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Static and dynamic modulus of elasticity of structural lightweight and modified density concrete with and without nanosilica–characterization and normalization

J. Alexandre Bogas[1,]*, Augusto Gomes[1]

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Abstract

This paper aims to characterize the elastic modulus of structural modified normal density concrete (MND) and lightweight aggregate concrete (LWAC) produced with different types of expanded clay lightweight aggregates (LWA). A comprehensive experimental study was carried out involving different concrete strengths ranging from 30 to 70 MPa and density classes D1.6 to D2.0. The influence of several factors on the LWAC elastic modulus, such as the cement content, initial wetting conditions, type and volume of coarse LWA and the partial replacement of normal weight coarse and fine aggregates by LWA are analyzed. The strength and deformability of LWAC seems to be little affected by the addition of high reactive nanosilica. Reasonable correlations are found between the elastic modulus and the compressive strength or concrete density. The obtained LWAC elastic moduli are compared with those reported in the literature and those estimated from the main normative documents. In general, codes underestimate the LWAC modulus of elasticity by less than 20%. However, the MND modulus of elasticity can be greatly underestimated. In addition, the prediction of LWAC elastic modulus by means of non-destructive ultrasonic tests is studied. Dynamic elasticity modulus and ultrasonic pulse velocity results are reported and high correlated relationships, over 0.95, with the static modulus are established.

Keywords: *Lightweight aggregate, Lightweight concrete, Modulus of elasticity,Nanosilica, Dynamic modulus of elasticity.*

1. Introduction

Although structural design with lightweight aggregate concrete (LWAC) is already provided in North American and European standards, some properties such as elastic modulus, tensile strength, shear, torsion, shrinkage and creep, are still poorly characterized [1-3]. The normative empirical expressions adjusted from those defined for normal weight concrete (NWC) must be assessed for new LWACs that offer higher performance and contain different types of binders, and also for modified density concretes with partial replacement of normal fine or coarse aggregates by lightweight aggregates (LWA). Furthermore, most studies that have been conducted involve LWAC made with a given type of aggregate. These studies are often limited to a small number of compositions, involving a narrow range of density and strength classes, so the conclusions are only valid for the specific case studied. In addition, there is still no defined procedure based on non-destructive tests that makes it possible to predict the LWAC elastic modulus in existing structures.

This paper aims to characterize the modulus of elasticity of LWAC produced with different types of expanded clay lightweight aggregates, involving different concrete compositions with mean compression strength from 30 to 70 MPa and density classes from D1.6 to D2.0. It is thus possible to cover the most usual LWACs, which increases the validity of the study. Concrete mixes produced with different cements and amounts of water, type and volume of aggregates and different initial LWA water contents are characterized and results are compared to those obtained by other authors and those estimated from the main European and American normative documents. Modified density concretes with different partial replacements of normal weight coarse aggregates by LWA are analysed and their structural efficiency is assessed. The incorporation of high reactive aqueous dispersion nanosilica and its repercussions on the LWAC's strength and deformability are also studied. To the best of the authors' knowledge no studies have been published that involve the use of such additions in LWAC.

Finally, the non-destructive ultrasonic pulse velocity test is used to predict the LWAC dynamic modulus of elasticity. The comprehensive experimental data obtained

* *Corresponding author: abogas@civil.ist.utl.pt*
1 Assistant Professor (PhD), Department of Civil Engineering and Architecture, Section of Construction, IST-Technical University of Lisbon, Av. Rovisco Pais, 1049-001 Lisbon, Portugal

in this study provides the basis for the establishment of a high correlation relationship between the static and dynamic modulus of elasticity or ultrasonic pulse velocity.

2. Literature Review

It is well known that lightweight aggregate concrete, usually having a greater volume of paste and lower stiff aggregates has a lower modulus of elasticity than normal weight concrete (NWC) of equivalent strength (e.g., [4-7]).According to FIP [5], the elastic modulus of LWAC of densities of nearly 1700 kg/m^3 is usually about 50% that obtained in NWC of same strength. ACI 213 [7] states that this ratio may vary between 50 and 75% for concrete strengths up to 40 MPa. On the other hand, Smeplass[8] documents LWAC modulus of elasticity only 20 to 30% lower than that of NWC of equivalent strength, for strength classes LC60 to LC90. Similar relations were obtained by Al-Khaiat and Haque[9] for LWAC of about 50 MPa. These studies show that concrete stiffness is highly dependent on the type of aggregate used.

There is an additional reduction of the elastic modulus of LWAC made with lightweight sand (ALWAC), [10,11]. However, similar moduli of elasticity were obtained for ALWAC and LWAC by Hammer [12]. This was due to the slight decrease of the w/c ratio in ALWAC and by the higher contribution of lightweight sand to the overall stiffness of the concrete, as there is a better bond between these aggregates and surrounding paste.

Videla and Lopez [13] concluded that the LWAC stiffness decreases as the volume of aggregate increases, with this reduction depending on the type of LWA. Faust [14], meanwhile, reports less influence of different LWA volumes on the modulus of elasticity of LWAC. This can be explained by the high elastic compatibility between LWA and the paste, especially in LWAC of low to moderate strength.

The compressive behavior of LWAC is strongly dependent on the *limit strength*, f_L, which corresponds to the strength for which the modulus of elasticity of the mortar is similar to that of the aggregate [15, 16]. Above f_L the concrete strength is also affected by LWA and is lower than the mortar strength. Therefore, the relation between f_c and the modulus of elasticity ought to be affected by f_L, too. For this reason, the analysis of the deformability of LWAC should involve different strength levels and aggregates with distinct porosity, in order to cover the various possible failure modes of LWAC. The present paper takes this into account.

The main normative expressions proposed for estimating the modulus of elasticity of LWAC are listed in Table 1. In general, these expressions are obtained from those defined for NWC, affecting them by an overall empirical safety coefficient that takes into account the lower density of LWAC. Unsatisfactory estimates with the recommended expression of ACI 318 [17] for LWAC strengths above 40MPa are mentioned by several authors (e.g., [4,18,19]). According to Hoff [20] this expression can overestimate the modulus of elasticity of high strength LWAC by 9 to 30%. Differences of the same order were obtained by Khaloo and Kim [18]. These authors and Gjørv and Zhang [4], found the expression suggested by NS 3473 [21] more appropriate. For LWAC produced with different types of aggregates and strengths between 20 and 70 MPa, Faust [11] obtained good estimations from the expressions proposed in EN 1992 [22].

Table 1 Estimation of the elastic modulus of LWAC from some normative documents

Document	Estimation of E_{cm} [MPa]	Domain [MPa]
ACI 318 [16]	$E_{cm,j} = 0.0427.(f_{cm,cyl}.\rho^3)^{1/2}$	$f_{cm,cyl}<40$
ACI 213 [7]	$E_{cm,j} = c.(f_{cm,cyl}.\rho^3)^{1/2}$ $c=0.043(f_c<35MPa); c=0.038(f_c=41MPa)$	$f_{cm,cyl}<40$
fib 8 [1]	$E_{cm,j} = 21500.(\rho/2200)^2.(f_{cm,cyl}/10)^{1/3}$	-
EN 1992-1 [22]	$E_{cm,j} = 22000.(f_{cm,cyl}/10)^{0.3}.(\rho/2200)^2$	$12<f_{cm}<80$
NS 3473 [21]	$E_{cm,j} = 9500.(f_{cm,cyl10})^{0.3}.(\rho/2400)^{1.5}$	-

Note: $E_{cm,j}$ - Average modulus of elasticity at age j; ρ - concrete density (kg/m^3)
$f_{cm,cyl}$;$f_{cm,cyl10}$ - Average compressive strength (cyl. ϕ150x300 or ϕ100x200 mm)

Some typical domains of the LWAC elastic modulus obtained by several authors are summarized in Table 2 for different strength levels [4, 9, 10, 13, 15, 18, 20, 23]. These results take into account several compositions with aggregates of different types and particle size and in varying volumes, different binder contents and w/c ratios and also different test conditions (specimen geometry and loading rate).

Nanosilica (NS) is an aqueous dispersion of very fine silica particles with high pozzolanic activity. This high purity silica, whose particle size varies between about 1 and 100 nm, is characterized by an amorphous silica content usually above 99% [6]. Studies on the use of NS in concrete are still scarce, especially with LWAC. Chandra and Berntsson[6] demonstrated the high reactivity of NS when they found that 4% of this addition consumes 60% more CH than 4 % of silica fume. Shih, et al. [24]analyzed the influence of different percentages of NS (0.2 to 0.8% by weight of cement) on the microstructure and strength of cement pastes with w/c ratios of 0.55. For an optimal NS content of 0.6% a strength increase of 61% at 14 days and of 44% at 56 days was obtained. Li, et al. [25] found that compressive and flexural strength increased in mortars with 3 to 10% of NS.

Table 2 LWAC elastic modulus for different strength ranges [4,9,10,13,15,18,20,23]

Range of compressive strength, f_{cm} (MPa)	Domain of modulus of elasticity, E_{cm} (GPa)
<20	7.5-15.5
20-30	9.3-18
30-40	12.5-23.8
40-60	20-26.5
60-90	22.3-31.9

Based on some of the few published works in this field, the major effects that may result from the inclusion of NS in concrete are summarized below (e.g., [24-26]):

- the extremely fine NS provides a better filler effect, with densification of the micro and nano structure of the cementitious matrix that improves their physical and mechanical properties;
- the aggregate-paste interface transition zone (ITZ) is improved by its microstructure refinement;
- NS promotes the nucleation of the hydration products of cement paste, which accelerates the hydration process;
- NS promotes the formation of smaller and more evenly distributed crystals;

the high surface area of NS allows more effective pozzolanic reactions, enabling high initial strengths with high consumption of C-H and additional formation of C-S-H.

3. Experimental Procedure

3.1. Materials

Three Iberian expanded clay lightweight aggregates were analysed: Leca and Argex from Portugal and Arlita from Spain. Their total porosity, P_T, particle density, ρ_p, bulk density, ρ_b, and 24h water absorption, $w_{abs,24h}$, are indicated in Table 3. They differ in terms of porosity, geometry and bulk density, which makes it possible to produce LWAC ranging from about 25 to 75 MPa [16,27]. A more detailed microstructural characterization of these aggregates can be found elsewhere [28].

Table 3 Aggregate properties

Property	Normal weight aggregates				Lightweight aggregates				
	Fine sand	Coarse sand	Fine gravel	Coarse gravel	Leca 0-3	Leca 4-12	Argex 2-4	Argex 3-8F	Arlita AF7
Particle dry density, ρ_p (kg/m^3)	2620	2610	2631	2612	1060	1068	865	705	1290
Loose bulk density, ρ_b (kg/m^3)	1416	1530	1343	1377	562	613	423	397	738
24h water absorption, $w_{abs,24h}$ (%)	0.2	0.5	1.4	1.1	-	12.3	22.9	23.3	12.1
Total porosity, $P_{T(\%)}$	-	-	-	-	59	60	67	73	52
Granulometric fraction (d_i/D_i)	0/2	0/4	4/6.3	6.3/12.5	0.5/3	4/11.2	4/8	6.3/12.5	3/10
Los Angeles coefficient (%)	-	-	33.3	30.5	-	-	-	-	-

Normal density coarse and fine aggregates (NA) were also used. For the reference NWC, two crushed limestone aggregates of different sizes were combined so as to have the same grading curve as Leca (20% fine and 80% coarse gravel). Fine aggregates consisted of 2/3 coarse and 1/3 fine sand. Their main properties are listed in Table 3. The two fractions of Argex were also combined to have the same grading curve as Leca (35% 2-4 and 65% 3-8F, Table 3). A water dispersed *RHEOMAC VMA 350* nanosilica (NS) with an average density of 1. 1and about 16.1% solids contentwas used. NS was composed by more than 99% of amorphous SiO_2 with a specific surface of about 500 m^2/gand a mean particle size of about 20 nm. Cement types I52.5R, I 42.5 R and II A/L 42.5 and a polycarboxylatebased superplasticizer (SP) were also used. The main physical and chemical properties of the cementitious materials are listed in Table 4.

3.2. Concrete mixing and mixture proportions

The concretes were produced in a vertical shaft mixer with bottom discharge. Except for initially dry or pre-wetted aggregates, the LWA was pre-soaked for 24h to better control the workability and effective water content of the concrete. The aggregates were then surface dried with absorbent towels and placed in the mixer with sand and 50% of the total water. After 2 minutes of mixing, the cement and the remaining water were added. The SP was added slowly with 10% of water, after 1 more minute. The total mixing time was 7 minutes. When used, NS was added with about 20% of water after 6 minutes of mixing and was then mixed for a further 4 minutes.

All the concrete compositions were designed according to Bogas and Gomes [16, 29] and are listed in Table 5. The w/c ratio signifies the effective water available for cement hydration. The Sp/c is the percentage of superplasticizer by cement weight. The denominations “NWC”, “L”, “A” and “Argex” correspond to the mixes with NA, Leca, Arlita and Argex. The prefix “V” refers to different volumes of aggregate. Designation “42.5AL” appears when CEM 42.5 A/L is used.Except for mixture LS450, natural sand was used in combination with coarse LWA. For LS450, coarse sand was replaced by the lightweight sand indicated in Table 3 (Leca 0-3).

Table 4 Main characteristics of the cementitious materials

Parameter		Standard	Cement I 52,5 R	Cement I 42,5 R	Cement II/A-L 42,5 R
Residue on the 45 μm sieve, (%)		EN 451-2	1.1	4.7	8.3
Blaine specific surface, (cm^2/g)		EN 196-6	5102	3981	4477
Compressive strength of reference mortar, (MPa)	2 days	EN 196-1	40.4	32.8	27.2
	28 days		62.7	54.9	51.4
Expansion, (mm)		EN 196-3	0.5	0.5	0.5
Loss on ignition (LOI), (%)		EN 196-7	1.64	3.06	5.34
$SiO_2 + Al_2O_3 + Fe_2O_3$, (%)		EN 196-2	29.1	27.6	26.1
CaO, (%)		-	61.6	63.5	61.6
Free CaO, (%)		EN 451-1	1.45	1.31	1.8
Density, (g/cm^3)		EN 196-6	3.11	3.11	3.05

Table 5 Concrete mix proportions, slump and fresh density

	Mixes	Coarse LWA (m^3/m^3)	Coarse gravel (kg/m^3)	Fine gravel (kg/m^3)	Coarse sand (kg/m^3)	Fine sand (kg/m^3)	Cement (kg/m^3)	Sp/c (%)	Effective water (L/m^3)	Effective w/c (L/m^3)	Slump (cm)	Fresh density, ρ_f (kg/m^3)
Leca	L42.5AL[b]	0.35	-	-	586	251	450	0.7	158	0.35	17.2	1920
	L350	0.35	-	-	653	280	350	0.6	158	0.45	5.5	1888
	L450	0.35	-	-	593	254	450	0.7	158	0.35	19.7	1897
	L450 PW	0.35	-	-	593	254	450	0.6	158	0.35	17.6	1811
	L450 PD	0.35	-	-	593	254	450	0.6	158	0.35	18.6	1853
	VL400	0.40	-	-	501	215	450	0.6	158	0.35	20	1839
	LS450	0.35	-	-	211[a]	280	450	0.5	158	0.35	18	1620
	LNS	0.35			630	270	414 (NS-5.4)[c]	1.0	146	0.35	17.6	1919
	L35%	0.12	476	120	592	254	450	0.6	158	0.35	16.5	2213
	L65%	0.23	256	65	593	254	450	0.6	158	0.35	18.4	2089
Arlita	A450	0.35	-	-	583	250	450	0.7	158	0.35	18.4	1982
	A345_0.6[b]	0.35	-	-	559	240	345	0.0	207	0.60	15	1867
	A440_0.45[b]	0.35	-	-	519	223	440	0.0	198	0.45	8	1887
	A460_0.4[b]	0.35	-	-	531	228	460	0.2	184	0.40	9.5	1905
	ANS	0.35	-	-	621	266	414 (NS-5.4)[c]	1.1	146	0.35	18	1954
	A35%	0.12	476	120	593	254	450	0.8	158	0.35	17.4	2249
	A65%	0.23	256	64	584	251	450	0.7	158	0.35	18	2120
	Argex450	0.35	-	-	592	254	450	0.7	158	0.35	21	1776
NA	NWC350	0.35	735	184	653	280	350	0.8	158	0.45	8.6	2396
	NWC450	0.35	732	184	592	254	450	0.7	158	0.35	17.7	2411

[a] - Ligthweight aggregate sand; [b] - Cement type I42.5 R; [c] - NS - 1.3% of nanosilica by weight of cement

LWAC with initially dry LWA (PD) or pre-wetted LWA (PW) were also produced to study the influence of pre-wetting the LWA. The PD aggregate is added during mixing and the PW aggregate is previously subjected to 3 minutes of wetting with 50% of the total water before mixing. The effective w/c ratio is controlled, taking into account the method proposed by Bogas, et al. [30]. Modified normal density concretes (MND) were produced with partial replacement of NA by 35 and 65 percent of Leca (L35, L65) or Arlita (A35, A65).The influence of NS on LWAC made with Arlita (ANS) and Leca (LNS) was studied. The NS content used was that recommended by supplier, based on previous studies with NWC (1.3% of cement weight).The maximum aggregate size was 12.5 mm. The SP was adjusted to give the mixes identical slumps.

3.3. Specimen preparation and test setup

For each mix, three ϕ150x300 mm cylinders were tested for compressive strength and two for modulus of elasticity. After demolding at 24 h, cylinders were kept in water until testing. All specimens were tested at 28 days except for reference mixes (NWC/L/A/Argex450), which were first tested at 7 days.

The static modulus of elasticity, E_c, was determined according to LNEC E397 [31], using a stiff *Enerpac* press frame with a capacity of 3000kN. The procedure consisted of at least 8 cycles of loading and unloading, where the applied stress varied between 1 MPa and 1/3 of the estimated compressive strength. The test was finished when the difference between the average strain for consecutive cycles was less than 10%. The loading rate was about

0.5±0.01 MPa/s, as mentioned in LNEC E397 [31], which is about twice that suggested in ASTM C469 [32]. Fouré [33] reported variations of less than 5% in the modulus of elasticity when the loading rate was doubled. Axial deformations were measured by two electrical strain gauges (SG) of 30 mm and 120 Ω, located at mid-height of the specimens and in diametrically opposite positions. In addition, two linear variable displacement transducers (LVDT) of 25 mm capacity were placed between the SGs, operating over an initial gauge length of 150 mm. The simultaneous use of SGs and LVDTs was intended to increase the measurement accuracy and to evaluate the differences between the two reading devices.

The dynamic modulus of elasticity, E_d, was also evaluated based on the well known Eq.(1) which relates the ultrasonic pulse velocity, *UPV*, to the material density and E_d. The Poisson ratio, υ, of 0.2 experimentaly determined in Bogas [27] and the densities at 28 days, ρ_{28d}, listed in Table 6, were adopted. The velocity *UPV* was determined according to EN 12504-4 [34]. Before the determination of the static modulus of elasticity, E_c, the propagation time of the ultrasonic waves transmitted along the cylindrical specimens was measured with accuracy up to 0.1 µs. *UPV*is the ratio between the length travelled by the pulse and the measured time. A previous detailed experimental work on the influence of different mix design parameterson the ultrasonic pulse velocity of LWAC can be found in Bogas, et al [35].

$$E_d=\rho_{28d}.UPV^2\times\frac{(1+\upsilon).(1\text{-}2\upsilon)}{(1\text{-}\upsilon)} \quad (1)$$

Table 6 Static and dynamic modulus of elasticity

	Mixes	Oven dry density, ρ_d (kg/m^3)	28 days density, ρ_{28d} (kg/m^3)	Compressive strength, $f_{cm,cyl,28d}$ (MPa)	Static modulus of elasticity, E_c (GPa) SG[a]	LVDT[a]	ultrasound velocity, UPV (m/s)	Dynamic modulus of elasticity, E_d (GPa)
Leca	L42.5AL	1738	1913	40.8	24.4	24.5	4319	32.1
	L350	1712	1876	35.5	22.7	22.2	4093	28.3
	L450	1740	1899	45.1	24[b]/25.2	25.6	4306	31.7
	L450 PW	1744	1841	46.3	24.4	25.5	4306	30.7
	L450 PD	1753	1854	46.4	24.7	27.0	4306	30.9
	VL400	1678	1834	41.6	22.1	24.8	-	-
	LS450	1435	1653	35.5	16.0	17.1	3796	21.4
	LNS	1754	1892	43.3	23.3	25.9	4269	31.0
	L35%	2112	2209	55.1	40.3	40.0	4917	48.1
	L65%	1950	2077	47.0	32.0	33.5	4715	41.6
Arlita	A450	1840	1949	61.7	26.1[b]/28.6	-	4370	33.5
	A345_0.6	1664	1872	38.1	22.8	23.0	-	-
	A440_0.45	1723	1901	51.8	26.0	26.7	-	-
	A460_0.4	1765	1913	57.4	26.8	26.5	-	-
	ANS	1838	1976	62.1	27.7	29.1	4370	34.0
	A35%	2150	2243	69.9	40.8	44.4	4877	48.0
	A65%	2008	2115	61.5	35.2	36.9	4585	40.0
	Argex450	1610	1729	30.4	21.1	21.5	4082	25.9
NA	NWC350	2264	2412	59.1	44.3	49.2	-	-
	NWC450	2358	2419	73.2	39.7[b]/48	51.8	5068	55.9

[a]SG - strain gauge; LVDT - linear variable displacement transducer; [b] modulus of elasticity at 7 days

4. Results and Discussion

The average dry density, ρ_d, the average compressive strength, f_{cm} and the static, E_c, and dynamic, E_d, modulus of elasticity are listed in Table 6. As expected, E_d, which does not consider the microcracking of test specimens (not loaded), is higher than E_c.The elastic modulus of LWAC in relation to that of NWC of same composition is shown in Figure 1.

The use of strain gauges can be less accurate because of their reduced basis of measurement, where the elastic modulus is more easily affected by local effects. LVDTs are better able to take the overall behavior of concrete into account.These effects should be more relevant the larger the aggregate's size and the lower the aggregate-paste elastic compatibility. This may explain the small differences obtained between SGs and LVTDs for LWAC (Table 6). Greater differences were obtained for NWC. Except when mentioned, the discussion of the results will be based on SG measurements.

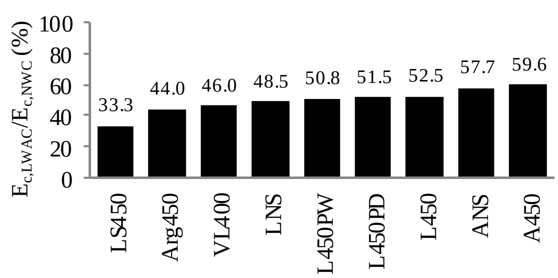

Fig. 1 Modulus of elasticity of LWAC, $E_{c,LWAC}$, in relation to that of NWC of the same composition, $E_{c,NWC}$

4.1. General characterization

The E_c ranged from 16 to 29 GPa for LWAC and 44 to 48 GPa for NWC.Taking into account the concrete strength, these results fall within the upper limit of the range of values obtained by other authors (Table 2). There is a reduction of the elastic modulus in LWAC that is higher for lower density aggregates.The elastic modulus of the reference concrete made with Arlita, Leca and Argex (A/L/Argex450) was about 40, 48 and 56 % lower than that of the NWC with the same composition (NWC450), (Table 6 and Figure 1).The stiffness loss in relation to the strength loss of LWAC (15, 36 and 59% for Arlita, Leca and Argex) is lower for more porous aggregates. This is because E_c is independent of the failure mode of concrete and grows less than f_c.

4.2. Relation between compressive strength and modulus of elasticity

In general, there is a good correlation between the average compressive strength, f_{cm}, and the E_c modulus of LWAC, regardless of the aggregate type (Figure 2). An exception is the LWAC made with lightweight sand, as discussed in 4.6. Zhang and Gjørv[4] and Hammer [12] also found good correlations between these properties.This is because the stiffness and strength of LWAC is affected by the characteristics of aggregates, contrary to what happens in NWC.

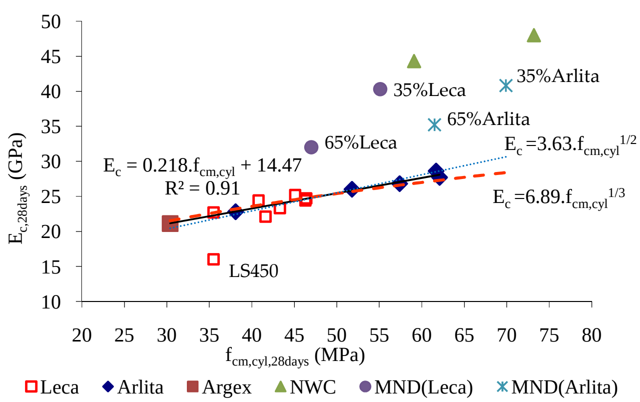

Fig. 2 Relation between modulus of elasticity, E_c, and compressive strength, f_c, at 28 days

The average modulus of elasticity, E_{cm}, relates to f_{cm} according to Eq. (2). Based on usual expressions of the type $E_{cm}=a.f_{cm}{}^{1/3}$ and $E_{cm}=b.f_{cm}{}^{1/2}$[4,10,13], Eq.(3) and Eq.(4) were obtained by linear regression. These expressions are more physically correct, since E_{cm} is null when f_c tends to zero.

$$E_{cm}= 0{,}22.f_{cm,cyl} + 14{,}5\ ;\ R^2=0{,}91 \quad (GPa) \tag{2}$$

$$E_{cm}= 6{,}89.f_{cm,cyl}^{1/3};\ R^2=0{,}87 \quad (GPa) \tag{3}$$

$$E_{cm}= 3{,}63.f_{cm,cyl}^{1/2};\ R^2=0{,}86 \quad (GPa) \tag{4}$$

However, the relation between f_{cm} and E_{cm} is different in NWC, confirming the influence of other factors, such as the density. In fact, changing the volume of normal density aggregate affects the stiffness but may not affect the strength, as usually happens in LWAC. As shown in Figure 2, LWAC made with Arlita has a modulus of elasticity about 37% lower than that of the NWC of equal strength.

In Figure 3 the results obtained in this study are compared with those of other authors. Since the results of Zhang and Gjørv[4] and Videla and Lopez [13] were obtained from cubic specimens, the following simplified relation was adopted: $f_{cm,cyl} = 0{,}9.f_{cm,cub}$. On average, the results are identical to those documented by Al-Khaiat and Haque[9] and are 5 to 15% higher than those of other authors (Figure 3). The results reported by Zhang and Gjørv[4] refer to ALWAC, which explains the lower values of E_c.

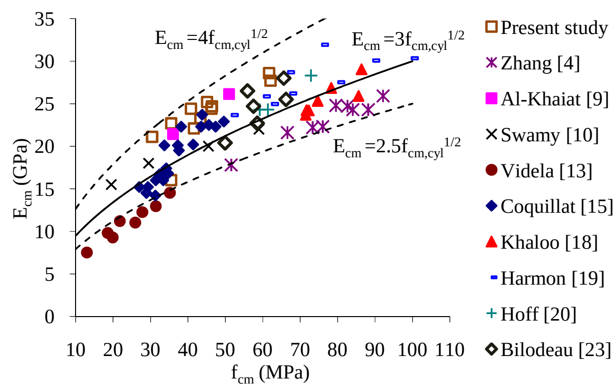

Fig. 3 Relation between the elastic modulus, E_{cm}, and compressive strength, f_c, (different references)

In addition to other factors, the scattering of the elastic modulus is related to the different volume, texture and stiffness of the aggregates used by other authors.For instance, varying the LWA volume in LWAC with $f_c<f_L$ affects the concrete stiffness without significantly changing the strength. Therefore, the variation of the failure mode of LWAC with its strength level hinders the definition of unique relationships between f_c and E_c.

In Figure 4 the results obtained in this study are compared with those estimated from the main normative expressions listed in Table 1. The dry densities for ACI 213 [7], ACI 318 [17] and NS 3473 [21] and the 28-day densities for EN 1992 [22] and fib 8 [1] listed in Table 6 were considered. For the expression of ACI 213 [7] it was considered that c = 0.038 (Table 1). E_c was underestimated for all normative expressions except ACI 318 [17] (Figure 4). In general, E_c was 4-21%, 8-19 %, 4-15% and 3-21% higher than the values estimated from EN 1992 [22], NS 3473 [21], fib 8 [1] and ACI 213 [7], respectively. The estimation is better for concretes made with higher density LWA. The expression suggested in ACI 318 leads to E_c estimates that are 2-7% lower for strength levels below the domain of validity ($f_{cm,cyl}$< 40 MPa) and 2% lower to 6% higher for higher strengths. The differences between normative estimates were generally less than 10%.

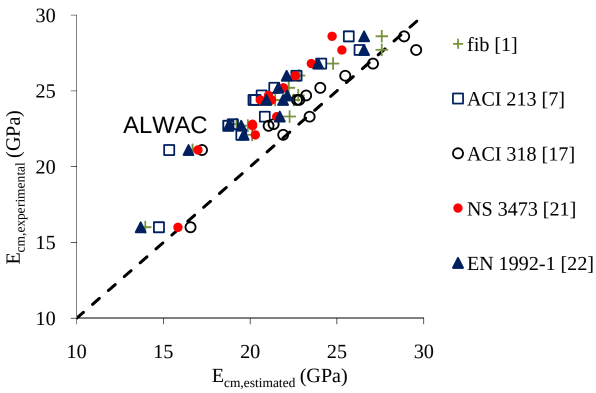

Fig. 4 Comparison of experimental results with those estimated from the main normative expressions (LWAC)

Based on all the results of Figure 3, the accuracy of the expressions proposed in EN 1992 [22] and ACI 213 [7] is evaluated in Figure 5. Since these expressions are dependent on the concrete density, common LWAC domains which cover equilibrium densities between 1700 and 1900 kg/m^3 and dry densities between 1600 and 1800 kg/m^3 were assumed. It can be concluded that these normative expressions provide reasonable estimates of E_c. The expression proposed in EN 1992 [22] underestimates E_c for high strength concretes and overestimates E_c for low to moderate strength concretes. Note that the expression in ACI 213 [7] was built for concrete strengths up to 41 MPa.

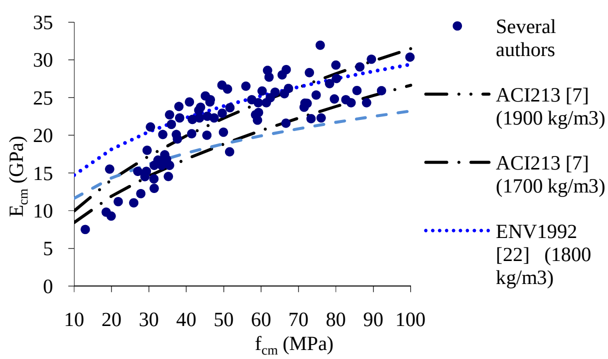

Fig. 5 Comparison between the experimental results from several authors (including the results of the present study) and those estimated by the main normative expressions

4.3. Evolution of the modulus of elasticity

The E_c evolution from 7 to 28 days was lower in concrete made with more porous aggregates. Whereas in NWC the modulus of elasticity increased 21%, in LWAC with Leca and Arlita it only increased 5 and 10 %, respectively (Table 6). The progressive hydration of the cement paste in NWC reduces the stiffness gap between the mortar and the aggregate, thereby increasing the elastic compatibility between phases. On the other hand, since LWAC contains aggregates of lower stiffness than the surrounding mortar the elastic compatibility diminishes as the mortar properties develop. Therefore, it is clear that there must be a different relation between f_c and E_c for NWC and LWAC.

4.4. Influence of w/c ratio and initial wetting conditions of the aggregates

As expected, E_c falls when the w/c ratio is increased. This reduction is not very significant, however. On average, E_c decreases only 1 to 1.3 GPa (≅ 4-5%) in LWAC made with Arlita and Leca for variations of 0.05 in the w/c ratio. Differences of 9 to 11% in the compressive strength correspond to these E_c variations of 4 to 5%. The consideration of different types of cement in LWAC with Arlita (CEM I 42.5 and CEM I 52.5, Figure 6) and with Leca (CEM II/AL 42.5 and CEM I 52.5, Table 6) had little influence on E_c, i.e. LWAC is little affected by the improved quality of the mortar.

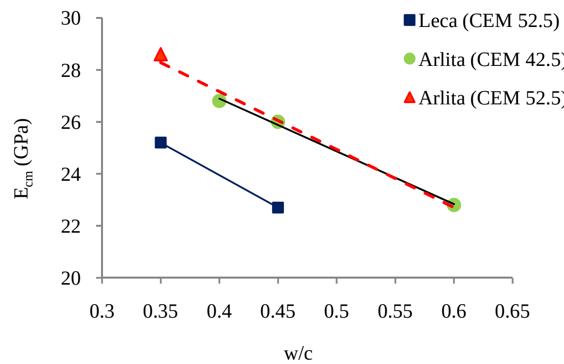

Fig. 6 The static modulus of elasticity, E_c, as a function of the w/c ratio

The modulus of elasticity of continuously water-cured concrete seems to be little affected by the initial water content of the LWA. The differences in E_c for LWAC with pre-saturated, pre-wetted and initially dry LWA were less than 3% (Table 6, Figure 1). This is only 0.8 GPa, which is within the range of the test variability. This shows that high quality ITZs can be obtained, regardless the initial wetting conditions of LWA.

4.5. Concrete with nanosilica

The addition of nanosilica (NS) led to a reduction of 3% and 8% in the static modulus of elasticity of LWAC made with Leca and Arlita, respectively.But these reductions are not confirmed for E_d and E_c determined from the LVDTs (Table 6). In general, it can be concluded that adding NS had a minor influence on the strength and stiffness of concrete, either by densification of the matrix or by improving the aggregate-paste ITZ. These results contradict the increase in E_c found by Luther [36] and Chandra and Berntsson[6] in LWAC made with silica fume.

It is likely that there was no effective dispersion of NS. According to Li, et al.[25], when the nanoparticles are not properly dispersed their aggregation can create weak regions in the form of voids, so lower strengths are expected. This phenomenon ought to be more relevant in mixtures of lower w/c ratios with less effective water in the system, which hinders the good NS dispersion. Other possible causes may be mentioned:

- Strength limitation imposed by LWA. Improving mortar by refining its porous structure will be less relevant for the strength development of LWAC;
- Less impact of the NS on improving the ITZ. The contribution should be greater when the failure occurs at the ITZ, i.e. usually when f_c is lower than f_L. This is more likely to occur in LWAC made with denser LWA, which may explain the better efficiency of NS in LWAC made with Arlita (Table 6);
- LWA absorption of part of NS during mixing.Unlike NA, LWA is an extension of the mortar's porous system.Zhang and Gjørv [37] documented the penetration of silica fume and cement particles in the more porous regions of LWA. Since nanosilica is composed of particles that are 1000 to 10000 times smaller than cement, this phenomenon becomes more relevant.

Taking the results into account, the investment in high reactive, more costly additions may be not advantageous in LWAC, at least if additional measures to better disperse the NS are not implemented.

4.6. Partial replacement of NA by LWA (ALWAC)

The partial replacement of normal weight fine aggregate by lightweight sand led to a reduction of 66.7 % and 36.5 % in the modulus of elasticity, respectively for NWC and LWAC of otherwise equal composition. This confirms the increased deformability of ALWAC, also mentioned by several authors (e.g., [7,9,11]). There is an E_c reduction of about 30% compared with the LWAC of equivalent strength and containing NA sand (Figure 2).However, taking into account the density of concrete, the relation between this property and the elastic modulus of ALWAC is identical to that of the LWAC (4.8).

In general, the modulus of elasticity of ALWAC is underestimated by the main normative expressions (Figure 4). Only the expression suggested in ACI 318 [17] led to a slight overestimation of E_c (about 4%). The greatest underestimates were obtained from EN 1992 [22] (about 14% lower).

There is an almost linear reduction of concrete stiffness as the NA coarse aggregate is replaced by LWA (Figure 7). The reduction is higher for MND with lower density aggregates (less stiffness). The ratio between the modulus of elasticity and the density of concrete is higher when the percentage of replacement is lower and the density of the aggregate is higher.However, the MND with 35% replacement of NA by LWA has a modulus of elasticity similar to that estimated by EN 1992 [22] for NWC of equal strength. Even taking into account 65% replacement of NA by LWA, the E_c modulus of MND is only 7% (Arlita) to 9% (Leca) lower than that estimated by EN 1992 [22]. Accordingly, the use of MND enables the overall weight of the structure to be reduced without significantly affecting its design deformability. This is very promising, since it greatly helps with the attainment of structurally more efficient solutions.

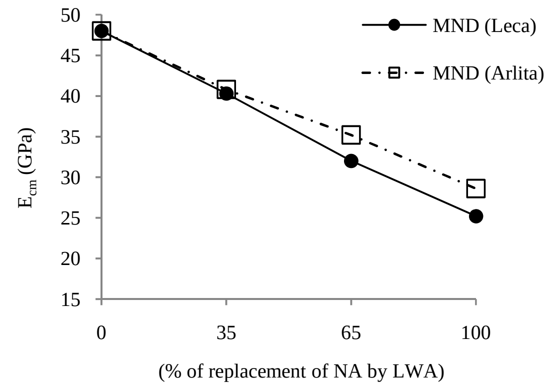

Fig. 7 Modulus of elasticity at 28 days for different replacement percentages of coarse normal density aggregate by lightweight aggregate

As is illustrated in Figure 8, the MND elastic modulus can be greatly underestimated by the main normative expressions, especially NS3473 [21] and ACI 213 [7] where differences of 20 to 40% are obtained. More reasonable differences of less than 20 % are obtained for the other normative expressions.

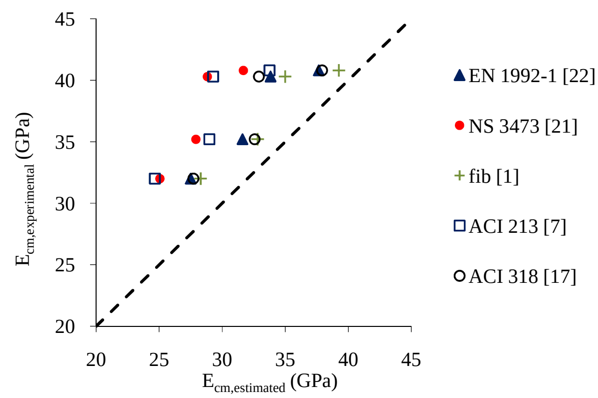

Fig. 8 Comparison of experimental results with those estimated from the main normative expressions (MND)

4.7. Relation between the static modulus of elasticity and density

Unlike relation between f_c and E_c, the relation between E_c and dry density, ρ_d, is independent of the type of concrete and aggregate (Figure 9). This relation between E_c and ρ_d does not depend on the mode of failure as is the case of E_c versus f_c. It seems thus appropriate to also consider this property to estimate E_c.

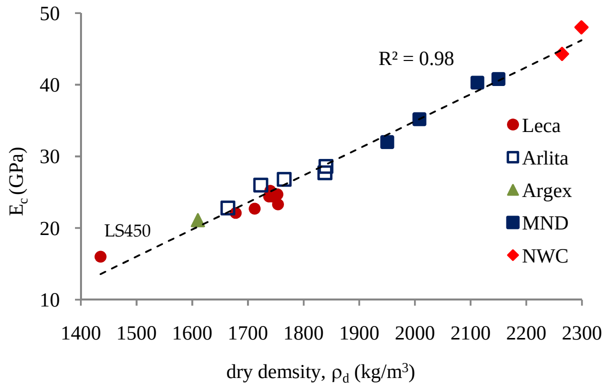

Fig. 9 Relation between the static modulus of elasticity, E_c, and dry density, ρ_d

4.8. Relation between E_c and E_d and between E_c and UPV

The static modulus of elasticity, E_c, varies approximately linearly with the dynamic modulus of elasticity, E_d, with a reasonable correlation between these two properties (Figure10). In this study, E_d was 20 to 30% higher than E_c in LWAC, 34% in ALWAC and 17% in NWC. These percentages correspond to mean differences of 6 to 7GPa, and are generally greater for higher strength concrete.

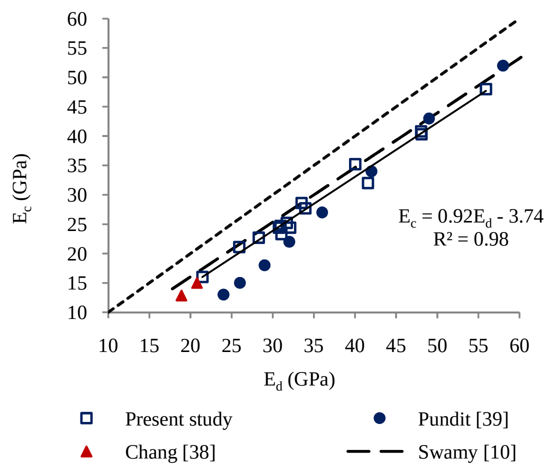

Fig. 10 Relation between E_c and E_d

Based on ASTM C215, Chang, et al.[38] obtained E_d values about 41% higher than E_c for LWAC with 17-23MPa (differences of about 6 GPa). These results are in line with those obtained in this study (Figure10). The results from this study almost coincide with the regression line determined by Swamy and Lambert [10] for LWAC of 20 to 60 MPa (Figure10).

The velocity *UPV* is related to E_c in Figure 11. Regarding the relation suggested in Pundit [39] for NWC, lower values of E_c were obtained for higher *UPV* (Figure 11). The greatest differences occur for MND and NWC. However, similar relations are obtained for LWAC with V_{us} up to 4.4 km/s.

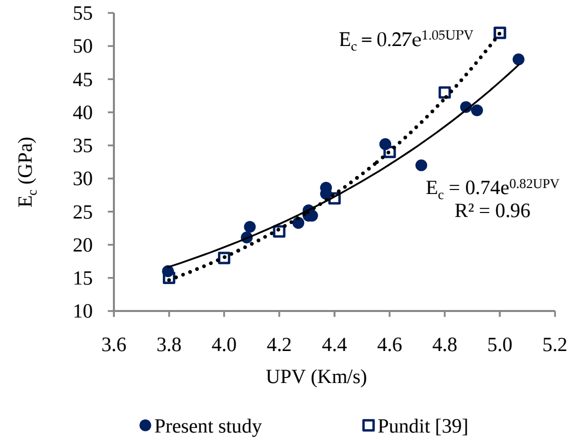

Fig. 11 Relation between E_c and *UPV*

5. Conclusions

The LWAC modulus of elasticity ranged between 21.1 and 28.6 GPa for compressive strengths between 30 and 62 MPa, which means an E_c reduction of 40 to 56% in relation to NWC of equal composition. This reduction of the LWAC elastic modulus increases as the density of the aggregate decreases and as the volume of aggregates and w/c ratio increases. For concrete of an equivalent grade the reduction of E_c was 37% in LWAC made with less porous LWA. The replacement of natural sand by fine LWA led to an E_c reduction of about 37% compared with LWAC of otherwise equal composition and 30% in relation to LWAC of equivalent strength.

To sum up, the MND and LWAC static and dynamic modulus of elasticity were characterized based on extensive experimental work involving different compositions using different types and initial wetting conditions of aggregates. The following important conclusions have been drawn from this experimental work:

- The addition of NS or the use of different cements had little influence on the strength and deformability of LWAC.The greater efficiency of LWAC made with NS is not confirmed;
- The stiffness of LWAC is little affected by the initial wetting conditions of LWA;
- The partial replacement of NA coarse aggregate by LWA implies an almost linear reduction of E_c.With up to 65 percent replacement of NA by LWA, an elasticity modulus the same or higher than that specified in EN 1992 [22] for equal strength NWC is obtained.This is very promising since it means that lighter solutions can be used without significantly affecting their design deformability;
- There is a good relation between f_c and E_c, regardless the type of LWA. The obtained results are within the range of those documented by other authors, which fall in the region bounded by the curves $E_{cm}= 3.f_{cm}^{1/2}$ and $E_{cm}= 4.f_{cm}^{1/2}$. However, this relation may vary slightly with the strength level of the LWAC if the failure mode is changed, which hinders the definition of singular relationships between E_c and f_{cm};
- Regardless of the type of aggregate, high

regression coefficients are obtained between E_c and dry density;

- The LWAC elastic modulus was underestimated by less than 20% for all the normative expressions analyzed except ACI 318 [17]. The MND elastic modulus can be greatly underestimated by the main normative expressions, especially NS3473 [21] and ACI 213 [7], which are not suitable for these concretes. Closer estimates are obtained by EN 1992 [22] and ACI 318 [17], which are more appropriate;
- From several results reported by the authors and other investigators, it can be concluded that the normative expressions from EN 1992 [22] and ACI 213 [7] provide reasonable estimates of the LWAC elastic modulus. However, the expression in ACI 213 (2003) is not recommended for high strength LWAC;

High correlations, of over 0.95, are obtained between the static and dynamic modulus or the elastic modulus and the ultrasonic pulse velocity, regardless the type of aggregate. This makes it possible to efficiently predict the elastic modulus of LWAC with non-destructive ultrasonic pulse tests.

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Acronyms list

ALWAC - LWAC made with lightweight sand
ANS - LWAC made with Arlita and nanosilica
E_d - dynamic modulus of elasticity
E_c - static modulus of elasticity
f_L - limit strength
ITZ - interface transition zone
LNS - LWAC made with Leca and nanosilica
LWA - lightweight aggregates
LWAC - lightweight aggregate concrete
NA - normal density aggregate
MND - modified normal density concrete
NWC - normal weight concrete
NS - nanosilica
SP - superplasticizer
UPV - ultrasonic pulse velocity

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