Available online at www.sciencedirect.com

SCIENCE DIRECT®

Cement and Concrete Research 35 (2005) 770–775

CEMENT AND CONCRETE RESEARCH

Taking into account the inclusions' size in lightweight concrete compressive strength prediction

Robert Le Roy*, Edouard Parant, Claude Boulay

Division Bétons et composites cimentaires, Laboratoire Central des Ponts et Chaussées, 58 Boulevard Lefebvre 75732, Paris, Cedex 15, France

Received 16 July 2003; accepted 1 June 2004

Abstract

This paper deals with the mix design and mechanical properties of very lightweight concrete (LWC) made of expanded polystyrene spheres (EPS) and very high performance matrix. To avoid the segregation of EPS spheres in the concrete, it is necessary to adjust the matrix threshold by modifying the superplasticizer dosage. Based on experimental data obtained on different EPS concrete, it is shown that the lower the inclusion size, the higher the compressive strength of the hardened concrete. An empirical model is proposed, to take into account these experimental results. Young's modulus was also measured, it was found that its evolution against strength followed usual physical models, like the well-known Hashin's sphere model, and not an empirical one. Finally, a simulation, based on criteria outlined in the paper, shows that quite new concretes can be proposed in a range of strength versus specific gravity not yet achieved.

Keywords: Lightweight concrete; Mixture proportioning; Mechanical properties; Stability; Composite

1. Introduction

Lightweight concretes (LWCs) can be used in various construction fields. It can be used for repairing wood floors of old buildings, carrying walls of low thermal conduction, bridge decks, floating quay, etc. For the first applications, the lightest possible material is used, i.e., usually it has a specific gravity of 0.5, the strength being of less importance. But for some structural applications, a compressive strength higher than 40 MPa is sometimes necessary, which leads the designer to optimise a material with a specific gravity close to 1.8. In such a case, lightweight aggregates, such as expanded glass or clay, take part in the resistance of the composite.

The possibilities offered by new cement-based materials suggest that it is possible to improve the compressive strength versus the specific gravity, or to reach equivalent strength for lower specific gravity. It is proposed to use very lightweight inclusions, like expanded polystyrene (EPS), having a specific gravity of about 0.02 in an ultra high strength matrix having a strength higher than 130 MPa.

However, the mechanical behaviour of such a material is quite different from that of an ordinary LWC. It is known that the stress distribution within a granular cement-based composite depends on the sizes of the inclusions and on the respective modulus of the matrix and of the inclusions. When the aggregate has a modulus higher than that of the matrix, stress concentrations appear in the vicinity of the aggregates. It is said that coarse aggregates channel the stresses in compression. However, the LWC rupture mechanism is quite different from the NWC rupture mechanism, because the inclusion modulus is very low, compared to that of the matrix. To predict the material compressive strength, it could be interesting to develop a model based on a composite approach. The models developed in Refs. [1,2] take into account the relative elasticity modulus of the two phases (matrix and inclusions). However, when dealing with very lightweight aggregate, like EPS, having a negligible modulus, the two-phase models are in their limit of applicability. Another way is to refer to models based on porosity, assuming that the concrete is described as a matrix containing voids (EPS spheres). In these models, the porosity is often taken into account through a power or a logarithmic function [3]. Most of the time, it is also necessary to evaluate the strength of the matrix at zero porosity.

Before developing such a model, it is necessary to assess the rupture mechanisms of these lightweight materials and, as a first step, to quantify the influence of the lightweight inclusion size on compressive strength. Indeed, in literature,

* Corresponding author. Tel.: +33-1-40-43-53-98; fax: +33-1-40-43-54-98.

E-mail address: robert.leroy@lcpc.fr (R. Le Roy).

0008-8846/$ – see front matter
doi:10.1016/j.cemconres.2004.06.002

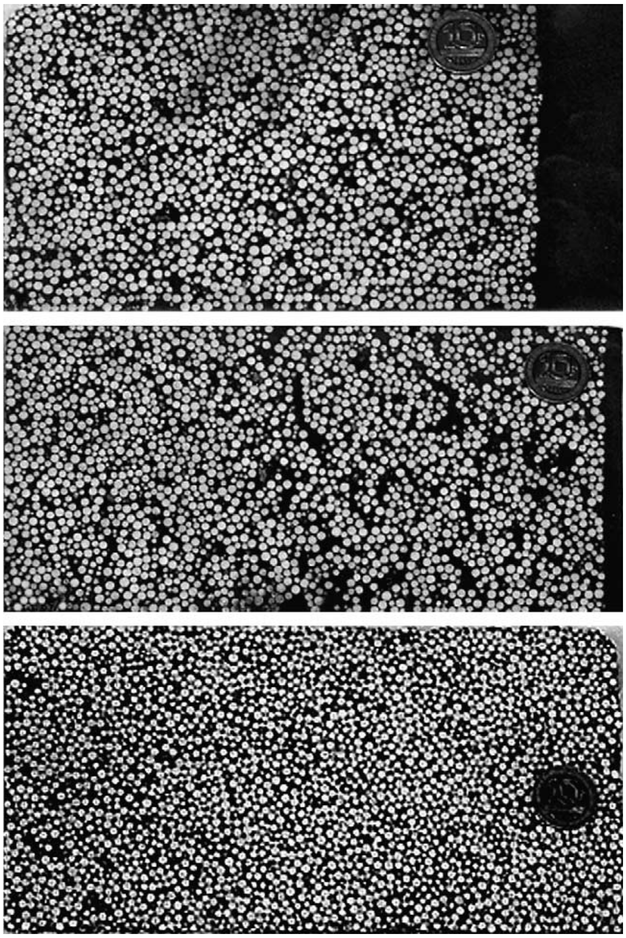

Fig. 1. Segregation evolution according to the sphere packing density observed on sections of 11 × 22 (cm) cylinders. From bottom to top, sphere packing density of 0.7, 0.4 and 0.3 (sphere diameter = 3 mm).

the fact that the compressive strength increases when the pore size or EPS sphere size decreases is well known [3,4].

The aim of this study is to propose a support for the mix design of a new type of LWC and to evaluate some main features of its other mechanical properties. To this end, the influence of the aggregate-packing density and of the EPS sphere size on the resistance and modulus of LWCs is studied. The bases of a model suitable to lightweight EPS concretes are proposed. Experimental results used in this paper come from Ref. [5].

1.1. Materials and mix design principles

The two-phase material is an ultra high strength mortar and expanded polystyrene spheres (EPS). The basic matrix is of the same type as that used for very high strength concretes (VHSC) [6]. It is made with CEM I 52.5 cement, class A silicafume (according to NF P 18 502), a rounded quartz sand having a maximum diameter of 400 μm, and a polycarboxylate-based superplasticizer. The lightweight inclusions are EPS of three different diameters: 1, 3 and 6 mm, each of one being used separately. It is possible to find in the market polystyrene spheres coated with a layer of polymers used to inhibit the material hydrophobia, to lower the electrostatic effects, and, to possibly create air voids in the mixture. To control the proportion of air voids in the concrete, and due to the fact that the paste had a good consistency that contributed to maintain the mixture homogeneity, no coated white spheres were used.

Two forces interact in the balance of a polystyrene sphere embedded in a viscoplastic fluid: Archimed's force and the resulting shear stress developed in the matrix especially at the matrix–inclusion interface. To maintain the concrete homogeneous, it is necessary that the matrix develops a threshold balancing the upward driving force. However, the presence of the other spheres influences this balance (Fig. 1). In the presence of a low sphere dosage, i.e., when the specific gravity of the LWC is high, the spheres are free to move, whereas for low specific gravity (≈ 0.6), the high sphere concentration is favorable to maintain the homogeneity.

In practice, it is possible to obtain homogeneous mixtures by adjusting the superplasticizer dosage. Indeed, a variation of superplasticizer dosage affects the matrix slump flow, which is itself directly linked to the shear resistance (Fig. 2). This can be shown by a dimensional analysis and in experiments on materials in which size of heterogeneity is

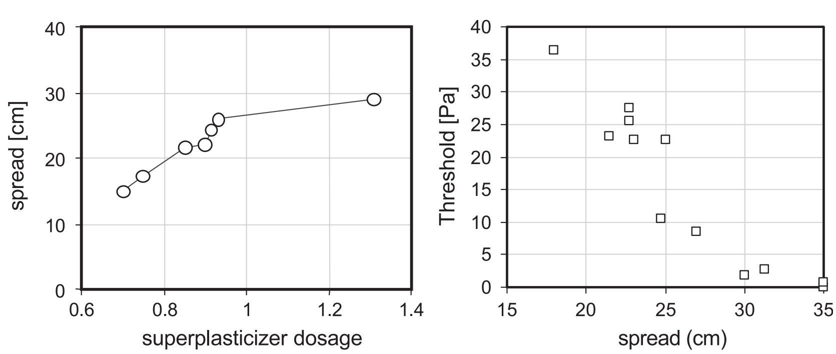

Fig. 2. Slump flow evolution (dim. B × b × h = 100 × 70 × 50 mm) according to superplasticizer dosage and correlation between paste threshold and spread. The threshold was measured by extrapolation on the y axis of the decreasing curve obtained on coaxial viscosimeter (Haake VT550).

Table 1
Mix design of the various LW concretes studied

Component [kg/m^3]	Concrete specific gravity					
	0.6	0.8	1.0	1.2	1.4	2.3 (matrix)
Polystyrene	23.31	21.86	19.05	16.05	13.14	0
Cement CEM I 52.5 "HTS du Teil"	287	330	416	502	588	982
Rounded quartz fine sand «Fontainebleau»	229	264	333	401	470	786
Silica fume	86	99	125	150	176	294
Superplasticizer (SP) dry extract Chryso THP [% of cement weight]						
1-mm-diameter specific gravity = 0.033	1.30	1.30	1.30	0.93	0.85	– *
3-mm-diameter specific gravity = 0.019	1.3	1.3	1.3	0.93	0.85	– *
6.3-mm-diameter specific gravity = 0.017	0.90	0.90	0.80	0.70	0.70	– *
Total water	74.5	85.7	108.1	130.4	152.8	255.4
Water–cement ratio	0.26	0.26	0.26	0.26	0.26	0.26
Silica–cement ratio	0.30	0.30	0.30	0.30	0.30	0.30

* Matrix SP dosage is 0.9%

low compared to cone dimensions (1/200th for the present work), or by experiments. The composition of the mixes is presented in Table 1.

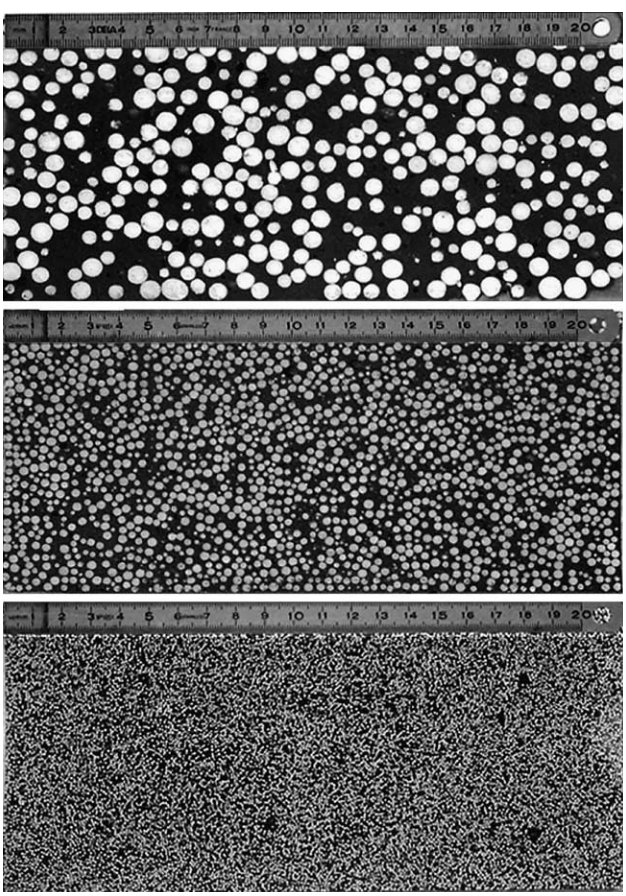

Fig. 3. Sample section at a same specific gravity for the three sphere diameters (from left to right 1, 3 and 6 mm).

The mixes were prepared in a standard concrete mixer. Water, superplasticizer, silica fume, sand and cement were successively introduced in the mixer. After 5 min of mixing, when the matrix became homogeneous, polystyrene spheres were introduced and the mixing maintained two more minutes at low speed. The LWC is poured without vibration to avoid segregation. After a setting time of 24 h, concrete samples were demolded and cured at 60 °C during 7 days. Sections of cutted samples are shown on Fig. 3.

2. Mechanical tests results

Compression tests were carried out after 7 days. Three samples were tested for each specific gravity and each sphere diameter. It was decided to account for each value and not for mean values, because samples' specific gravity slightly varies from one sample to another. For packing densities of EPS ranging between 0.3 and 0.7, strength evolution is quite linear (Fig. 4). However, including the results related to the matrix, this evolution follows in fact a power law (Fig. 5). By neglecting the stiffness and the strength of inclusions, which is a reasonable approximation for EPS, one obtains an evolution of compressive strength according to the porosity of LWC. The matrix being considered as a homogeneous material, with a neglected porosity, the porosity is here considered as the packing density of the EPS. The ratio between the LWC strength of a mixture with a porosity of 0.5 and that of the matrix is only approximately 10%, showing that the strength decreases very rapidly when the porosity increases. This evolution is qualitatively similar to curves given in the literature for various building materials [7]. In the following, for the sake of simplicity, porosity and packing density of EPS have the same signification.

The other significant phenomenon to emphasize is that the resistance depends of the sphere size, especially as the

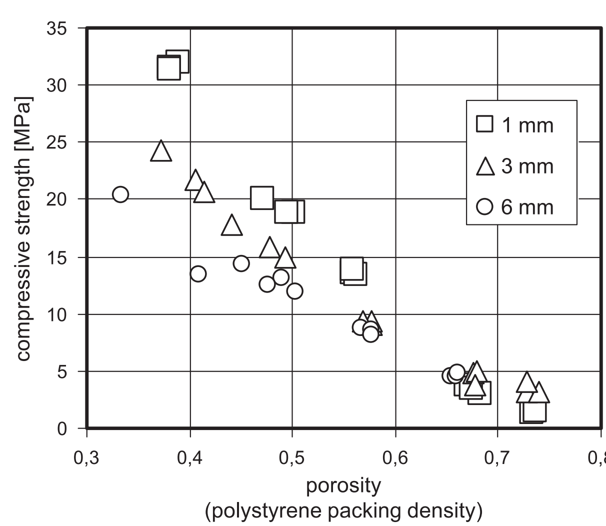

Fig. 4. LWC strength versus EPS packing density.

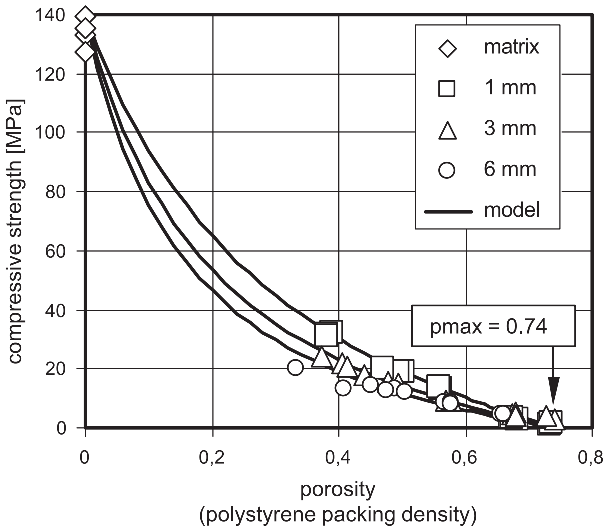

Fig. 5. Comparison between experimental data and modelling.

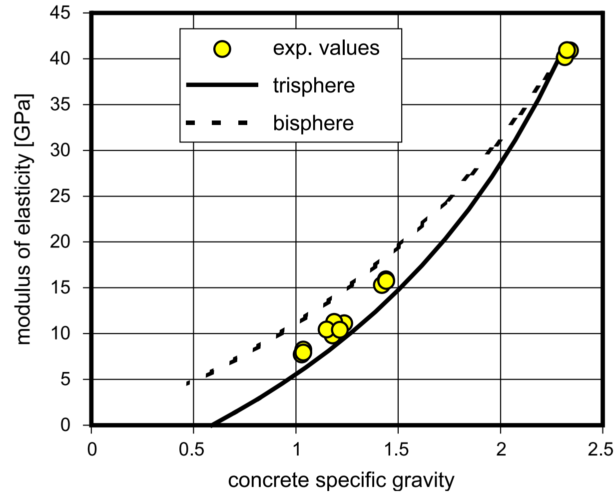

Fig. 6. Young's modulus evolution versus concrete specific gravity and comparison with Hashin's sphere model (bisphere) and trisphere model [1].

EPS spheres' packing specific gravity is low. This fact was already mentioned in other works [4]. For a 0.4 porosity, M1 strength is almost twice that of M6. Close to the maximum packing density, that is to say 0.74 for spheres, the size inclusion dependency upon strength is not so clear. A greater material heterogeneity could explain why the strength depends on the presence of a local defect rather than on bead size.

3. Compressive strength modelling

In the literature [3,7], a dependence of the quantity of spheres on the compressive strength is usually searched, that is to say a function of the material porosity. Moreover, it is necessary to take into account the scale effect related to the LW inclusion size. For that, the following hypothesis were stated:

- LWC strength is proportional to the matrix strength;
- the model remains valid when no inclusions are present. In other words, whatever the sphere size, the strength evolution at low porosity tend towards the strength matrix;
- strength is minimal when the inclusion size is maximum. However, close to the maximum packing density of spheres, noted $p_{\max}$, and according to experimental results, the strength does not depend on the sphere size and tends towards zero.

Table 2
α Values according to sphere diameter

Polystyrene diameter (mm)	α
1	.46
3	.29
6	.22

A hyperbolic function in accordance with the precedent conditions is proposed. It takes the following form:

$$f_{cc} = \left(\frac{\alpha \left(1 - \frac{p}{p_{\max}} \right)}{\alpha + \frac{p}{p_{\max}}} \right) f_{cm} \tag{1}$$

where f_{cc} is the LWC compressive strength in MPa, f_{cm} is the matrix compressive strength in MPa, p is the porosity due to the inclusions, $p_{\max}$ is the maximum porosity (maximum packing specific gravity of EPS, here 0.74 for spheres) and α is an adjustment coefficient which depends on sphere size. The α values, calculated by numerical adjustments, are given in Table 2.

The model matches quite well with experimental data as it can be seen in Fig. 6. The model shows that better performance is obtained when the size of inclusions is small. It can be argued that the scale effect is due to the EPS sphere sample size's ratio, that is to say, to the fact that the biggest sphere size is too big compared to the sample size. However, this ratio, equal to 5%, can be considered as low.

It can be expected that, by mixing spheres of three sizes, it is possible to obtain a strength inside the extreme curves of Fig. 5, except in the field of high packing density. In this domain indeed, the polydispersity, which leads to a larger maximum compactness, will generate an improvement of the coating, therefore of strength. In other words, according to the fact that $p_{\max}$ is greater in presence of polydisperse inclusions, then, for a given p value, the $p/p_{\max}$ ratio is lower and the strength higher.

4. Other properties

To evaluate the serviceability of such a material, the deformation properties were studied. Young's modulus of

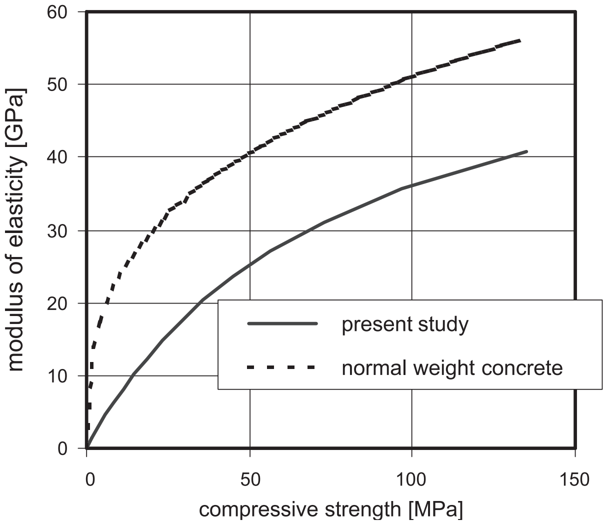

Fig. 7. Young's modulus evolution versus compressive strength. Comparison between EPS LW concrete and normal weight concrete (French regulation BAEL).

different mixes was measured, shrinkage being evaluated from that of the matrix.

4.1. Young' s modulus

The modulus of the matrix is closed to 40 GPa. Generally, that of LWC is lower than that of the normal-weight concrete, for a same specific gravity. Using polystyrene inclusions, this tendency is even more pronounced, which could be a drawback for some structural applications such as structures sensitive to deflections. Hashin's type model [8] allows to predict the modulus of elasticity with a quite good accuracy (Fig. 6). Hashin's spheres model coincides with the Hashin–Shtrikman bounds of a two-phase composite [9]. The dotted line in Fig. 6 represents the upper bound. The "trisphere" model [1] was proposed to account for the effective packing density of concrete inclusions, which cannot exceed a certain maximum value. Here this value, named p_{max}, is taken as 0.74, with respect to the maximum packing density of the spheres. At this value, concrete modulus of elasticity is close to that of the inclusion, i.e., close to zero for polystyrene. Experimental data show that any dependence of inclusion size on modulus was not founded. It is worthy to note that a strength-based model is inoperative for such a material, because these models are calibrated from data of normal-weight concrete, made of stiff aggregates (Fig. 7).

4.2. Shrinkage

Very high performance concrete (VHPC) shrinkage has been studied in different laboratories. The literature values [10] and the LCPC experience on materials available on the French market show that VHPC develops rapidly a great autogenous shrinkage, between 400 and 500×10^{-6}, and a negligible drying shrinkage. The LWC's shrinkage studied in the present work being mix designed from a very high strength matrix can be deduced from that of VHPC. However, it is interesting to see if the inclusions modify the shrinkage. In fact, when aggregates modulus is nonnegligible, aggregates contribute to a decrease of composite strains, because of their stiffness. In the case of EPS, the inclusion modulus being close to zero, they have no influence on the shrinkage of the composite, which is then of the same order of that of VHPC, i.e., 500×10^{-6}. Care must then be taken at early age to avoid cracking development [11], as for high-performance concrete, but the long-term shrinkage is low, because drying shrinkage is negligible.

5. Is there a progress in LWC performance?

To assess the serviceability of LWC, made of polystyrene inclusion or any inclusions having no strength, in structural applications, the model proposed can be used. Simulations are represented in Fig. 8 for a 180-MPa matrix and 1-mm inclusions, which leads, among the three balls size tested, to the best performance. It appears that it is possible to design a material in a domain of "strength-specific gravity" that have not yet be reached in cement-based materials. According to the fact that the properties of such an LWC would be lower in the frame of an industrial process than in laboratory conditions, and to account for safety factor, the strength class of concrete which can be industrially produced can be assessed. Considering a larger security interval for high-strength concrete, it is then expected, considering strength classes usually encountered, that a C25 (characteristic strength of 25 MPa) concrete having a specific gravity of 1.3 or a C60 having a specific gravity of 1.8 can be achieved.

Surely, other properties dealing with durability aspects have not yet been studied. One of the most important

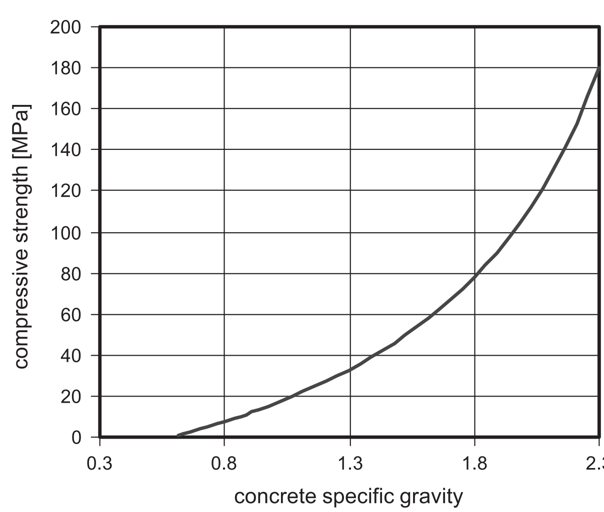

Fig. 8. Theoretical strength evolution versus concrete specific gravity, using 1-mm soft inclusions and 180-MPa matrix.

phenomenon is diffusion process, which is involved in chloride penetration or carbonation. These phenomena are functions of the gas permeability of the matrix and of the interfacial paste aggregate zone. In the case of low water–cement ratio and high silica fume content, it is known that the matrix and interfacial zone permeability are greatly lowered. It is then expected that the LWC behaviour formulated from such a matrix will trend to the same high durability.

6. Conclusions

In this work, a mix design method of LWC made of extra light aggregates and very high performance matrix is given. The study of segregation risk led us to propose a control of the initial threshold of the matrix, and to account for the packing density of LW aggregate. Experimental data shows that the compressive strength depends on the inclusions' size, the smallest the size the highest the performance. Experimental results were fitted to an empirical model. This model takes into account the packing density and the EPS diameter. Simulations were made using this model, using a very high performance matrix of 180-MPa compressive strength and weightless inclusions. It appears that new materials can be designed in a domain not yet explored on cement-based materials. What seems to be interesting, is that the concept associating fine LW aggregate to VHS matrix can be explored to propose other cement-based materials leading to new applications. For instance, using very fine inclusions, such as hollow glass microspheres, the performance, in terms of strength to specific gravity ratio, would probably increase.

References

[1] F. de Larrard, Concrete Mixture Proportionning, A Scientific Approach, E&FN Spon, London, 1999.
[2] C.C. Yang, R. Huang, A two phase model for predicting the compressive strength of concrete, Cem. Concr. Res. 26 (1996) 1567–1577.
[3] J.J. Beaudoin, R.F. Feldman, P.J. Tumidajski, Pore structure of hardened Portland cement pastes and its influence on properties, Adv. Cem. Based Mater. 1 (1994) 224–236.
[4] K. Ganesh Babu, D. Saradhi Babu, Behaviour of lightweight expanded polystyrene concrete containing silica fume, Cem. Concr. Res. 33 (2003) 755–762.
[5] E. Parant, Optimisation des bétons de densité inférieure à 1 (Concrete optimisation of specific gravity less than 1), LCPC Internal Report, Mémoire de DEA, 1999.
[6] P. Rossi, High performance multimodal fiber reinforced composite: the LCPC experience, ACI Mater. J. 94 (1997) 436–439.
[7] A.M. Neville, Properties of Concrete, 4th ed., Longman, Harlow, England, 1995.
[8] Z. Hashin, S. Shtrikman, A variational approach to the theory of the elastic behaviour of multiphase materials, J. Mech. Phys. Solids 11 (1963) 127–140.
[9] Z. Hashin, The elastic moduli of heterogeneous materials, J. Appl. Mech. 50 (1962) 143–150.
[10] A. Loukili, A. Khelidj, P. Richard, Hydration kinetics, change of relative humidity, and autogenous shrinkage of ultra-high-strength concrete, Cem. Concr. Res. 29 (1999) 577–584.
[11] P.C. Aïtcin, The durability characteristics of high performance concrete: A review, Cem. Concr. Compos. 25 (4–5) (2003) 409–420.