Optimisation of the Mechanical Behaviour of Lightweight Aggregate Concrete by the use of High Performances Cementitious Matrixes

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Summary

This paper presents the results of compression and extensometric experiments performed on 16x32cm high performance lightweight aggregate concrete cylindrical specimens. The test parameters of this investigation were the mechanical characteristics of the matrix (compressive strength and elastic modulus) and the volumic fraction of lightweight aggregates. These experiments have allowed to measure the compressive strength of the specimens and to determine the behaviour laws and the elastic modulus of the lightweight aggregate concrete.
An equivalent parametric study based on an explicit homogenisation process was led in parallel. The confrontation of the obtained results with the experimental one proves good agreement between models and experiments. These results demonstrates that this kind of models could be used to develop a numerical tool able to estimate the mechanical behaviour of a lightweight aggregate concrete from the physical and mechanical characteristics and from the dosages of its constitutive elements.

Keywords: compressive strength; dilute approximation; elastic behaviour; expanded clay aggregates; high performances matrix; homogenisation; lightweight concrete; Young modulus.

1. Introduction

To extend the application field of lightweight aggregates concretes (LWAC) to structural use and make these concretes attractive in spite of the high production cost of the artificial lightweight aggregates, it is interesting to raise their mechanical performances by using high performances concretes technology and by optimising the volumic fraction of the lightweight aggregates. These high performance lightweight concretes are of interest for structures of which self-weight load is a critical problem, such as bridges [1] and offshore structures [2].
The work presented hereafter is an experimental and numerical study of the effect of the composition parameters of LWAC on their elastic characteristics. Our goal was to test models of the elastic behaviour of LWAC so as to lay the basis of a numerical tool useful to their design.

2. Experimental Program

2.1. Materials of the study

2.1.1. Lightweight Aggregates

8/16mm granular size fraction of expanded clay aggregates was chosen for this study. Table 1 presents the characteristics of the aggregates.
The value of the elastic modulus of grains was deduced from their density, according to the relationship quoted by Arnold and Virlogeux [3]. Because of their porous character, lightweight aggregates have low mechanical strength and elastic modulus.
To control their water content, aggregates were saturated in water for 48 hours and drained 15 minutes before use. This allows obtaining stable free water content that was measured so as to control the water supply of aggregates during the mixing of concrete.

Table 1 Properties of lightweight aggregates.

Granular size fraction	8/16 mm
Density of grain (kg/m^3)	700
Specified Strength (MPa)	5
Absorptivity (%vol) after 2 h	5
after 48 h	8
Equivalent Elastic Modulus (MPa)	6700

Table 2 Properties of the six mortar matrixes.

Mortar matrixes	M1	M2	M3	M4	M5	M6
Cement	CEM I 52.5	CEM I 52.5	CEM I 52.5	CEM I 52.5	CEM I 52.5	CEM II 42.5
W/C (mass ratio)	0.45	0.35	0.32	0.31	0.275[†]	0.33
S/C (mass ratio)	1.24	1.24	1.24	1.2	0.8	1.2
Silica fume (% of C)	/	/	/	/	7	/
Superplasticizer (% of C)	0[a]	1[a]	2.1[a]	1.3[b]	1.95[b]	0.4[b]
Compressive strength (MPa)	50	61	70	69	86	63
Young modulus (MPa)	23630	25000	25880	32109	28868	25230

[†] water on binder ratio; binder includes cement and silica fume.
[a] superplasticizer A.
[b] superplasticizer B.

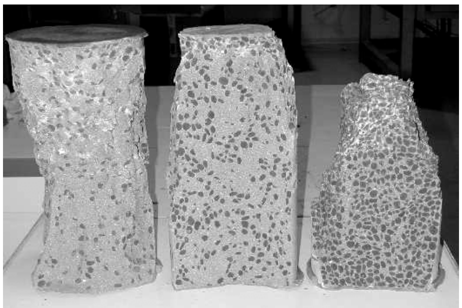

Fig. 1 Lightweight aggregates volumic fraction of 0.125, 0.375 and 0.45.

2.1.2. Matrixes of mortar

Six different mortar matrixes were tested to evaluate the influence of the mortar strength on the concrete strength. Cement was a CEM I 52.5 Portland cement, except for mix M6 (CEM II 42.5). We have used fine sand (0/2mm) and polycarboxylate based superplasticizer. Silica fume was introduced in mix M5. These six mixes were determined to be insensitive to the segregation of lightweight aggregates (lightweight aggregates have a tendency to come up to the cement paste surface when the paste fluidity increases). Table 2 gives the mixture proportions and the mechanical properties of the six mortar matrixes.

2.1.3. Composition of Lightweight Aggregates Concrete Sample

In order to determine the influence of the aggregate content on the LWAC strength, 16x32mm cylindrical specimen were made using four volumic fractions of aggregates: 0.125, 0.25, 0.375 and 0.45 of the total volume of concrete (Fig. 1). Curing was made at constant temperature and moisture (20°C, 90% relative humidity; M1 to M3 based LWAC) or in water (M4 to M6 based LWAC).

2.2. Experimental Setup and Measurements

2.2.1. Compressive Tests

A force controlled compression device was used to perform the compressive test on the 16x32mm concrete cylinders. The tests were conducted with respect to the NF P 18-406 [4] french recommendations. Compressive stress was imposed to the concrete cylinder with a 0.2 MPa/s increase rate (4 kN/s). The measurement of the compressive stress is obtained with±1% accuracy.
For some of the tests that we have performed, a breaking of a few lightweight aggregates localized in the vicinity of the compression device's platens was responsible for a premature breaking of the specimen. In this case, the compressive strength was not taken into account but the extensometric measurements were considered as correct.

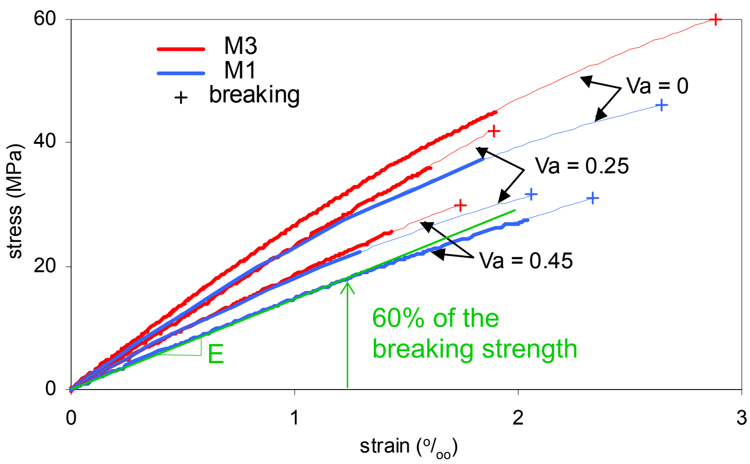

Fig. 2. Examples of measured behaviour laws for LWAC.

2.2.2. Extensometry

A concrete extensometer was used to measure the axial strain of the 16x32mm cylinders during the compressive tests. It recorded the axial displacement of the top of the specimen relative to its bottom (±1% accuracy).

Compressive tests were performed until compressive failure of the specimen. The extensometer was removed when the compressive stress reached 70 to 90% of the predictable compressive strength of the specimen. The elastic modulus of the concrete was calculated from the stress-strain curve as the secant modulus obtained for a stress level of 60% of the compressive strength (Fig. 2). Fine lines are 2nd degree polynomials extrapolated from the experimental curves. Va is the volumic fraction of lightweight aggregates.

2.2.3. Density measurements

The density of the concrete specimen was deduced from mass measurements made during the preparation of the compressive tests. As LWAC specimens were stored in a 90% relative humidity atmosphere, the measured densities are wet densities.

3. Experimental results

3.1. Influence of the density on the mechanical performances of LWAC

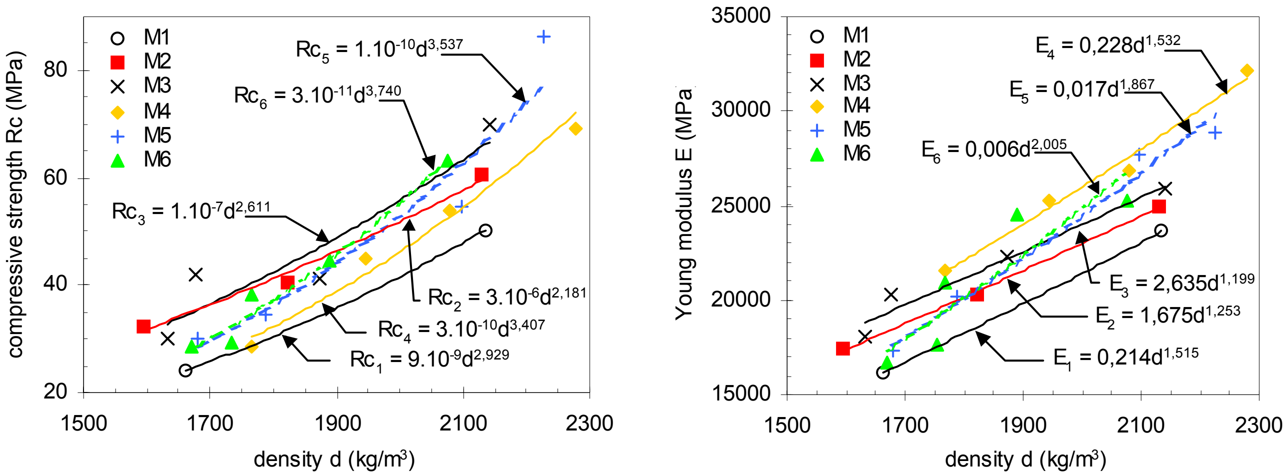

Fig. 3. Relationship between the density and the compressive strength and Young modulus of the lightweight aggregates concrete obtained from matrixes M1 to M6.

Matrixes M1 to M6 have respectively a compressive strength of 50, 60, 70, 69, 86 and 63 MPa and an elastic modulus of 23630, 25000, 25880, 32109, 28868 and 25230 MPa.
The different volumic fractions of aggregates allow obtaining wet densities ranging from 1595 to 2278 kg/m^3, which correspond to estimate dry densities ranging from 1460 to 1930 kg/m^3. Figure 3 gives the evolution of the compressive strength and elastic modulus of the different LWAC we have tested relatively to their densities. As the density falls with the introduction of lightweight aggregates in the mortar matrix, and because lightweight aggregates are 3.5 to 4 times less rigid than the mortar matrix, with compressive strength about a tenth of the mortar matrix one (5 MPa), the compressive strength and elastic re increasing functions of the density. The experimental results have been fitted with power laws adjusted by the use of the least square method. The numerical values of the constants of the power laws are given in Figure 3. In the case of the elastic modulus, the exponent of the power law ranges from 1.25 to 2, witch is comparable to the 1.5 value retained by ACI code [5].

3.2. Influence of the matrix mechanical properties

With regard to the elastic modulus, matrix values vary from 23630 MPa to 32109 MPa. Figure 4 (left) shows that the use of a stiffer matrix allows to improve LWAC modulus whatever the lightweight aggregate content is. As the concrete modulus depends both on matrix and aggregates moduli, the improvement obviously decreases with the volumetric fraction of aggregates. Thus, for volumic fraction of 0.45, the concrete modulus is slightly improved when the matrix modulus increases, when for higher volumic fractions, the improvement is more important. It is noticeable that for volumic fraction of 0.125, 0.25 and 0.375 the concrete to matrix moduli ratio E_c/E_m stays almost constant when the matrix modulus increases. For volumic fraction of 0.45, E_c/E_m decreases markedly (from 0.7 to 0.5).
With regard to the compressive strength, matrix values range from 50 to 86 MPa. Figure 4 (right)

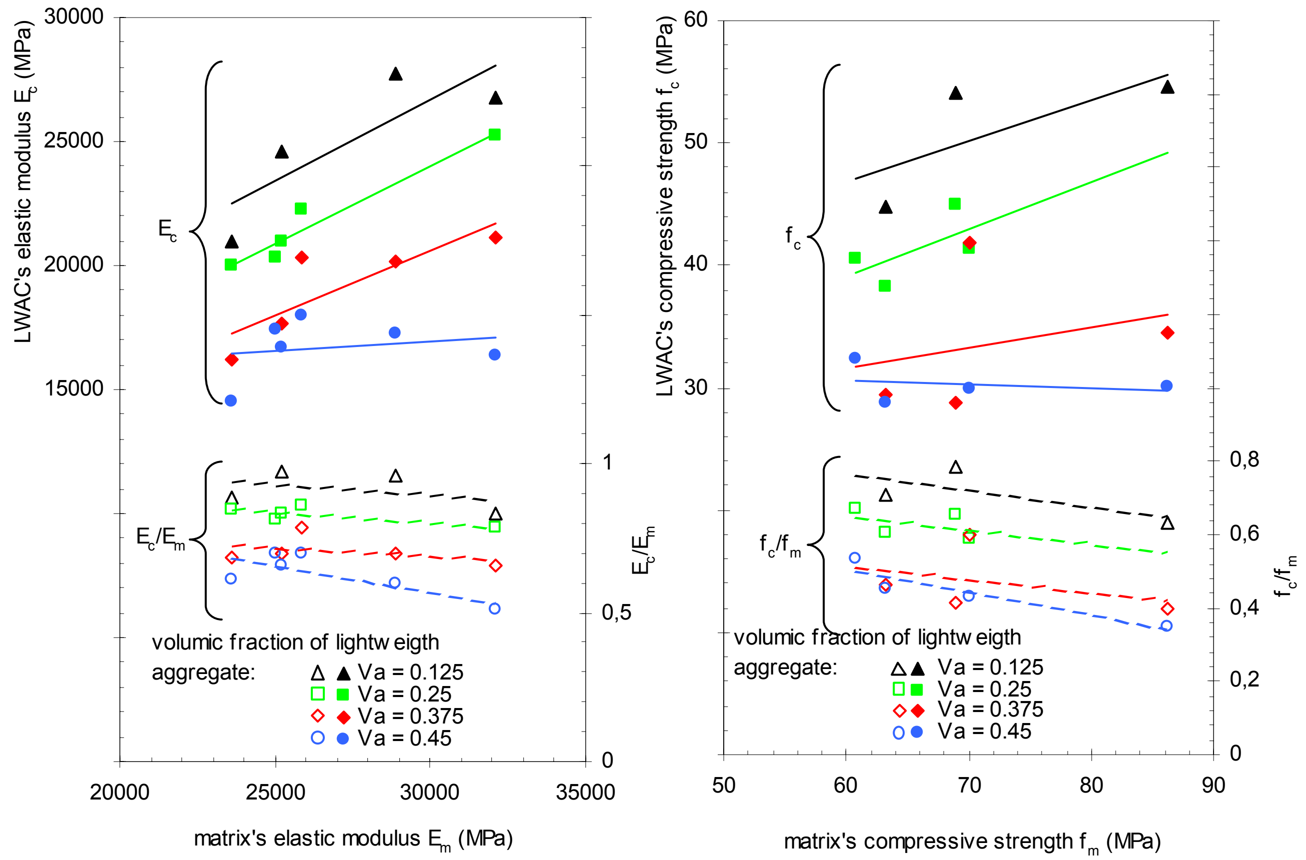

Fig. 4. Relationship between LWAC and mortar matrix elastic moduli (left) and compressive strength (right).

shows that the LWAC strength is an increasing function of the matrix strength and that the increasing rate of these function is largely influenced by the lightweight aggregate content: the concrete strength remains almost constant for aggregate volumetric fraction of 0.375 and 0.45 when it sharply increases for volumetric fraction of 0.125. In this case, the concrete to matrix compressive strength ratio f_c/f_m is always a decreasing function of the matrix strength. This shows that the strength gain for LWAC is smaller than the elastic modulus gain when the mechanical properties of the matrix become better.

From a certain volumetric fraction of lightweight aggregates upward (over around 0.3, which correspond to LWAC densities under 1800 kg/m^3), the LWAC strength is not governed anymore by the mortar strength.

3.3. Empirical relationship between the elastic modulus and the compressive strength

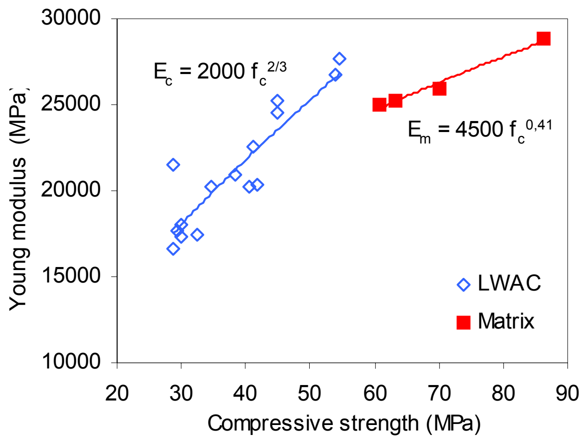

Fig. 5. Relationship between the elastic modulus and the compressive strength.

Figure 5 shows the empirical relationship between the elastic modulus and the compressive strength for LWAC and for mortar matrixes.

Measured values on LWAC samples point out that the elastic modulus can be deduced from the compressive strength by the following relationship:

$E_c = 2000\ f_c^{2/3}$ (1)

This results concerns the same kind of lightweight aggregates (expanded clay aggregates, $f_a = 6$ MPa, $E_a = 6700$ MPa). As the different tested mortar matrixes have all better mechanical properties than aggregates ones, the compressive strength and the elastic modulus were mostly influenced by the same parameter: the content of lightweight aggregates (the weaker link). So it is justified to establish relationships between the two values.

Obviously, the relationship between E and f_c is different for the matrixes; their compressive strength and elastic modulus are depending on the porosity of the mortar.

4. Numerical simulation of the LWAC's behaviour

A numerical parametric study has been led in parallel of the experimental program and the aim of this part is to confront the numerical simulations based on homogenization techniques with the experimental results obtained on LWAC in order to propose a predictive tool of their elastic behaviour. First, the chosen method is briefly presented, and second, some of the results calculated for different test parameters are discussed and compared to those obtained for the experimentally tested specimens.

4.1. Description of the homogenization process

The exploited numerical model was based on the common micromechanical model of the dilute approximation [6]. The representative volume element refers to a single particle imbedded in an infinite continuous medium. Also, the interactions between the inclusions are neglected and the effective behaviour of the equivalent homogeneous material is all the more accurate that the volumic fraction of aggregates V_a is small. In order to supply this approximation, the current rates of inclusions in concretes are reached by coupling the homogenization process of the dilute approximation with an iterative computation [7].
The two phases of the composite materials here studied are the cimentitious matrixes and the lightweight aggregates of which geometry is supposed to be ideally spherical. The results calculated for the experimentally tested specimens, showed in previous sections, are presented and discussed in the next paragraph.

4.2. Confrontations with experimental results

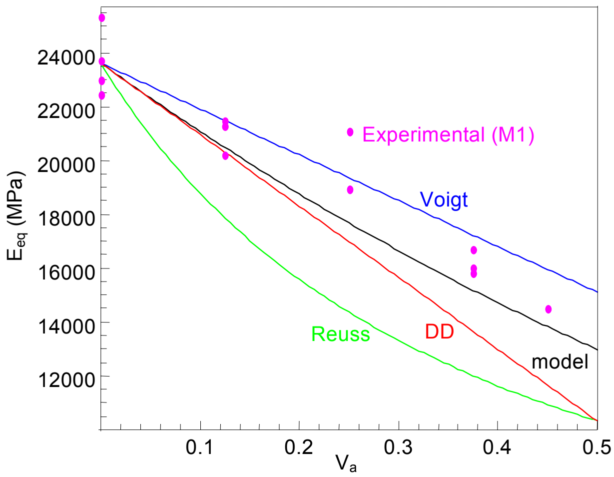

Fig. 6. Sensibility of LWAC's behaviour with volumic fractions of aggregates.

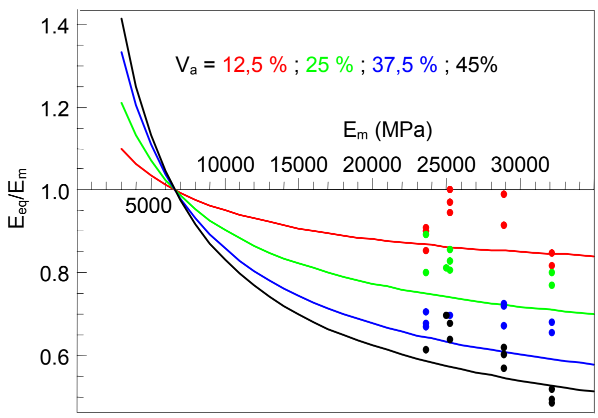

Fig. 7. Sensibility of LWAC's behaviour with the matrix rigidity.

The sensibility of the equivalent LWAC's behaviour has been analyzed for several test parameters like the rate of the lightweight aggregates, the rigidity of the high performance cementitious matrix and the Young modulus of the lightweight aggregates. The sensibilities of LWAC's behaviour with the volumic fraction of lightweight aggregates are plotted on Figure 6 for the first cementitious matrix tested (E_{m1} = 23630 MPa). Because of the weakness of the used inclusions, the introduction of lightweight aggregates in concrete degrades its mechanical performances. The equivalent behaviour calculated with the developed iterative process is compared with a direct computation of the dilute approximation (without iterations) and the classic models of Reuss and Voigt approximations which give the lower (stress approach) and upper (strain approach) bonds of the equivalent homogeneous behaviour. This both equivalent procedures effectively frame the equivalent behaviour experimentally observed. It must be notice that coupling iterative process with the dilute approximation increases the domain of validity of this method, as the accuracy of the equivalent modulus for large rates of inclusions is improved. Figure 7 illustrates the benefit on concrete behaviour from the use of high performance cimentitious matrixes. The numerical simulations are confronted with the behaviours determined for the experimentally tested specimens. Each colon of points corresponds to a high performance matrix. The gains are plotted with

the dilute approximation coupled with an iterative process and they show good agreement with the observed experimental points. The numerical model gives a bond of the equivalent modulus that must be expected, as for example, a modulus of 60 % of the matrix modulus for concrete with 37,5 % of aggregates or a modulus of 85 % of the matrix modulus for concrete with 12,5 % of aggregates.
The confrontations of the computed results with the experimental one prove good agreements between models and tested specimens for large rates of aggregates in the concretes, and for the different high performances cimentitious matrixes used. Also they show that this kind of approach could be used as predictive tool in order to optimize the mechanical behaviour of lightweight aggregate concretes. In order to improve the accuracy of the computed equivalent modulus, others homogenization methods, which allow to take into account the grain size distribution of the aggregates or to use not ideal geometry of aggregates (like ellipsoidal inclusions for example) are under interest.

5. Conclusion

Compressive and extensometric experiments have been realized on lightweight aggregates concrete made from six different cementitious matrixes and four volumic fraction of expanded clay lightweight aggregates.
The elastic modulus of the lightweight concrete is a nearly linear increasing function of the elastic modulus of the mortar matrix, whose slope is uninfluenced by the volumic fraction of lightweight aggregates, except for the highest volumic fraction used ($V_a = 0.45$) for which the influence of the matrix is strongly reduced. The compressive strength of the lightweight concrete is also a quasi-linear increasing function of the compressive strength of the mortar matrix. In this case the influence of the volumic fraction of lightweight aggregates is more marked and is sensible from the 0.3 volumic fraction onwards.
A numerical study completes the experimental study. It consists in calculating the elastic characteristics of the lightweight concrete from those of its components (mortar matrix and aggregates) by the use of the dilute approximation model coupled with an iterative calculation. The results show that this kind of model is able to predict suitably the experimental results and can therefore be the basis of a reliable predictive tool able to help the design of lightweight aggregates concretes.

6. References

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