Pre-normative results related to very high strength concrete

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Summary

A summary of pre-normative research results related to very high strength concrete (VHPC: C80/95 to C120/150) is presented, regarding tensile strength, concrete contribution to shear strength, and delayed strains. Experiments carried out have helped constituting an important data base for improving code provisions (and their possible extension to the C80/95 to C210/150 range) in the sense of their scientific basis and control of uncertainties. The validity of AFREM model for creep can be extended, provided the maturity at age of loading is high enough. Due to wider mix-design possibilities for this range of VHPC, some provisions concerning tensile strength and shear verifications should not be extrapolated without care.

Keywords: code calibration ; delayed strains ; design ; design code provisions ; HPC ; shear ; tensile strength ; VHPC.

1. Introduction: context

A national joint R&D program called "BHP 2000" was carried on in France from 1995 to 2002, in order to favour a disseminated use of innovative and high performance materials in the field of concrete construction. Within this program, the task group "BTHP" (stands for “bétons à très hautes performances”, i.e. VHPC) was established to meet pre-normative research needs identified by the AFREM (the French branch of RILEM, presently replaced by AFGC) Task Committee "Knowledge and use of HPC" led by de Larrard [1]. Namely, it was expected to verify, by specific experiments and analyses, that the critical design code provisions could be safely extrapolated to very high strength concrete (in the range of C80/95 to C120/150). This task could not be carried out with respect to every aspect of structural concrete, therefore only some major critical fields for VHPC: tensile strength, its measurement and its evolution with time, creep and shrinkage, and concrete contribution to shear strength. These questions were selected because of their critical role in the design and optimisation of VHPC projects, especially bridges [2].

Experiments carried out were aimed to constitute an important original database for improvement of the design codes [3]. Six specific mix-designs were established [4], ranging from 50 to 120 MPa mean compressive cylinder strength. Particular care was taken in specimen casting, and a complete material characterization was carried out, so that tests on structural elements could be fully interpreted and compared with each other [5].

2. Tensile strength: determination procedure and time-evolution

The problem of VHPC tensile strength is all the more important that scattering in the tensile / compressive strength ratio is larger due to wider possibilities of mix-design. Present BAEL 99 [6] relationship between actual tensile and compressive strengths is calibrated at 28 days, when the tensile strength is evaluated on the basis of splitting tests on standard cylinders, 32 cm long, 16 cm in diameter, stored in water. In fact, whatever the disadvantages of this indirect determination, it is rather precise and easy to perform. This determination is thus used as a reference and other testing procedures were compared to it (fig. 1).

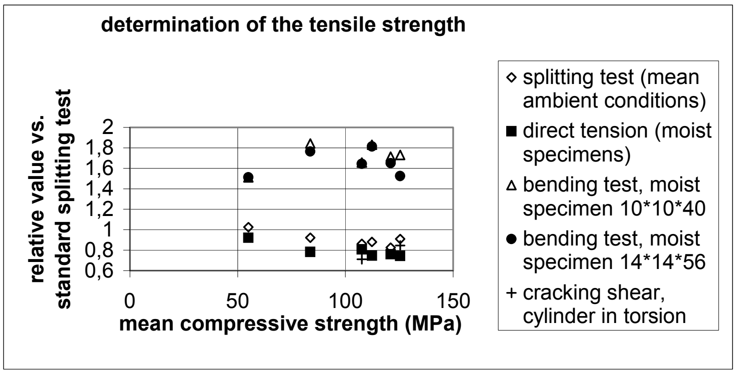


Fig. 1 Different determinations of the tensile strength.

Splitting tests performed on informative specimens, i.e. standard cylinders stored in ambient laboratory conditions, as companion samples for experiments on structural elements, exhibit a significant influence of moisture conditions on the tensile strength. This effect increases with the compressive strength. Another significant effect of the compressive strength is the decreasing ratio of the direct tensile strength (even on moist specimens) versus the result of the standard splitting test, which is as low as about 75 % for 120 MPa concrete.

The relevance of this result is confirmed by the results of tests performed on cylinders in torsion. The onset of first cracks can be interpreted as a limit in shear, and the value of this limit is almost equal to the tensile strength in direct tension. So the conventional determination of the tensile strength may overestimate the real tensile properties or cracking limit of concrete in the structure, even for elements prevented from desiccation. Keeping this code estimation of the tensile strength, it is thus advisable to include a 1/0.75 = 1.33 safety margin in design projects using HPC and especially VHPC, concerning the admissible tensile stresses especially at SLS, if other relevant data are not available. This margin is approximately accounted for if the EC2 [7] formula is used, since *ftk* is estimated as a logarithmic function of *fck* in this range.

Results of standard bending tests are also reported on fig. 1. It turns out that the indirect estimations of the tensile strength (modulus of rupture) tend to increase for HPC. The scattering of bending tests seems important. Hence, since the ratio of the bending / splitting test results varies from about 1.5 for regular concrete to 1.7 to 1.8 for HPC, the use of bending tests as reference determination of concrete tensile strength seems not suitable for HPC. It could lead to the risk of overestimating the "true" tensile strength of the material in some circumstances (restrained shrinkage, shear in slightly reinforced zones) where favourable bending effects shall not be taken into account.

The increasing use of pozzolanic additions in VHPC may lead to unexpected strength evolutions. Thus, the real safety of ageing structures might vary with time. More precisely, it was questioned whether, on the experience of presently built HPC structures, tensile strength remained stable or in progression, similarly to regular concrete, and with a similar evolution as compressive strength. This question was particularly addressed due to some data in the literature, indicating tensile strength losses for HPC kept in laboratory conditions for a tenth of years. Practical related consequences concern material parameters used for the reassessment of ageing structures, and validity of design code provisions which precise the evolution with time of mechanical properties. Check of EC2 ageing factor $[\beta_{cc}(t)]^{\alpha}$ for the tensile strength was thus carried out using numerous data collected from laboratory samples, old HPC bridges and industrial facilities (Fig. 2).

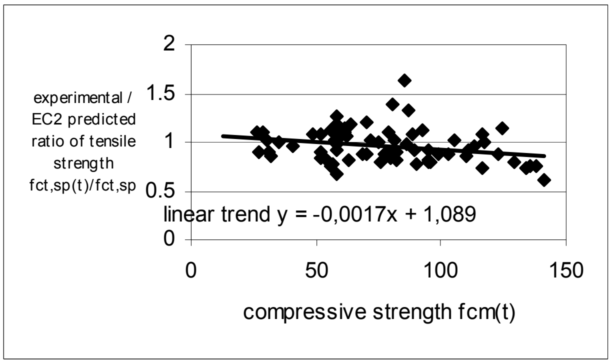


Fig. 2 Check of calibration of $[\beta cc(t)]^{\alpha}$ for $t \geq 90$ days (107 values). Bad trend for VHPC

The negative trend turns out significant (especially beyond C80/95). Further on, the quality of code prediction of the tensile strength was questioned, both at 28 days where it is mainly used for determination of minimum reinforcement, and at long term where it should be used for serviceability verifications. Predicted characteristic values are plotted versus experimental determination using splitting tensile test (Fig. 3). The BAEL 99 provisions turn out well calibrated for predicting splitting tensile strength at 28 days.

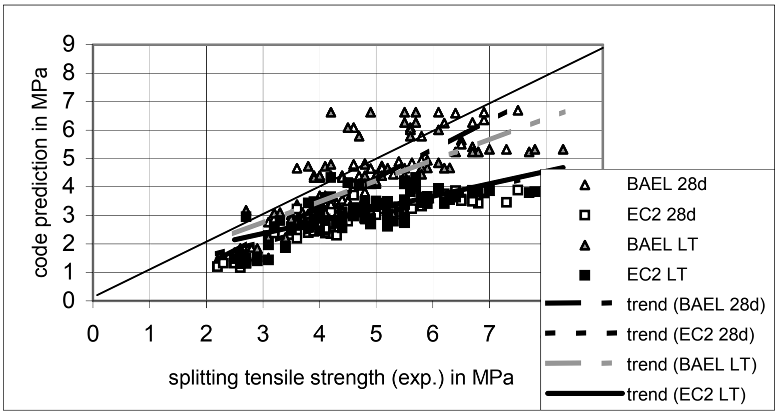


Fig. 3 BAEL & EC2 predictions at 28 days and at long term

As a 2/3-power function of the compressive strength for VHPC, it leads to a trend close to y=x, and only a few values are overestimated, which is consistent with the notion of characteristic value. But, due to the tensile strength degradation with time, some values of long-term tensile strength, especially beyond C80/95, are clearly overestimated. EC2 leads to much smaller short and long-term predictions, with significant underestimations beyond C80/95 ($f_{ctk\,0,05}$ is hardly predicted higher than 4 MPa).

For practical use, one should be aware of the safe way to use code provisions. Within the present French context, at the design stage, the BAEL 99 helps estimating a realistic value of the tensile strength which is representative of the actual tensile strength of "young" concrete having been correctly cast and cured. It is safely used for determining minimum reinforcement, ensuring crack control, etc. But for long term (serviceability) verifications, either the EC2 estimation, or a reduced value should be used. This last value should consist [8] in the product of f_{t28} predicted by the BAEL formula, by the term (1 - 0.0025 f_{c28}), with f_{c28} equal to the characteristic compressive strength obtained for concrete (f_{ck} according to EC2). When the concrete mix-design is undertaken, it is recommended to verify that the tensile strength measured at 28 days in a standard splitting test exceeds the BAEL 99 prediction, which is a condition for safely applying other design formulae, particularly those concerning shear verifications. Namely, typical scattering around the code prediction for this property is about ± 30 %. Alternatively, in the future EC2 context, the significant underestimation of short-term tensile strength of concrete and especially VHPC should be accounted for in the rules related to crack control, where it might not be on the safe side. Whatever further refinements in anticipating the tensile strength of concrete and its evolution, safe design with HPC clearly has to apply mainly the high compressive strength of such types of concrete, and to avoid a high tensile stress level compared to the admissible values. This requirement leads to probable evolutions of typical and classical structural shapes.

3. Delayed strains

Early loading, which is an important economical advantage of HPC and VHPC, implies delayed strains or stress relaxation within concrete, at a rather high level. Yet, the amplitude of delayed strains of HPC is considered as significantly lower than for conventional concrete, except for autogeneous shrinkage. Most of the results supporting this comparison, however, are based on tests on concrete loaded at *j* days, having a maturity (quantified with the strength ratio as *fc(j) / fc(28)*) higher than 0.6, and strengths lower than 110 MPa. Experiments were thus conducted on VHPC in the range 110 to 130 MPa. Creep and shrinkage tests were carried out, for early creep tests the specimens were loaded at an age of 26 to 43 hours. At these ages, *fc(j)* range from 28 to 65 MPa, but for two mixes *fc(j) / fc(28)* was only 0.26. Creep tests were also conducted with load applied at 7 and 28 days, which significantly extends the domain of validation of present code formulae.

Total shrinkage of these mixes in a 50 % R.H. laboratory is lower than 350. 10^{-6} after 200 days, about one third is due to desiccation, the amplitude of the part of shrinkage due to desiccation hardly depends on the age at which desiccation has begun for the samples. Important measurement difficulties still have been encountered concerning the proper determination of autogeneous shrinkage, due to the important proportion of very early strains (just after setting). The magnitude of the asymptotic value of the delayed strains is relatively well predicted by the French design code [9] extrapolated to such high strength values.

Computed and experimental specific creep amplitudes of this experimental program are presented on Table 1 (values after 200 days). Creep turns out to be underestimated when *fc(j) / fc(28)* is low, especially lower than about 0.6. At this low maturity, the evolution of concrete strength is very important (about 3 MPa / h). Even for VHPC, the part of creep due to desiccation is no more negligible. Consequently, if HPC has to be loaded at this low maturity, which is probably not recommended, present design code formulae concerning creep are not valid and a specific experimental quantification has to be undertaken, due to the risk of large underestimation of viscous strain at early age. On the contrary, it can be seen that when concrete is loaded at a sufficiently high maturity, BPEL 99 formulae [9] give rather satisfactory predictions, even for concrete strengths largely in excess of the range of validity of the present design code. Moreover, extrapolating EC 2 formulae [7] which were calibrated without accounting for the possible addition of silica fume, leads to an important overestimation of delayed strains for VHPC. Thus, at least for this range of concrete and its application in bridges, alternative formulae based on AFREM model have been added to the more recent drafts of EN 1992 part 2, also précising the validity of the provisions [10].

Table 1 Creep tests on 100 to 120 MPa concrete, loaded at different ages. Amplitude of delayed strains after 200 days on 1 m long, 16 cm in diameter cylinders, stored at 20 °C, 50 % R. H.

Creep	delayed strains in 10-6 / MPa after 200 days							
fc28 (MPa)	**100**			**120**			**120**	
age at loading	31 h	28 d	26 h	7 d	28 d	43 h	7 d	28 d
fcj (strength at j days) / fc28	***0,26***	**1**	***0,26***	**0,76**	**1**	***0,54***	**0,82**	**1**
experimental instantaneous strain	39	18	32	21	19	22	18	17
BPEL 99 instantaneous strain	32	18	29	21	17	22	18	17
experimental basic creep	**32**	**11**	**39**	**10**	**11**	**15**	**9**	**10**
BPEL 99 basic creep	21	11	18	10	10	14	9	10
experimental desiccation creep	**29**	**0**	**5**	**4**	**0**	**7**	**5**	**1**
BPEL 99 desiccation creep	4	3	3	1	1	2	1	1
experimental total creep	***61***	**11**	***44***	**14**	**11**	***22***	**14**	**11**
BPEL 99 total creep	***25***	**14**	***21***	**11**	**11**	***16***	**10**	**11**

4. Design provisions related to shear stresses

Accounting of HPC shear strength in design formulae was considered as poorly documented, for a possible extension to the 80 to 120 MPa strength range. Co-ordinated experiments were thus carried out on structural elements using the same material mixes [5], in order to validate the fc, fc1/2 or fc2/3 dependency versus the compressive strength fc, used in codes [6, 7] for varied detailing cases: lightly shear reinforced joists and girders, joints, short corbels and zones submitted to concentrated loads. The correct determination of minimum reinforcement in these zones was investigated.

For joints, the interest of exposed-aggregate finishing of the first layer has been demonstrated, so that 70 to 90 % of the monolithic shear strength is recovered. With this type of joint finishing, the formulae of both BAEL 99 and EC2 are safe, and the safety margin increases with the concrete strength. On the contrary, the regulatory ultimate shear evaluation is overestimated for HPC in case of formed or untreated surface, which results in a cold joint due to fluidity of fresh HPC.

Experimental results obtained on C80/95 and C120/150 short corbels have been analysed within a large state-of-the art review [11] and confirm design formulae proposed by Fouré [1]. The strength dependency of the strut maximum compression is correctly accounted for using a 2/3 power-law, while the shear estimation which leads to determination of the distributed reinforcement is correctly accounted for using a square-root dependency of the compressive strength.

Within the frame of French design code shear verifications, the dependency of concrete contribution to shear strength has been validated as correctly accounted for by a $fc^{1/2}$ formula, up to C120/150. An $fc^{1/3}$ dependency is postulated by EC2 for structures without shear reinforcement, which turns out excessively safer for 30 cm-high beams. For these joists the determination of minimum reinforcement has been proven sufficient up to this strength level.

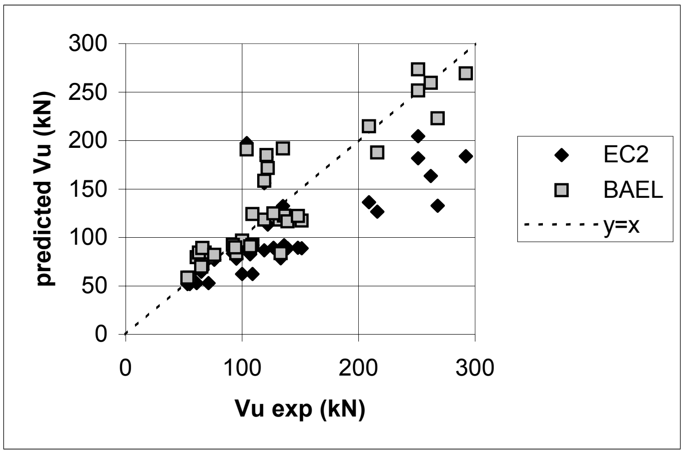


Fig. 4 Shear strength: quality of code prediction

However for deeper beams, size effects seem to become important and insufficiently accounted for in present French design formulae, especially for VHPC where the ratio of tensile vs. compressive strength decreases (fig. 4). The formulae proposed by EC2, which do not assume an additive contribution of shear taken by the stirrups and shear taken by the concrete section, appear as significantly safer, even if worse correlated to experimental data, since they ensure an average "model safety factor" of 1.25 (fig. 5). It has yet to be noticed that an important experimental scatter was observed for this case of loading.

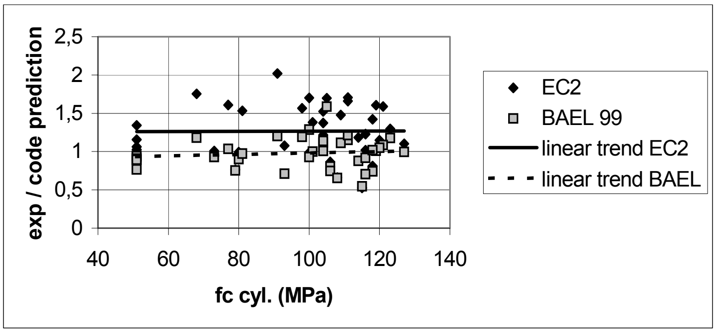
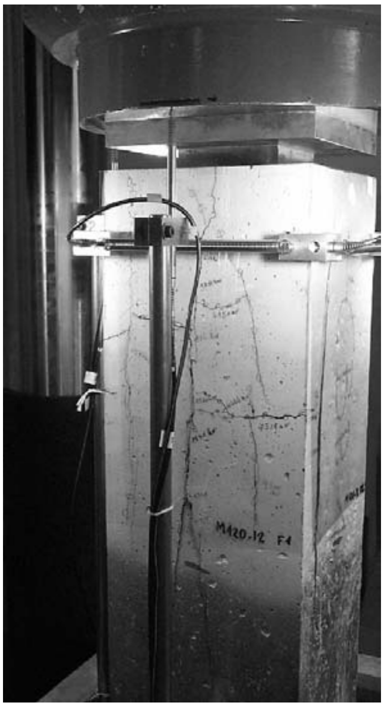


Fig. 5 Shear strength: code prediction of dependency vs. fc

Artefacts (cover scabbing at the bottom of the strut) have been observed which tend to underestimate the capacity of tested beams. Due to the aggregates used in some of the concrete mixes, similar tensile strengths have been obtained for concrete ranging from C80/95 to C210/150, leading to stagnation of derived shear properties. For all these reasons, supplementary experiments and analyses should be carried out to validate VHPC shear design methods and formulae.



Finally, the extension of design methods for end or anchoring zones, submitted to concentrated loads, was studied in details with thoroughly instrumented prisms (Fig. 6). The ultimate load for design corresponds to the onset of vertical splitting cracks around the bursting zone, with possible unstable cracking. It turns out that this ultimate load, presently limited by a geometric factor multiplied by the compressive strength, should rather be expressed as depending on the tensile strength, or on the compressive strength at the 2/3 power [12]. For strengths higher than 100 MPa, the safety margin on this load leading to possibly unstable cracking with cover scabbing significantly decreases, if present BAEL 99 formulae are extrapolated. However, since the transverse reinforcement is directly related to this estimation of the ultimate load, present provisions lead to an increased ductility. In sum, even if the global safety is not immediately concerned, future VHPC code provisions should account for a stress limitation, in these zones of localised compressions, related to the tensile strength, or to the compressive strength with a 1/2 to 2/3 power-law. Moreover, the evaluation of required transverse re-bars should be consistent with this limitation. Yet, this is presently not the case either in the BAEL 99 [6], or in EC2 [7], and detailed provisions had thus to be added in EC 2 part 2 (and are effectively added in the present draft [10]).

Fig. 6 Test of prisms submitted to localised compression. Measured vertical and transverse strains.

5. Conclusions

Experiments carried out helped constituting an important original database for improvement of the design codes. Analysis of the results leads to an important background for checking the safety and the scientific base of code provisions, and for controlling uncertainty, particularly in the range C80/95 to C120/150. As a complement to studies aiming to apply VHPC in bridge projects, the data collected have put in evidence the limits of some present provisions. Actually these provisions may be either too safe due to ignorance or to scattering of results, or non-conservative due to possible discrepancies in the average relationships between material design properties, made possible by the wider possibilities of mix-proportioning (as compared to regular-strength concrete). These studies have also risen some new questions, e.g. regarding tensile strength time evolution, which would require further research efforts. They shall contribute to a better future accounting of VHPC above 80 MPa. The work, already in progress, of elaborating EN 1992 and converting it in national standard, shall take benefit of these data, and integrate them in the available scientific background. Finally, questions of structural safety, delayed deformations, or time stability of material properties, cannot be dissociated from a global approach for the durability of structures. While specific deeper investigations have to be pursued as far as necessary, the methodology for an integrated rationally-based compromise of all requirements having an incidence on structural durability still has to be developed.

6. References

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