Tensile, compressive and flexural basic creep of concrete at different stress levels

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Abstract

Concrete is brittle and highly sensitive to cracking, which is detrimental to the sustainability of its applications. Although it is well known that cracks occur mainly in tension, research on the mechanical behaviour of concrete is usually limited to compression and investigations of creep behaviour, a major concern for concrete structures, are no exception in this respect. This paper is intended to help remedy the situation. First, the new experimental set-ups developed to achieve tensile and bending creep are presented. The precautions taken to obtain relevant experimentation are also described. Results for specimens subjected to sustained stresses of 30, 40 and 50% of the tensile or compressive strength are then presented. The final discussion compares basic creep under the different types of loading for the three stress levels.

Keywords: concrete, basic creep, shrinkage, damage, compression, tension, bending

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I Introduction

Concrete is brittle and highly sensitive to cracking. Its poor strain capacity and low tensile strength have negative impacts on the lifetime of concrete structures. Besides, its mechanical properties in tension are non-negligible for the design of concrete structures. Corres-Peiretti and Caldentey [1] summarize the designer's point of view with regards to tensile strength considerations in two points: the stiffening effect (which limits deflections of reinforced concrete members due to the tensile capacity of the material) and the risk of brittle failure (which leads to the minimum reinforcement required in concrete structures). Because of the possible interaction between delayed behaviour (creep and relaxation) and damage, the former has to be perfectly understood in order to evaluate the risk of cracking in concrete elements. Stresses induced by shrinkage can be relaxed of more than 50% due to tensile creep which can thus hinder crack formation according to Altoubat and Lange [2]. However, it does not mean that cracking is totally stopped by such relaxation phenomenon. Actually microcracks can still propagate even if the external load decreased due to stresses relaxation, mostly for high stress levels at which viscoelatic behaviour of concrete becomes non-linear [3]. The final aim of this paper is to improve knowledge of tensile creep in concrete by comparing basic creep in tension, basic creep in flexure and basic creep in compression at different loading levels.

II Literature review

Tensile tests on cement-based materials are not easy to perform because the material is brittle and the strains are small, thus difficult for most extensometers to measure accurately [4]. How to fix the samples to the loading device [5] is also an important issue. For all these reasons, very few studies have been devoted to tensile creep of concrete. Most tensile creep experiments on cement-based materials have been performed at early age [6, 7] and even at very early age, just a few hours after casting [8–11]. During this period, concrete undergoes large dimensional changes, induced by hydration reactions (Le Chatelier contraction), drying and thermal variations in the case of massive elements, which generally result in a net contraction (shrinkage) of the material. Depending on ambient conditions, the magnitude of the shrinkage strain may reach high values (500 to 1000 µm/m at 50% RH [12]), much greater than the elastic deformation (about 100 to 200 µm/m [12]). It is necessary however to take into account the viscoelastic strain components when considering the actual state of stress, especially in the case of partially or fully restrained shrinkage [13, 14]. Some investigations on tensile creep of concrete at early age have addressed the effects of various parameters (W/C ratio, stress level, etc.) on the time-dependent strain magnitude and kinetics. In some others, creep in direct tension and creep in compression were compared [15, 16], bringing to light similarities as well as differences. Concerning similarities, at early age, the tensile and compressive creep rates are very large, but decrease sharply over time. The ageing effect appears to be very significant, especially during the first few days after casting. As for differences, Atrushi [16] has pointed out that compressive creep is higher than tensile creep just after loading. But, as the phenomenon stabilizes more quickly in compression, the amplitude of tensile creep becomes higher a few days later. These results are, however, in contradiction with Illston's findings [15] which reveal an opposite trend.

As the aforementioned tests were carried out a short time after casting, the coupling between creep and the effects of hydration (increase in strength and stiffness, shrinkage, etc.) remained very strong [9] and the results obtained could be different in the case of older concrete. Accordingly, in the model proposed by De Schutter for basic compressive creep at early age, the degree of hydration at loading becomes an important parameter influencing the strain evolution as well as its final value [17]. Tensile creep data for cement-based materials older than 28 days, i.e. when hydration reactions are almost stabilized, are rare. Based on the few reported studies, tensile creep experiments on mature concrete have also dealt with basic aspects as the concrete composition and the stress level [18–20] and the comparison between tension and compression behaviours [21–23]. A fundamental feature that differentiates tensile creep from compressive creep is that, for a fully dried concrete, compressive creep is almost negligible [24, 25] while tensile creep remains significant [26]. These findings suggest that the two delayed strains may result from different mechanisms such that further comparative studies could be instrumental in gaining a better understanding of tensile creep. One of the most relevant studies dealing with this aspect is that performed by Brooks and Neville at the University of Leeds in 1977 [21]. According to these authors, basic creep in tension and basic creep in compression are similar during the first 20 days of loading. After 40 days, strain variations measured on the specimens in compression slow down while opposite trend is observed for strain variations measured on the specimens in tension. Thus the creep behaviour seems to deviate in tertiary after 60 days of loading in tension. Findings for total creep (basic creep + drying creeps) were quite different: total tensile creep and compressive creep appear to behave similarly after two or three days of loading. Recent studies [22, 23] reveal that compressive basic creep is two to three times larger than tensile basic creep, which is in contradiction with the results obtained by Brooks and Neville. However, the rare available experimental data have to be interpreted carefully, especially when considering the difficulty inherent to the measurement of really small strains and the potentially quite different experimental conditions involved in the various studies. For instance, the extensometers used for strain measurements were not the same (embedded acoustic gauge for Brooks and Neville [21] and LVDT transducers fixed on the specimen for Reviron et al. [22] and Rossi et al. [23]). As for the test conditions, the term autogenous used by Brooks and Neville [21] actually corresponded to a test involving immersion in water. It is worth mentioning that tensile creep appears to be practically irreversible [19, 21], unlike compressive creep.

Finally, although all authors agree on the existence of a stress threshold beyond which the behaviour can change dramatically in tertiary creep and cause the failure of the specimen in tension without any further increase in applied load, the limit value is not well established. Depending on the authors, this threshold would reach about 40% and 85% of the average strength for concrete cured in water and between 60% and 90% for autogenous curing conditions [18, 27-28]. Therefore, during this study, tests were not carried out at stress levels higher than 50% of the ultimate stress beyond which, according to Pigeon and Bissonnette [29], the relation between creep and stress probably becomes non-linear and time-dependent failure is possible.

In summary, tensile creep data for concrete loaded more than 28 days after casting, notably sound comparisons with compressive creep, are scarce in the literature. This paper presents the results of a comparative study focusing on creep in direct tension, creep in direct compression and creep in flexure and intended to improve the understanding of the delayed behaviour of concrete subjected to creep in flexure sustained loading. Three stress levels assumed to fall within the linear creep regime were chosen: 30%, 40% and 50%. The experimental set-ups developed to achieve these tests are described hereafter. Then, experimental shrinkage and creep are presented and analysed with a special emphasis towards correlations and coupling between the various phenomena.

III Materials and methods

III.1 Material characterization

A High Performance Concrete developed for Andra (French Agency for Nuclear Waste Management) for deep storage of nuclear wastes was used in this study. Its mix proportions are given in Table 1. Six batches were cast: three batches for compressive creep tests and three other for tensile creep tests (in direct tension and in bending). The strength and Young's modulus in compression were measured for the six batches: the average values are respectively 69.7 MPa and 41,925 MPa with a dispersion of about 5%. The direct tensile strength was only measured for the three batches used for the tensile creep and the flexural creep tests. Table 2 shows the mean values measured for direct tensile strength, direct compressive strength and modulus in compression at 28 days for the three batches used for the tensile creep and flexural creep tests (first three lines) and the overall average 28-days value (last line), along with the corresponding coefficients of variation and the numbers of samples tested. For each batch (B-30%, B-40% and B-50% stand for the three loading levels: 30, 40 and 50% of the mean tensile strength respectively - Table 2), a series of mechanical characterization tests in direct tension and in compression were performed in order to obtain a precise value of the strength of the batch used for each creep test. As can be seen, direct tensile strength data exhibit a larger dispersion than compressive strength data. From a statistical point of view, there is a smaller dependence of the ultimate stress on local defects in compression than in tension. Because of the scatter characterizing tensile strength results, the effective stress level can differ significantly from the desired value, which can lead to very different results in terms of creep, particularly at high stress levels [28].

After demoulding, all the specimens dedicated to instantaneous mechanical tests at 28 days and to creep tests were kept in water for 15 days in order to prevent the specimens from self-desiccation. Then they were dried superficially and covered with triple layers of self-adhesive aluminium foil, a procedure that has proven to be effective for moist-proof sealing [30]. Finally, the specimens devoted to creep tests were equipped with extensometers for strain measurement and were stored in the test room in a controlled atmosphere (temperature: 20°C, relative humidity 50%) until loading at 28 days.

Shrinkage and creep occur simultaneously, the common practice for many years has been to consider the two phenomena as additive, which is appropriate for many practical applications [32, 33]. Actually, they are not independent and the principle of superposition cannot rigorously be applied. Tensile creep strains are low and are of the same order of magnitude as additional strains (autogenous shrinkage, thermal strain, etc.) [34]. By assuming the effects of autogenous shrinkage to be significantly reduced beyond 28 days, the principle of superposition could be applied provided that some precautions are taken, particularly an accurate assessment of shrinkage strain. For this purpose, strain measurements were performed on non-loaded companion specimens having the same shape and size as the loaded specimens. Deformations of the specimens were monitored over a long period of time using long-service-life strain gauges, 60 mm in length and equipped with a stainless steel metallic support that provides resistance to capillary water rise. Special glue allowed firm and durable contact between the specimen and the strain gauge.

Autogenous shrinkage results obtained for three different batches (batches 1, 2 and 3 in Figure 1, corresponding to creep levels at 30, 40 and 50% of the concrete tensile strength) and for two different specimen sizes (specimens 1 were 70×70×280 mm prisms and specimens 2 were 100×100×500 mm prisms) are reported in Figure 1. As expected, shrinkage strain values were low and did not exceed 20 µm/m after 80 days of measurement. When the measurement accuracy was taken into account, results indicated a low dispersion among specimens, either from the same batch or from different batches. During this experimentation, it has been verified that the use of three aluminium layers prevented mass loss (no mass variation was detected during the first 100 days; the weighing scale resolution was of 1 g for mass higher than 3 kg).

III.2 Creep devices

- Compressive creep test apparatus

The experimental device, the loading process, and the specimens have been described in detail by Munoz [35] and Ladaoui [36]. Compressive creep devices are equipped with hydraulic jacks. Each one allows simultaneous loading of 2 specimens. Longitudinal deformations are recorded by means of inductive transducers located within a reservation created during casting by placing a removable metallic insert in the mould axis. The central steel rod (along the central axis of the specimen, Figure 2) is fixed to the lower part of the specimen by a steel nut embedded in the concrete during casting. The LVDT sensor is fixed to the upper part of the specimen. The displacement of the magnetic core located on the steel rod provides the deformation of the specimen which was measured on a base length of 115 mm. Previous studies [35] showed that the strain measurement uncertainty is equal to 9 µm/m and that the difference with an external measurement (on three lines on the surface of the specimen) was lower than 5%. The loading and strain measurements were performed in accordance with the RILEM recommendations [37].

- Tensile creep test apparatus

A schematic description of the tensile creep test apparatus is given in Figure 3. The tensile creep test set-up was a rigid frame with a hinged lever arm (① in Figure 3). The lever arm ratio was 5/1. A 70×70×280 mm prismatic specimen ② was loaded by using calibrated weights stacked on a platen ③. The load was transmitted to the specimen through a cable, one end of which was welded to a steel cap glued on one side of the specimen while the other end was hinged to the frame ④. A screw system located at the bottom of the rig ⑤ allowed the horizontality of the lever arm to be controlled. A stopping device located below the lever arm (⑥ in Figure 3) prevented sudden fall of the weights in case of failure of the loaded specimen. Due to the sensitivity of tensile creep to temperature changes, all the experiments were performed in a test room where temperature and RH were controlled. During the test, additional precautions were taken: two specimens, one loaded to measure tensile creep and the other unloaded (control specimen) to measure shrinkage strain, were positioned side by side in a thermally insulated box and so had the same thermo-hygrometric history. One of the difficulties with tensile tests on cement-based materials is the load transfer between the specimen and the loading device [5]. In this study, the solution of gluing specimens with methacrylate adhesive was opted for. The connection between the cable and the loading frame was achieved with a cylindrical roller ⑦. It is worth mentioning that the use of flexible cable instead of rigid attachments significantly reduced parasite bending effects in the specimen. The same long-service-life gauges (60 mm in length) than for shrinkage strain measurements were used for the specimens in tension.

- Flexural creep test apparatus

The flexural creep apparatus (Figure 4) was similar in principle to the oedometric device used in soil mechanics. In this case, the soil specimen was replaced by prismatic concrete specimens. The load was applied, as in the case of tension, by means of calibrated weights stacked on a platen (① in Figure 4) fixed to a hinged lever arm②. The lever arm ratio was also 5/1. Through I-shape steel beams equipped with two metal rollers acting as simple supports and a rigid frame ③ connected to the lever arm, two 100×100×500 mm prismatic concrete specimens were loaded in a four-point bending configuration with a distance of 460 mm between the lower supports and 175 mm between the upper supports. The specimens, which were placed in a thermally insulated box to minimize the impact of an accidental variation of temperature, were tested simultaneously. In bending, concrete creep causes deflection. If creep in tension and in compression were different, a displacement of the neutral axis would also be observed. In order to characterize this behaviour, at least two measurements were necessary. Therefore, strain was measured with strain gauges on the upper and lower sides of the beam and on the initial neutral axis on each specimen. The strain monitoring system used for the flexural test was the same as the one used in direct tensile tests.

IV Experimental results

IV.1 Modulus of elasticity upon creep loading

The loading was applied quasi-instantaneously at the beginning of the creep test in order to avoid both dynamic and time-dependent effects in the apparatus and in the specimen [25]. During loading, the material first underwent instantaneous (elastic) strain followed by viscous strain. The Young's modulus of concrete could be calculated from the stress applied and the instantaneous strain measured. Table 3 summarizes the different values of modulus of elasticity obtained in direct tension, compression and bending for the three different loadings (each value is the mean Young's modulus obtained on two specimens, with the corresponding deviation in brackets). The applied stresses were equal to 30, 40 and 50% of the strength in tension ft for the tensile and flexural creep tests and 30, 40 and 50% of the strength in compression fc for the compressive creep. The moduli of elasticity were calculated upon loading and at the end of the creep experiments, after removal of the load. The modulus values obtained during conventional compressive tests as recommended by RILEM [38] are presented in Table 2.

The Young's modulus values range between 40,610 and 45,610 MPa for all specimens upon loading. Taking into account the scattering due to measurement inaccuracies and concrete heterogeneity, the differences between the moduli at loading appeared to be small for the three batches and the three types of loading. These values were not significantly different from the Young's modulus obtained during a conventional strength test [38]. The loading intensity did not affect initial stiffness, which indicates that the mechanical behaviour was quite linear for a stress level ranging up to 30 to 50% of the compressive or tensile strength. After removal of the load, an increase in stiffness could be observed for all specimens, except for the batch corresponding to compressive creep at 30%. It may have been caused by the effect of material ageing due to continuing hydration of anhydrous cement grains or by a consolidation effect of the material due to creep [19, 39].

IV.2 Results of creep measurements

The aim of this study was to assess the effect of the stress level (applied stress / quasi-instantaneous strength ratio) on compressive creep and tensile creep. The stress levels were chosen between 30% and 50% of the compressive or tensile strength because the mechanical behaviour is assumed to be linear in this stress range and, in practice, civil engineering structures are subjected to stress levels close to such values. The precise values of stress levels are difficult to know, especially in the case of tension, because of larger variability characterizing the concrete tensile strength. Moreover, sustained loading could impact the material microstructure [19, 40] and thus affect the material strength and the actual stress level.

The total strains (including instantaneous strain, creep and shrinkage) obtained during tests in compression, direct tension and flexure the same concrete mixture are plotted in Figure 5-a and b, Figure 5-c and d, and Figure 5-e and f respectively. In the adopted sign convention, the tensile strains (extensions) were considered positive, while the compressive strains (contractions) were assigned the negative sign. Strains first increased in magnitude during the early days, regardless of the type of loading. These findings are in agreement with usual observations on short-term basic creep and can be explained by the micro-diffusion of water under stress from the smaller pores to the capillaries. Differences in behaviour occurred after about five days:

- **Direct compression loading:** the strain kinetics was first very fast, then decreased slightly but remained significant even after 200 days of loading (Figure 5-a and b).
- **Direct tension loading:** the strains decreased regardless of load intensity (Figure 5-c and d). The strain slope was different for the two specimens tested at 30% of the tensile strength even though they came from the same batch and were subjected to the same load (Figure 5-c). Such a difference was not observed with the specimens loaded at 50% of the tensile strength (Figure 5-d).
- **Bending loading:** flexure-induced compression showed the same evolution as in direct compression (Figure 5-e and f); the total strains measured on the stretched parts of specimens (positive curves in Figures 5-e and f) did not have a significant negative slope as observed for direct tensile tests, but rather stabilized.

Compressive creep results exhibited irreversible behaviours (with residual deformation). For the tensile creep (direct tension and flexure-induced tension), strains became negative after the total removal of the load.

All these observations highlight the very important role of shrinkage on creep and recovery in tension. Shrinkage causes negative strain as compressive creep and thus has effects that oppose tensile creep. Moreover, shrinkage is comparable in magnitude to tensile creep. The analysis of the creep results has to take the influence into account.

V Analysis and discussion

V.1 Specific basic creep

Specific creep results (obtained after deducting instantaneous strain and shrinkage strains presented in Figure 1) in direct tension, in compression and in bending have been plotted in Figure 6 for the three stress levels.

Typical compressive creep curves exhibiting high initial kinetics were obtained (Figure 6-a). The results show that compressive creep depends on load level: for two different stress-strength ratios, namely 30% and 50%, compressive creep strains diverge from each other after a few days of loading. For the HPC mixture studied in this paper, non-linearity apparently occurs between 30 and 50%.

Tensile creep strains were expected to be small [21-23] and of the same magnitude as shrinkage strains. In order to analyze such results, it was necessary to obtain shrinkage strains for stress-free specimens in the same curing conditions as for loaded specimens. Each specimen in tensile creep was associated with a control stress-free specimen (same shape, same size and cast in the same batch in order to minimize scatter). Both specimens were kept in the same thermally insulated box. Shrinkage strain was measured on the control specimens with gauges identical to the ones used for the loaded specimen. The shrinkage subtracted to the total strain of each specimen was the mean of the two measurements performed on the control specimen. This way of superposing creep and shrinkage is a common approach that assumes that the shrinkage of a loaded specimen is equal to the shrinkage of an unloaded one [3, 41]. Tensile basic creep curves (obtained after the deduction of shrinkage strains) evolved practically in the same way as compressive creep with high creep rates during the first five days regardless of the stress level (Figure 6-b). After about 10 days, five specimens started shrinking while the shrinkage strains measured on the control stress-free specimens have been subtracted. The results were more scattered than for compressive creep and no specific trend was found with regards to the stress level. It is important to note that the scatter of strain measurement is quite small between two gauges stuck on a same specimen and mainly due to small flexural moment during loading (the deviation between two gauges appeared at the beginning of the test with little evolution during the creep tests – Figure 5-c and d). Moreover, the same gauges were used for bending creep tests which present smaller dispersion (Figure 6-c). Therefore, the scatter was not mainly caused by the measurement system. Scatter of tensile creep strain appears between different specimens and can be explained by usual scattering of concrete response in tension. Concrete properties are usually more scattered in tension than in compression (Table 2) and than in bending. It can explain why tensile creep is more scatter than compressive and bending creep. The dispersion of the results can be explained by three main factors: the very low magnitude of measured strains, the dispersion of the concrete shrinkage strains and the dispersion of the direct tensile strength. First, the scatters observed for the direct tensile creep results and for the autogenous shrinkage are comparable in magnitude. Secondly, it is difficult to evaluate the stress level precisely in tension because of the large dispersion of the direct tensile strength results (Table 2). The stress level could thus be overestimated or underestimated. As creep is sensitive to stress level, the effects on the measured creep strains could be significant.

For the flexural creep test, creep measured in the compression area and the one in the tension area presented similar evolutions: high early rate of deformations and strains consistent with the type of stress (Figure 6-c). The specific creep strains in flexure-induced tension (obtained after deduction of the shrinkage strains measured on the control specimens) were positive throughout the experiments, unlike the creep strains obtained in direct tension. While the shrinkage was quite identical for the control specimens associated with the tension and with the flexural tests, the consequence for the creep is not the same: a negative slope was noticed for the tensile creep while a positive slope was observed for the flexural creep. Creep strain curves were practically symmetrical in flexure-induced compression and tension for the 40% and 50% stress levels (Figure 6-c), but not for the 30% level.

V.2 Creep recovery

The results of creep recovery in compression, in direct tension and in bending are presented in Figure 7. Metrological problems prevented to record the recovery for the 30% loading level in direct compression and bending. Creep recovery recorded under the different types of loading (compression, tension, flexure) did not exhibit significant discrepancies when various types of loading (tension, compression, bending) were considered, unlike the observations made by Brooks and Neville [21], who reported differences between direct tension and direct compression.

V.3 Limit of the superposition of basic creep and of autogenous shrinkage strains

Direct compressive creep results exhibited a usual trend. The non-linearity between 30 and 50% of ultimate strength can be explained by the dependence of basic creep on the density of microcracks occurring during the creep test, as already observed and explained in [23,41]. In the case of direct tensile creep, the experimental results can be considered as unexpected, with most of the specimens exhibiting a tendency to 'contract' after a few days under load (Figure 6-b). However, the shrinkage strains measured on the control specimens have already been deducted from the total strains (assuming that the hydration evolution is the same for a specimen loaded and unloaded one) and thus the contraction cannot be explained by the usual shrinkage due to regular continuous hydration. The slope of contraction for all the specimens in tension is low (less than -0.1 µm/m/MPa/day). However, it is important to remind the particular attention paid to obtain representative shrinkage strain with the association of one stress-free specimen for each loaded specimen. It must also be noted that tensile creep curves of five (on the six) specimens tested in tension present negative slopes while all the flexural tensile creep curves obtained in the same conditions with the same measurement tools exhibit positive slopes. Even if the negative slope is small, the result appears to be systematic and could have a physical explanation other than the only uncertainty of the shrinkage measurement.

Such results had already been reported by Reinhardt and Rinder for basic creep at high loading levels on high performance concrete loaded after 28 days [28]. As already explained by these authors, the increase in creep cannot be negative. It implies that the shrinkage of loaded specimens may be greater than the shrinkage obtained on control, stress-free samples. When concrete is loaded, it will crack even at a stress levels lower than 20% in direct tension [26]. According to Rossi et al. [23], these cracks could generate a brutal internal hydric imbalance resulting in a phenomenon similar to drying which causes additional shrinkage. Cracks could also cross anhydrous grains of the cement paste and increase their hydration kinetics. This continuation of hydration would induce further autogenous shrinkage and could partially compensate damage and even lead to an increase in strength. This is in accordance with Reinhardt and Rinder's observations pointing out that the relative humidity decreased more in the loaded specimens than in the stress-free specimens during basic tensile creep experiments [28]. It can be concluded that the more microcracked the concrete is, the greater the additional shrinkage strain will be. This interaction between the two phenomena is similar to the Pickett effect demonstrated for the creep of concrete in compression [25, 42, 43]. Indeed, this effect has been explained through the role of skin cracking and of the decrease of humidity [25]. For specimens in tension under stress level lower than 50% of the tensile strength, the creep loading does not cause localized cracks and the subsequent failure. However, the instantaneous loading could cause damage as observed with acoustic measurements or with ultrasonic pulse velocity techniques in [27, 44-45]. Using these non-destructive techniques, authors reported that the first damages were detected from 30% of tensile strength. Moreover, microcracks have been detected for creep test at stress level of 30% of the strength and it has been noticed that creep strains is proportional to the number of microcracks created in the material [23, 41]. As a consequence, creep is associated to damage. Notwithstanding the propagation of microcracks could be limited by the presence of voids or aggregates. In that case, induced damage could have a less effect on mechanical properties than the continuous hydration of cement and could not be detected at unloading. In such conditions, during the tensile creep tests, damage would not lead to increase the strain due to localized cracks. However it could be sufficient to cause additional contraction strains due to the decrease of humidity (due to continuation of hydration) as for the Pickett effect. Even small damage and consequences on shrinkage could cause the variation of capillary depression necessary to induce additional shrinkage which could explain the observed negative slope.

In this analysis, the strain recorded during the flexural creep tests contributes additional information. In the bending creep tests, only a small fraction of the volume is loaded up to the nominal stress level. The measured compressive strength was about 20 times larger than the tensile strength. The compressed zone in the bending specimen was thus loaded at a level less than 2% of the compressive strength. In the tension zone, only the lowest portion (extreme fiber) of the beam was really loaded at the nominal stress level. Although the cross-section remained plane [46-47], only a fraction of the specimen height was subjected to a really high stress rate. In bending tests, the average stress level over the cross section is less than 50% of the nominal stress, thus restricting damage. Moreover, the non-uniformity of the stress and strain fields in flexure specimens contributed to stable microcracking control. It allowed larger local deformations than in a uniform field case without unstable propagation of cracks [48]. Consequently, the additional cracking-induced shrinkage was no longer significant, explaining why the curve slopes corresponding to creep strains in direct tension and bending-induced tension were not identical (Figure 6-b and c). In flexure, creep strains appeared to be the same in flexure-induced compression and in bending-induced tension as already observed for direct tension and compression performed in water [21]. In this case, the effect of shrinkage on concrete is probably cancelled or at least largely reduced. No significant differences were observed for the three loading levels and basic creep appeared to be fairly linear in flexural creep (flexure-induced tension and flexure-induced compression) between 30 and 50% of the tensile strength, in contrast with the non-linearity observed for compressive creep (Figure 6).

While basic creep appears to be different in tension, in bending and in compression, the recovery in the direct tensile creep experiments was roughly the same as in bending and compression. As a consequence, the reversible part of creep appears to be the same for the three loading modes and the difference of basic creep should possibly be searched in the irreversible part of creep for which damage plays a prominent role. But it also means that during recovery, shrinkage was quite the same for all the specimens. If shrinkage strains were really modified for loaded specimens compared to stress-free specimens (perhaps in interaction with damage), probably due to the closure of microcracks this effect stopped when the specimens were unloaded. On-going experimentations with longer recovery period will allow these points to be clarified.

V.4 Comparison of tensile, compressive and flexural basic creep

The specific basic creep in compression, in tension and in bending obtained after deducting instantaneous strain and shrinkage strain (presented in Figure 1) is plotted in Figure 8. To make comparison easier, absolute values of creep strains have been used. During the first few days of loading, creep strains did not appear to be significantly different, whatever the type of loading (direct tension, compression, flexure-induced tension or flexure-induced compression). All strain curves evolved in accordance with the loading conditions. Tensile creep data recorded in direct tension and flexure creeps were quite similar (between 3 and 5 µm/m/MPa) for all the specimens, whatever the stress level, while compressive creep was twice as large (between 7 and 9 µm/m/MPa).

After 5 days, quite a clear partition appeared: compressive creep strains were the largest, flexure-induced tension and flexure-induced compression were intermediate, while tensile creep strains were the smallest and began to decrease after 5 to 10 days of testing (Figure 8).

Compressive creep was the largest, but the results obtained for the 30% stress level were not significantly larger than those recorded in flexure. Two specimens in direct tension (taken to be loaded at 30 and 40% of the tensile strength) exhibited creep strains quite close to the creep obtained in flexure, while the other four exhibited negative strains after 5 or 10 days of loading. As explained above, flexural creep should be less affected by the coupling between damage and shrinkage. It could thus be expected to obtain flexural creep strains in between the compressive creep strains (which could be increased by the coupling with shrinkage) and the tensile creep strains (which could be decreased by the coupling with shrinkage), as observed in Figure 8. The difference between direct tensile creep and flexural tensile one appears to be systematic and could be explained by the impact of microcracking on shrinkage strains. However, experimental evidence of damage had not been obtained on the specimens studied. Additional tests are required in order to determine and to quantify the potential effect of microcracking on shrinkage and subsequent effect on the creep behaviour of the material.

VI Conclusion

Few studies have been devoted to tensile creep of concrete, particularly for concrete older than 28 days, i.e. when hydration reactions are almost stabilized. In the field, sound comparisons with compressive creep are scarce. This contribution presents the results of a comparative study focusing on creep in different modes of loading: direct tension, direct compression and flexure. Basic creep test results obtained under these different types of loading have been analysed and compared for three stress levels. For this purpose, specific devices devoted to tensile and to flexural creep were developed. Results show that the behaviour depends on the type of loading. It is unnecessary to specify that a realistic modeling of concrete response requires knowledge of the creep under these different types of loading. During experiments, attention was paid to avoid artifacts that could be induced by thermal variations. Shrinkage strains were measured with great care and high accuracy.

In terms of stress levels, non-linearity was found for compressive creep to arise somewhere between 30 and 50% of the compressive strength for the HPC studied. For direct tension tests, the tensile strength variability made it difficult to conclude, and for flexure creep, the loading-induced damage appeared to have limited effects in the stress level range investigated (between 30 and 50% of the tensile strength).

Shrinkage plays an important role in the estimation of creep and analysis is made difficult due to the low strains magnitude, the dispersions of the shrinkage strains and uncertainty on the tensile strength of the concrete. In spite of these difficulties, the differences between direct tensile creep, compressive creep and flexural creep measured in this work are systematic. The assumed superposition of basic creep and autogenous shrinkage could be relevant only if the specimen did not undergo significant damage (flexural test at stress levels equal or lower than 50% for the tests performed in this study). Initiation of first microcracks in the case of uniform loading (direct tension or compression) made the interpretation of results complicated due to the strong interaction between shrinkage and damage. Such interaction could increase the shrinkage strain of the loaded specimens compared to the shrinkage of control specimens (stress-free specimens). The recovery appears to be the same for the three modes and the differences of basic creep for the three loading modes should probably be sought in the irreversible part of creep. The conventional assumption that the two phenomena can simply be superimposed ceases to be valid. Such assumption would lead to overestimate the basic creep in compression and underestimate the basic creep in direct tension. The main problem in analysing the behaviour of concrete under sustained loading in tension and in compression is then to quantify the relation between shrinkage and damage. This should be done through complete modelling that enables such coupling to be considered. It is the purpose of the current phase of the undergoing research program. On-going experiments are focusing on quantification of this damage due to low stress levels on the magnitude of shrinkage strain.

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TABLES

Table 1: Composition of concrete mixture

Composition of concrete in kg/m³	
Cement CEM I 52.5R PM-ES (Val d'Azergues), Lafarge	400
Limestone sand 0/4 mm, Boulonnais	858
Limestone aggregate 4/12.5 mm, Boulonnais	945
Superplasticizer Glénium 27, MBT	2.2
Total water	178

Table 2: Mechanical properties at 28 days (CV: coefficient of variation)

	Tension			Compression			Modulus in compression		
Batch	**Mean (MPa)**	**CV**	**Tested samples**	**Mean (MPa)**	**CV**	**Tested samples**	**Mean (MPa)**	**CV**	**Tested samples**
B-30%	3.48	19%	6	74.6	1.7%	2	42040	2.4%	3
B-40%	3.59	10%	8	67.5	2.6%	6	40610	2.9%	4
B-50%	2.99	13%	10	73.5	4.0%	6	41705	1.8%	4
All batches	3.31	16%	24	71.1	5.4%	14	41438	2.8%	11

Table 3: Instantaneous elastic modulus upon loading and after unloading (in MPa – the values are the mean obtained on two specimens, maximal deviation compared to the mean value is given in brackets, fc and ft stand for compressive and tensile strengths respectively)

	At loading			**After unloading**		
	30% fc or ft	**40% ft**	**50% fc or ft**	**30% fc or ft**	**40% ft**	**50% fc or ft**
Compression	45610 (4350)		44570 (5460)	41885 (250)		53235 (14250)
Tension	41215 (415)	44300 (345)	43740 (625)	42160 (340)	46850 (770)	45375 (1010)
Bending	44065 (0)	42655 (1275)	44810 (2005)		44290 (1030)	47670 (2270)

FIGURES

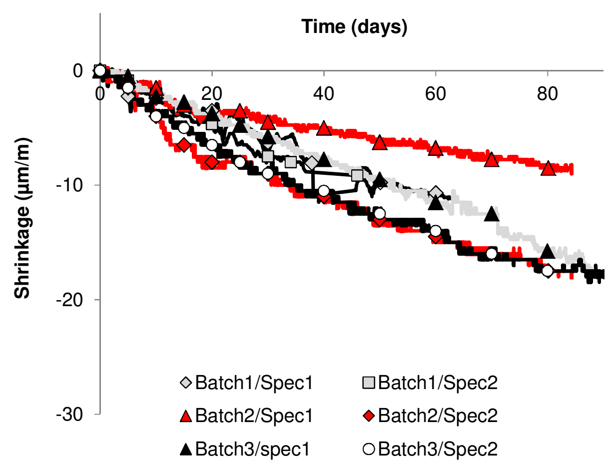


Figure 1: Shrinkage strains for specimens kept in an insulated box from 28 days after the casting. For each batch, results for two different sizes of specimen (Spec1 correspond to 70×70×280 mm prisms and Spec2 to 100×100×500 mm prisms) are presented.

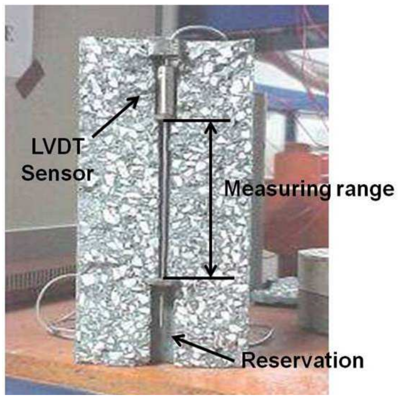


Figure 2: Longitudinal measurement for compressive creep test (inductive transducer in the reservation)

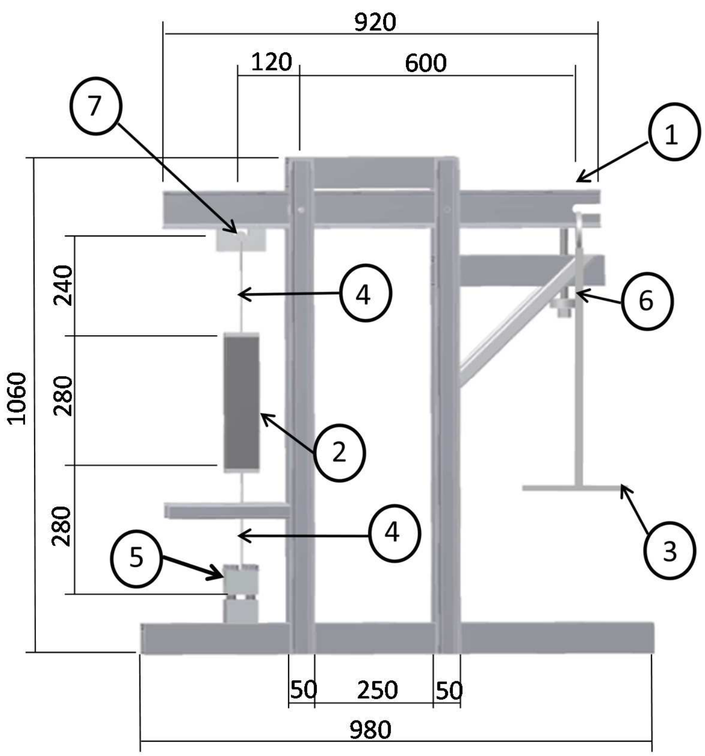


Figure 3: Tensile creep device (① lever arm, ② 70×70×280 mm prismatic specimen, ③ platen, ④ cable, ⑤ screw system to control the horizontality of the lever arm, ⑥ stopping device, ⑦ cylindrical roller).

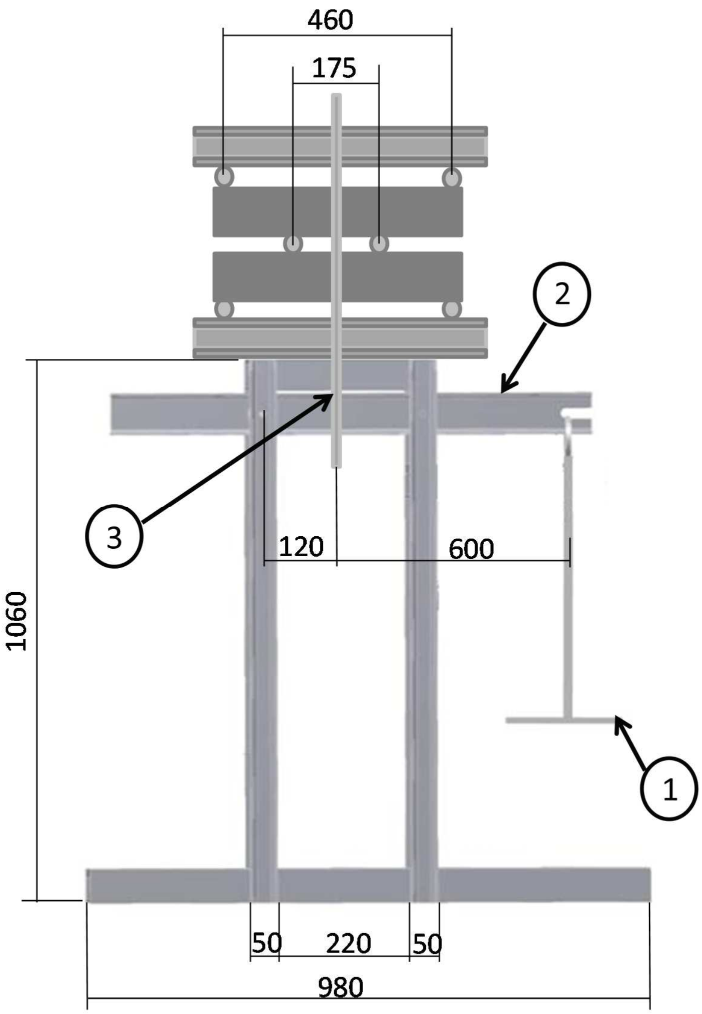


Figure 4: Flexural creep device (① platen, ② lever arm, ③ rigid frame to ensure the transmission of the loading from the lever arm to the specimens)

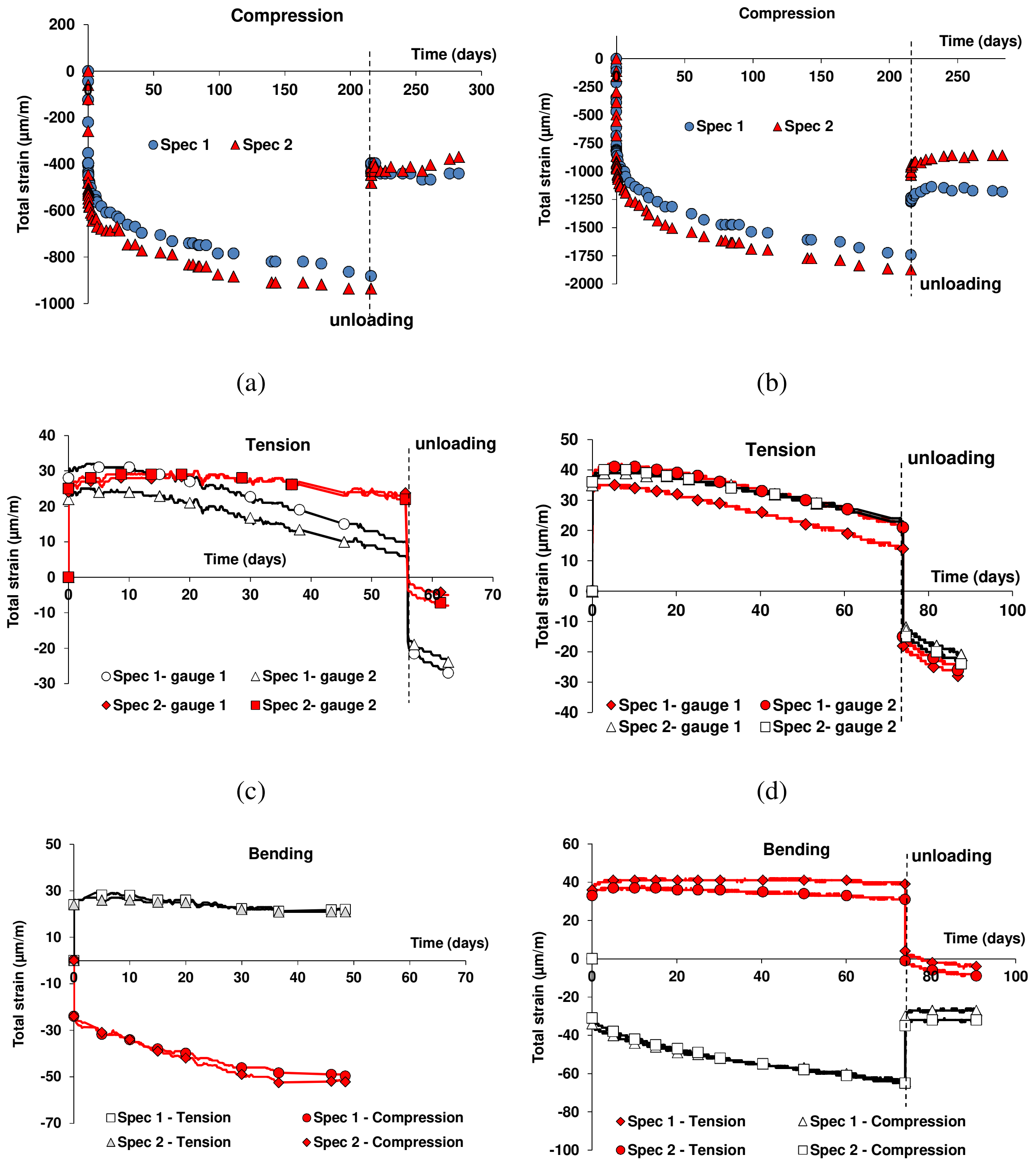
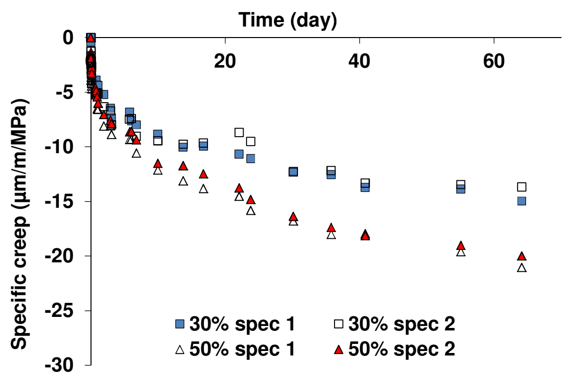
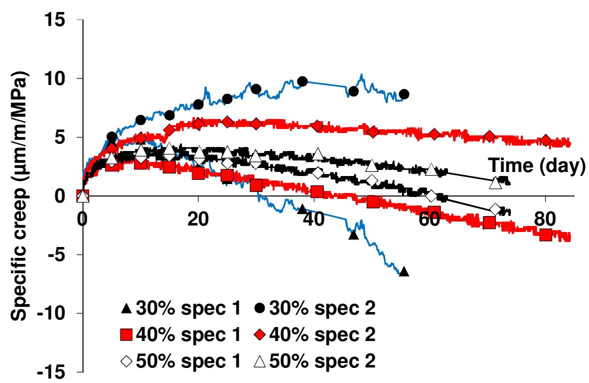


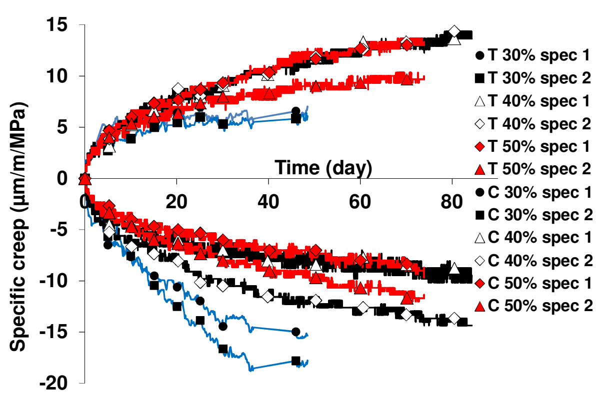
Figure 5: Total strains (elastic strains included) in compression at 30% and 50% of fc (a and b), in tension at 30% and 50% of ft (c and d), and in flexure at 30% and 50% of ft (e and f)



(a)

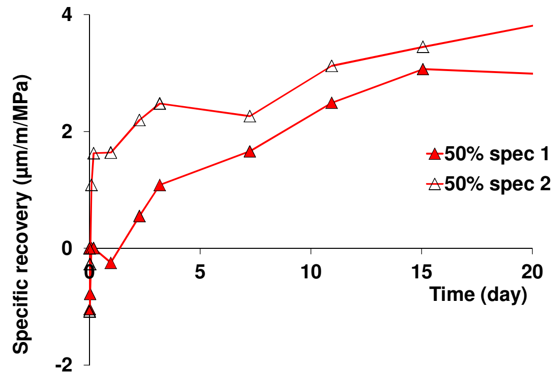


(b)

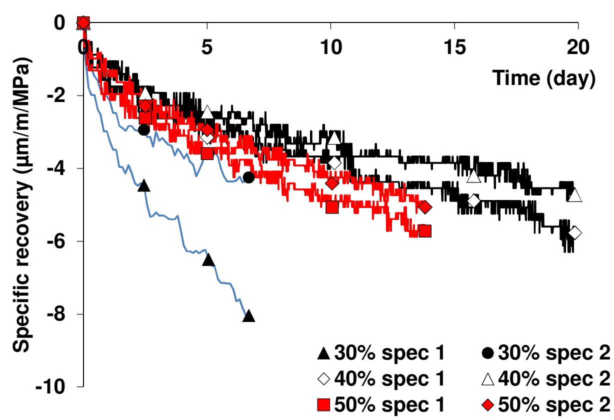


(c)

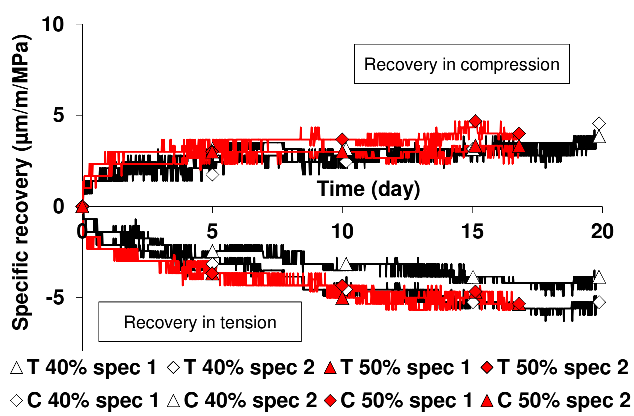
Figure 6: Specific creep in compression (a), in tension (b) and in flexure (c)



(a)



(b)



(c)

Figure 7: Specific recovery in compression (a), in tension (b) and in flexure (c)

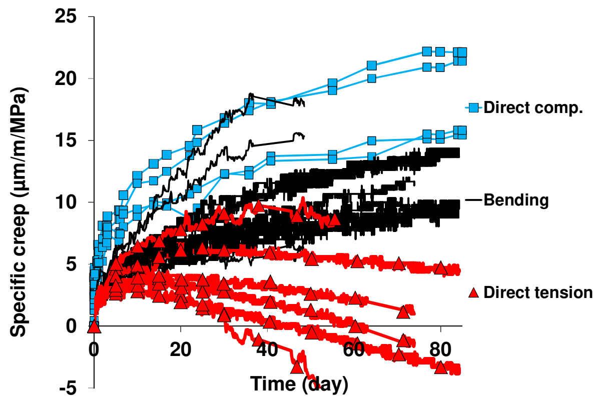


Figure 8: Comparison of direct tensile creep, direct compressive creep and flexural creep in terms of specific basic creep (for the three stress levels)