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Prediction and measurement of the elastic modulus of the RCC: Case of the low cement proportioning

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The Roller Compacted Concrete (RCC), which is presented as an evolutionary technology for a large diversity of applications (Dams, roads...), is considered, like conventional concretes and other construction materials, as an elastic material. The RCC in pavement supports many stresses which involve deformations and reciprocally. The knowledge of the relation between strength and deformation, for a material such as the RCC, presents a capital interest for the structural design of rigid pavements. The authors treat, in this work the experimental evaluation and the estimation, through a model, of the Young's elastic modulus E of the RCC for pavement manufactured with low cement proportioning. This work includes experimental measurements of the elastic modulus E on standardized specimens prepared according to the method of the French National Project "BaCaRa". It contains also the comparison of the measured modulus with those estimated by the models.

Key words: Roller Compacted Concrete (RCC), granular materials, Elasticity, Elastic modulus, models.

INTRODUCTION

The laboratory tests on the RCC can be carried out for several reasons. They deal, in general, to determine the numerical values which characterize physically and mechanically the material. They lead to fix the characterristics of material in the form of coefficients which define the behaviour under certain state of stresses, either under normal conditions of service, or in exceptional circumstances. In addition, the RCC, like the conventional concrete, can be regarded as an elastic material. Among the initial parameters of this material, the elastic modulus is distinguished as a mechanic constant which characterizes the RCC as a homogeneous material.

The measure tests of elastic modulus are classified as non-destructive mechanical tests, since we can repeat the test on the same specimen without destroying it with the condition of remaining in the elastic zone of the concrete and without exceeding the value of 40% of the yielding stress. The experimental study of a material like the RCC, intended to determine its behaviour under the action of the applied loads, leads to fix with precision, all the values which we usually obtain by calculation, such as the strengths and the deformations.

Some applied studies are done by Gauthier et al. (Gauthier and Marchand, 2002) and Ouellet (Ouellet, 1998) to characterize and to value RCC mixtures with cement proportioning varying between 225 and 300 kg/m3. In many works, especially in USA, Canada and in China, natural pozzonalas or fly ashes are used as additions. Ouellet (1998) showed in his experimental studies that the elastic modulus of the RCC is influenced by the properties of the two phases present in this mixture, which are the hydrated cement paste and the aggregates (Ouellet, 1998).

The objective in this work is to estimate, in a first phase, the elastic modulus of the RCC and to measure, in a second phase, this modulus by the experimental methods. Then, a comparison is presented between the results

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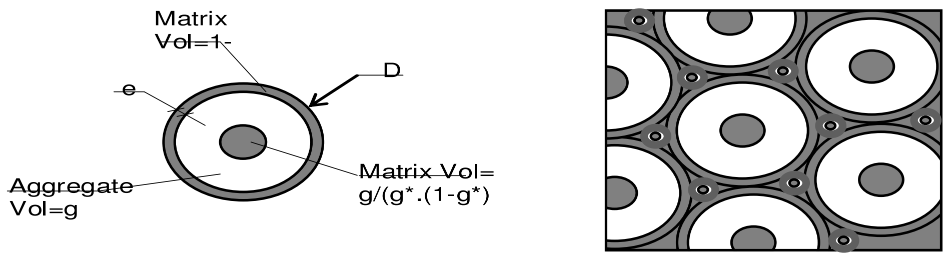

Figure 1. Three-spheres model (De Larrard, 1999).

considered theoretically and those given by experimental tests.

Relation stress-strain and elastic modulus

The analysis of the behaviour of the materials under the action of the loads is usually, presented by the relation between the deformation and the force which causes it. In experiments, this relation is obtained in the form of a diagram or a graph. The form of this diagram is the principal characteristic of technical materials because it allows classifying them according to their potential use in various types of works (Neville, 1995).

The diagram stress-strain of the RCC is obtained by testing specimen in axial compression, with a constant rate loading and in a way very close to a static loading. Theses tests are a simulation which approaches a phenomenon corresponding to the loading of this material in service once it is set up in real road works, especially that it will have to support, in the majority of the cases and even at early age, the total road loads for which it was designed.

By studying the stress-strain function represented on a diagram, it's considered that the term "elastic modulus" of a material, can be applied only to the linear segment of the stress-strain curve. In case where the curve does not present a linear part, we define a modulus in the tangent of the curve at its origin called "tangent elastic modulus" (Neville, 1995).

Estimation of the elastic modulus E through empirical models

As the compressive strength increases, the elastic modulus of the concrete increases also. This same assumption can be applied to an identical granular mixture like the RCC. Moreover, the exact form of this relation cannot be estimated, because the elastic modulus of the RCC is conditioned by the elastic modulus of the aggregate and the cement paste and by the volumetric proportions introduced into the mixture and this by analogy with the idea suggested by Neville (1995) for the conventional concrete (Neville, 1995). To estimate the evolution of the elastic modulus of the RCC, the models developed initially for the conventional concrete was applied.

If we consider that the increase of the elastic modulus Ec of the RCC, like it is the case for the conventional concrete, is gradually slower than the increase of the compressive strength *fc*, then we can apply the empirical model 1 used by standard ACI 318-02 for the elastic modulus E_C of the RCC, characterized by the following equation 1 (Neville, 1995):

$$E_c = 4.73 \times (f_c)^{0.5} \tag{1}$$

Where Ec is expressed in GPa and *fc* in MPa.

Model 2 use density ρ of the RCC in the calculation of the elastic modulus. This density range between 2200 and 2400 kg/m^3 and consequently the RCC were regard as being a concrete with a normal density. Standard ACI 318-02 use also this model which take in account the density, and which gives Ec through the equation 2 for this category of concrete:

$$E_c = 43 \times \rho^{1.5} \times (f_c)^{0.5} \times 10^{-6} \tag{2}$$

Moreover, the French standard of concrete calculation "BAEL" (BAEL, 1992) provides that the instantaneous elastic modulus can be calculated, according to the empirical model 3, as function of its compressive strength, basing to the following empirical model

$$E_{ij} = 11000 \times (f_c)^{1/3} \tag{3}$$

The results of the application of the three models on the RCC a re summarized on the Figure 1.

Prediction of the elastic modulus through the three spheres model: homogenisation theory

The "three-spheres model" was applied because the hardened RCC sections can be presented as a large

Table 1. Values of the elastic modulus of the four RCC mixtures by the three spheres model.

Cement proportioning 250 kg				
Mixture	M1	M2	M3	M4
Dmax (mm)	20	20	16	16
Measured compactness g	0.719	0.713	0.717	0.722
Porosity	0.174	0.249	0.208	0.193
Calculated compactness g* (CPM)	0.826	0.751	0.792	0.807
Compressive strength Fc (Mpa)	15.742	17.284	18.077	18.136
Elastic modulus of the paste (Mpa)	5650	5650	5650	5650
Elastic modulus of the aggregate (Mpa)	49500	49500	51500	51500
Elastic modulus of the RCC (Mpa)	25950.22	28885.80	28036.07	27733.11

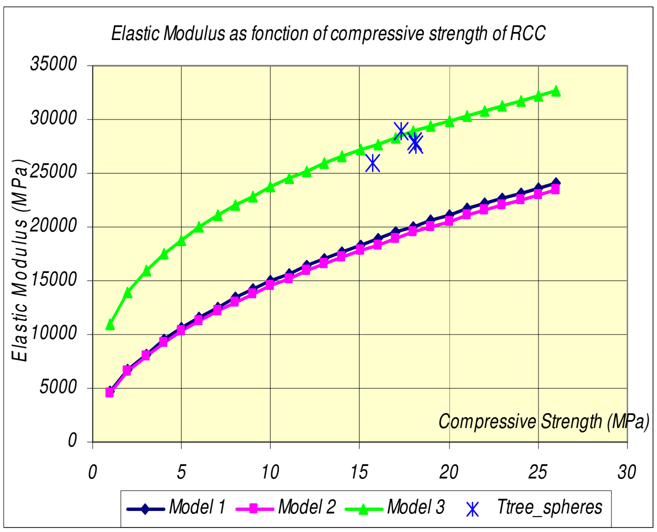

Figure 2. Variation of the elastic modulus versus the compressive strength of the RCC (by the 4 models).

spectrum of granular material (aggregate grains) dispersed in a continuous matrix. By this way the hardened RCC was modelled as a composite where fine gravels and mortar respectively take place as inclusions and matrix. The idea of the "three-spheres model" is to consider that the mixture is a stacking of composite spheres which fill up completely the vacuum. The composite spheres are made up of a spherical aggregate surrounded by a matrix crown. We used also the assumption considering that a null porosity is physically impossible to reach with a real random stacking of the grains. To illustrate the matrix-aggregate arrangement, the model can be represented by fitted spheres of which the core and the external layer correspond to the matrix. The transition course represents the aggregate (Figure 1). In this model all the matrix does not play the same role but it remains a homogeneous phase. The external layer is regarded as a workability layer (De Larrard, 1999).

By adopting the model trisphère, the elastic modulus of the RCC mixture is calculated by the equation 4 (De Larrard, 1999):

$$E=\left(1+2g\frac{E_g^2-E_m^2}{(g^*-g)E_g^2+2(2-g^*)E_gE_m+(g^*+g)E_m^2}\right)E_m \quad (4)$$

Where *g:* is the aggregate volume in a unit volume of RCC. *g** : is equal to the aggregate compactness assimilated to a granular mixture, It can be measured or calculated with the Compressible Packing Model (CPM). *Eg* and *Em*: are respectively the elastic modulus of aggregate and matrix.

The values of the elastic modulus of the RCC mixtures obtained par the "three-spheres model" are presented in Table 1 and Figure 1:

Interpretations

The values of elastic modulus of the RCC, estimated by two models 1 and 2, are very close and are sometimes equal especially for low resistances.

If we compare the values of the elastic modulus given by models 1 and 2 with those given by model 3, we notice a difference almost uniform along the resistance variation. This difference is due to the taking into account of the safety margin in the case of models 1 and 2.

The values of the elastic modulus obtained by the "three-spheres model" forms a group of points along the curve of model 3. This superposition of the points prove consequently that these two models gives closer results compared to the two other models 1 and 2

Experimental measurements of the elastic modulus E

Test schedule

For the experimental determination of the elastic modulus E of RCC, we achieved compression tests. These tests are uniaxial,

Table 2. Characteristics of the used aggregates.

Aggregates	Type	Source	Relative density ρ kg/m^3	Los Angeles	Micro-deval	Flatting ratio %
Sand Kh	Rolled sand 0/5	Khlidia[(1)]	2575	-	-	-
Sand JO	Crushed sand 0/5	Djebel Ouest[(1)]	2530	-	-	-
Gravel 4/8	Crushed gravel 4/8	Djebel Ouest[(1)]	2614	28.25	21	12.83
Gravel 4/16	Crushed gravel 4/16	Djebel El-Ressas[(1)]	2650	28.30	18	19.37
Gravel 0/20	Crushed gravel 0/20	Djebel El-Ressas[(1)]	2631	26.50	12	25.58

[(1)] Career in the North of Tunisia.

Table 3. Constituents of the used aggregates mixtures (%).

N°	Mixture	Cement	Sand Kh	Sand JO	Gravel 0/20	Gravel 4/16
M1	Sand Kh and Gravel 0/20	11.22	26.62		62.13	
M2	Sand JO and Gravel 0/20	11.22		26.63	62.14	
M3	Sand Kh, Sand JO and Gravel 4/16	11.22	22.50	21.91		44.41
M4	Sand Kh, Gravel 4/16	11.22	35.52			53.29

centred and applied to surface or facets of a specimen presenting a ratio of height/diameter equal 2. We used a press-machine whose plates are articulated, and which gradually compress well centred material, in the shape of cylinder. Longitudinal deflections are measured by the sensors fixed on the specimen. The tests are carried out on 16/32 cylindrical specimens with dimensions of 159.6×320 mm (because the diameter of 159.6 mm gives a cross-section of 20000 mm^2). The compressions are made with two bearings of loading-unloading in a number of cycle equal 3.

The speed of loading is a very significant factor because it influences the form and the extent of the deformations. When the loads are applied with high speeds, then we cannot regard the phenomenon as being a static type. Whereas, with very slow speeds, it appears the phenomena of creep and relieving. Each test is carried out in a 10 min time. This time is normally sufficient to carry out the test on a specimen with a classic press. We noticed that the increase in the deformation in this case is relatively low.

Tests were carried out on the zone of elastic strain and the elastic modulus determined is the secant elastic modulus. The secant modulus is a static modulus, because it is given from the relation stress-strain experimentally measured by axial compression on cylindrical specimen.

Preparation of the specimens

In general, the used binder is a hydraulic Portland cement, which represents the permanent element for the RCC manufacture. In study, the used cement, C.E.M/C-L 32.5, was from the Kharrouba cement factory (North of Tunisia) and had a relative density equal to 3029 kg/m^3. In this work, we could not use additions such as the fly ashes, slag, silica fumes and pozzonalas because of their non availability in Tunisia (expensive on import). Moreover, different classes of aggregates are necessary to fill at the maximum the inter-aggregate space. We used two types of aggregates: rolled for the siliceous sands and crushed for the limestone sands, and gravels (Zdiri et al., 2006). Characteristics and data relative to these aggregates are presented in Table 2. Basing on the various aggregates beforehand identified, we considered four mixtures obtained by combination of the two types of sand: siliceous and limestone, and of the two gravel classes 4/16 and 0/20.

For the formulation of these mixtures, we applied the Compressible Packing Model, developed at "Laboratoire Central des Ponts et Chaussées en France (LCPC)" (De Larrard, 1999). Through the software "Rene LCPC" (Sedran and De Larrard, 2000), we determined the percentages of the various components. The components of the four mixtures are presented in the Table 3.

The confection was made according to the National French Project Method "BaCaRa" (1996). The specimens are released from the mould after 24 h and they were conserved in water at a temperature of about 20°C and hygrometry more than 95%. The elastic modulus tests were made by the Compression machine "Model Form-Test" of 3000 KN capacity at 28 days of age. For the reproducibility of the results, three specimens are tested to each point and an average has been taken.

First method

In this semi-automatic method, the load was applied automatically by the "tensile and compression test Machine C70-Matest" of capacity 3000 KN. On a graph, the stress-strain curves were plotted. The form of this curve depends specially on the conditions of test. This representation was analyzed only in the elastic range of the RCC while taking as assumption that this function follows the Hooke's law characterizing the behaviour of material. The results are presented on figure 3 and Table 4.

Figure 3 is a representation of the relation stress-strain of the RCC. This graphic shows the typical evolution of the longitudinal deflections under the effect of the increasing loads of axial compression. These loads were applied gradually to these cylindrical specimens type 16 × 32 (169.6 × 320 mm).

In parallel the same tests were applied to the Conventional Concrete (CC) made by the same components. The values and

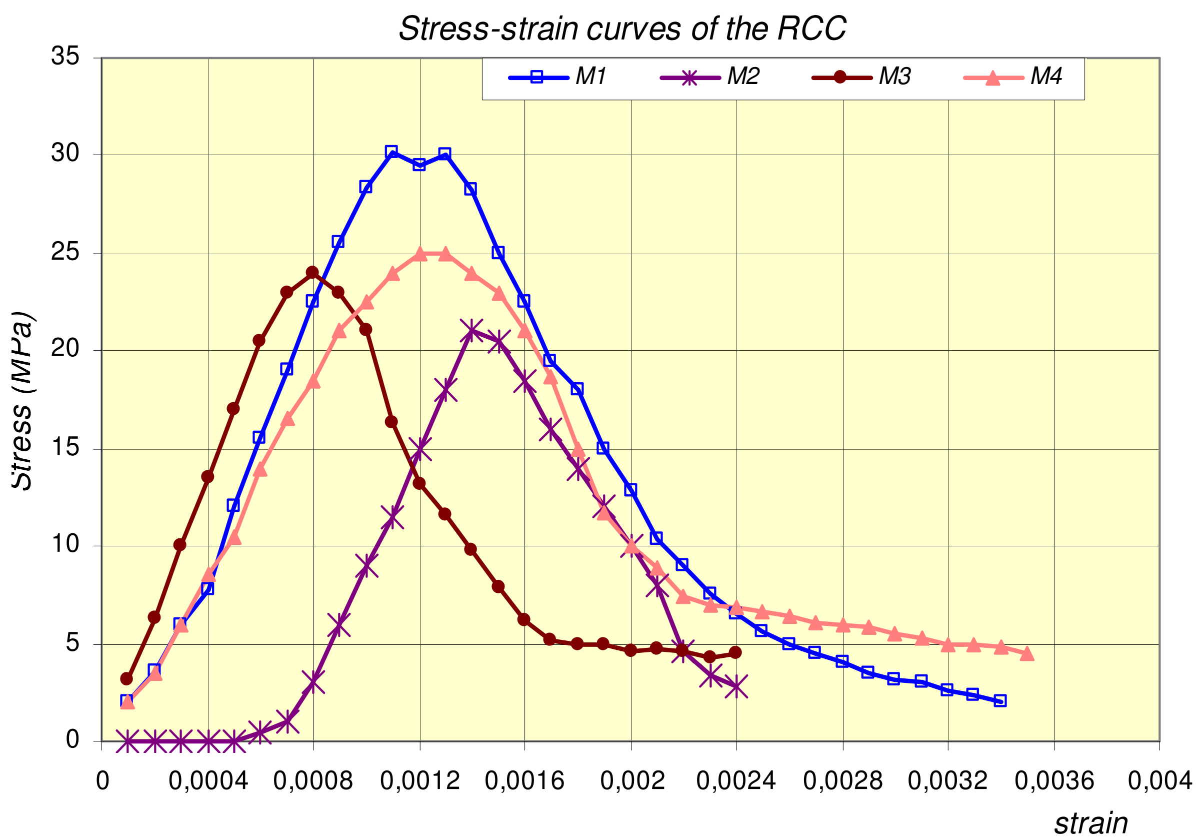

Figure 3. Stress-strain curves of the RCC for the 4 mixtures.

Table 4. Values of elastic modulus (experimental and with models) four the 4 mixtures.

Serial / Mixture	Experimental (MPa)	Model 1 (MPa)	Model 2 (MPa)	Model 3 (MPa)	Three-spheres Model 4 (MPa)
M1	30250	20617	20004	29352	25950
M2	25625	21153	20523	29858	28885
M3	29714	18319	17774	27128	28036
M4	21500	14957	14512	23698	27733

the evolution of the CC elastic modulus were different from those of the RCC.

Interpretations

The representations of the relation stress-strain for the four mixtures of RCC give us an idea about the shape of these curves. On the one hand, the shape of the stress-strain curve for the RCC does not have very apparent concavity; on the other hand it presents a stiff slope, affirming the elasticity of this material.

- The elastic modulus determined by this method vary from 21500 MPa for the mixture M4 to 30250 MPa for the mixture M1 and these values are higher than the modulus estimated by the suggested models while remaining closer to the values given by model 3.
- The first method of measurement presents the disadvantage that it is not very precise considering the means used in measurements.

The more precise determination of the elastic modulus for these mixtures requires the use of more sophisticated equipment.

- Unlike to the Conventional Concrete (CC) and according to Figure 4, we notice that the digraph stress-strain of the RCC presents a stiffer characteristic curve in the elastic zone and the values of elastic modulus of the RCC can reach 1.2 times that of the Conventional Concrete (CC).

Second method

In the second method, the stress and deformations measurements were given digitally by the computer ordering the operation of the machine in stress or displacement. The press used was type FORM TEST of capacity 3000 KN (Figure 5). The calculation of the modulus was carried out and posted with its graph by the software. The

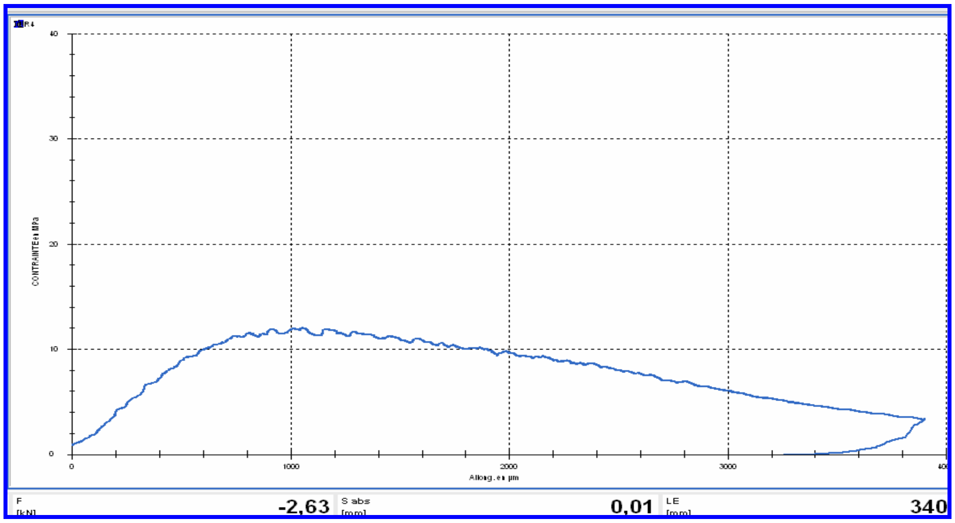

Figure 4. Example of the representation of the relation stress-strain of the CC for mixture M4.

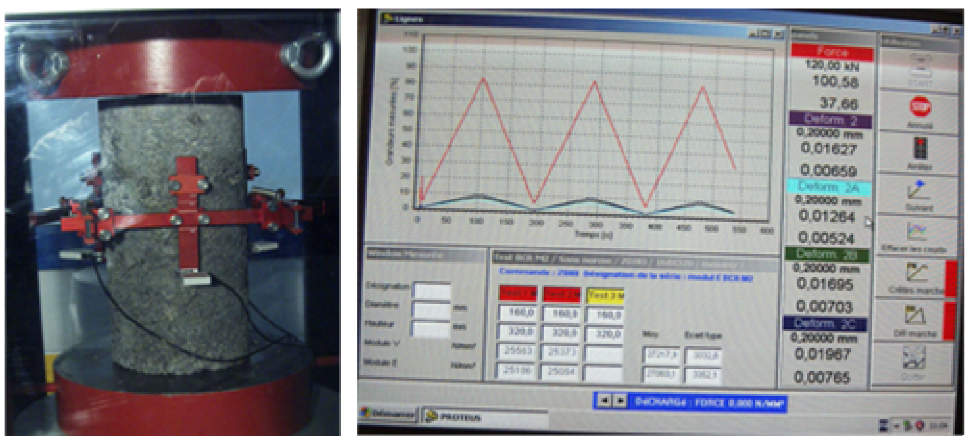

Figure 5. The transmitter's equipment of deformations on the RCC cylindrical specimen and test schedule of measurement of elastic modulus in three cycles of loading- unloading.

Table 5. Values of the elastic modulus (MPa) of the RCC and the Conventional Concrete (CC) for the 4 mixtures.

Mixture	RCC				CC
	Series 1	Series 2	Series 3	Average	
M1	30807	30287	29537	30210	26474
M2	25189	28041	26834	26688	22274
M3	29380	26042	29328	28250	17762
M4	20651	26725	26249	24542	15540

results are presented on Table 5. In the measure test of elastic modulus, the maximum stress to reach was taken equal to the threshold of 30% of the yielding stress of the RCC. This choice is in order to guarantee that the selected stress must always remain in the elastic range of the RCC. This method is in conformity with the standard BS 1881 (Neville, 1995) which specifies that the maximum stress represents the percentage of 33%. However in standard ASTM this threshold is 40% of the yielding stress.

Three cycles of loading and unloading were chosen until the maximum stress which will be applied during the test and this to eliminate the effects of creep, and also to ensure a good chock of the sensors. The minimal stress chosen is equal to 0.5 MPa and this is in accordance with standard BS 1881 presented by Neville for Conventional Concrete (Neville, 1995).

In the measure test of elastic modulus, we observe sometimes that the curve presents a small vertical segment which is due to contact with the plates of the machine with the specimen (Figures 5 and 6). Whereas in other case we observe that the curve presents a rather concave segment to the top with the beginning of the loading. This phenomenon is due to the closing of pre-existent cracks and it is in agreement with the idea developed by Baron and

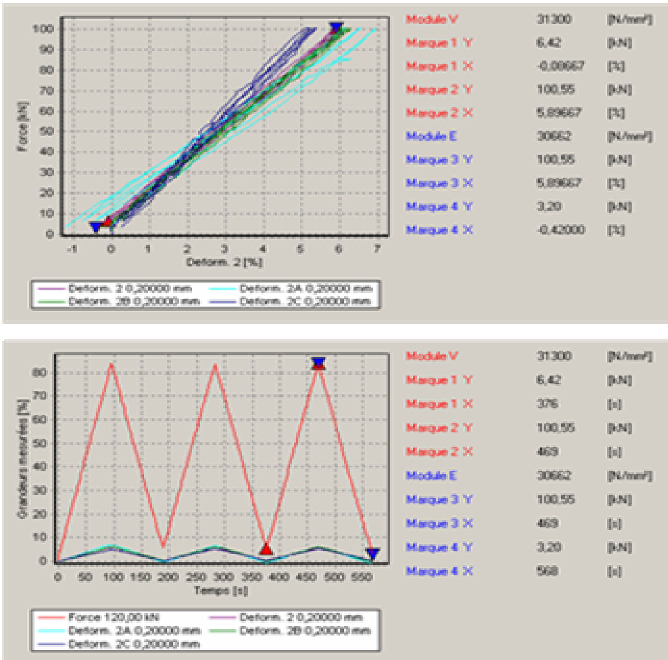

Figure 6. Example of measurement results of the RCC elastic modulus - Mixture M1.

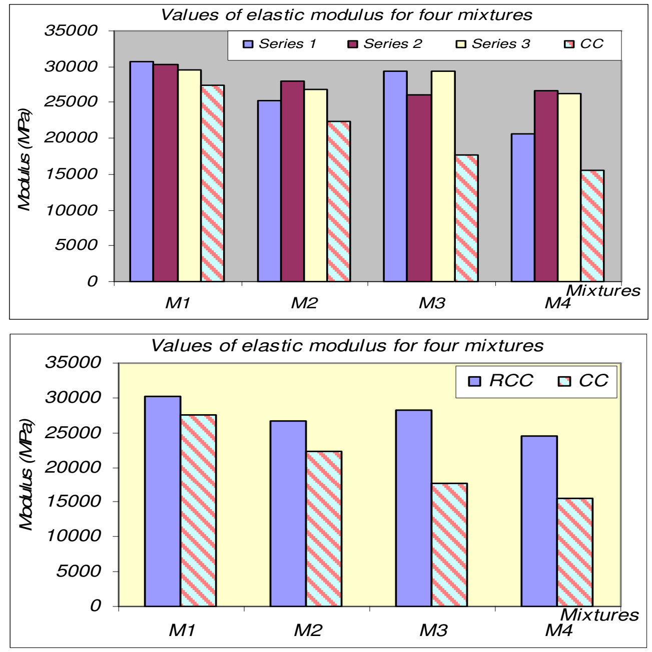

Figure 7. Histogram of the elastic modulus values of the RCC and the CC for the 4 mixtures.

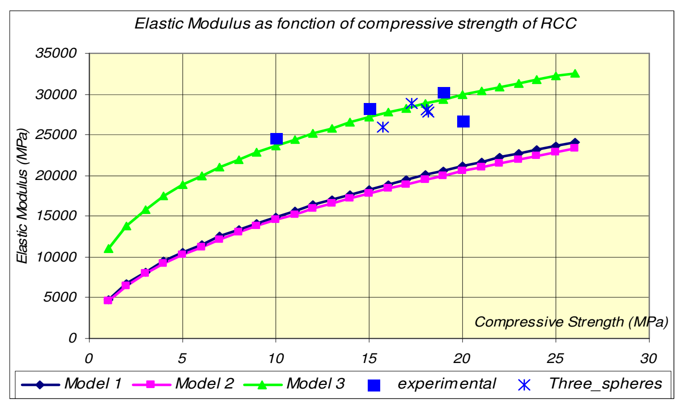

Figure 8. Elastic modulus versus compressive strength of the RCC: (by models and experimental).

Sauterey for Conventional Concrete [CC] (Baron and Sauterey, 1995).

Interpretations

- Unlike the first method, the values of elastic modulus are determined by second method with a high degree of accuracy, initially because we took the average of the three series for the four mixtures of RCC and moreover for each series, three specimens were tried in order to determine these modulus.
- The RCC mixture M1 presents the values of the highest elastic modulus (30210 MPa) compared to the other mixtures because this mixture comprises very significant percentages of sand Kh and aggregate of the class 0/20 which have, coupled, the highest densities (Table 2).

The difference is significant between the values of elastic modulus of the RCC and the Conventional Concrete (CC) comprising the same components. The elastic modulus of the RCC, generally, exceeds that of the CC, and this difference varies between 14% for the mixture M1 and an average of 58% for the three other mixtures (Figure 7).

Comparison between the experimental and models results

- To compare the results obtained by experimental tests with those estimated by models 1, 2 and 3, we report them on a graph revealing the form of the evolution of the elastic modulus as function of resistance (Figure 8).
-The values of elastic modulus determined experimentally are situated at the top of the curves of the two models 1 and 2 and on the curve of model 3 and the Three spheres Model (Figure 7). - According to Figure 7, we notice that the RCC presents an elastic modulus which can vary between 1.3 and 1.7 times of the estimated values by models 1 and 2, whereas these values are found confused with the curve of model 3 and the Three spheres Model.

Measure of dynamic elastic modulus and prediction of the static modulus

The static elastic modulus studied in the first part expresses the deformation in response to a stress of known intensity. In this, another type of modulus was studied, called dynamic elastic modulus, which is given by vibrating an RCC specimen. The determination of the dynamic elastic modulus Ed was made by ultrasosonic measurements using the Ultrasonic apparatus type "Test

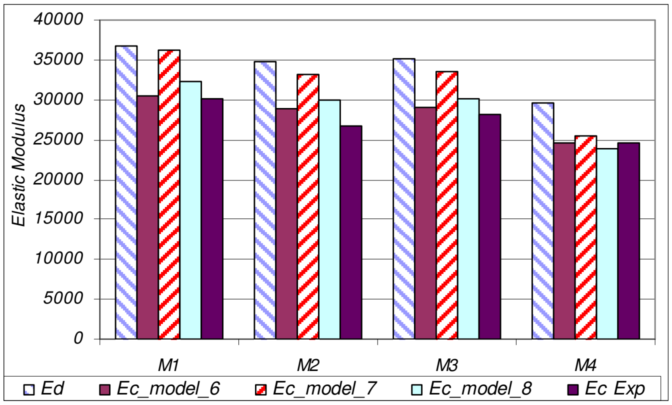

Figure 9. Histogram of the elastic modulus through the dynamic modulus (with three models and Experimental).

standard 58-E0049". These tests were made by velocity measurement of ultrasonic wave propagation through cylindrical specimen of RCC (169.6 × 320) placed between a transmitter and a receiver. The dynamic modulus can be given by the following relation:

$$E_d = \rho \times V^2 \times \frac{(1+\nu)(1-2\nu)}{(1-\nu)} \qquad (5)$$

With ρ is the density of the RCC (Kg/m^3), V is the wave speed (m/s), and ν is the Poisson's ratio of the RCC.

For the prediction of the dynamic elastic modulus, this latter is regarded as being appreciably equal to the tangent elastic modulus determined in the static tests. It's so definitely higher than the secant modulus determined by the application of a load on an RCC specimen (Neville, 1995).

We applied consequently the three following models for the prediction of the static modulus through the dynamic modulus (Neville, 1995). The first is that proposed by Lydon and Balendran:

$$E_c = 0.83 \times E_d \qquad (6)$$

The second is that of the British standard CP110:1972 used for the structural design:

$$E_c = 1.25 \times E_d - 19 \qquad (7)$$

Where the two modulus are expressed in GPa. And if we suppose that the RCC is a concrete with normal density, we can use the relation 8, between the dynamic and static modulus which is a function of the density of the concrete, as in the case of the relation between the static modulus and resistance:

$$E_c = k \times E_d^{\,1.4} \times \rho^{-1} \qquad (8)$$

Where ρ is the RCC density and k taken equal to = 30 and depending on the measuring units. The results of these predictions and measurements are presented in Figure 9 and Table 6.

Interpretations

- The dynamic elastic modulus is a reliable tool which can be used to predict the static elastic modulus of the RCC
- The relationship between the static elastic modulus and the dynamic elastic modulus, which is always lower than the unit, is all the more high when the resistance of the concrete increases.
- The results given by models 6 and 8 are close to the experimental results as presented in figure 9. However there is a difference between the results given by models 7 and the experimental results which varies from 4 to 24%
- The results of model 6 are much closer to the experimental results and are sometimes equal as it is the case for mixtures M1 and M4.

Conclusion

The following conclusions can be drawn from the present study:

- The "three-spheres model" can be regarded as the most suitable and reliable model for the prediction of the static elastic modulus of the RCC.
- In the first method, the representations of the relation stress-strain for the four mixtures of RCC give us an idea about the shape of these curves and the values of elastic modulus of the RCC can reach 1.2 times that of the CC.
- In the second method of measurement, the difference is significant between the values of elastic modulus of RCC and those of CC, and the RCC develops an elastic modulus higher from 14 to 58% then of the CC with same components.
- The RCC mixture M1 presents the value of highest elastic modulus (30210 MPa) because this mixture comprises very significant percentages of sand Kh and aggregate of the class 0/20 which have, coupled, the highest densities and the maximum diameter of granulometry is equal to 20 mm
- The RCC mixture M4 presents the value of the lowest elastic modulus (24542 MPa) because it comprises only granulometry whose maximum diameter is equal to 16 mm. Moreover, it is clear that the elastic modulus is not influenced by ripening, but by the elastic modulus of the coarse aggregate employed in the concrete. This dependence is a consequence of the biphasic nature of the RCC.
- The RCC presents also an elastic modulus ranging between 1.3 and 1.7 times of that estimated by models 1 and 2, whereas these values is found confused with the curves of model 3 and three spheres model.
- The model 6 proposed by Lydon and Balendran can by used for the prediction of the static elastic modulus through the dynamic modulus of the RCC.

Perspectives

Other results can be obtained but they are not evaluated in this work such as the variation of the Elastic Modulus of the RCC according to the compactness and the cement proportioning and also the influence of the additions and the admixtures on the Elastic Modulus.

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Table 6. An example of the values of the dynamic elastic modulus by experimental measure and the three Models for the prediction of the static modulus for the mixture M4.

Measure N°	1	2	3	4	5	6	7	8	9	10	Average I	Average II
L (cm)	320	320	320	320	320	320	320	320	320	320	320	320
V (m/s)	3879	3898	3871	3898	4206	4156	4201	3906	3914	3875	3980.4	3965
t (µs)	82.5	82.1	82.7	82.1	76.1	77	76.2	81.9	81.7	82.6	80.49	
V (km/s)	3.879	3.898	3.871	3.898	4.206	4.156	4.201	3.906	3.914	3.875	3.9804	3.965
Ed [5]	28284.43	28562.19	28167.89	28562.19	33254.19	32468.26	33175.18	28679.55	28797.15	28226.13	29817.72	29552.50
Ec [6]	23476.08	23706.62	23379.34	23706.62	27600.98	26948.65	27535.40	23804.03	23901.64	23427.69	24748.71	24528.58
Ec [7]	23426.65	23843.29	23251.83	23843.29	30881.29	29702.39	30762.77	24019.33	24195.73	23339.19	25726.58	25328.76
Ec [8]	22261.78	22568.44	22133.46	22568.44	27924.05	27004.49	27831.20	22698.37	22828.78	22197.56	24001.66	23671.48

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