10th International Conference on Fracture Mechanics of Concrete and Concrete Structures
FraMCoS-X
G. Pijaudier-Cabot, P. Grassl and C. La Borderie (Eds)
https://doi.org/10.21012/FC10.233050

TENSILE STRENGTH OF CONCRETE AT EARLY-AGE: NEW EXPERIMENTAL PROCEDURE AND INFLUENCE OF MIX-DESIGN PARAMETERS

EMMANUEL ROZIERE[*] **, AHMED LOUKILI**[*]

[*] Ecole Centrale de Nantes
Institut de Recherche en Génie civil et Mécanique (GeM) – UMR CNRS 6183
1 rue de la Noe, 44321 Nantes, France
e-mail: emmanuel.roziere@ec-nantes.fr
ahmed.loukili@ec-nantes.fr

Key words: Tensile strength, Tensile strain capacity, Early age, Aggregates

Abstract: Experimental values of early-age tensile strength/strain capacity are relatively scarce in literature due to practical difficulties in performing direct tensile testing during setting and early hardening stages. Existing methods do not allow determining the tensile strain capacity from fresh state to hardening stage. A new experimental procedure has been designed to provide a continuous evolution of tensile strength and tensile strain capacity of concrete from fresh state to the age of 24 hours. The measure of displacements was deduced from digital image correlation. The output data allow determining stress–strain curves and tensile strain capacity. This is defined as the strain when the main crack appears. The parameters of the study were the water-to-cement ratio, the paste volume, and the type of coarse aggregates. The evolution of the tensile strain capacity showed a minimum between final setting time and early hardening stage. This age actually corresponds to a critical period for early-age cracking risk. The elastic modulus actually increased from very early ages whereas tensile strength did not show significant development before final setting. This shift between the developments of both properties implied a minimum for the evolution of tensile strain capacity. The coarse aggregate type had a limited influence on tensile behavior. The water-to-cement ratio and the paste volume had a significant effect, which could be taken into account for early-age cracking control.

1 INTRODUCTION

As concrete is a quasi-brittle material with relatively low tensile strength, cracking is taken into account as an assumption in the design of reinforced concrete structures. Model codes allow determining the reinforcement needed to comply with the requirements on crack widths. In spite of significant improvements of mechanical and physical models, avoiding excessive cracking remains a challenging task. Cracking is likely to occur at early age, even before any external load is applied. The properties involved in thermal cracking and shrinkage-induced cracking vary significantly during the first hours and days. Most of the methods described in standards can be used on hardened concrete only. As a common stress-inducing phenomenon, shrinkage has been widely studied and some experimental procedures allow a continuous monitoring from fresh to hardened state [1]. This is not the case of most of other properties, such as strength, fracture energy, elastic modulus, creep, coefficient of thermal expansion, etc. Their evolution is still not well known at early age and the experimental values remain scarce, although some recent advances [2-4].

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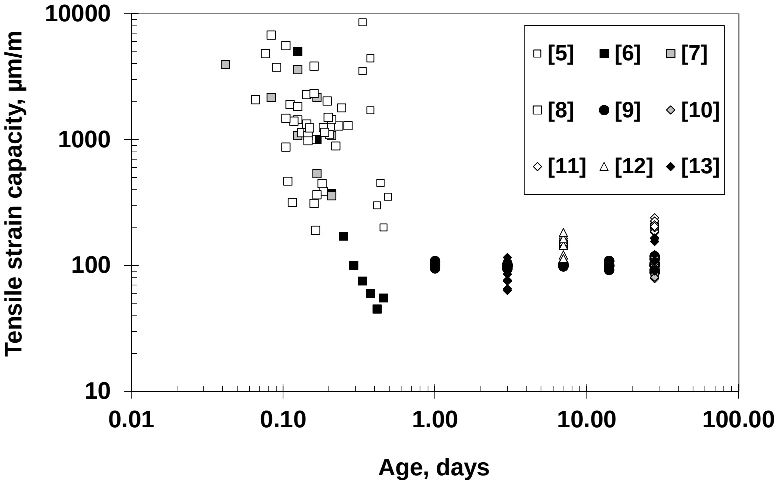

Figure 1: Evolution of tensile strain capacity: experimental data from literature.

This is not due to a lack of interest or relevance. Tensile strength and tensile strain capacity are input data of design methods [13-14]. Hammer et al. [5] have shown that the period that includes the setting time and early hardening is a critical time period for cracking.

The lack of data is most likely due do practical difficulties, especially for direct tensile testing. The methods designed for hardened concrete can be used for relatively early ages (1 day) and rapid hardening materials. These methods cannot be used at earlier ages as fresh concrete cannot carry the loads due to its own weight and hardening concrete specimens cannot to glued to the testing frame due to poor quality of the interface. Horizontal uniaxial tests have thus been developed. However stress concentrations and possible sliding between the concrete sample and the mold made it difficult to define reliable stresses and strains from these tests. These issues become even more critical as studied materials stiffen. A review of existing literature actually showed that: i) data related to very early ages vary over several orders of magnitude, thus their consistency can be questioned; ii) relatively few data can be found about concrete aged from 7 to 24 hours (Figure 1). A comprehensive dataset of tensile strengths/strain capacities of cement-based material from 2 to 24 hours did not exist.

A new direct testing procedure has been recently developed [15] with the objective of providing reliable measurements of the displacements of concrete specimens. In this study the method has been used to investigate the influence of major mix-design parameters – water-to-cement (W/C) ratio, volume of paste (Vp), aggregates type – on the evolution of tensile strength and tensile strain capacity during the first 24 hours.

2 EXPERIMENTAL PROGRAM

2.1 Experimental procedures

Figures 2 and 3 show the different parts of the experimental setup stored in a room at controlled temperature of 20°C. The horizontal steel mold consists in two halves with curved transition to a central prismatic volume of 100x105 mm² cross section. The inner face is covered with PTFE and a polyethylene (PE) sheet containing the concrete sample. The left half is linked to the frame by a spherical pin connection and the right half to a 40 kN electric actuator. The relative displacement of the two halves can be measured using LVDT sensors. These also allow checking that bending remains negligible.

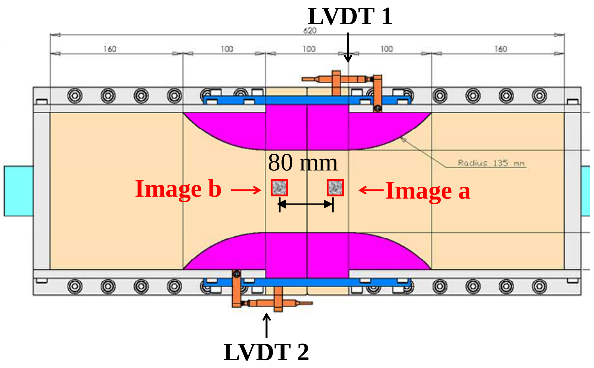

Figure 2: Mould and positions of digital images.

A 12-litre concrete sample is cast into the mold then vibrated using a vibrating needle and covered with a PE sheet to avoid drying. One hour before loading, the PE is removed. White then black painting is sprayed onto the surface of concrete specimen to create a contrast and allow the use of Digital Image Correlation (DIC) technique (Figure 3).

The loading rate was 5 µm per second. The actual loading rate of the concrete specimen was lower due to sliding between the concrete specimen and the mold during loading. LDVT cannot be used to determine the displacements within concrete, hence the use of cameras. Two images of 320x240 pixels are recorded each second.

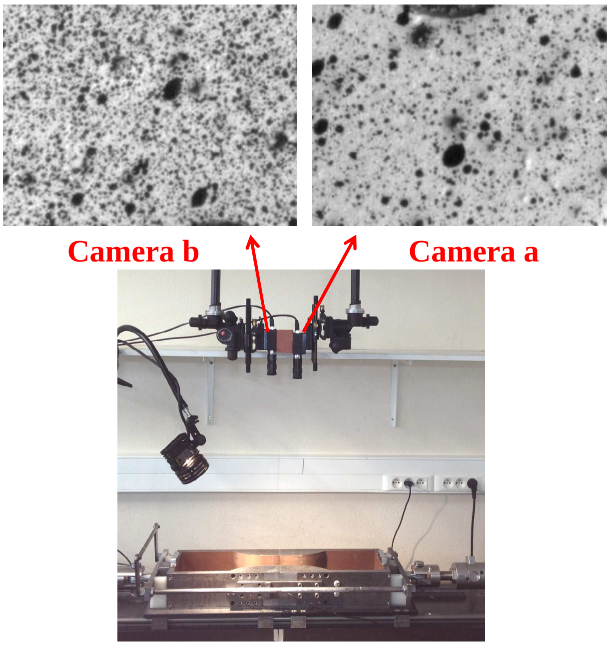

Figure 3: Test rig and cameras.

The software VIC2D® is used to determine the displacements of the two regions in the loading direction. The difference between both values provides the relative displacement, used to assess the longitudinal strain in the concrete specimen. The stress is calculated from the load and the cross section in the central part. The stress-strain curve can be plotted (Figure 4). From very early age the specimens show a brittle behavior and the post-peak stage cannot be described. The tensile strength and the tensile strain capacity are respectively defined as the tensile stress and strain at failure (Figure 4).

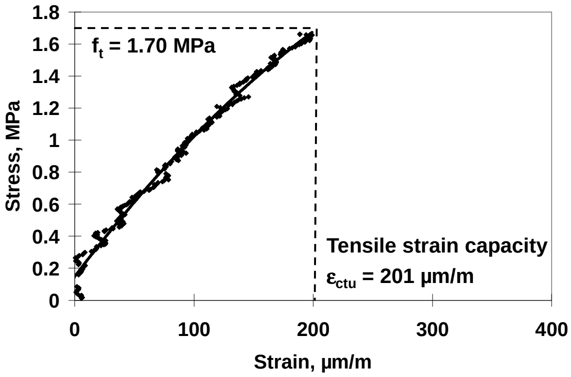

Figure 4: Determination of tensile strain capacity from stress-strain curve.

2.2 Materials and mixtures

The studied concrete mixtures were derived from an initial mixture based on Portland cement and siliceous gravels. The cement CEM I 52.5 had C_3S, C_2S, C_3A, and C_4AF contents of 58.5%, 10.0%, 11.8%, and 7.5% respectively. Its Blaine fineness was 3680 cm^2/g. Crushed limestone sand from Boulonnais, France, and sea sand from Le Pilier, France, were used at equal proportions to obtain well-graded mixed sand. The concrete mixtures are described in Table 1. Siliceous gravels S were quartzite aggregates from Palvadeau, France. They were substituted by the same volume of dense limestone LS1, porous limestone LS2, and lightweight aggregates LW at constant volume of coarse aggregates. The effective water-to-cement ratio (W/C) and the Coarse aggregates to Sand (V_G/V_S) volume ratio were varied keeping the

Table 1: Composition and properties of studied concrete mixtures.

	VP_0	**0.4**	**Vp_0+20**	**Vp_0-20**	**0.6**	**VP_0_1**	**LW**	**LS1**	**LS2**
W/C	0.50	0.40	0.50	0.50	0.60	0.50	0.50	0.50	0.50
Vp (L/m^3)	288	288	346	231	288	288	288	288	288
Coarse aggregates	S	S	S	S	S	S	LW	LS1	LS2
V_G/V_S	1.43	1.43	1.43	1.43	1.43	1.00	1.00	1.43	1.43
Sp/C (%)	0.57	0.63	0	1.39	0	0.51	0.69	0.51	0.37
Slump (mm)	182	104	195	151	150	128	168	160	180

volume of paste (Vp) constant (288 L/m^3), and the volume of paste was varied at constant W/C of 0.50. A superplasticizer (Sp) was added when needed and its content was adjusted to obtain a minimum slump of 100 mm.

3 RESULTS AND DISCUSSIONS

3.1 Influence of aggregates and correlation with setting and hardening stages

The experimental procedure allows the determination of the tensile strength (f_t) and tensile strain capacity (ε_{ctu}) during the first 24 hours. The repeatability has been estimated in a previous study: ±10% of f_t and ±10 µm/m of ε_{ctu}. [15] Figure 5 shows the influence of aggregate type. The four studied concrete had approximately the same properties. Aggregates influence the microstructure and the macroscopic behavior of concrete. This is mainly due to their elastic modulus, strength, and the interfacial transition zone (ITZ) generated at the interface between aggregates and cement paste. For instance limestone aggregates have been reported to result in higher tensile strength, as the properties of ITZ were improved by the formation of carboaluminates [16]. This mainly concerns hardened concrete and it was not observed here at early age. The contrast between the elastic modulus of paste/mortar and coarse aggregates could also have produced different behaviors of studied in concrete in tension, but this effect was not significant in experimental data. Finally the properties of studied concrete were mainly influenced by the evolution of cement paste.

The setting time was determined according to standard EN 196-3 on mortar samples extracted by sieving fresh concrete using a vibrating table. Final setting time was defined as the time when the penetration of Vicat needle becomes lower than 2 mm. Initial and final setting times have been plotted on the graphs of Figure 5. During setting, the tensile strength started increasing slowly and the tensile strain capacity decreased of several orders of magnitude and reached a minimum value at defined final setting. Thus this age correspond to critical stage in terms of mitigating early-age cracking. Previous studies showed that this also corresponds to a critical period for shrinkage-induced cracking [5].

In order to understand this evolution, the f_t/ε_{ctu} ratio has been plotted as a first estimate of Young's modulus. However the obtained values include plastic and creep strains. Creep strain depends on concrete properties and test duration. This significantly increased with testing age from final setting time, which resulted in an apparent decrease of f_t/ε_{ctu} ratio during this period. In order to avoid creep effects, the evolution of Young's modulus has also been deduced from the velocities of ultrasonic waves. The FreshCon method allows determining a so-called «dynamic» elastic modulus E_{dyn} from the density of fresh concrete and the velocities of compressive and shear waves [17].

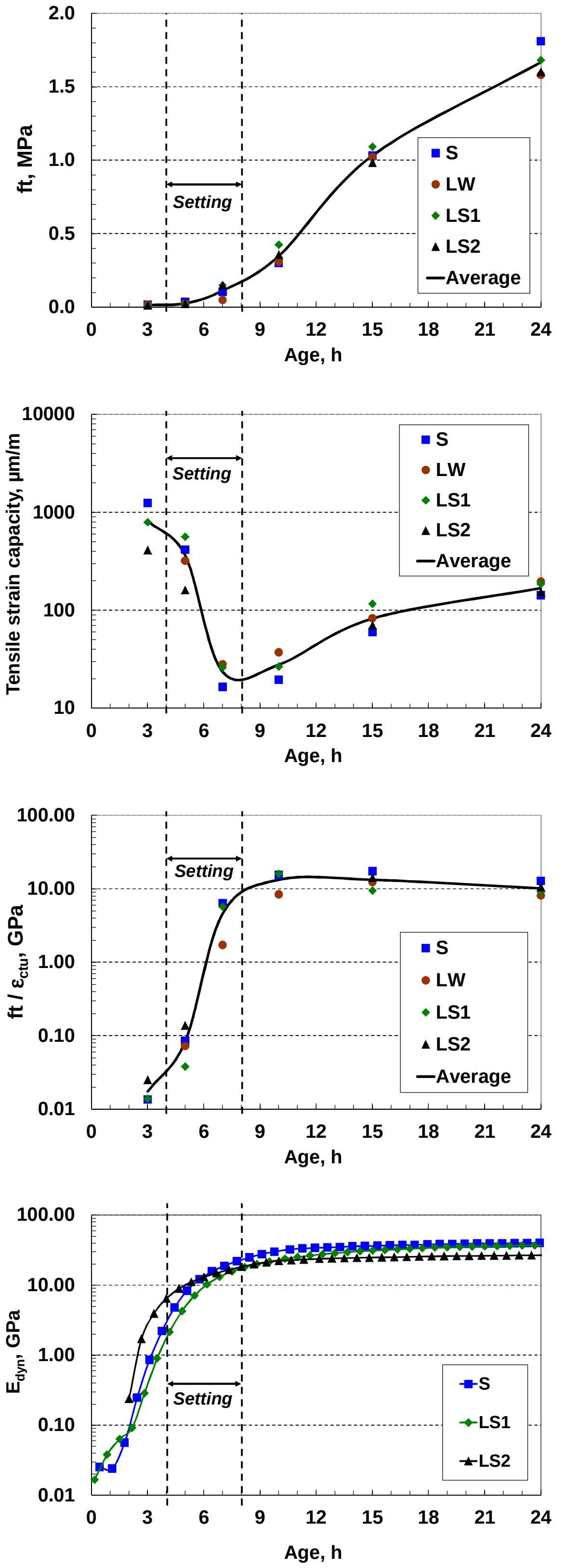

Figure 5: Evolution of mechanical properties during setting and hardening stages: A. Tensile strength (ft), B. Tensile strain capacity (ε_{ctu}), C. ft/ε_{ctu} ratio,D. Young's modulus from ultrasonic monitoring.

The results are plotted in Figure 5.d. The modulus increased by several orders of magnitude until final setting then became evolved much more slowly, which globally confirms the previous graph. The development of f_t/ε_{ctu} ratio was shifted in concrete age when compared with E_{dyn}. This could be due to effects of settlement and compaction that could not be captured by direct tensile testing, and/or creep effects at very early age. The initial setting of cement paste corresponds to a percolation threshold of hydration products [18]. The f_t/ε_{ctu} actually increased from initial setting, whereas E_{dyn} increased earlier [19].

Whatever the actual evolution of Young's modulus, the minimum of tensile strain capacity is due to a shift between the development of the modulus and the tensile strength of concrete. The value of f_t at final setting time was 20% of its value at 24h while it was 80% for E_{dyn} (for S concrete). This had been indirectly pointed in previous studies [20-22] and it can be related to the evolution of the microstructure of cement paste. The proportions of hydration products, such as C-S-H, portlandite, and ettringite, significantly vary during the first hours of cement hydration [23], as well as the morphology of C-S-H [24], thus the properties of hydrating cement paste significantly evolve.

3.2 Influence of water-to-cement ratio and paste volume

The phenomenology described in previous section can be used to understand the influence of the other mix-design parameters investigated in this study. Direct tensile tests were performed after 3, 5, 7, 10, 15 and 24 hours.

At very early age, tensile strength increased with the volume of paste (Vp) then it showed a decreasing evolution from the age of 15 hours (Figure 6). The results at 15 and 24 hours are consistent with the influence of Vp on elastic modulus and compressive strength [25, 26]. Increasing the volume of paste has a restricted effect on strength, but it has also been shown to make concrete more brittle and the width of the fracture process zone increased [27]. These phenomena cannot explain the increasing trend observed between 5 and 10 hours, i.e. during setting. The three concrete mixtures had the same W/C ratio but their Sp/C ratios were respectively 1.39%, 0.57%, and 0%. The used Sp is known to delay the setting process. This effect actually increased with Sp/C ratio.

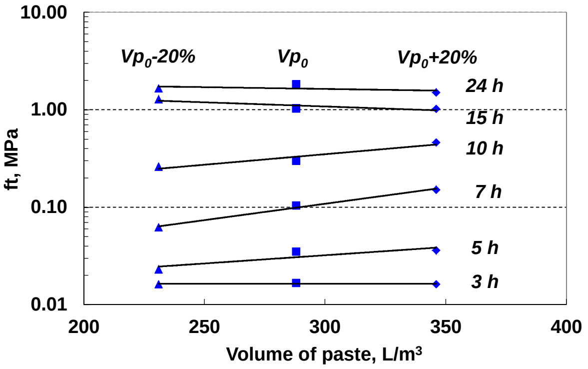

Figure 6: Influence of paste volume on tensile strength.

The influence of W/C ratio on f_t and ε_{ctu} can be observed in Figures 7 and 8 respectively. From the age of 10 hours the tensile strength significantly decreased with W/C ratio, but at 7 hours it increased with W/C and at earlier ages it was almost constant. The evolution of ε_{ctu} can be used to understand that of f_t. The minimum of the curve is actually shifted to higher ages for decreasing W/C ratios. This is apparently conflicting with existing knowledge on setting process. The percolation threshold depends on the W/C ratio. It appears earlier for low W/C ratios [18]. Thus the influence of Sp can be pointed out again. The three concrete mixtures actually had Sp/C ratios of 0.63%, 057%, and 0% respectively. Assuming that the minimum of the curve corresponds to final setting time, this was shifted from 6 h for W/C=0.6 to 8 h for W/C=0.5 and 10 h for W/C=0.4. Thus it seems that the whole setting period is affected by the delaying effect of Sp.

It should be noted that the lowest W/C ratio of 0.4 lead to significantly higher ε_{ctu} at all ages especially at the minimum. This ε_{ctu} minimum actually corresponds to relatively low hydration degree – around 0.35 for W/C=0.5 [15]. Byfors [28] has shown that a given amount of hydration products per gram of cement results in higher compressive strength for low W/C ratios.

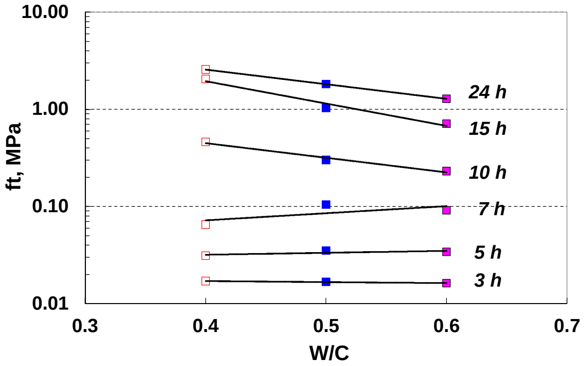

Figure 7: Influence of W/C on tensile strength.

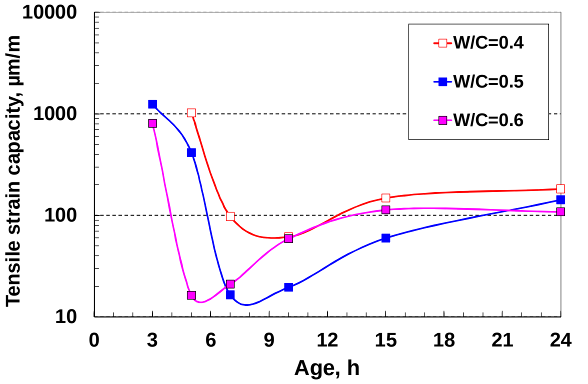

Figure 8: Influence of W/C on tensile strain capacity.

The influence of W/C on the tensile strength at later ages is consistent with the well-known influence on the compressive strength of hardened concrete as predicted by Féret's and Bolomey's equations. Abel and Hover [29] observed the same influence on tensile strength. Lower W/C ration actually result in lower porosity and higher volume of hydration products.

3.3 Discussion

The results presented in sections 3.2 and 3.3 have revealed common phenomena whatever the investigated composition parameter.

The delay in the development of tensile strength and tensile strain capacity of several concretes has been attributed to the retarding effect of superplasticizer. However other parameters varied in the same time. Among these, the W/C ratio is known to affect the setting process. Figure 9 presents the influence of Sp/C on tensile strength at constant W/C ratio of 0.5. The 24-hour tensile strength $f_{t,24h}$ was not significantly affected by the other studied parameters: it ranged from 1.50 MPa for Vp$_0$+20% concrete to 1.89 MPa for Vp$_0$_1 concrete. Thus the $f_t/f_{t,24h}$ ratio is plotted against Sp/C.

At very early ages the strength decreased with Sp/C ratio. This is not a continuous evolution as a threshold appears between 0.5 and 0.7%. This effect was stronger at 7 hours than at 10 hours. This could correspond to the saturation proportion of superplasticizer [30]. Sp molecules are bound to cement particles until saturation is reached. As the studied Sp based on modified polycarboxylate has a steric effect; cement particles covered with Sp repel each other. Above the saturation content the Sp in excess remains in the pore solution and does not affect the microstructure of cement paste. From 15 h all the concretes showed the same behavior, thus the effect of Sp was temporary.

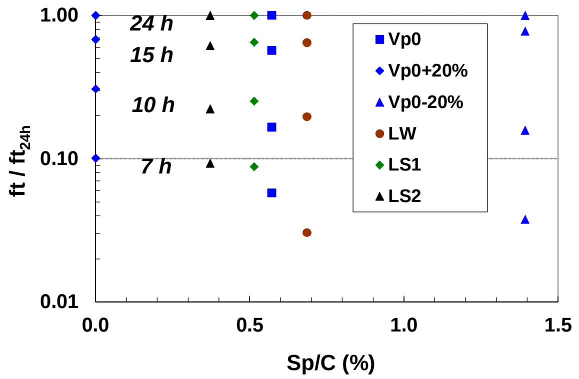

Figure 9: Relative tensile strength and Sp/C ratio.

Whatever concrete mixture, the evolution of ε_{ctu} showed a minimum due to the shift between the developments of tensile strength and elastic modulus. After this minimum corresponding to final setting, the tensile strain capacity increased. The values of ε_{ctu} during this hardening stage have been plotted against f_t in Figure 10. Tasdemir et al. [31] found a better correlation with the Tensile strength/Modulus of elasticity ratio. However they used data from concrete specimens loaded at longer term, with a stronger effect of aggregates properties. Here the effect of aggregates modulus and ITZ was apparently not significant at early age. Moreover this kind of correlation depends on experimental procedure. The tensile strain capacity was found more sensitive to loading rate than tensile strength [15].

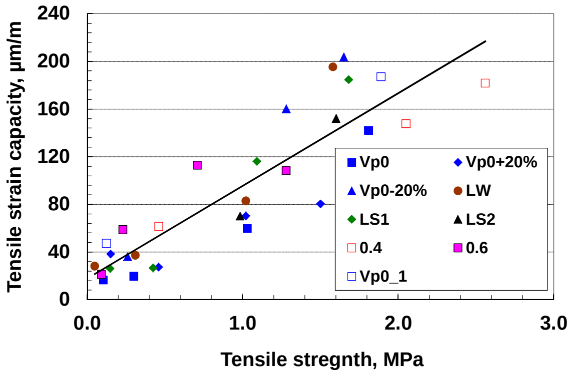

Figure 10: Tensile strain capacity and tensile strength between 7 and 24 hours.

4 CONCLUSIONS

A new experimental procedure has been designed to allow a continuous monitoring of tensile strength and tensile strain capacity from fresh to hardened state. The method combines direct tensile loading on a 12-litre concrete specimen cast in a horizontal steel mold, and digital image correlation to assess the displacements. The testing procedure has been used to investigate the effect of the main composition parameters on early-age properties: water-to-cement (W/C) ratio, volume of paste (Vp), aggregates type. From the results of the experimental study the following conclusions can be drawn.

- The tensile strain capacity decreased of several orders of magnitude until final setting time then increased to reach values commonly found in literature for hardened concretes. This minimum is due to a shift between the development of elastic modulus and tensile strength. This critical period should be taken into account to mitigate the cracking risk at early-age.

- The evolution of tensile strength and strain capacity was mainly driven by the evolution of cement paste. Aggregates properties are known to influence the microstructure and macroscopic behavior of hardened concrete but these effects were not significant at early age.
- The lowest values of W/C and Vp allowed increasing significantly the values of tensile strain capacity, which is interesting to reduce the cracking risk.
- After setting, the tensile strength decreased with the volume of paste and the W/C ratio. Until the end of setting, the development of strength was strongly affected by the retarding effect of the used superplasticizer. The final setting time was actually delayed.
- After final setting, the experimental data show a correlation between tensile strength and tensile strain capacity. This could be of practical interest as the determination of strength is easier and more repeatable.

Besides the development of tensile strength, several other phenomena occur in cement-based materials at early-age, such as shrinkage, heat release, and creep. Any variation in the kinetics and magnitude of the related properties is likely to affect the competition between strength and stress developments, especially at the critical period of setting and early hardening stage.

ACKNOWLEDGEMENTS

The French “Federation Nationale des Travaux Publics” (FNTP) is gratefully acknowledged for their support to the project.

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