Influence of the aggregate-paste interface (ITZ) on the mechanical behavior of structural lightweight aggregate concretes (SLWAC)

João Miguel Ortega de Oliveira Paulo

May 2018

Key-words

Interfacial transition zone (ITZ); lightweight aggregates; mechanical properties; aggregate-paste bond; structural lightweight aggregate concrete (SLWAC).

---

1 Introduction

Nowadays, it's well-known that the characteristics of the thin surrounding paste close to the aggregates in concrete differ from the bulk paste. These regions play an important role in the concrete's behaviour, physically, mechanically or in terms of durability. The present paper is devoted to study the influence of the interfacial aggregate-paste transition zone (ITZ) on the mechanical behaviour of structural lightweight aggregate concrete (SLWAC), taking into account different types of aggregates, concrete curing conditions and aggregate's pre-wetting conditions. Therefore, an extensive experimental campaign was carried out, involving mechanical characterization and aggregate-paste adhesion tests, complemented by qualitative analyses of scanning electron microscopy (SEM). The behaviour of SLWAC is compared to that of normal weight concrete (NWC) produced with different types of normal weight aggregates.

Three types of lightweight aggregates of distinct porosity and two types of normal weight aggregates were considered in concrete production. Lightweight aggregates of higher porosity were subjected to different initial wetting conditions, in order to analyse their influence on the ITZ's quality. Concretes subjected to moist-curing and severe drying conditions were also analysed. The most common structural concrete with compressive strength classes from LC25/28 to LC40/44 in SLWAC and from C35/45 to C40/50 in NWC were covered. The concretes were mechanically characterized, in terms of compressive strength, splitting tensile strength and direct tensile strength.

In general, it is concluded that the way ITZ influences the mechanical behaviour of concrete depends on the type of aggregate. It was found that concretes with aggregates of higher porosity and lower initial water content tend to develop ITZs of better quality, with stronger aggregate-paste bonds. The better quality of the ITZ in lightweight aggregates of higher porosity was shown by mechanical tests and SEM analysis. Regarding NWC, it was confirmed that the incorporation of lime gravel leads to ITZs of better quality, justifying the greater compressive and tensile strength achieved in these concretes, compared to NWC produced with stronger granitic aggregates.

2 Experimental program, materials and mixture proportions

The experimental program was developed in two phases. The first phase involved the production and mechanical characterization of concretes with different types of aggregates of different density, varying the curing conditions to which the concretes were subjected, as well as the lightest aggregate's (Leca) initial moisture conditions. The mechanical characterization involved tests of compressive and splitting tensile strength, with the analyses of the failure mode and possible ITZ's contribution.

In the second phase, direct tensile tests were carried out and aggregate-paste adhesion assays were designed in small concretes, produced with different types of aggregates. The influence of the initial wetting conditions was also studied at this phase. In addition, a qualitative analysis of the ITZ's microstructure was carried out using scanning electron microscopy (SEM).

2.1 Materials

Three types of lightweight aggregates of different porosity and density classes were analysed: expanded clay, Leca; sintered fly ashes, Lytag; expanded slate, Stalite. In the case of the normal weight aggregates, were considered two types: lime gravel and granite. The main characteristics of the aggregates are given in Table 1, namely: bulk density, particle dry density, water absorption at 24 h.

Table 1 - Aggregates properties

Aggregate	Bulk density (Kg/m^3)	Particle dry density (Kg/m^3)	24h Water absorption (%)
Fine sand	1500	-	-
Coarse sand	1544	-	-
Fine lime gravel	1363	-	-
Coarse lime gravel	1323	2654	0,7
Leca	573	966	16,6
Lytag	730	1299	19,0
Stalite	763	1452	4,4
Granite	-	2722	0,7

2.2 Mixture Proportions

The compositions of the different concretes produced over the different stages of this study are presented in Table 2.

It should be noticed that lightweight aggregates were pre-soaked for 24h and their surface dried with absorbent towels before their incorporation in the mixture, except one composition with Leca, in which it was intended to analyze the influence of using initially dry lightweight aggregates. In this case, in order to control the effective water of the mixture, it was considered that the Leca's absorption during the mixing would be equivalent to 30 minutes of absorption in water, and the equivalent amount of water was added to the mixture.

Table 2 - Mixture proportions for each test

Test	**w/c**	**Aggregate**	**Cement (Kg/m^3)**	**Coarse aggregate volume (l/m^3)**	**Sand volume (l/m^3)**		**Effective water (l/m^3)**
					Sine sand	Coarse sand	
Compressive strength / Splitting tensile strength	0,5	Leca	380	343	118	178	190
		Lime gravel		346	119	172	190
		Lytag		346	53	263	190
		Stalite		339	46	285	190
Direct tensile strength / MEV Observations	0,47	Different aggregates[(1)]	460	250	146	210	216
Adhesion strength	0,47	Leca pre-wetted, Stalite, lime gravel, granite	460	-	146	210	216
	0,7		436	-	200	300	306

[(1)]: Leca (pre-wetted and pre-dried), Lime gravel, Lytag, Stalite, Granite e glass spheres.

2.3 Cure conditions

The specimens produced during the first phase were subjected to two types of cure: moist-cured and air-cured. The specimens cured in wet conditions were placed in a conditioned chamber with relative humidity greater than 95%. On the other hand, the specimens subjected to "dry" cure were placed in a conditioned chamber with a temperature of 20 ± 2 °C and a relative humidity of 50 ± 5%. The concrete’s specimens produced during the second stage were only subjected to wet curing.

3 Test results

The average compressive strength and splitting tensile strength for each concrete obtained in the first phase of this study are given in Table 3, as well as the slump and the fresh density for each mix. The results of direct tensile test and adhesion tests, relative to the second phase are illustrated in Table 4, namely: direct tensile strength, tensile strength of the aggregates and the adhesion using mortars with w/c 0,47. In Table 5 are presented the results obtained in adhesion tests with mortar of higher w/c relation (0,7).

Table 3 – Slump, cure conditions, compressive strength, Splitting tensile strength

Aggregate (aggregate's initial moisture conditions)	Concrete's fresh density (kg/m^3)	Cure conditions	Slump (mm)	Compressive strength (MPa)			Splitting tensile strength at 28 days (MPa)
				2 days	7 days	28 days	
Leca (pre-dried)	1690	Moist-cured	110	-	31,3	34,7	2,6
Leca (pre-wetted)	1695	Moist-cured	108	26,1	32,0	36,5	2,2
Leca (pre-wetted)	1696	Dry-cured	107	-	33,1	39,3	1,6
Lytag (pre-wetted)	1813	Moist-cured	107	28,5	36,4	40,1	2,9
Stalite (pre-wetted)	1911	Moist-cured	102	32,1	42,8	48,3	3,3
Lime gravel	2301	Dry-cured	101	-	43,5	49,8	3,0
Lime gravel	2302	Moist-cured	102	33,0	42,8	51,2	3,7

Table 4 – Results of direct tensile strength and adhesion tests with mortars with w/c 0,47

Aggregate (aggregate's initial moisture conditions)	Direct tensile strength (MPa)	Tensile strength,$_{agr}$ (MPa)	Adherence (MPa)	Age of the concretes (days)	Cure
Leca (pre-wetted)	1,4	1,6	-	28	Moist-cured
Leca (pre-dried)	1,8	1,4	-		
Lytag (pre-wetted)	2,0	3,2	-		
Stalite (pre-wetted)	2,2	4,0	-		
Lime gravel	3,3	4,8	-		
Granite	2,0	5,3	-		
Glass spheres	1,0	-	-		
Mortar	3,1	-	0,2		

Table 5 – Results of adhesion tests with mortars with w/c 0,7

Aggregate (aggregate's initial moisture conditions)	Tensile strength,$_{agr}$ (MPa)	Adherence (MPa)	Age of the concretes (days)	Cure
Leca (pre-wetted)	1,2	-	28	Moist-cured
Stalite (pre-wetted)	3,6	1,3		
Lime gravel	-	2,3		
Granite	-	1,2		

4 Discussions

4.1 Compressive tests

The evolution curves of the compressive strength for each concrete over time are given in Figure 1. The percentages of strength obtained in the LWC relative to NWC of equal composition are shown for each of the test ages in Figure 2.

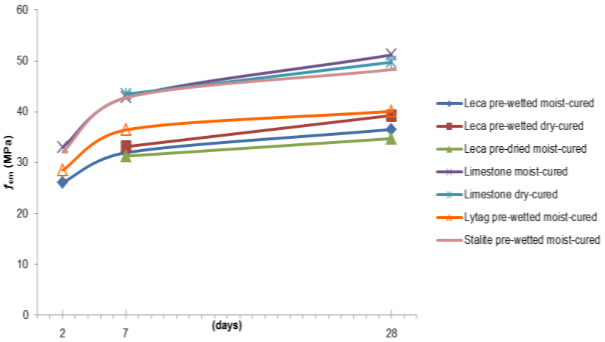

Fig. 1 - Concretete's compressive strength evolution over time

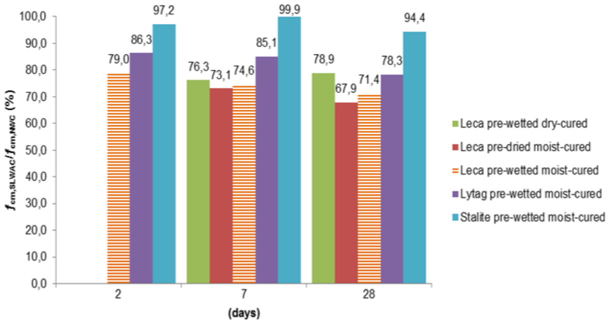

Fig. 2 - Compressive strength of SLWAC relative to NWC

Three 150 mm cubic specimens, according to NP EN 12390-1, of each mix and for each age test were cast for compressive strength.

The failure surface crossed the aggregates in SLWAC, showing that the compressive strength in SLWAC is governed by the aggregates. Although in early ages it can be observed failure through the ITZ, especially when denser aggregates are used. In NWC, the failure surface is controlled by the ITZ.

The average compressive strength, in SLWAC ranged from 26,1-32,1 MPa, 31,3-42,8 MPa and 34,7-48,3 MPa, at 2, 7 and 28 days, respectively. The loss of compressive strength in SLWAC relative to NWC of the same composition varied according to the type of aggregate, cure and aggregate's pre-wetting conditions, between 3-21%, 0-27% and 6-32% at 2, 7 and 28 days of age, respectively.

4.1.1 Curing conditions

The cure conditions seem to don't affect significantly the compressive strength. However, in SLWAC with Leca subjected to moist-cured, there were reductions of 3-5% at 7 days and 7-12% at 28 days compared to air-cured concretes of the same composition. Higher compressive strengths in concretes subjected to drying is reported by other authors (Bogas 2011, Neville 1995, Mehta e Monteiro 2006). In air-cured NWC, the reduction was 3% at 28 days, but led to a slight increase at 7 days.

The reduced contribution of the curing conditions to the SLWAC's compressive strength may be due to the fact that the strength of these concretes is conditioned by the lightweight aggregates capacity. In fact, mortar, having less influence on the SLWAC's strength, especially in concretes with lower density aggregates, as in the case of Leca, will prevent that the hydration break due to the water deficit stands out in these concretes. On the other hand, the SLWAC are presentee by the internal curing effect promoted by their pre-wetted aggregates.

4.1.2 Initial wetting conditions

In general, it was found that the pre-wetting conditions had no significant influence on the SLWAC's compressive strength. This can be justified by the fact that in both cases (SLWAC with pre-dried or pre-wetted aggregates), the fracture surface has crossed the aggregates without mobilizing the capacity of the ITZ, as discussed below. However, when Leca was initially dry, there was a strength reduction of 2% at 7 days and 5% at 28 days, compared to SLWAC with saturated Leca.

4.2 Splitting tensile strength

Fig. 3 shows the percentages of tensile strength by splitting tensile tests obtained in SLWAC in relation to conventional concretes of same composition.

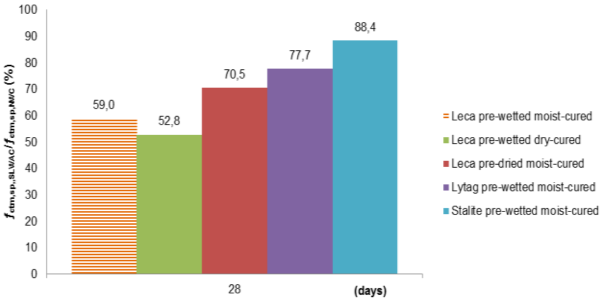

Fig. 3 - Relation between SLWAC and NWC for splitting tensile strength at 28 days

For each mix and test age, three φ150x300 mm cylinders were cast for splitting tensile strength, according to NP EN 12390-1.

Once again, it can be noticed that the strength, in this case splitting tensile strength of SLWAC is limited by the lightweight aggregates strength and by the ITZ in NWC.

The average splitting tensile strength at 28 days varied between 1,6 and 3,3 MPa in SLWAC and between 3,0 and 3,7 MPa in NWC. Considering the concretes cured in saturated environment, the strength to splitting tensile can be reduced by 29%, 41%, 22% and 12% by replacing normal weight aggregates by dry Leca, saturated Leca, Lytag and Stalite, respectively. These losses of strength were higher than the reductions in compressive strength. This is due to the fact that aggregates do not benefit from the confinement of the paste when subjected to tensile strength (Bogas 2014).

4.2.1 Curing conditions

Contrary to the observed for the compressive strength, there was a generalized decrease of tensile strength in the concretes subjected to dry curing. Taking into account the different curing conditions, tensile strength reductions of 27-38% were observed in the SLWAC with Leca, depending on the aggregate's initial wetting conditions. In conventional concretes, these reductions were around 19%.

The difference in moisture gradient generated by subjecting the concretes to dry curing can cause microcracks in the aggregate's vicinity (ACI 213R 2003, Bogas 2011). This phenomenon appears to be the justification for the reported strength reductions in SLWAC air-cured. In fact, the fracture through the ITZ was occasionally observed in the SLWAC with Leca subjected to dry curing.

4.2.2 Initial wetting conditions

There were verified reductions in tensile strength in splitting tests for SLWAC with pre-saturated Leca, regardless of the curing conditions. In the cured concretes in a saturated environment, the reductions in SLWAC with initially saturated Leca aggregates were 16% compared to SLWAC with initially dried Leca. Same observations were made by Bogas (2011).

The introduction of pre-wetted lightweight aggregates can be detrimental since Leca will behave as a normal weight aggregate, as it prevents the interpenetration of paste into the aggregate and does not eliminate bleeding phenomenon. On the other hand, the Leca when introduced initially dry promotes the reduction of porosity and microcracking in ITZ, as a consequence of the lower concentration of water around the aggregates, as reported by other authors (Bogas 2011, Chandra e Berntsson 2003, Wasserman e Bentur 1996, Lo et al. 2007).

4.3 Characterization of the aggregate-paste interface

It should be noted that the direct tensile and adhesion tests are associated with great variability, resulting from the various difficulties inherent to their instrumentalization and realization.

4.3.1 Direct tensile strength

Three prisms of 160x40x40 mm^3 of each mix were cast for direct tensile test. In SLWAC with Leca, the fracture surface was developed preferably through aggregates. On the other hand, for SLWAC with Lytag and Stalite it was found that the breaking surface occurred both at the ITZ or through the aggregates, suggesting that the direct tensile strength was affected by these two phases for these concretes. In concretes with lime gravel the fracture surface was developed preferably by the aggregates, indicating that the tensile strength was limited by the aggregates capacity. Nevertheless, in the concretes with granite, the fracture surface propagated tendentially by ITZ.

The average direct tensile strength at 28 days varied between 1,4-2,2 MPa in SLWAC, being lower in SLWAC with more porous aggregates and higher in SLWAC with higher density aggregates. In the NWC, the tensile strength was 2,0-3,3 MPa, for the concrete with granite and lime gravel, respectively.

The direct tensile strength is reduced by about 47%, 57%, 41% and 35% when lime gravel aggregates are replaced by pre-dried Leca, pre-wetted Leca, Lytag and Stalite, respectively. SLWAC's tensile strength was lower than that of the reference mortar, showing that, regardless of the type of aggregate, the incorporation of lightweight aggregate leads to a reduction in tensile strength. Even in the concretes with less porous lightweight aggregates strength's reduction was even higher than the reductions observed in splitting tensile tests. This may be due to the lower strength of the aggregate, which is most importantly reflected in the direct tensile tests. In addition, the test results are affected by the position and shape of the aggregates being distributed on the fracture surface, possibly leading to eccentricities during the test that promote the early fracture of these concretes. On the other hand, in concrete with granite the strength is limited by the bonding capacity between the paste and the low porous surface of these aggregates. This allowed the SLWAC with Lytag and Stalite to exhibit tensile strength from similar to slightly higher than those concretes with granite.

In concrete with glass spheres the strength reached was only 1,0 MPa, since the aggregate-paste bond was weakly mobilized, being further away from the strength capacity of the mortar.

4.3.1.1 Initial wetting conditions

As observed for splitting tensile strength, the incorporation of pre-wetted Leca resulted in greater tensile strength reductions than the pre-dried Leca. The SLWAC with saturated Leca showed a 22% strength's reduction at 28 days compared to SLWAC with dry Leca. In this way, it is confirmed that the aggregate's initial wetting conditions affect the mechanical behaviour of the SLWAC. For the same reasons explained in 4.2.2. In fact, since Leca is an aggregate with great absorption capacity, if it is introduced initially dry, it allows the moisture balance between the two phases (aggregate and mortar), promoting the mechanical adhesion between them. Thus, eventual bleeding phenomenon that potentially lead to ITZ's a greater porosity and microcracking are eliminated.

4.3.2 Adhesion tests

For each mix four cubic specimens of 40 mm edge were cast for adhesion tests. These tests were carried out in two phases, initially with the regular mortar (w/c = 0,47) and complementary a mortar with a w/c ratio of 0,70. The tests with weaker cementitious matrix aimed the estimation of the aggregate-paste adhesion strength, by limiting the aggregate's influence on the results obtained.

4.3.2.1 Compositions with w/c ratio 0,47

At this stage, involving compact mortars with w/c ratio of 0,47, the breaking surface crossed the aggregates, regardless of the type of aggregate. In this way, the information obtained was the tensile strength of the aggregates and not the aggregate-paste adhesion, as originally intended.

Compared to granite, average strength reductions of approximately 72%, 40% and 25% were observed for the aggregates Leca, Lytag and Stalite, respectively. These differences between aggregate's strength do not support the trends observed in direct tensile tests in 4.3.1, which shows the ITZ's significant role in the concrete's mechanical strength. This feature becomes evident when comparing the relative behaviour of lime gravel and granite concretes. In spite of the fact that the firsts presents less strength capacity, their incorporation allows the development of concretes with greater compressive and tensile strength, due to the better quality achieved in ITZ's properties.

4.3.2.2 Compositions with w/c ratio 0,7

In the specimens with Leca the fracture surface went through the aggregates. The weak Leca's tensile strength, allied with the good quality achieved in the ITZ, promoted this failure mode. In this way, it can only be concluded that the aggregate-paste adhesion strength was higher than the fracture strength of these aggregates. In relation to Stalite the fracture surface developed through two aggregates and through the ITZ in the remaining two particles. In the case of the specimens with normal weight aggregates, the fracture occurred at the ITZ, as was intended. The surface of the aggregates was clean, with no adherent paste present, suggesting a weak aggregate-paste bond. As expected, it was verified a decrease in adhesion strength of about 8-45,6% when replacing granite aggregates with Stalite and lime gravel aggregates, respectively.

4.4 Qualitative ITZ's analysis

There are differences between the ITZs developed in the different concretes. Apparently the aggregates with lower density (Leca and Lytag) have a more efficient binding to the paste, since the transition aggregate-paste occurs gradually. The use of dry Leca and pre-saturated Leca allowed to evaluate the effect of the pre-wetting conditions of the aggregates on the bond aggegate-paste. Apparently there were no marked differences. However, it is possible to observe the formation of small pores near the surface of the pre-wetted aggregates, which may be associated with "wall effect" or localized bleeding. Either way, due to the Leca's porous characteristic surface, the penetration of paste into the aggregates was often observed, mechanically strengthening the aggregate-paste bond.

In the case of aggregates of Stalite, the adhesion between the aggregates and the cementitious matrix is apparently not as efficient as observed in the other lightweight aggregates. The behaviour of these aggregates is similar to that observed in the natural aggregates.

In the aggregates of lime gravel, the adherence in the ITZ seems to be superior to the concretes with granite. However, in both cases it is possible to identify the separation between aggregates and the paste, unlike the more porous lightweight aggregates.

The glass spheres aggregates, given their low porosity, promote the "wall effect" and increase the w/c ratio on their surface. As a consequence, the formation of a weak aggregate-paste bond is observed.

5 Conclusion

The main conclusions obtained in this study are summed below:

a) Apparently, the SLWAC's compressive strength was poorly affected by the different cure conditions. The internal curing effect of the pre-wetted lightweight aggregates reduces the sensitivity of these concretes to severe dry cure conditions. On the other hand, it was verified that the behavior of the concretes in splitting tensile strength was significantly influenced by the curing conditions of the concrte, with generalized strength reductions in the concrete subjected to drying. This reduction results from moisture gradients during drying, which promote the development of microcracks in the ITZ;
b) The SLWAC behaviour to compressive strength wasn't significantly affected by the pre-wetting conditions of the aggregates, since their strength was limited by the aggregates themselves. However, the tensile strength seems to have been susceptible to this variation. It has been found that the use of pre-dried Leca aggregates led to higher tensile strength in both splitting tensile and direct tensile tests. This may be related with a possible improvement in the bonding between phases in the SLWAC with Leca previously dried, since it was possible to observe the sporadic fracture through the ITZ in concretes with pre-wetted Leca;

c) The adhesion tests, showed that Leca aggregate-paste adhesion was stronger than the aggregates, regardless the initial wetting conditions;

d) The direct tensile strength was affected by the characteristics of the ITZ. In this case, the substitution of normal aggregates by lightweight aggregates led to greater reduction of strength to NWC with lime gravel, even in SLWAC with aggregates of higher density;

e) It was possible to confirm that although granite aggregates exhibit higher tensile strength than the other aggregates, they lead to lower tensile strength concretes as a result of the worse quality achieved in ITZ. Only the SLWAC with more porous aggregates are able to develop less strength than the NWCs with granite, due to the weak aggregate's strength capacity;

f) Finally, it can be concluded that, depending on the aggregate's type, the characteristics of the ITZ can significantly affect the mechanical behaviour of the concrete. In general, it is confirmed that the quality of the ITZ tends to be lower in the aggregates with higher density and higher initial moisture content. Nevertheless, the lime gravel aggregates were able to exhibit reasonable quality ITZs, allowing to reach higher mechanical strength concretes.

References

ACI213R-03. "Guide for Structural Lightweight-Aggregate Concrete", American Concrete Institute, 2003.

Bogas J.A. "Caracterização de betões estruturais com agregados leves de argila expandida", Lisboa: Tese para obtenção do grau de Doutor em engenharia civil. Universidade Técnica de Lisboa, Instituto Superior Técnico, 2011. pp 2.1 – 9.80

Bogas J.A., Nogueira R. "Tensile Strength of Structural Expanded Clay Lightweight Concrete Subjected to Different Curing Conditions", KSCE Journal of Civil Engineering, Vol 18 (6), 1780-1791, 2014.

Chandra, S., e Berntsson, L. "Lightweight aggregate concrete. Science, Technology and applications", Noyes Publications-Wiliam Andrew Publishing, USA, 2003.

Lo, T. Y., Tang, W. C., Cui, H. Z. "The effect of aggregate properties on lightweight concrete", Building and Environment, Vol. 42, 2007. pp 3025-3029

Mehta, P. Kumar, e Monteiro, Paulo J.M. "Concrete. Microestructure, properties and materials", Third edition, Mc Graw Hil, 2006.

Neville, A. M. "Properties of Concrete", Fourth edition, Longman, 1995.

NPEN12390-1. "Ensaios do betão endurecido. Parte 1: Forma, dimensões e outros requisitos para o ensaio de provetes e para os moldes", 2003.

Wasserman, R., Bentur, A. "Interfacial interactions in lightweight aggregate concretes and their influence on the concrete strength", Cement and Concrete Composites, Vol. 18, 1996. pp 67-76