness;
- A percentage of air arbitrated for all compositions was 3%, it means, 30 l/m^3;
- The volume of coarse sand used corresponds to 2/3 of volume of total sand and the volume of fine sand used corresponds to 1/3 of the total sand volume;
- The dosage of cement used was 350 kg/m^3 in the concrete with w/c=0,60; 400 kg/m^{3}in the concrete with w/c=0,45 and 450 kg/m^{3}in the concrete with w/c=0,35;
- In the concrete with w/c rate of 0,45 and 0,35 was necessary to use superlasticizer to obtain desired workability corresponding to about 120±20 mm of slump;

The analysis of granulometric composition of the coarse aggregate in the conventional concrete was defined in a way to be identical to the Leca coarse aggregate. Thus, the proportion of fine lime and coarse lime were defined so the grading curve of the mixture is adjusted to grading curve of the Leca. So, in accordance with the methodology used, it was obtained a coarse lime composed of30% of fine lime and 70% of coarse lime 1.

Table 3, resumes the mass of the constituents used in each concreting, and taking into account the correction of amount of water due the water absorption of the aggregates.

Table 3–Concrete compositions

	Type of coarse aggregate	w/c	$M_{\text{(coarse aggregate)}}$(kg)	$M_{\text{(fine lime)}}$ (kg)	$M_{\text{ (coarse sand)}}$ (kg)	$M_{\text{ (fine sand)}}$ (kg)	$M_{\text{ (cement)}}$ (kg)	$M_{\text{ (water corrected)}}$ (kg)	SP (g)
BN 1	Coarse lime 1	0,6	41,213	17,297	32,061	16,030	21,747	13,223	-
BN 2	Coarse lime 1	0,45	49,301	20,692	40,211	20,068	29,731	13,588	119,0
BN 3	Coarse lime 1	0,35	41,951	17,297	34,111	17,087	27,960	9,961	199,3
BL 1	Leca	0,6	23,337	-	32,061	16,030	21,747	14,912	-
BL 2	Leca	0,45	27,917	-	40,211	20,068	29,731	15,609	59,5
BL 3	Leca	0,35	23,275	-	34,111	17,087	27,960	11,645	154,7
BL 4	Leca	0,35	23,275	-	13,437	17,087	27,960	12,987	139,8

*a – Coarse aggregate replaced by lightweight sand Leca (BL 4)

3. Energy simulation

The energy simulation will analyze the case study, concerning energy consumption and the heat exchange of the external envelope, using EnergyPlus program. For each location energy simulations were executed for structural elements of apartments with different types of normal weight and lightweight concrete, using results of the experimental program, namely, the density and coefficient of thermal conductivity of the different types of concrete.

The analysis of energy consumption has as an objective, compare the results and check what types of concretes present better thermal performance. The thermal performance of buildings depends on various factors, mainly the climatic conditions and the thermal properties of the buildings envelope.

The energy consumptions in winter and summer seasons are going to be analyzed for each location representing respectively the energy needs for heating and cooling. 12 locations were selected, with the objective of performing energy simulation tests. The national locations are: Bragança, Oporto, Lisbon and Faro. The international locations are: São Paulo (Brazil), Canberra (Australia), Sofia (Bulgaria), Berlin (Germany), London (England), Copenhagen (Denmark), Hong Kong (China) e Cape Town (South Africa).

The heat exchanges results for apartments that used normal weight and lightweight concrete of similar compositions for their construction will be analyzed. The results will be analyzed for heat exchanges in the summer and winter seasons for the apartments in five locations, and for different climatic conditions: Lisbon, São Paulo, Hong Kong, Copenhagen and London. To make it simple, for each location three types of concrete – BN 1, BL 1 and BL 4 -,will be analyzed using the coefficient of thermal conductivity in the dry state.

4. Results and discussion

4.1. Fresh concrete properties

The results indicated in Table 4 represent the slump Abrams cone and density in the fresh state.

Table 4 – Results of the fresh concrete tests

Type of concrete	Slump (mm)	Fresh density (kg/m^3)
BN 1	120	2298
BN 2	115	2317
BN 3	120	2331
BL 1	120	1789
BL 2	140	1796
BL 3	120	1821
BL 4	130	1487

According to what is established, the mixtures present values of slump ranging between 120±20 mm, independently of the type of aggregate and water/cement ratio. It was found a slight reduction of the workability in the normal weight aggregates concrete, since they have a less spherical shape and, as a consequence of that higher internal friction.

As expected, a reduction in the fresh density of the concrete was verified when aggregates of normal density were replaced by lightweight aggregates of high porosity. The replacement of normal coarse aggregates by lightweight aggregates has led to a reduction of 22% in the fresh density. In its turn, the partial replacement of 67% of the fine aggregates of normal density by lightweight sand (BL 4), has led to a reduction of 19,4% in the fresh density.

4.2. Mechanical properties

The results indicated In Table 5 represent the values of compressive strength, tensile strength, modulus of elasticity, Poisson coefficient and dry density.

Table 5 – Results of the dry density and the mechanical properties of the concrete

Type of concrete	Density dry (Kg/m^3)	$f_{cm\,7}$ (MPa)	$f_{cm,\,28}$ (MPa)	$f_{ctm\,28}$ (MPa)	$E_{c\,28}$ (GPa)	ν
BN 1	2343	35,4	45,7	3,43		
BN 2	2285	54,3	62,6	4,8	42,6	0,22
BN 3	2260	66,7	75,6	5,87		
BL 1	1629	27,3	34,1	2,22		
BL 2	1706	-	39,8	3,01	20,5	0,4
BL 3	1801	-	49,9	3,94		
BL 4	1406	30,7	34,8	2,55		

Taking into account the values presented in Table 5, it can be observed that the replacement of coarse aggregates of normal density by lightweight aggregates leads to average reductions of the compressive strength of 25, 36 and 34%, respectively for concrete with water/cement ratio of 0,60, 0,45 and 0,35.

As could be expected, it can be confirmed that, the percentage of reduction of compressive strength of the LWAC versus the normal weight aggregate concrete (NWAC), tends to increase with the reduction of the w/c ratio, given the aggregates greatest influence for levels of superior resistance.

It was confirmed that the use of lightweight aggregates leads to a reduction of compressive strength, being more important in the aggregates of lower density.

Indeed, the various concretes analyzed, showed a good relation between the compressive strength and water/cement ratio for the values we considered. As would be expected, for both the normal weight and lightweight concrete, it appears the compressive strength is inverse to the water/cement ratio.

Only in concrete with water/cement higher (w/c=0,60) most efficient solutions were achieved with a mixture of lightweight aggregates, meaning these concretes are preferable for the production of concrete with moderate to high resistance. The concrete of high water/cement, where the compactness of the paste assumes a more important role in resistance than lightweight aggregates, the structural efficiency was higher in LWAC. For all other concretes, it was observed that when the quality of the paste increases, the aggregate limits more the resistance and a structural efficiency is increasingly less relevant.

In concretes of similar compositions, it was verified that tensile strength in normal concretes is reduced around 35,3, 37,3 and 32,9%, when replacing the coarse aggregates by Leca, for water/cement ratios of 0,60, 0,45 and 0,35, respectively. On its turn, the lightweight concrete with lightweight sand (BL 4) in replacement of the coarse sand, achieved a reduction of 35,3% in the tensile strength comparatively to the lightweight concrete of similar composition (BL 3). As observed previously in the compressive strength, the introduction tends to prejudice seriously the mechanical properties of concrete.

Finally it should be noted that the modulus of elasticity of lightweight concrete (BL 2) is about 52% of the obtained in the conventional concrete of similar composition. The results obtained corroborates document FIB (1983), that for densities of about 1700 kg/m3 are referred average reductions of 50% compared to NWAC of identical composition, similar to the analyzed concrete.

4.3. Thermal conductivity

It can be observed that the coefficient for thermal conductivity varies proportionally with the water content, naturally higher in more humid concretes. According to a document FIB (1983) variations 2% at 6% are usually refered in the thermal conductivity by each variation of 1% in water content of the concrete. In average terms, it was observed variations of 4,3, 4,6 and 5,1% in the coefficient for thermal conductivity for each additional degree of humidity, respectively for normal weight aggregate concrete, concrete with lightweight coarse aggregates and concrete with lightweight coarse and lightweight fine aggregates.

It is confirmed that the lightweight concrete presents lower coefficient for thermal conductivity comparatively to the normal weight concrete of similar composition, since aggregates of lower density were incorporated. Taking into account only concrete in dry state, the lightweight concrete has demonstrated reductions of 50%, 45% and 39% compared with conventional concrete of similar composition, respectively taking into consideration mixtures with water/cement ratio of 0,60, 0,45 and 0,30.

The solutions structurally more effective imply pastes of water/cement ratio higher than 0,45, the coefficient of thermal conductivity can to be twice lower than the value observed in the conventional concrete of similar composition. Taking into account the current solutions into equilibrium with environmental relative humidity, the average reduction is around 50% for concrete with water/cement ratio of 0,60.

Therefore, the lightweight concrete BL 4 presents a reduction of approximately 60% of the coefficient of thermal conductivity in comparison with the lightweight concrete BL 3, due to the replacement of the coarse sand by lightweight sand. Although these concrete show low structural efficiency they show bigger relevance in thermal isolation capacity, meaning a thermal strength four times higher than the conventional concrete.

4.4. Energy needs

In the heating season, the replacement of the normal concrete by lightweight concrete in structural elements, proved to be favorable in all locations. The heating energy needs (winter) showed lower energy needs in the lightweight concrete in relation to the normal concrete of similar composition. The greatest energy savings came using lightweight concrete, it was verified in the locality of Copenhagen because it has a harsh winter compared to the remaining locations.

In the cooling season (summer), in general, it was observed lower energy needs for lightweight concrete in relation to the normal concrete of similar composition, except for Copenhagen and London. This fact can in part be explained by the outside daily average temperatures that are lower in these locations compared to the remaining locations, translating into a bigger heat loss by structural elements of the envelope, during the summer.

By putting a lightweight concrete of high insulation, it will be limiting these heat losses, in this respect, increasing the cooling energy needs in comparison with cases of normal concrete. It can note which yearly level, analyzing the heating and cooling stations, that lightweight concrete leads a better thermal performance than normal concrete. The energy needs varies from location to location according if the climate is more severe over time periods analyzed.

Depending on the climate conditions, on the location of buildings and composition of concrete (water/cement ratio of mixtures), the replacement of lightweight aggregates lead to a reductions of 0,7 to 4,4% in the energy needs of summer and 3,7 to 19,4% in the energy needs of winter. The introduction of lightweight sand allowed the higher levels of energy efficiency, leading to reductions of the energy needs of up to 6,4% in summer and 40,0% in winter.

4.5. Heat exchanges

In general, heating and cooling stations, the parcels of heat loss with higher contribution in the distribution of total losses, they are through of the air renewal and fenestration equipments.

Analyzing the lightweight concrete and comparing with the normal concrete of similar composition, it was verified in all locations a reduction of heat loss of the opaque envelope, as can be expected, almost exclusively through structural elements.

In the heating season, the locations with climatic conditions more severe, namely Copenhagen and London, they do not possess heat gains through the opaque envelope, unlike the other locations with winter season milder and temperate. In the summer season, the gains through fenestration equipment present a significant contribution in the distribution of gains of the apartment, owing the direct transmission of solar radiation inside the building.

In the cooling season, comparing the lightweight concrete in relation to the normal concrete of similar composition, it was verified that Hong Kong presented a slight increase of heat loss of the envelope through structural elements, even though verifying a small reduction of heat loss of the opaque envelope. Indeed, Hong Kong is characterized with mild summer; the average temperature is about 28 ˚C close to the comfortable temperature, leading to reduced heat loss through the opaque envelope.

In general, it can be observed in summer season, an increment in relation to gains through the opaque envelope and air renewal, compared with winter season situation, due to the higher intensity of the solar radiation and outdoor air temperature.

4.6. Coefficients of thermal transmission of the structural elements and minimum thickness of thermal insulation

According to the REH (2003), the coefficient of thermal transmission of the zones of flat thermal bridges (non-current zones) needs to be limited to a maximum value regulatory (which depends on the climatic zones of location) and double of the coefficient of thermal transmission of the current zone, that in this case is brick masonry. These checks may be dispensed whenever that the coefficient of thermal transmission of the zone of flat thermal bridges less than or equal to0,9W/m2ºC, which is not the case.

The compliance with the requirement of thermal quality of the structural elements leads to the need to use layers of material of thermal insulation, with the thermal correction, and therefore limit the heat loss by these zones of heterogeneity.

In the Table 6 present the values of coefficient of thermal transmission of the structural elements (pillars and beams) which constitute the zones of flat thermal bridges of the exterior vertical external opaque envelope and minimum thickness of a layer of thermal insulation in polyester extruded apply in the structural elements in Portugal, constituted of different concrete tested and used in the present study.

It was verified that, as expected, the use of lightweight concrete reduces the thickness which is necessary of thermal insulation in structural elements. The reduction of the thickness of insulation varies between 13% and 22%, for concrete with similar composition. This reduction of the thickness of insulation increases as the water/cement ratio increases. In the case of BL 4 (with lightweight sand) the reduction of the minimum thickness of thermal insulation was of 60%.

Table 6 - Coefficients of thermal transmission of the structural elements and minimum thickness of thermal insulation

	λ (W/m°C)	$U_{\text{pillar and beams}}$ (W/m²°C)	U_{current} (W/m²°C)	$2U_{\text{current}}$ (W/m²°C)	$U_{\max}$ (I_1) (W/m²°C)	$U_{\max}$ (I_2) (W/m²°C)	$U_{\max}$ (I_3) (W/m²°C)	min($2U_{\text{current}}$; $U_{\max}$) (W/m²°C)	thickness $_{\text{minimum}}$insulation (m)
BN1	1,97	3,36	0,67	1,34	1,75	1,6	1,45	1,34	0,017
BN2	2,16	3,46							0,017
BN3	2,20	3,48							0,017
BL1	0,99	2,51							0,013
BL2	1,19	2,75							0,014
BL3	1,34	2,90							0,015
BL4	0,54	1,77							0,007

5. Conclusions

In this study, the thermal performance of the building envelope in lightweight concrete was analyzed. Through the analysis of all the results, in the course of this dissertation, it can be concluded that:

- the percentage of reduction of compressive strength of the LWAC versus the normal weight aggregate concrete (NWAC), tends to increase with the reduction of the w/c ratio, given the aggregates greatest influence for levels of superior resistance;
- only in concrete with water/cement higher (w/c=0,60) most efficient solutions were achieved with a mixture of lightweight aggregates, meaning these concretes are preferable for the production of concrete with moderate to high resistance;
- it is confirmed that the lightweight concrete presents lower coefficient for thermal conductivity comparatively to the normal weight concrete of similar composition, since aggregates of lower density were incorporated. The coefficient of thermal conductivity is half of the value observed in the conventional concrete of similar composition for concrete with water/cement ratio of 0,60;
- in general, it was observed lower energy needs in the lightweight concrete in relation to the normal concrete of similar composition in the summer and winter seasons;
- depending on the climate conditions, on the location of buildings and composition of concrete (water/cement ratio of mixtures), the replacement of lightweight aggregates lead to a reductions of 0,7 to 4,4% in the energy needs of summer and 3,7 to 19,4% in the energy needs of winter;
- the introduction of lightweight sand allowed the higher levels of energy efficiency, leading to reductions of the energy needs of up to 6,4% in summer and 40,0% in winter;
- it can note which yearly level, analyzing the heating and cooling stations, that lightweight concrete leads a better thermal performance than normal concrete in all locations;
- In general, heating and cooling stations, the parcels of heat loss with higher contribution in the distribution of total losses, they are through of the air renewal and fenestration equipments;
- it was verified in all locations a reduction of hat exchanges of the opaque envelope, as can be expected, almost exclusively through structural elements;

- In general, it can be observed in summer season, an increment in relation to gains through the opaque envelope and air renewal, compared with the situation of winter season, due to the higher intensity of the solar radiation and outdoor air temperature.
- It was verified also the use of lightweight concrete reduce a minimum thickness of thermal insulation in structural elements to comply with the minimum requirements of thermal quality of the external opaque envelope;
- in the locations of Portugal, it was verified that the reduction in the minimum thickness of thermal insulation is between 13 and 22% (for concrete BL 3 and BL 1) and reaching reductions of 60% of the thickness for concrete BL 4.
- The structural lightweight concretes provide better constructive solutions for improving thermal performance and to minimize the heat exchanges and also save energy necessary to guarantee the intended comfort levels.

6. References

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