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HIGH STRAIN RATE TENSILE BEHAVIOUR OF CONCRETE : SIGNIFICANT PARAMETERS

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Abstract

Recent results are presented concerning direct tensile behaviour of concrete at high loading rates, ranging from 5.10^{-5} to 50 GPa/s. A very linear quasi-brittle constitutive law can be derived even at high strain rates. A relatively low increase in Young's modulus with increasing loading rate is reported (about +0.9 GPa by $\log_{10}$ unit of loading rate). The absolute increase in tensile strength with increasing strain rate has been quantified for samples prevented from moisture gradients. The mean trend is about +0.7 MPa by $\log_{10}$ unit of loading rate. Given mix-design characteristics of the concretes which have been tested, significant parameters have been identified, which help better estimating the observed rate effect. These parameters are the CSH content and the relative packing density of the aggregates. Consequences of this analysis are drawn, aiming to material optimization against shocks and impulses.

1 High strain rate direct tensile tests

It has been demonstrated that the increase in microconcrete strength with increasing strain rate, in the range $10^{-6}s^{-1} \leq \dot{\varepsilon} \leq 1\,s^{-1}$, either in compression, Gary et al. (1991), or in tension, Rossi et al. (1992), can be mainly related to non chemically bonded water inside pores of the cement paste. A possible physical explanation using the so-called Stefan effect has been proposed by Rossi (1991). Tests were then conducted on a more realistic concrete, either in compression, Gary & Klepaczko (1992), or in tension, Rossi et al. (1994). They confirmed the fact that, for loading rates in the range $10^{-5}GPa/s \leq \dot{\sigma} \leq 10^{2}GPa/s$, dry concrete exhibits no rate effects, while concrete prevented from dessiccation does.

Possible parameters which could modify this rate effect for water-saturated concrete are thus the pores size and structure, and the paste content. Therefore, relevant control mix-design parameters can be chosen as the water/cement ratio, the maximum aggregate size and the cement content. Direct tensile tests were performed to point out the influence of these parameters. Raw results have been reported by Rossi et al. (1994) and Boulay et al. (1994). For moderate loading rates, the experiments were conducted using a classical testing machine. High loading rate tests were carried out using a modified Split Hopkinson Bar. For the last experimental series, strains were directly measured on the sample, which allowed properly estimating concrete Young's modulus in tension.

All these data have to be processed according to following objectives: deriving a realistic constitutive law for concrete at high strain rates; quantifying mean rate effects with the smallest possible scattering for various concretes; precisely determining the basic physical phenomenon underlying rate effects (though a full micro-macro calculation is hardly conceivable); and computing the variability of rate effects according to concrete mix-design, thus possibly optimizing this design with the aim of higher material shock strength. This paper will focus on the conclusions which can be drawn from this data processing.

2 Description of the rate effects

2.1 Young's modulus

Complete stress-strain evolutions were measured for direct tensile tests and are detailed in Boulay et al. (1994). For three concretes with a similar paste content and a maximum aggregate size ranging from 2 to 10 mm, it turns out that the mean deformation in tension even at high loading rates is very linearly related to the measured stress. More, strain localization, which is detected when the signals of the three longitudinal gauges at 120° significantly diverge, only appears when the maximum stress is reached. An example of the observed behaviour is given Fig. 1. So, the whole longitudinal behaviour in tension may be characterized as elastic quasi-brittle and quantified only by Young's modulus and tensile strength.

A mean value of the Young's modulus has been determined as a function of the average loading rate during the loading process. In fact, even for the shocks using the Split Hopkinson Bar, the loading rate fluctuations have almost no visible influence on the apparent modulus, which can be verified by superimposing the stress signal and the delayed strain signal multiplied by the constant modulus previously determined (Fig. 2). No artefact due to viscous dissipation has been measured in high rate tests, for the incident and transmitted stress waves are superimposable up to the maximum transmitted stress, i.e. the tensile strength. In sum, a reliable small evolution of the Young's modulus with the strain rate has been identified (Fig. 3), which is consistent with previous limited data (obtained only for $5.10^{-5} GPa/s \leq \dot{\sigma} \leq 5.10^{-3} GPa/s$). A global trend of about +0.9 GPa / $\log_{10}$ unit of strain rate is obtained. Given the relative deviation on the measure, there is no sense in refining the quantification of this often negligible increase.

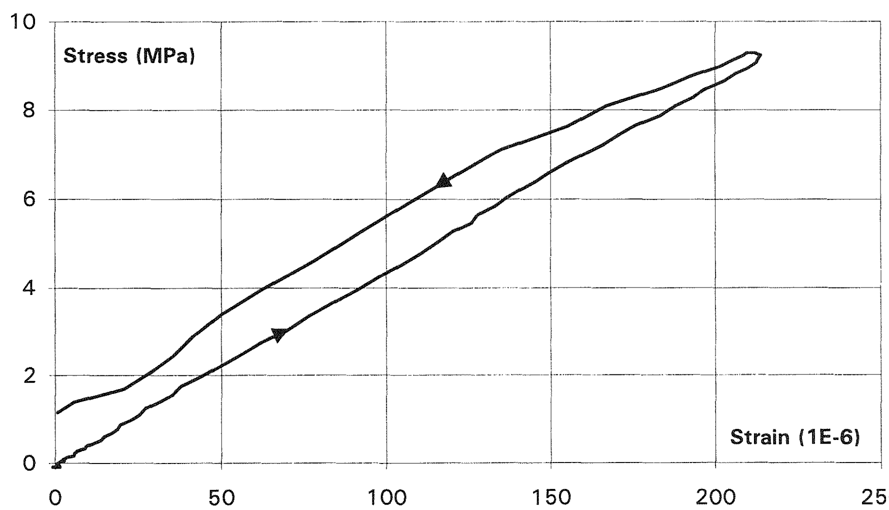

Fig. 1. Stress-strain evolution for mini-concrete tested at 60 GPa/s

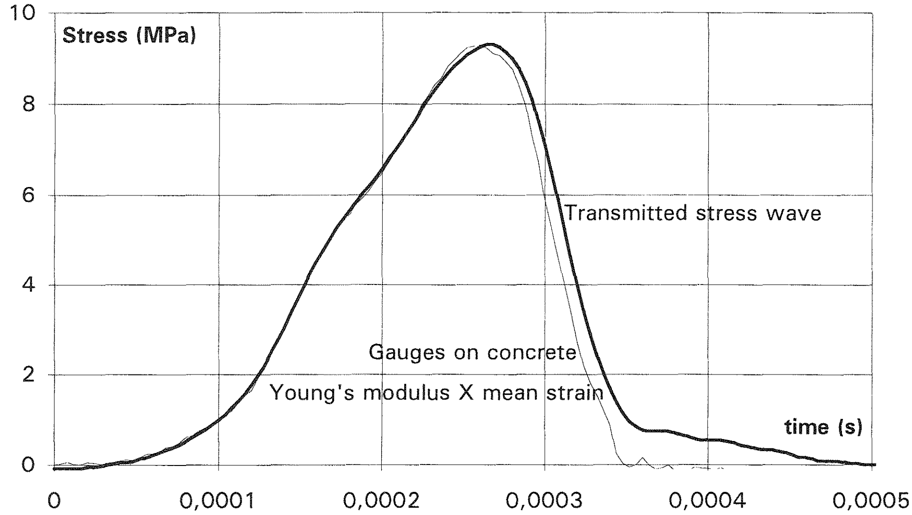

Fig. 2. Constancy of the Young's modulus during a shot. Mini-concrete.

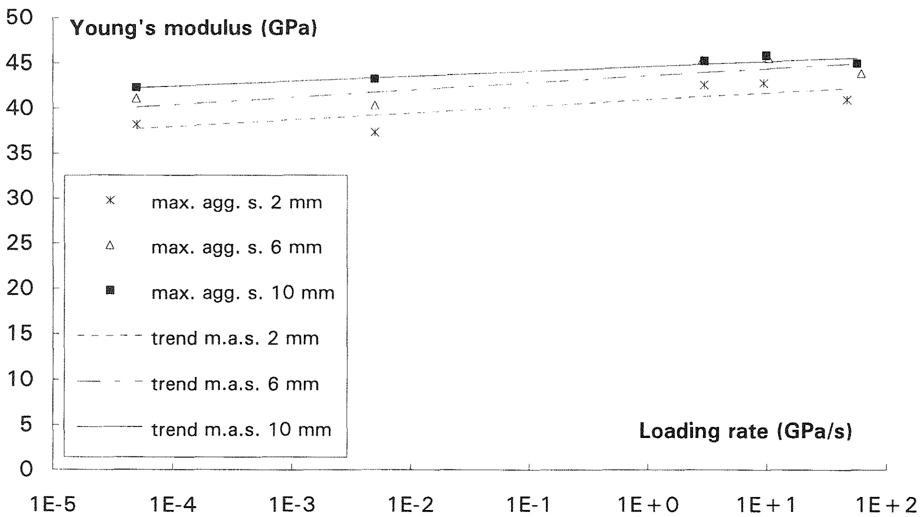

Fig. 3. Young's modulus evolution vs loading rate

2.2 Mean trends on tensile strength

In comparison with the Young's modulus, measuring the tensile strength is an easier task even under high strain rate, especially using the (modified) Split Hopkinson Bar device. Therefore data have been collected for a larger sample of concretes, Toutlemonde (1994). All the specimens have been prevented from dessiccation, in order not to superimpose moisture gradients, and to isolate the rate effects. Concretes from 35 to 120 MPa mean cylinder compressive strength have been tested (16 cm in dia., 32 cm high). The most relevant way to present the results has turned out to be plotting the difference (dynamic minus static strength) versus the (decimal) logarithm of the loading rate. Fig. 4 shows the obtained graph for all tested concretes. Each dot stands as the mean for at least 3 and on average 6 specimens, tested in the same conditions.

A linear average trend of + 0.70 MPa / $\log_{10}$ unit of loading rate may be computed (correlation coefficient 0.95), while the trend for oven-dried reference concrete is about + 0.21 MPa / $\log_{10}$ unit of loading rate, corresponding to about 10% of the initial moisture left inside the material, namely in the cement paste nanopores, Toutlemonde (1994). Thus it is suggested to predict concrete dynamic tensile strength f_t using eq. 1, where the index *0* stands for the reference quasi-static rate, *H* is the moisture content (%) and α the empirical trend obtained for wet concrete, for which $\varphi(H)$ = 1. The tensile reference loading rate is 0.05 MPa/s. The tensile static strength may then be measured, or estimated using a design code formula. Since water in the nanopores is mainly concerned with rate effects, $\varphi(H)$ may be equalled to 1 provided H > 50%, which is often the case. Only possible moisture autostresses are to be accounted for extra. For general use this linear expression seems accurate enough.

$$f_t = f_{t_0} + \alpha\ \varphi(H)\ \log(\dot{\sigma}/\dot{\sigma}_0) \tag{1}$$

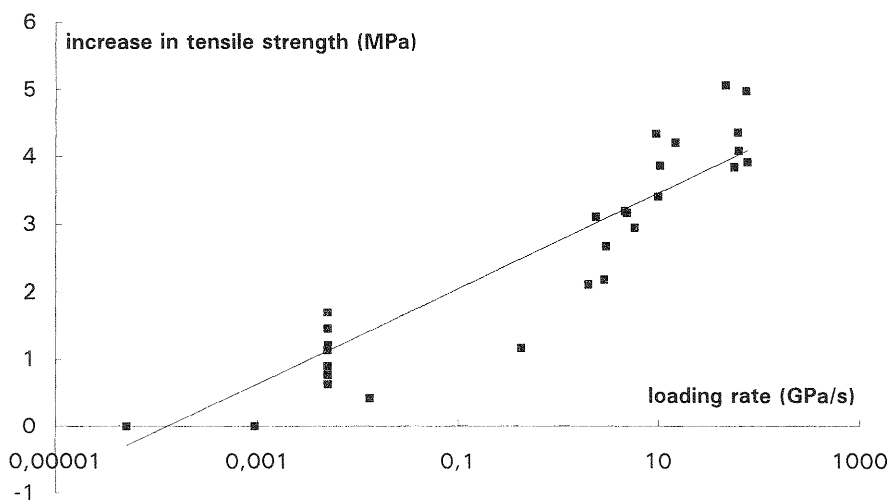

Fig. 4. Increase in tensile strength for various "wet" concretes

3 Significant physical parameters

3.1 Identification of relevant variables

Surprisingly enough, it has been possible to quantify the increase in tensile strength rather precisely for a large range of concretes with the same formula (eq. 1), provided care has been taken to deduce artefacts due to moisture gradients. It is thus suggested that the same phenomenon with the same amplitude basically underlies observed rate effects. As far as non chemically bonded water is concerned, the porous texture of the material is involved. But it has turned out that the water-cement ratio has almost no direct influence on the increase in strength. Thus, free water in the capillary pores is not responsible of the rate effects, but water inside the remaining pores, namely the nanopores of the cement paste (in fact, in a first approach, water contained in the pores of the aggregates is neglected). Therefore, the α coefficient which has been determined previously on average has to be related to physical parameters which more precisely describe the fine porosity of the considered concrete.

In a first approach, the quantity of fine pores (possibly active in rate effects) can be directly estimated for most of concretes by the quantity of hydrated calcium silicates (CSH), Baroghel-Bouny (1994). Knowing the cement content and composition, the quantities of pozzolanic additions, the water-cement ratio which helps determining the present and final degrees of hydration, Waller (1993), one can evaluate the massic content in CSH. For the materials considered in Toutlemonde (1994), it ranges from 237 to 364 kg/m^3. This variable (M_{CSH}) will be used to evaluate more precisely the increase in tensile strength, which ranges for the same considered materials from 0.36 to 0.79 MPa / $\log_{10}$ unit of loading rate.

It has also been demonstrated, de Larrard & Le Roy (1992), that homogenization techniques applied to cement and aggregates in order to compute concrete properties, have to account for the specific geometrical structure of the cement paste, which fills the aggregate packing. Given the granular range and proportions of the aggregates, a maximum packing density g^* can be computed, Sedran & de Larrard (1994). The ratio of the actual aggregate proportion g to the ideal maximum one g^* gives a quantification of the "excessive" paste in a mechanical sense. The closer to 1 the ratio g/g^*, the compacter the aggregate skeleton, thus the smaller the critical paste zone where failure can take place. For the concretes considered in Toutlemonde (1994), this relative packing density g/g^* ranges from 0.811 to 0.926 for a paste content ranging from 0.30 to 0.38.

3.2 Discussion

Both M_{CSH} and g/g^* parameters seem appropriate to quantify the variability in the linear trend of tensile strength vs logarithm of loading rate. Thus a double linear regression has been carried out on data collected in Toutlemonde (1994), which reads:

$$\alpha = \left[\underset{\text{MPa}}{\underset{\uparrow}{\Delta f_t}} \Big/ \Delta(Log \underset{\text{GPa/s}}{\underset{\uparrow}{\dot{\sigma}}}) \right] = 6.57\ 10^{-4}.\ \underset{\text{kg/m}^3}{\underset{\uparrow}{M_{CSH}}} + 3.59\ g/g^* - 2.79 \tag{2}$$

Experimental and fitted α values are reported in Table 1, and the improved prediction is illustrated Fig. 5. More precise mathematical expressions could have been adopted, however this formula has been chosen for the sake of simplicity. It helps keeping in mind that a too high cement content is not the unambiguous right answer when high dynamic strength is searched. Furthermore, the physical significancy of the positive correlation between α and M_{CSH} or g/g^* appears clearly.

This correlation may be explained simply. First, for higher g/g^*, the critical paste zone where failure is initiated, which is statistically along the path of bigger aggregates, is smaller. Thus the occurrence of a defect, which is less rate sensitive, is reduced, and the crack initiation is delayed. More, a denser aggregates packing is more efficient as crack arrestor. Concerning the effect of M_{CSH}, it seems obvious that a higher nanopores content in the cement matrix is directly related to a higher strength at high loading rates, either for crack initiation in a critical paste zone, or for crack propagation inside the cement matrix.

Table 1. Rate-induced increase in tensile strength vs mix-design parameters (details in Toutlemonde (1994))

w/c	c, kg/m^3	m.a.s., mm	fc, MPa	M_{CSH}, kg/m^3	g/g^*	α exp, MPa/log u.	α eq. 2, MPa/log u.
0.5	365	10	53.6	290	0.911	0.6	0.67
0.5	380	6	52.4	302	0.926	0.67	0.74
0.5	400	2	51.5	318	0.923	0.79	0.74
0.7	265	10	35.3	237	0.911	0.69	0.64
0.3	450	10	122.4	349	0.911	0.75	0.71
0.5	459	10	42.0	364	0.811	0.36	0.36

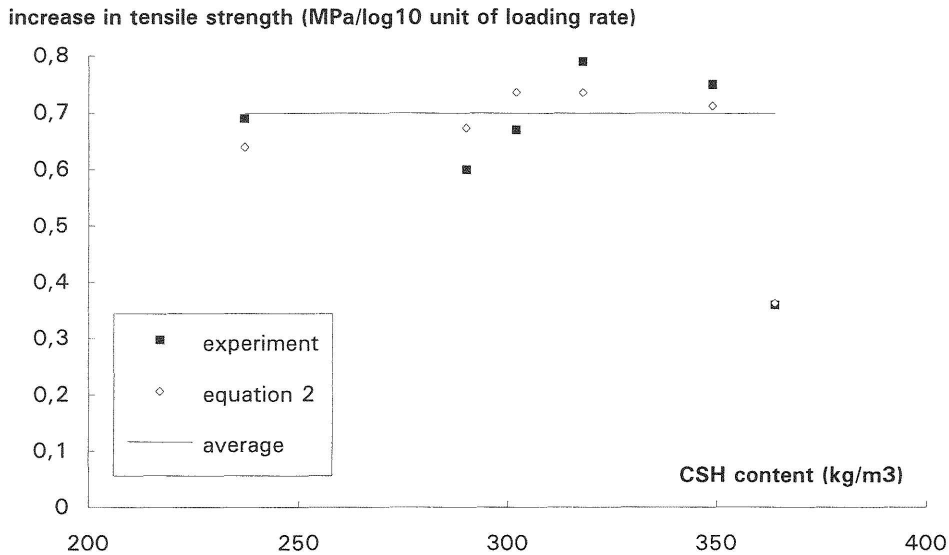

Fig. 5. Experimental values of α and prediction using eq. 2.

The accuracy of eq. 2 has been tested. Due to a certain non-linearity in tensile strength increases, it results in a bias of 0.12 MPa, and a standard deviation of 0.43 MPa, obtained for data reported by Toutlemonde (1994). These statistical data have to be compared with the evaluation obtained using the mean trend of + 0.7 MPa/log unit, which results in a bias of 0.19 MPa and a standard deviation of 0.50 MPa. Concerning data from Reinhardt (1982), eq. 2 always overestimates the results, by 60% on average. However, samples were not prevented from dessiccation, and most of them were cored along the casting direction, which reduces rate effects, due to the orientation of defects under large aggregates. Uncertainties in computing M_{CSH} and g^* have also to be mentioned. Nevertheless, for some concretes tested, the prediction is quite realistic. Therefore, it seems essential to collect more experimental reliable data to obtain a better validation of this formula. One has also to remind that it gives an upper limit of the rate effect, because of following factors: moisture gradients, coring direction, bending artefacts during the test, etc.

Even though eq. 1 and 2 lack for a more complete validation, they can help drawing some conclusions on the optimization of concrete mix-design in case of high rate dynamic loadings. A major result is that, for common mix-proportions, high strength concrete and regular one exhibit the same absolute increase in tensile strength when the same loading rate is considered. This result is consistent with a relative increase (f_t/f_{t_0}) less important for high strength concrete, as generally reported. Eq. 2 allows understanding that the similar absolute increase is related to a similar relative packing density (*g/g** generally equals 0.9 to 0.92 for properly designed concretes), and to a similar CSH content. This latter fact results from a generally higher cement content, but a reduced degree of hydration - even if accounting for pozzolanic effects.

Considering the search for a high tensile strength in case of dynamic loadings, it finally turns out that a high static strength has first to be reached, which is in favour of high performances concretes. However, the same absolute gain in strength is to be expected, which does not result in the same material "safety index" (ratio (f_t/f_{t_0})) when high rate loadings are considered as an accidental exception related to static design loadings.

4 Conclusion

Recent results from direct tensile tests on various concretes are detailed and analysed. An elastic quasi-brittle behaviour is confirmed. A small increase in Young's modulus (+0.9 GPa by $\log_{10}$ unit of loading rate) is reported, which might generally be neglected. The absolute increase in tensile strength can be described for all tested wet concretes by a general trend of +0.7 MPa by $\log_{10}$ unit of loading rate. Variability of this trend can be accounted for using 2 significant material parameters: the relative packing density and the CSH content. A fitted expression of the dynamic strength is thus proposed (eq. 1 & 2). The interest of high performances concrete for high static and dynamic strengths is pointed out.

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