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Cement and Concrete Research 35 (2005) 27–33
CEMENT AND CONCRETE RESEARCH

Bending and compressive behaviors of a new cement composite

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Received 8 August 2003; accepted 28 May 2004

Abstract

The Laboratoire Central des Ponts et Chaussées (LCPC) has recently developed and patented a new cement composite, the $CEMTEC_{multiscale}$, which is stress hardening in tension and has a very high uniaxial tensile strength, more than 20 MPa.

This paper is about the determination of the compressive and bending behaviors of the $CEMTEC_{multiscale}$ used in the frame of ribbed slabs.

The principal results obtained are the following:

- the characteristic modulus of rupture is equal to 42 MPa for the "slab" function;
- the characteristic modulus of rupture is equal to 48 MPa for the "rib" function;
- the ultimate tensile strain is around $5\ 10^{-3}$;
- the characteristic strength and ultimate strain in compression are equal to 205 MPa and $4\ 10^{-3}$, respectively; and
- the Young modulus is equal to 55 GPa and the Poisson coefficient is equal to .21.

Keywords: Cement composite; Fiber reinforcement; Bending strength; Compressive strength

1. Introduction

For a few years, the Central Laboratory for Bridges and Roads (French State Laboratory located in Paris, France) has worked on the development of new cement composites. These materials are the direct implementation of the "Multi-Scale Fibre Reinforced Concept" developed by Rossi et al. [1]. The idea is to mix short fibers with longer fibers in order to intervene at the same time on the material scale (increase of the tensile strength) and on the structure scale (bearing capacity and ductility). A multiscale cement composite (MSCC) is then obtained. One can quote as an example an MSCC, developed in the past [2], constituted by a mix of 5% of straight cylindrical fibers (made of drawn steel) of 5 mm in length and 0.25 mm in diameter and 2% of cylindrical hooked fibers (made of drawn steel) of 25 mm in length and 0.3 mm in diameter.

The uniaxial tensile behavior of this MSCC is stress hardening and its average tensile strength is about 15 MPa.

The research is about the development and the mechanical characterization of a new cement composite, always based on the Multi-Scale Fibre Reinforced Concept, with an aim of obtaining a material sufficiently resistant and ductile to design structures or elements without other reinforcements than the fibers.

2. Material: $CEMTEC_{multiscale}$

$CEMTEC_{multiscale}$, which was the subject of a world patent in March 2001, is conceived starting from the same concept as MSCC, but with some evolutions compared to the last. These evolutions are declined as follows:

- Whereas the MSCC contains two different metal fiber geometries, $CEMTEC_{multiscale}$ contains three of them.
- $CEMTEC_{multiscale}$ contains 11% per volume of fibers whereas the MSCC contains 7% of them.

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doi:10.1016/j.cemconres.2004.05.043

Table 1
Formulation of $CEMTEC_{multiscale}$ (kg/m^3)

Cement	1050.1
Silica fume	268.1
Sand	514.3
Water	180.3
Superplasticizer	44
Steel fibers	858
Water/cement = 0.201	
Water/binder = 0.16	
Air entrained = 20 l	

The LCPC launched, in 2000, a vast study over 4 years on $CEMTEC_{multiscale}$, study which comprises mechanical tests to characterize the various mechanical behaviors of the composite (behavior in statics, in fatigue, at high strain rates, etc.), tests of durability, tests on structural elements, and tests to optimize the manufacturing process (mixing and casting). In this article, only the first results related to static tests are presented.

The composition of $CEMTEC_{multiscale}$ is given in Table 1.

It is important to recall that some previous works were performed in the past on fiber-reinforced high-performance concretes, those concretes containing, like $CEMTEC_{multiscale}$, high percentages of fibers [3]. However, the principal and important difference between $CEMTEC_{multiscale}$ and those materials is that they contained only one dimension of fiber, in the circumstances short fibers, and consequently they had a high tensile strength but a very brittle behavior in tension.

3. Experimental procedures

One of the industrial application aimed with this new composite material relates to slabs and strongly charged floors, such as slabs of steel–concrete composite structures for example. However, in comparison with the potential cost of such a material (the material not being marketed yet, it is impossible to speak about the problem of the cost), which will be obligatorily very high compared to the "traditional" concretes (including the high performances concretes), it is essential to optimize the mechanical performances/cost ratio. Bearing this in mind, it is necessary to save the matter and to use it only at the useful places from a mechanical point of view. The material avoiding the use of traditional reinforcements (it is the goal to reach) this saving in material is perfectly possible. In the case of a composite structure slab, the economy can pass through the choice of a simple and mechanically natural form, which constitutes the ribbed slab. Indeed, in a ribbed slab, the "slab" function consists in taking into account at the same time the secondary bendings and punchings whereas the "rib" function has to deal with the principal bendings and to increase the structure total rigidity. Within the framework of the study, it was decided to dissociate these two functions in order to characterize them separately. Mechanical tests were thus carried out on specimens representative of the «slab» function and on specimens representative of the «rib» function. To dimension a structure or a structural element made up only of $CEMTEC_{multiscale}$ necessarily implies to do it by taking into account in a very controlled way of safety. It is consequently essential to reach characteristic mechanical behaviors that integrate the dispersion problems inherent in all materials. Thus, the tests evoked above were carried out on a sufficient number of specimens to determine these characteristic behaviors. The first tests presented in this study aim on the one hand at determining the characteristic bending behavior of the «slab» part and of the «rib» part, and on the other hand the characteristic compressive behavior of $CEMTEC_{multiscale}$ within the ribbed slab. In order to optimize the dimensions of the specimens with respect to the scale effects and of preferential orientation of fibers, and in addition to lead to a use that could be economically viable of $CEMTEC_{multiscale}$, it was selected, respectively, to retain following dimensions concerning the specimens representative of «slab» and «rib» functions:

- «Slab» function: The specimens have a 600-mm length, a 200-mm width, and a 40-mm thickness. They are cast flat and are vibrated during the casting on a mobile plate. The specimen width/largest fiber length ratio (200/25) and the specimen casting procedure allow an orthotropic orientation of the fibers representative of this existing in a slab.
- «Rib» function: The specimens has a 600-mm length, a height of 200 mm, and a thickness of 40 mm. They are cast vertically and are also vibrated during the casting on a mobile plate. The specimen thickness/largest fiber length ratio (40/25) as the specimen casting procedure must allow a preferential orientation of fibers parallel to the length of the specimens (the largest fibers are perpendicular to the potential cracks orientation created by the bending of the specimen). The 200-mm height must make it possible to strongly rigidify a ribbed slab.

Concerning the compressive tests, it was decided to take the specimens by sawing, within additional specimens representative of the «rib» function in order to obtain a realistic orientation of fibers compared to that which exists in the compressive zone of the ribbed slab. The specimens for compressive tests are thus prismatic. It is known that with the ultrahigh cement composites, which is $CEMTEC_{multiscale}$, the use of a heat treatment makes it possible to increase the mechanical performances of the matrix [4]. Also, in the present study, two types of cure were applied:

- a cure with traditional water; and
- a heat treatment that consists in placing the specimens in a drying oven at 90 °C during 4 days, 48 h after their release from the mould.

The heat treatment was used for the three types of specimens, the specimens representative respectively of the «slab» function and of the «rib» function and the specimens for compressive tests, whereas the cure with water was used only for the specimens representative of the «slab» function and the specimens for compressive tests.

Thus, one can make the logical and reasonable assumption that with respect to the bending behavior, the effect of the type of cure is similar for «slab» functioning and for «rib» functioning.

It is significant to specify that the water cure duration was 1 month for the specimens representative of the «slab» function and 6 months for the specimens used in the compressive tests.

With the compressive tests on the prismatic specimens, compressive tests were also realized on cast cylindrical specimens. Thus, six cylindrical specimens with a diameter of 11 cm and of height 22 cm were used to determine the compressive strength, and three cylindrical specimens with a diameter of 16 cm and height of 32 cm were used to determine the Young modulus and the Poisson coefficient. All the cylindrical specimens were thermically treated.

3.1. Four points bending tests on specimens representative of the «slab» function—test set up

During these deflection tests, the distance between the lower supports is 420 mm and between the higher supports is 140 mm. The test is carried out at an imposed deflection rate equal to 0.3 mm/min. The deflection is measured using a special extensometer, placed on the specimens, designed to eliminate parasitic displacements on the level from the supports.

Nine specimens have undergone a heat treatment, and six specimens have undergone a cure with water.

3.2. Four points bending tests on specimens representative of the «rib» function—test set up

The procedure relates identical to that of the specimens representative of the «slab» function.

Nine specimens have undergone a heat treatment. For all the specimens, an LVDT sensor was stuck on the face opposed to that on which the extensometer being used was fixed to measure the deflection. This sensor was positioned at the level of the bottom fiber of the specimens in the zone of constant moment.

3.3. Compressive test on prismatic specimens—test set up

Six specimens having undergone a heat treatment and six specimens having undergone a cure with water were tested. They are prismatic specimens of the dimension $180 \times 80 \times 40$ mm. On each specimen, two strain gauges of 7 cm long are stuck to the center of each one of its faces, this in order to record the stress–strain curves. The test is carried out at an imposed displacement rate of the plates of the press using an LVDT placed between these plates.

3.4. Compressive test on cylindrical specimens—test set up

Concerning the determination of the compressive strength, it should be announced that on the one hand, horizontal surfaces of the specimens with a diameter of 11 cm and height of 22 cm were ground beforehand, and that on the other hand, the tests were carried out at an imposed stress rate of 0.5 MPa/s. For the determinations of Young modulus and the Poisson coefficient a special extensometer, the J2P [5] was used. This extensometer consists of three displacement transducers (LVDTs) arranged at 120° to measure the Young modulus and of three displacement transducers diametrically placed to measure the Poisson coefficient. The displacement transducers are supported by aluminum rings in contact with the specimen through elastic heads.

4. Experimental results

4.1. Bending tests

Presented in Figs. 1 and 2, respectively, are the results related to the specimens representative of the function «slab» and those related to the specimens representative of the function «rib», the two types of specimens having undergone a heat treatment.

These results are presented in the shape of equivalent tension stress–deflection curves.

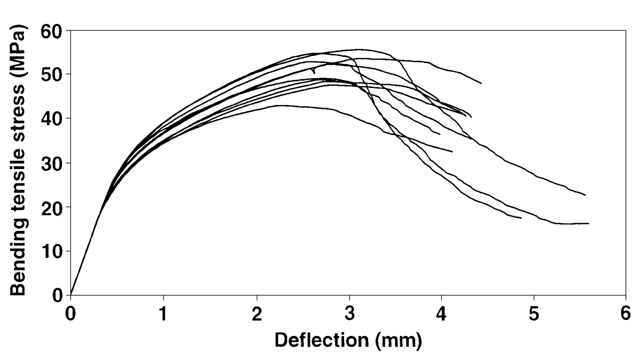

Fig. 1. Results related to the bending deflection tests on the specimens representative of the «slab» function.

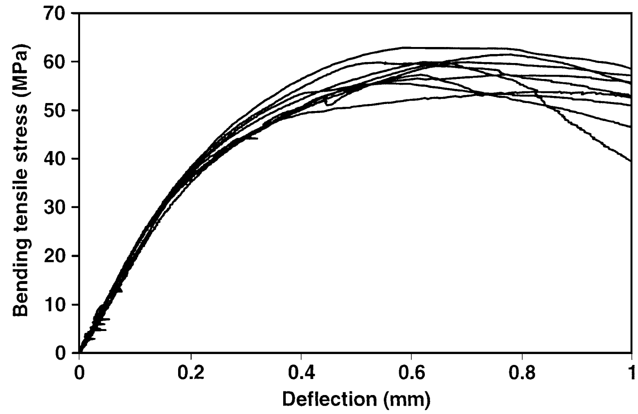

Fig. 2. Results related to bending deflection tests on the specimens representative of the «rib» function.

Presented in Fig. 3 are the average curves related to the two types of specimen. These average curves are given up to the stress peak.

In comparison with Figs. 1, 2, and 3, one can make the following comments:

Average bending tensile strengths, still called average modulus of rupture, are very high. They respectively reach:

- «slab» function: 50 MPa;
- «rib» function: 58 MPa.

The more significant value for the specimen representative of the «rib» function is related to a better orientation of fibers compared to the direction of the crack propagation.

Presented in Fig. 4 is an example of a bending tensile stress–strain curve related to a specimen representative of the «rib» function the strain being calculated starting from the measurement of displacement carried out with an LVDT placed on the level of the bottom fiber of the specimen.

Taking Fig. 4 into consideration, one notes that the strain at the stress peak of is approximately 6×10^{-3}.

Presented in Fig. 5 are the bending tensile stress–deflection curves related to the six test specimens (representative of the «slab» function) having undergone a water cure and tested at 28 days.

Presented in Fig. 6 are the average bending tensile stress–deflection curves related to the specimens representative of the «slab» function and having undergone the two types of cure.

In comparison with Fig. 6, one notes that the passage of the thermal treatment to the cure with water leads to a reduction of approximately 20% in the modulus of rupture. This reduction can be explained by a reduction in the compactness of the matrix, which induces a general reduction in its mechanical characteristics, and in this case surely of its adherence with fibers.

To finish with the bending tests, it is significant to announce that all the specimens representative of the «slab» function or of the «rib» function, no visible crack could be observed before the stress peak.

4.2. Compressive tests on prismatic specimens

Presented in Figs. 7 and 8 are the stress–strain curves related, respectively, to the specimens thermically treated and the specimens having undergone the water cure.

Presented in Fig. 9 are the average stress–strain curves related to the two types of cure.

The average compressive strength related to each type of cure is as follows:

- heat treatment: $R_{\mathrm{c\ aver.}} = 220$ MPa;
- cure with water (6 months): $R_{\mathrm{c\ aver.}} = 230$ MPa.

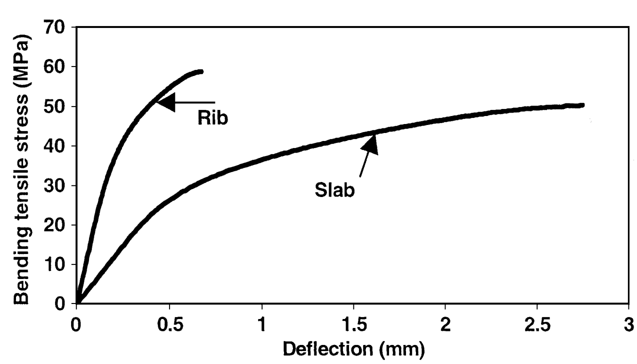

Fig. 3. Average curves respectively related to the two types of specimen.

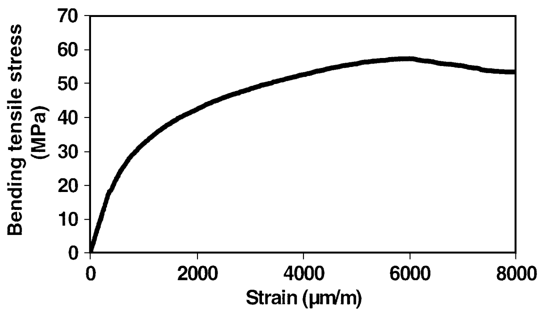

Fig. 4. Example of a bending tensile stress–strain curve related to a specimen representative of the «rib» function.

The average ultimate strain related to each type of cure is as follows:

- heat treatment: $\varepsilon_{c\ aver.} = 4.5\ 10^{-3}$;
- cure with water (6 months): $\varepsilon_{c\ aver.} = 4.7\ 10^{-3}$.

The Young modulus (calculated starting from the strain gauges) related to each type of cure is as follows:

- heat treatment: $E = 54$ GPa;
- cure with water (6 months): $E = 56$ GPa.

4.3. Compressive tests on cylindrical specimens

Average compressive strength determined on the cylinders having a 22-cm height and an 11-cm diameter is as follows: $R_{c\ aver.} = 215$ MPa.

The Young modulus and the Poisson's ratio determined on the cylinders having a 32-cm height and a 16-cm diameter are as follows:

- $E = 55$ GPa;
- $v = 0.21$.

Taking into consideration these results, one can make the following comments:

- Whereas for the deflection tests, one observes that a 1 month water cure led to a reduction of 20% compared to a thermal cure of the modulus of rupture, 6 months water cure seems to lead to a compressive strength similar and even slightly higher than that related to the thermal cure. This report is surely explained by the fact that on one hand, $CEMTEC_{multiscale}$ thermically untreated has a nonnegligible porosity (some porosity measurements made by using the water penetration and the mercury intrusion techniques indicate that the total porosity of $CEMTEC_{multiscale}$ is two or three times higher when it is water cured than when it is thermal cured [6]), and that on the other hand, its degree of hydration is very weak (water/binder equal to 0.16). Thus, at the end of 6 months in water, $CEMTEC_{multiscale}$ could very well permit the penetration of water in its porosity to constitute a considerable quantity of new hydrates that come to increase in a significant way its compactness and its mechanical behavior.
- The compressive tests on prism and cylinder lead to similar results concerning the compressive strength and the Young modulus. The small differences, which one can note surely, depend on one hand on the mechanisms of rupture in compression of the specimens and on the other hand on the conditions of specimen/plates of the press interfaces, which are different for the cylinder and the prism.

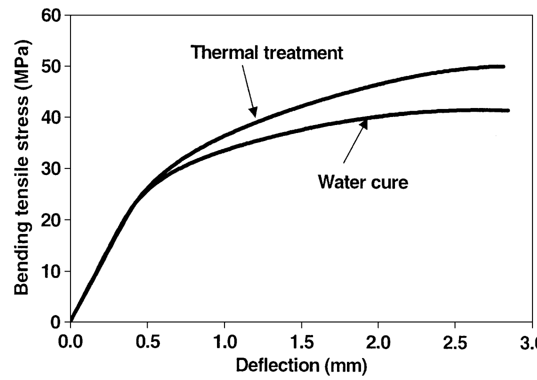

Fig. 6. Average bending tensile stress–deflection curves related to the two types of cure.

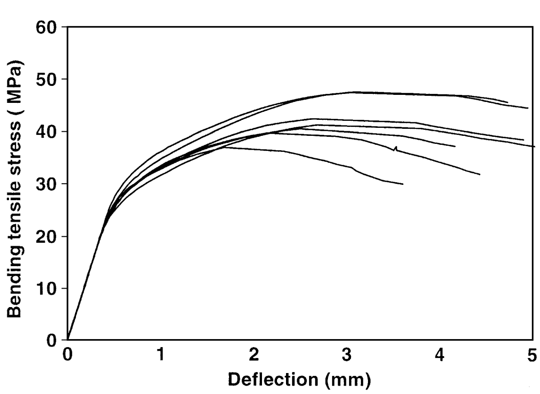

Fig. 5. Bending tensile stress–deflection curves related to the specimens having undergone a water cure.

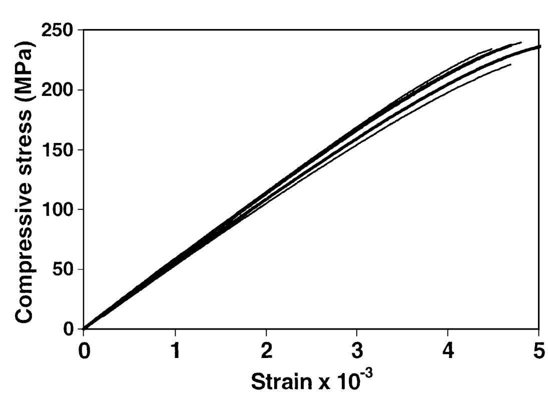

Fig. 7. Stress–strain curves related to the specimens having undergone the heat treatment.

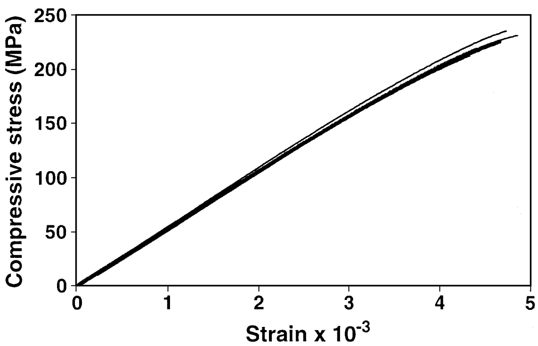

Fig. 8. Stress–strain curves related to the specimens having undergone the water cure.

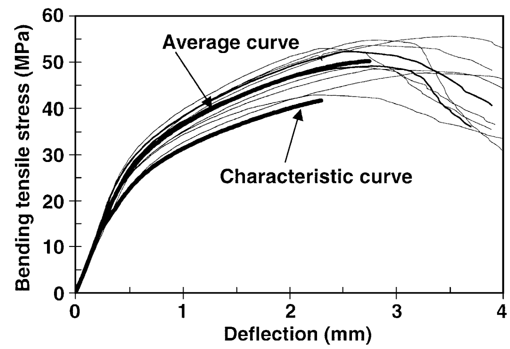

Fig. 10. Average and characteristic curves for the specimen related to the «slab» function.

5. Analysis of the results

From the average curves, and individual curves, it is easy to determine characteristic curves. With this in mind, one proceeds in the following way:

1. One distinguishes for all the curves, which they relate to the bending tests or the compressive tests a linear elastic part and a nonlinear part. To distinguish these two parts, one traces, for all the individual curves, their derivative compared to the *x*-coordinate. One thus obtains curves made up of a portion of right-hand side quasi-constant and of a portion of nonconstant curve according to the *x*-coordinate. The border between these two portions of curve constitutes the limit of the linear elastic field of the primitive curve.
2. One determines then the linear part of the characteristic curve in the following way:

- for the slope of the curve, one takes the average slope;
- for the limit of the linear part, one takes the average limit (obtained with the average curve): less $k(n) \times$ S.D. on this limit (obtained starting from the individual curves), $k(n)$ being the coefficient of Student for a fractile of 5% that depends on the number n of tests carried out (thus of curves taking part in the analysis).

3. One determines then the nonlinear part of the characteristic curve in the following way:

- First of all, one calculates the characteristic value related to the compressive strength or to the modulus of rupture as following: $R_{\mathrm{char.}} = R_{\mathrm{aver.}} - k(n) \times s(R)$, where $R_{\mathrm{aver.}}$ is the average value of the compressive strength or of the modulus of rupture and $s(R)$ is the standard deviation on this value, $k(n)$ being the coefficient of Student for a fractile of 5% that depends on the number n of tests carried out.
- One multiplies then, for each value of strain (compressive behavior) or for each value of deflection (bending behavior) of the average curve, the corresponding stress by the $R_{\mathrm{char.}}/R_{\mathrm{aver.}}$ ratio. One thus plots a characteristic curve up to the value of characteristic strain or characteristic deflection.

The characteristic curves of CEMTEC$_{\mathrm{multiscale}}$ with respect to the bending behavior of the «slab» part or the «rib» part of the ribbed slab constitute reference curves for structure dimensioning in relation with the ultimate limit state.

The average and the characteristic curves of the specimens related to the «slab» and «rib» functions are presented in Figs. 10 and 11, respectively.

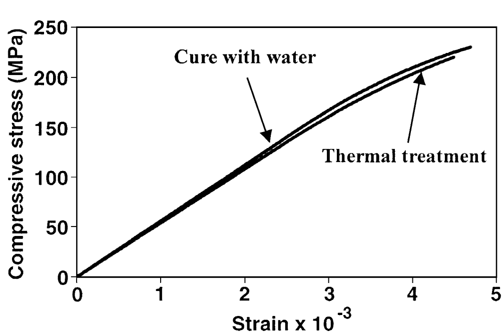

Fig. 9. Average stress–strain curves related to the two types of cure.

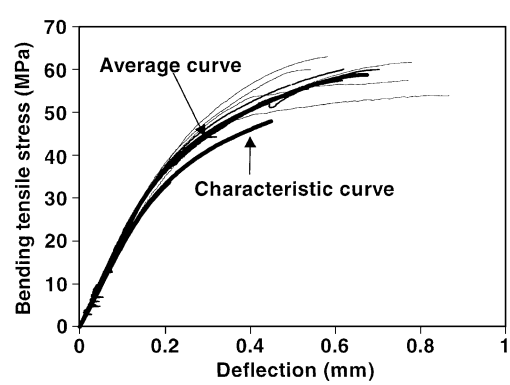

Fig. 11. Average and characteristic curves for the specimen related to the «rib» function.

In comparison with Figs. 10 and 11, one can note that the characteristic curves such as they were given seem to present a good safety.

Concerning the compressive tests, the characteristic values related to the strength and the ultimate strain are as follows:

- heat treatment: $R_{c\ char.} = 205$ MPa, $\varepsilon_{cu\ char.} = 4\ 10^{-3}$;
- cure with water (6 months): $R_{c\ char.} = 215$ MPa, $\varepsilon_{cu\ char.} = 4.3\ 10^{-3}$.

6. Conclusion

This article relates to $CEMTEC_{multiscale}$, which is a new cement composite recently developed and patented by the LCPC. An experimental study related on one hand to the bending behavior of this material in the case it is used in the slab or in the rib of a ribbed slab and on the other hand to its compressive behavior is presented. The mechanical performances obtained when $CEMTEC_{multiscale}$ undergoes a thermal cure are as follows:

For the «slab» function

- the average modulus of rupture is equal to 50 MPa;
- the characteristic modulus of rupture is equal to 42 MPa.

For the «rib» function

- the average modulus of rupture is equal to 58 MPa;
- the characteristic modulus of rupture is equal to 48 MPa.

The material is very ductile in tension, the ultimate tensile strain being approximately equal to $5\ 10^{-3}$.

For the compressive behavior

- the average strength and ultimate strain in compression are equal to 220 MPa and $4.5\ 10^{-3}$, respectively;
- the characteristic strength and ultimate strain in compression are equal to 205 MPa and $4\ 10^{-3}$, respectively.

The Young modulus is equal to 55 GPa and the Poisson coefficient is equal to .21.

It is interesting to compare these above results related to $CEMTEC_{multiscale}$ with some results obtained on other ultrahigh performance fiber-reinforced cement composites that appeared on the market during the last two decades. The more well known between these cement composites is Ductal, developed and patented by French firms. This material also designed to be tough and ductile contains only one dimension of fiber (2% of fibers per cubic meter).

The average modulus of rupture related to this material (any results have been published concerning characteristic values) is between 25 and 35 MPa [7,8] so approximately two times less than the value related to $CEMTEC_{multiscale}$.

It is also important to point that concerning $CEMTEC_{multiscale}$ no visible cracks are observed before the stress peak, which is not the case for Ductal.

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