DURABILITY OF EXTERNAL CARBON EPOXY REINFORCEMENT OF CONCRETE

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SUMMARY: Composite materials find their application in civil engineering in the strengthening of reinforced concrete and pre-stressed concrete structures. The design method of these reinforcement is based on classical methods used for reinforced concrete structure, taking into account the slip phenomena at the interface. The mechanical behavior of each material and particularly the damage states of steel, concrete and composite are also considered. If short term and long term behavior law of steel, concrete and composite has been well identified for, it's different for concrete composite interface. Varastehpour has brought out the necessity to determine the shear mechanical law behavior of the concrete/composite interface [1]. The environmental action on concrete-composite adhesive layer should modify this law. It is necessary to identify the influence of combined effects "time-temperature-water-strength" on composite reinforcement.

KEYWORDS : carbon epoxy reinforcement, creep, thermo-stimulate test, moisture, temperature.

INTRODUCTION

Technical literature on the subject relates that durability of structure strengthened by carbon epoxy composite depends on the environmental exposure of the structure [2,3,4]. Most of authors test the durability of reinforced structure under static loading by exposing specimen to a specific environmental condition (frost, high temperature, moisture). The aim of this paper is to determine the influence of combined effect of loading-temperature-moisture on the behavior of the beam. This behavior depends on the stress transfer between the composite and the concrete structure. So the shear mechanical law evolution of the adhesive layer is predominant on the behavior of all the reinforced structure.
We have carried out a set of tests on reinforced concrete specimens (Fig 1).
The tests consists in applying shear stress during six months, with two environmental conditions. The first samples are exposed to 60°C environmental condition and the second are placed in water (20°C). For all the time of exposure, a constant stress is applied on the interface. Composite reinforcements made of two carbon fabric strips with dimension of 425.50 mm^2. The strip assemble two concrete block on 200 mm length. The fabric as been design to avoid failure of the composite. The failure mode is delamination of the interface.

The level of long term loading is specify with thermo-stimulated tests for several levels of shear stress. When the stress level is determined, the creep test allows to set up, the durability of the repair, and the creep of the composite reinforcement under combined effect of stress and environment. The thermo-stimulated test is compare to a six-month-long test period. The use of thermo-stimulated tests allows the prediction of creeping using the master curve construction with the time temperature principle. The identification of mechanical behavior law allows to determine the level of shear stress to be applied to the reinforcement in the case of a flexural behavior. We have studied several epoxy polymer with three different values of glass transition temperature (40°C, 50°C, 85°C). The result allow to select the most appropriate polymer to use for the strengthening of a structure. The durability of the repaired or reinforced structure depends on the behavior of the adhesive layer between concrete and composite.

METHODOLOGY AND MATERIALS

Test principle of the measurement device

In order to evaluate the performance of a composite repair, we propose to determine the evolution of the polymer shear modulus (G) of the composite according to the time, temperature or other environmental conditions (moisture). A long test, at 60°C and less than 20 % of humidity, and a short term thermo-stimulated test have been carried out in order to determine the evolution of the shear modulus. These two tests allow the determination of high temperature and time influences on the evolution of the mechanical characteristics.
The main characteristics of the composite reinforcements are given by table 1.

	Yield stress (MPa)	Young modulus (GPa)	Ultimate strain (%)	Section of fibers (cm^2/m)	Polymer Tg
Composite A	700	50	1.3	1.68	40
Composite B	700	50	1.3	1.11	50
Composite C	600	45	1.4	0.90	85

Table 1 : Mechanical characteristics

A carbon fabric and an epoxy polymer connect two concrete blocks separated by 20 mm. The displacement of the two blocks () is due to the lengthening of the reinforcement element (Δl_2), and to the slippage (Δl) at the interface between the concrete and the composite. The value of ΔL is given by Δl_1-Δl_2. The reinforcement elements bonded on the two opposite faces present a surface of 50 x 415 mm^2. A constant shear load is applied. This load corresponds to 50 % of the failure load determined by a static test at 60°C (Fig.6). This failure (under static loading) occurs by delamination of the reinforcement element.
The reinforcement lengthening is measured by gauges (350 ohms) bonded on the composite central part. The space between the concrete blocks is measured by two displacement sensors (types RDP D5 ±20 mm). The displacement sensors present a temperature of use ranging from -20°C to 120°C. The displacement induced by the lengthening of the composite is subtracted from the spacing of blocks (Fig.4a).
The global slipping of the composite plates is measured.
The shear modulus is calculated in a first approach with the relation (1).

$$G = \frac{\tau_{moy}}{\Delta l2 - \Delta l1} \cdot s \qquad (1)$$

with : G : shear modulus (MPa); τ_{moy} : mean shear stress (MPa)
Δl_2 : concrete bloc displacement (m), Δl_1 : composite displacement (m); Lc : polymer thickness (m)

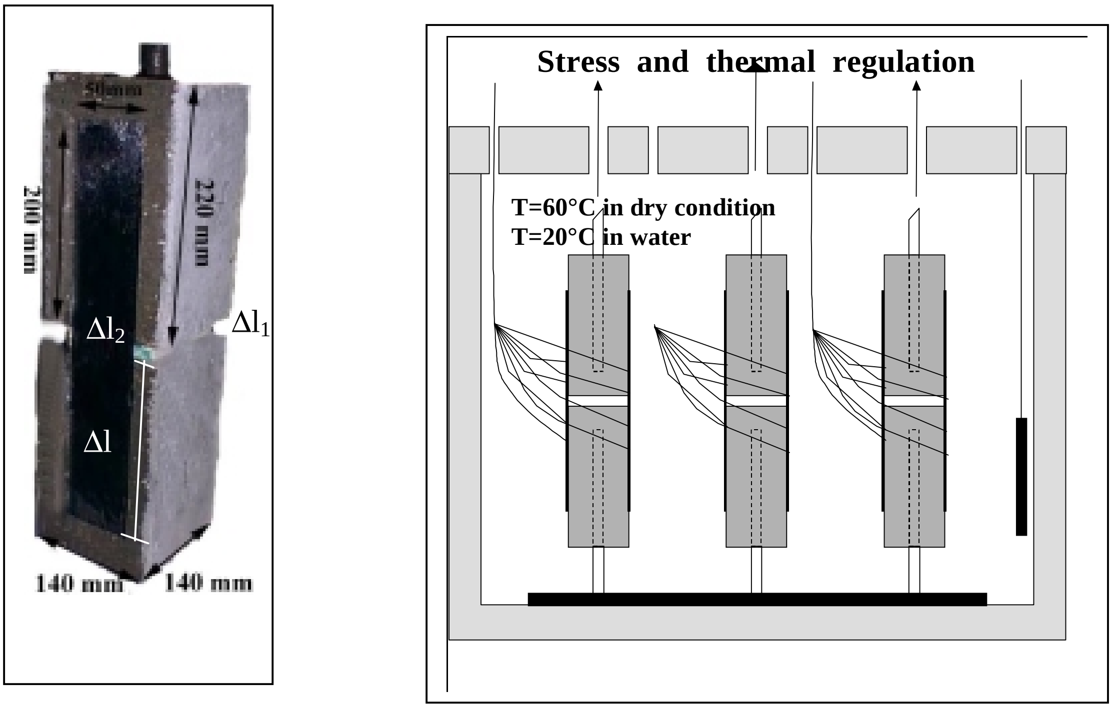


Fig. 1: Test Principle of Measurement Device

Determination of the Loading Level for Creep Tests.

Once direct tensile-shear tests are carried out, we determine the creep load corresponding to 50 % of the failure load at 60°C. This creep load is 4.5 KN for composite A, and 9 KN for composite B and C. This creep level corresponds to a linear behavior of the polymer (Fig.2). The polymer thickness is 0.20 mm.

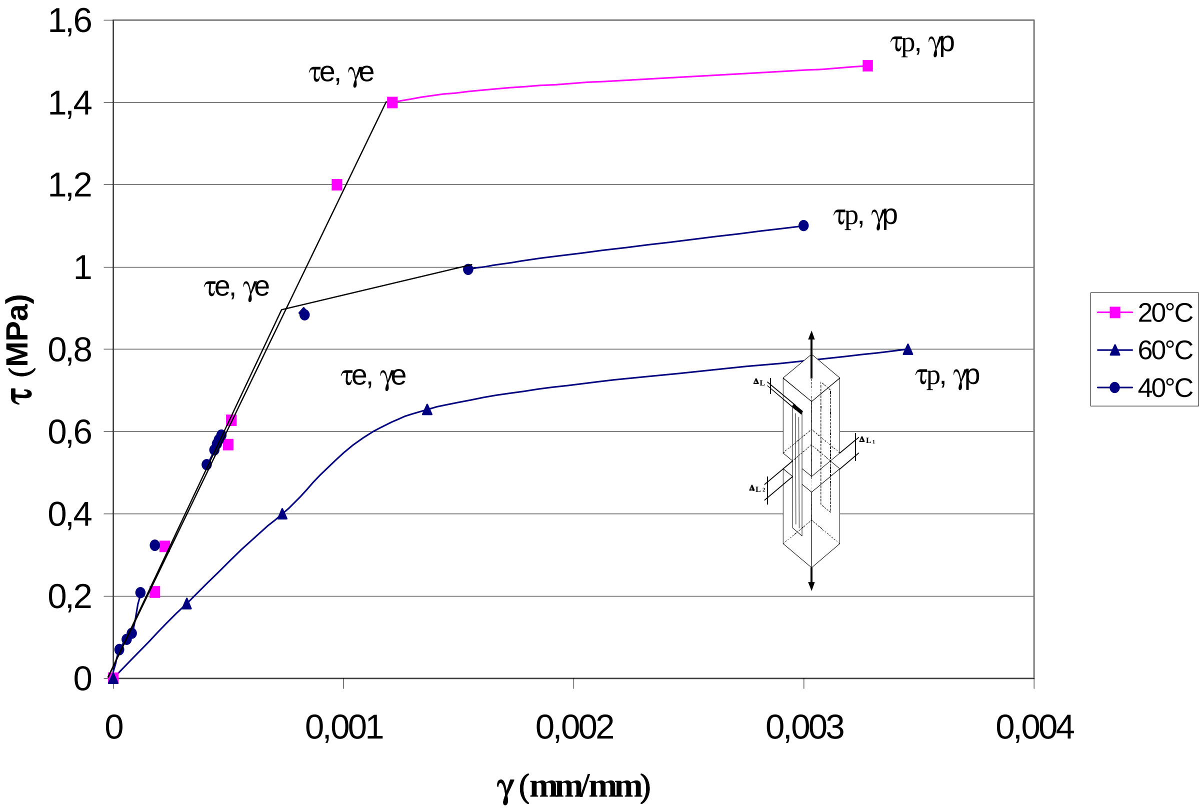


Fig. 2: Mechanical shear behavior of the concrete–composite interface (composite B)

RESULT AND DISCUSSION

Study of temperature effect on the creep of concrete – composite adhesive layer

Thermo-stimulated Tests, Construction of the Shear-Creeping Master Curve

The test specimens are placed in a thermo-regulated room at 20°C and a load of 4.5 KN is applied, i.e. an average shear stress of 0.20 MPa. The slipping is measured during three-hour-periods, up to 60°C. The results of these tests allow to determine the long-term creep behavior of the composite by using the principle of time-temperature superposition given by WLF [4]. The construction of the master curve can be done step by step with the superposition of each temperature curve. This construction allow to assess the value of the shift factor for each temperature. The result of this construction (Fig. 3) show that the shift factor (a_t) can be calculated using the master curve construction following a bilinear law. As a first step, we neglected the vertical shift factor, considering that the polymer does not have any volume variation or aging. The results of these tests shows on composite A that the shear modulus decreases from 400 down to 100 MPa during the first month that follows the loading (Fig. 4a). On composite B from 1200 MPa to 820 MPa (Fig. 4b). On composite C, the result shows that the shear modulus decreases from 2000 MPa to 1500 MPa during the same time (Fig. 4c).

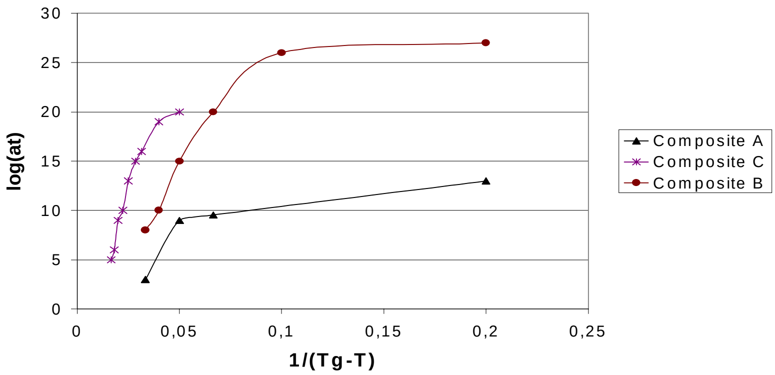
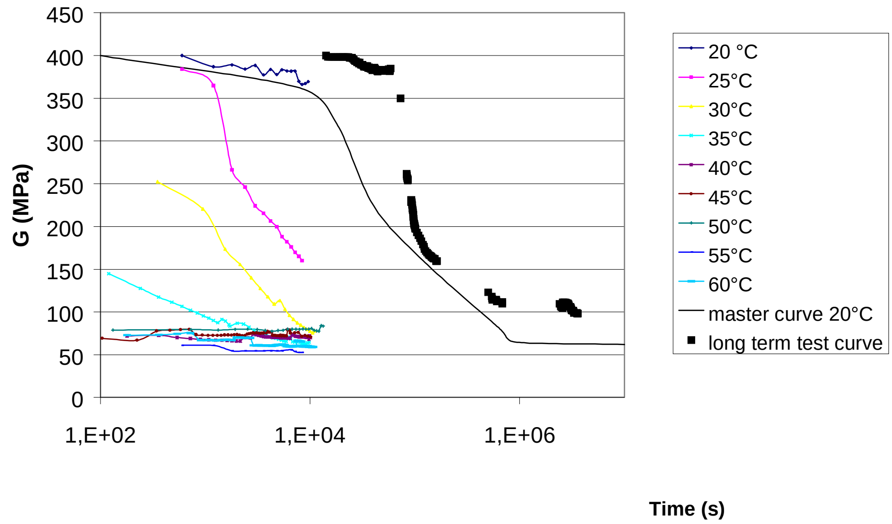


Fig. 3 : Shift factor for each temperature at 20°C

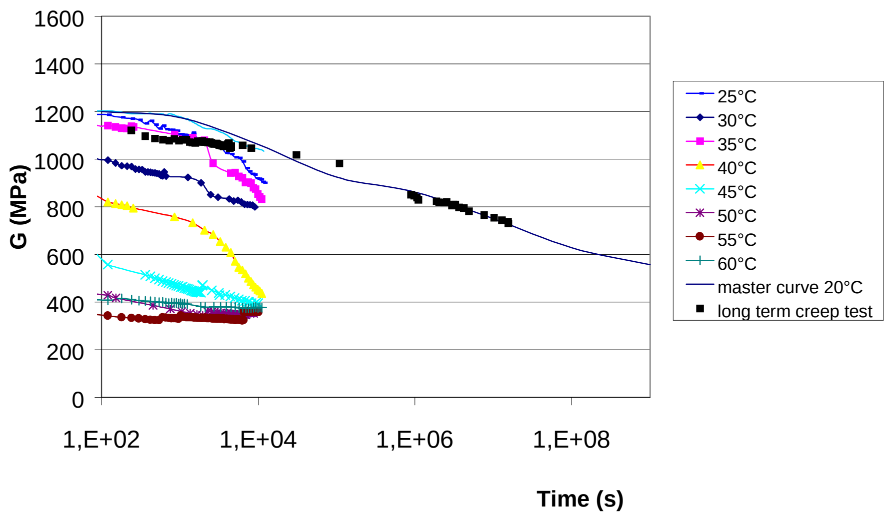
To verify the master curve construction, we use a six-month-long-term-test under the same creep level.

Long term Shear Creep Tests at 60°C

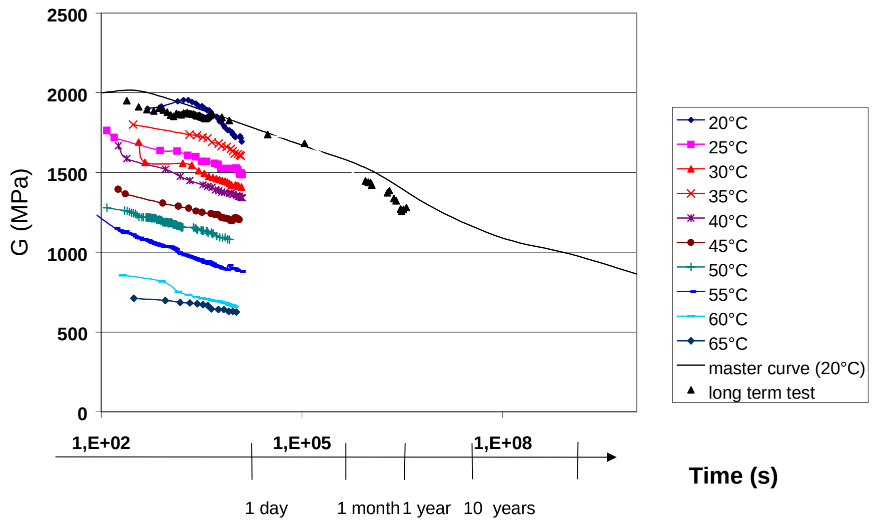
We have carry out this test at 60°C to evaluate the higher creep effect on the adhesive layer. To compare with the master curve construction at 20°C, we plot the curve at the same scale of shear modulus. A stress of 0.20 MPa is applied on composite A for a one month period, under 60°C and dry environmental conditions. A stress of 0.50 MPa is applied on composite B and C in the same condition. The evolution of the shear modulus is represented by the curve in Fig 9a and 9b. On composite A, we observe that the decrease of the shear modulus is important. The value of shear modulus at 60°C is 70 MPa, a decrease of 70 % during the first month is observed. On composite C, the value of shear modulus at 60°C is 1200 MPa, it decreases of 20 % during the first month, on composite B, the value of shear modulus at 60°C is 800 MPa, it decreases of 35 % during the same period. The comparison between the two tests is assessed by superposition of the long term test and the master curve. This long term test curve is fitted from it initial values toward the initial value of the master curve, then each value of the long term test is fitted with the same factor. The comparison between the two tests illustrates the opportunity to obtain values of the long-term shear modulus from a thermo-stimulated test. Those tests have shown that thermo-stimulated test can be used to identify the long term creep behavior of epoxy polymer tested (Fig.10).



(a) composite A



(b) composite B



(c) composite C

Fig. 4: Evolution of the shear modulus at 60°C for composite A and B and C

Study of temperature effect on the creep of concrete composite adhesive layer for several levels of loading (composite B)

The test specimen is placed in the thermo-regulated room at 20°C and a load is applied. The slipping is measured during a three hour period, up to 60°C. The results of these tests allow to determine the long term creep behavior of the composite by using the principle of time temperature superposition given by WLF [4].

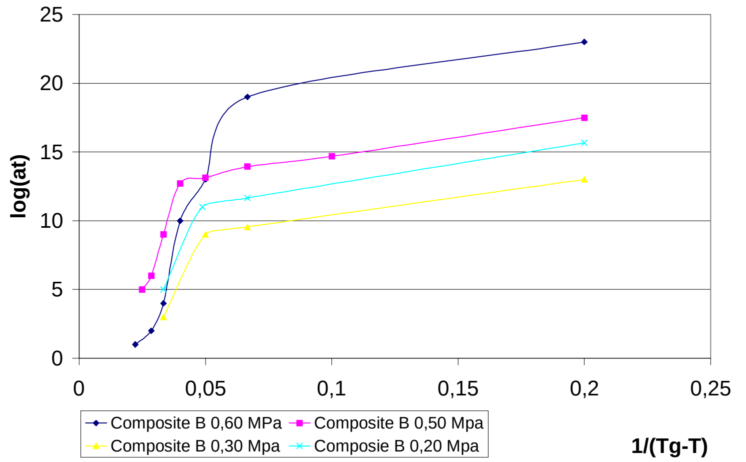


Fig. 5:Log(at)=f(T-Tg)

The result of these tests shows that the shear modulus decreases from 1200 MPa down to 500 MPa. The result with an average shear stress of 0.60 MPa shows that the shear modulus decreases from 1200 MPa to 400 MPa during the same time.

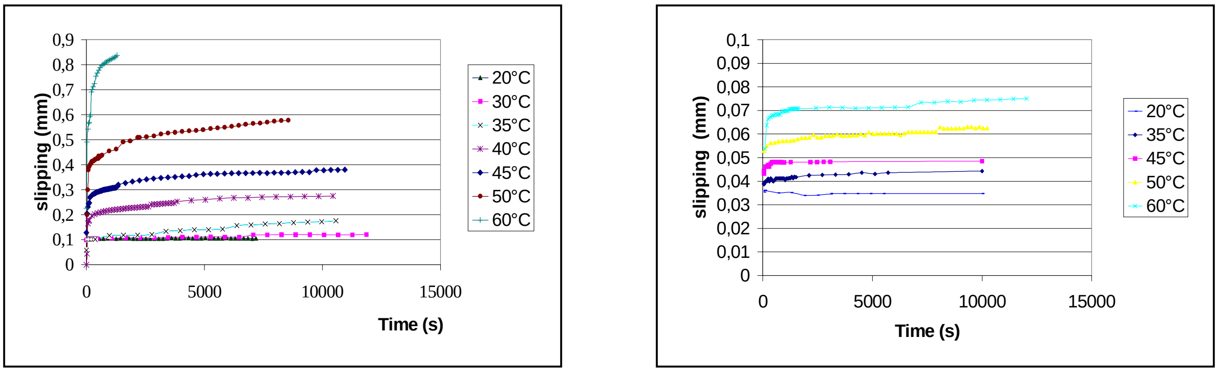


Fig. 6: Thermo-stimulated tests (τ=0.60 MPa; τ=0.20 MPa)

The non linearity upon the value of 0.60 MPa is shown by Fig. 5 and 6. The shift factor given from several level of shear stress presents a difference between those calculated for a shear stress of 0.20 – 0.50 MPa and the one calculated from 0.60 MPa. On the creep curve (Fig. 6) the test show an important creep beginning from 40°C to 45°C. In the case of the test assessed under a creep level of 0.60 MPa and 60°C the creep increases rapidly to failure. This non linearity can be explain by the fact that polymer studied in this research has a low glass transition temperature, and thus law mechanical properties. Those properties decrease rapidly when the shear stress in the double lap joint increases. The test allows to assessed the limit of stress to apply to an adhesive joint for a concrete structure reinforced with a composite plate. In the case of composite B, the level of shear stress should be limited to 0.50 MPa to have a linear behavior of the adhesive layer.
The same result could be observed with the two other composites, the main conclusion of this part is the fact that the ultimate strength to take into account for an adhesive joint should be balance by a factor to guaranty a linear behavior of the bonded composite plate.

Study Of Moisture Effect On Creep Of Concrete – Composite adhesive layer

To identify the effect of moisture on the concrete composite interface the tensile shear test is used at 20 °C with 100 % of moisture. The shear modulus determined shows that the interface properties decrease (fig 12), during the first 2 months of loading. During the test, moisture absorption is measured on the composite. A decrease of 30% of mechanical properties has been observed for a total absoption of water of 0.60 %.

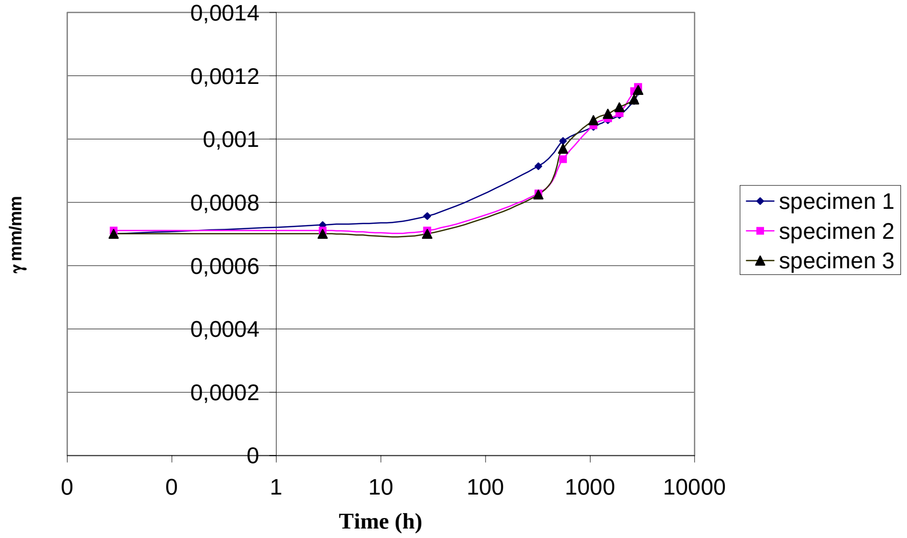


Fig. 7: Slipping by length of anchorage function as time exposure

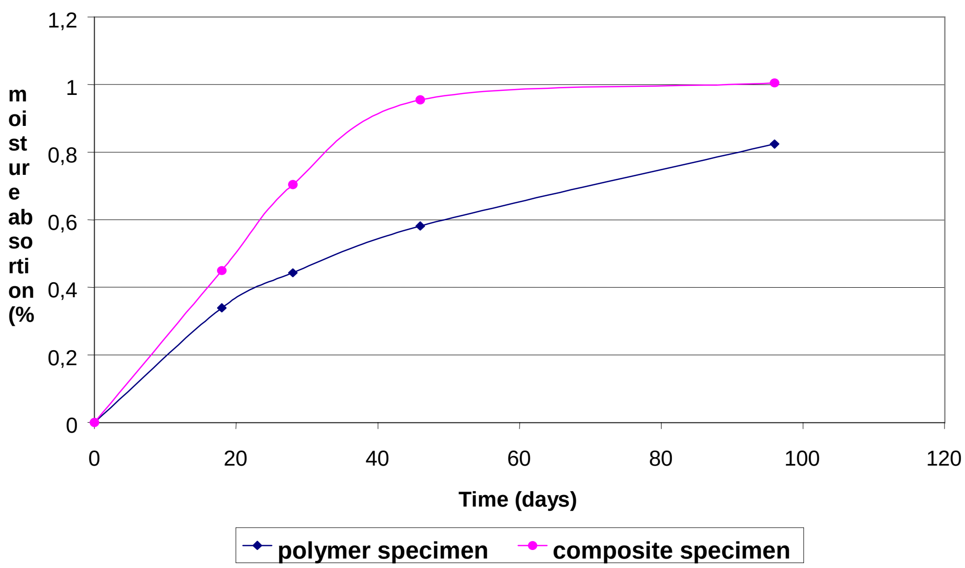


Fig. 8: Evolution of moisture absorption for composite B and for polymer

The result of this study has shown that the polymer specimen absorb more water and less rapidly than the composite specimen. This can be explain by the thickness of the specimen (3 mm/0.8 mm). The comparison between the long term creep curve and the master curve shows that the influence of the water absorption on the mechanical behavior are not so important. To validate this result tensile tests on aging specimen are under-going to evaluate the influence of water absorption on the mechanical law behavior. It seems that the behavior is not so dependent of moisture absorption. This justifies the fact that for the master curve construction the vertical shift factor can be neglected with our polymer.

Rheology model for creeping function identification

The rheological model chosen for this modelling is shown in Fig. 9. The evolution of shear modulus is given for all the test curve assessed in this study.

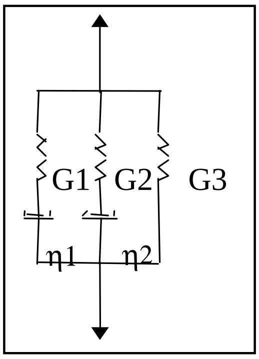


Fig 9: rheological model

The shear modulus given by the eqn 2, results from the rheological model. The evolution of the shear modulus of the double lap joint is given by the rheological model:

$$G(t) = G_1 + G_2 \cdot \exp(\frac{-t}{\eta_1}) + G_3 \cdot \exp(\frac{-t}{\eta_2}) - \frac{G_4}{t} \qquad (2)$$

The parameters of the rheological model are fitted with experimental data with the use of the software curve expert V 6.0(Fig 10). The test curve are determined with a correlation factor of 0.90. The parameter G_4/t is added to the rheological relation to rewedge the beginning of the creep curve. For all the test or master curve the parameter are given in the table 2. The use of rheological model allows to determine the long term shear modulus of the interface with any level of shear stress. The result of this study shows that the polymer with a high T_g and a high shear modulus presents a lower decrease of its mechanical behaviour. The polymer with a glass transition temperature lower than 50 °C should be avoid in civil engineering application because of a high decrease of mechanical characteristics and because of its high creep.

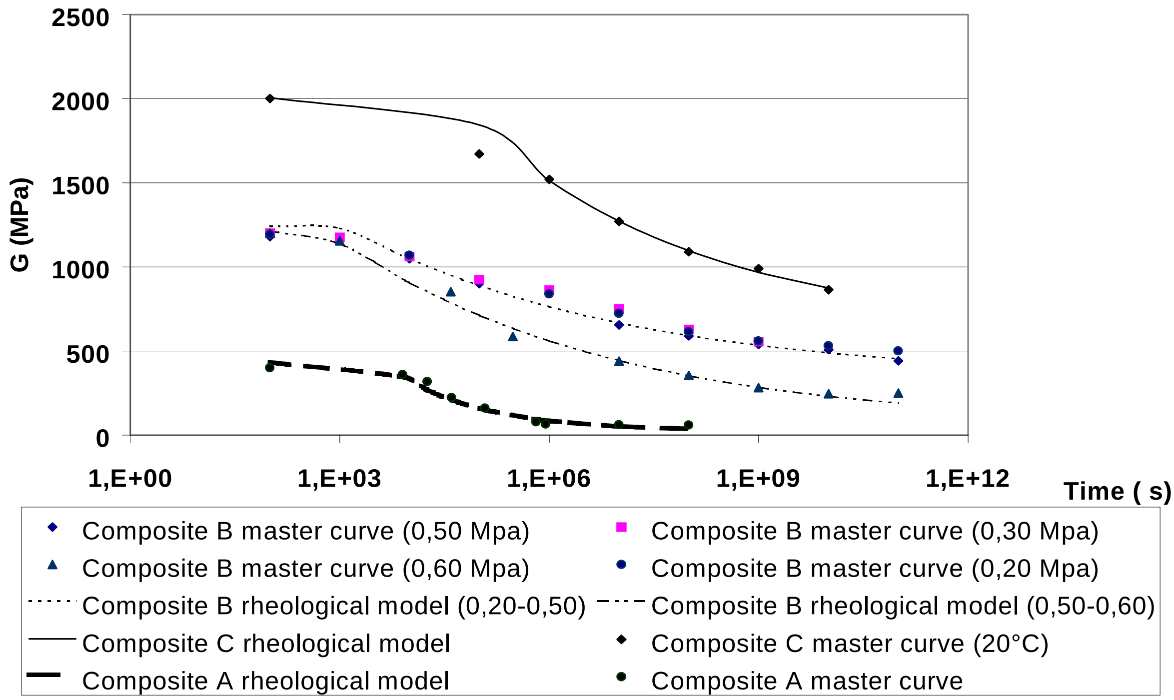


Fig. 10: theoretical and long term experimental creep compliance for composite A, B and C

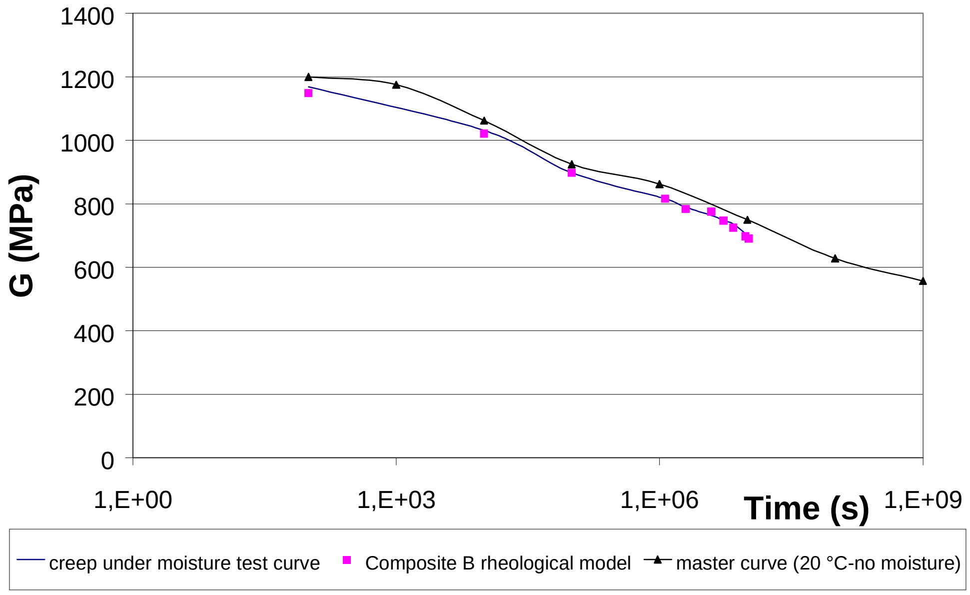


Fig. 11: theoretical and long term experimental creep under moisture effect

	E_1	E_2	E_3	E_4	η_1	η_2
Composite A	***27.80***	***4442***	***1.19***	***4442***	***1.19***	***1.19***
Composite B τ***=0.20-0.50 Mpa***	***334***	***994***	***3.92***	***994***	***3.92***	***3.92***
Composite B τ***=0.60 MPa***	***55***	***1221***	***3.81***	***1221***	***3.81***	***3.81***
Composite B water exposure τ***=0.80MPa***	***-158***	***2039***	***4.47***	***2039***	***4.47***	***4.47***
Composite C	***618***	***3021***	***3.50***	***3042***	***3.50***	***2.78***

Table 2 : rheological parameter

In the case of structural application structure, the mechanical law assessed with this method is used to determine the long term displacement of a beam.
The rheological relations are used to determine the slipping in the adhesive layer, this shear-strain in the adhesive layer brings out a loss in strength in the composite during long term loading. The loss in strength is then recalculated with the stress equilibrium of the section.
This iterative calculation method assessed the mid span displacement of the bearing structure, and with suitable failure criteria, the safety factor to applied to the structure is then determined.
With the tensile shear tested, and the rheological relation, the influence of any formula of polymer can be tested. With the thermo-stimulated test the polymer with the most accurate behavior can be chosen.
With this method, it is possible to used any aging mechanical law (creep, fatigue….) for each material, and the strength evolution in each material can be evaluated.

CONCLUSION

The mechanical characteristics of the polymer at the interface between the concrete and carbon fibers are evaluated by performing thermo-stimulated creep tests of. These tests have brought out the following points:

- the shear modulus in dry environmental conditions at 20°C, decreases of 80 % during the first month of loading for a polymer with a T_g of 40°C,
- the shear modulus in dry environmental conditions, at 60°C, decreases of 70 % during the same period for the same polymer,
- the shear modulus in dry environmental conditions at 20°C, decreases of 33 % during the first month of loading for a polymer with a T_g of 85°C,
- the shear modulus in dry environmental conditions at 60°C, decreases of 20 % during the same period for the second polymer,
- the 100 % moisture effect on the shear modulus consists in a decrease of 35% for two months of exposure.

In conclusions, it seems essential to use high shear modulus polymers with high glass transition value, and to evaluate the modulus decrease as a function of time to determine the durability of the beam. The repaired concrete structure quality depends on the adhesive layer performance. The bending design of structure can take into account this slipping phenomena. This prediction can be done with the non-linear calculus method by taking into account the rheological behavior of each material (concrete, composite) [1], but also by taking into account the shear behavior law identified in this study. The long term slippage effect in the composite plate is carried out with the P. Hamelin and H. Varastehpour method.
This method uses major calculation rules of the reinforced concrete, by taking into account the composite fabrics slippage from its support. The identification of concrete-composite shear behavior law with various environmental conditions allows to take into account the coupled effect of loading – temperature – moisture of a reinforced concrete structure. This effect can be more or less predominant according to the structure exposure (building or civil engineering structure). These conclusions are actually less catastrophic and do not question the repair principle insofar as the classical mechanical functioning of the beam in tension is challenged by the anchorage length of the composite. If the length is high enough, the shear stress in the adhesive layer is very low, and so the loss in strength in the composite is not so important.

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