Behavior of Concrete at High Rate of Loading

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INTRODUCTION

To accomplish a rational design of concrete structures subjected to impact loading, it is necessary to determine the constitutive properties of the concrete material within a wide range of loading rates. This paper presents a study of the behavior of hydraulic binder and polymer binder concrete specimens under uniaxial compression.

A bibliographical search [1] on the subject makes it clear that the mechanical properties of concrete are quite susceptible to the rate of applied loading. For the particular case of hydraulic concrete, the results of the different investigations show wide scattering. Some of the authors have found out that for a strain rate equal to 0.01/s the compressive strength of concrete is similar to that obtained under quasi-static testing conditions, whereas other researchers have determined values of the strength 20 to 40 percent higher at such rate. On the other hand, research work carried out for polymer concrete is not abundant and the limited results only show that the behavior of polymer concrete differs appreciably from that of hydraulic concrete. The most relevant characteristic refers to the high energy absorption capacity [1, 2, 3].

EXPERIMENTAL WORK

Experimental procedure

A compressed-air gun was developed [1] to have a wide range of load rates available and to eliminate the rebound effects of a projectile. The impact-loading machine is a steel structure with the following features: a compressing tank of 0.324 m^3 capacity, a gun of 30 cm of inside diameter and an effective launching length of 1.40 m, and a cylindrical projectile with a mass of 308 kg.

The projectile velocities upon impact did not exceed 5 m/s. The load rates ranged from 25 to 450 GPa/s and the strain rates between 0.5/s and 10/s. These values were selected is such a way as to encompass the seismic-type loading rates determined from Reinhardt's classification system [4].

The experimental set-up included an extensometer measuring system made up of a 16-channel central recording station, an analog-digital converter with a storage capacity of 250000 measurements, a four channel oscilloscope and a microprocessor, and a high-speed camera (36000 frames per second). Measurements of applied loads and deformations were carried out by means of strain gages. The specimens were of a cylindrical shape, 8 cm in diameter and 16 cm long. They were located immediately after the load cell.

As it is well know the experimental investigation of the behavior of materials when subjected to impact loading has the shortcoming of the evaluation of the actual force applied to the specimen during the loading cycle. This is because the force recorded by the load cell is the combined result of a multiple superposition of transmitted and reflected waves. In order to correct the amplitude of the force recorded by the cell, a mathematical model was developed [1] based on the theory of longitudinal waves and taking into consideration the degrading effects of the material. In most cases, the sensor registered a maximum force 20% larger than that incurred on the test piece. The differences among the amplitudes registered are mainly affected by the ratio between the impact duration and the natural period of the experimental set-up.

Materials

Two types of concrete were studied: one of them with hydraulic binder and the other with polymer binder. Three mix proportions were selected for the concretes as indicated in table 1; Portland cement of the CPA55 type [6] was used and the aggregates have a silica-calcareous origin.

With the polymer concretes two mix proportions were prepared, one of them using epoxy resin and the other with the vinylester resin, the aggregates were siliceous and kaolin. The proportioning used was based on two criteria: one from on economic point of view to minimize the amount of resin, while the other refers to durability so as to achieve a high relative density of the material and therefore good mechanical properties and an adequate rheological behavior [7]. Proportions employed are shown in table 2.

Table 1. Mix proportion of hydraulic concrete by volume and aggregate gradation

Concrete	Cement	Sand 0.5-5 mm	Gravel 5-20 mm	Water	Additive	C/W
b1	0.177	0.277	0.421	0.196	0.0009	0.90
b2	0.129	0.312	0.391	0.202	------	0.64
b3	0.177	0.264	0.391	0.192	------	0.94

Table 2. Mix proportion of polymer concrete by volume and aggregate gradation

Concrete	Binder*	Filler 0.1mm	Sand 0.1-4.0 mm			Gravel 2.5-10 mm	
		S2	F3	G2	G5	G6	G7
RP	12%	0.190	0.135	0.070	0.080	0.116	0.411
RE	12%	0.190	0.135	0.070	0.080	0.116	0.411

* percentage by concrete weight
RP - vinylester concrete RE - epoxy concrete

RESULTS

In this section, only the results of the test series performed with hydraulic concrete and with polymer concrete specimens, 28 days old are presented. The extensive analysis of hydraulic concrete subjected to impact loading has been reported in a separate paper [5].

The strength-strain relationships of the test materials subjected to impact loading were determined and compared with those obtained from quasi-static loading conditions; a typical example of these relationships are shown in Fig. 1. The comparison of these two relationships makes it clear that a characteristic threshold exists, after which the agreement between the impact loading curves and the ones obtained from quasi-static tests differ appreciably.

The concrete cylinder made out of vinylester resin showed an identical behavior than those manufactured with epoxy resin.

Curves relating the strength to impact to the strain rate (Fig. 2) show that the strength increases once a critical value of the strain rate is achieved; for hydraulic concrete, this value is lower than that corresponding to polymer concrete.

The analysis of the strain energy as a function of the strain rate [1] shows that the polymer concrete has a quasi-static strain energy more than the peak estimated values corresponding to the hydraulic concrete under impact loading conditions. For values of strain rate higher than 3/s the strain energy for the polymer concrete increases faster than the strain energy for the hydraulic concrete.

From the relationships between the impact duration and the strain energy three modes of behavior can be appreciated, namely: mode I, where the energy transmitted by the projectile is less than the rupture force, mode II, where the energy transmitted is capable of partially crushing the specimen; and mode III, where the energy transmitted by the projectile completely crushes the specimen. The transition between mode I and mode II defines a critical energy threshold. The boundaries between each of the modes are different for the two types of concrete, and they vary in accordance with the strain rate. It can be concluded that for the two first modes, the polymer concrete shows a less brittle behavior than the hydraulic concrete. For mode III the impact duration is practically the same for both materials and their behavior is of the brittle type.

PHYSICAL MODELS

Models used to define the behavior of concrete under impact loading have been recently developed [8, 9, 10], although in terms of the thermal activation energy and of the microstructural inertial effects.

Thermal activation energy

In this model it has been assumed that the sensitivity of the concrete to the strain rate can be explained in terms of an analysis dealing with the thermal activation [11]. The expression for the rupture stress as determined from Arrhenius' equation can be written as follows:

$$\frac{\sigma_1}{\sigma_\varepsilon} = \frac{\sigma_s}{\sigma_\varepsilon}\left[1 - \left(1 - \frac{\sigma_o}{\sigma_s}\right)\left(\frac{kT}{F} \ln \frac{\dot{\varepsilon}_o}{\dot{\varepsilon}}\right)^{1/2}\right] \qquad (1)$$

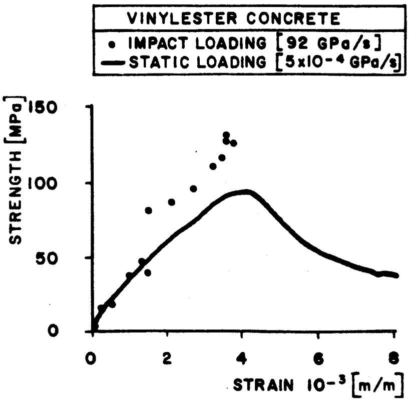

Figure 1. Typical strength-strain curves.

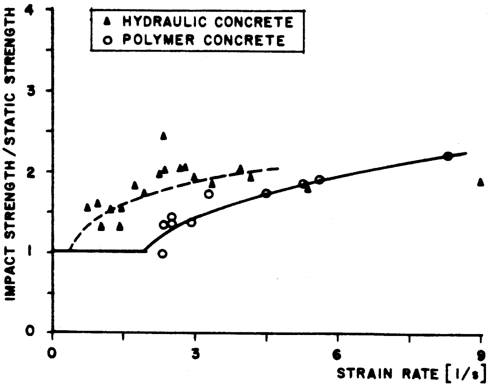

Figure 2. Effect of strain rate on the impact compressive strength

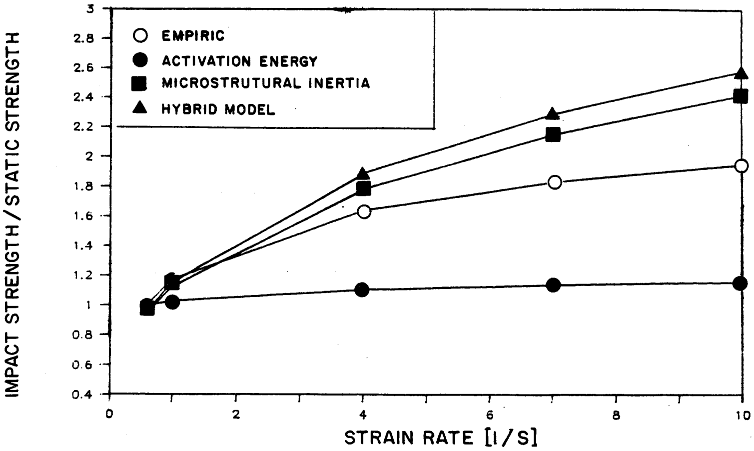

Figure 3. Physical model representation of hydraulic concrete.

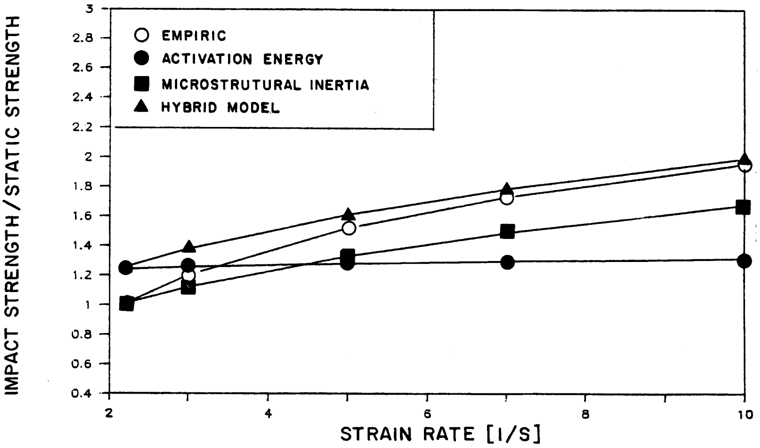

Figure 4. Physical model representation of polymer concrete.

where:

σ_I - strength to impact loading
σ_E - quasi-static strength
σ_S - upper bound of the strength
σ_O - lower bound of the strength
k - Boltzman's constant
T - absolute temperature
F - thermal activation energy
$\dot{\varepsilon}$ - strain rate
$\dot{\varepsilon}_O$ - strain rate corresponding to the upper bound of strength

In order to be able to apply equation 1, it is necessary to define the upper and lower bounds of the strength and the values define the upper and lower boundaries of the strength, and the values of F, $\dot{\varepsilon}_o$ and $\dot{\varepsilon}$. These parameters were determined with a semi-empirical approach from the experimental results obtained by other authors in mortar and basalt [9, 10, 12].

Microstructural inertia

Microfissuring of concrete is a phenomenon intrinsic to this material and it should be considered as one of its constitutive elements, not only because it leads to an increase in the porosity which in turn causes a variation in the strength, but also because it induces potential points of rupture.

Green, Kipp and Chen [13, 14] where they studied rocks specimens subjected to impact loads. The results showed that the sensitivity of the rupture stress to the strain rate is governed by a theory well established by fracture mechanics concepts. They have found that the increase in the rupture stress seems to be a consequence of the effects induced by the microstructural inertia which makes the material susceptible to the variation of the strain rate. The theoretical expression representing the results obtained by them is as follows:

$$\sigma_{IT} = \left[\left(\frac{9\pi}{16}\,\frac{E\,K_{IC}^2}{C}\right)\dot{\varepsilon}\right]^{1/3} \qquad (2)$$

where: σ_{IT} - tensile fracture stress, E - Young's modulus, K_{IC}- critical factor of the stress intensity, C - celerity of longitudinal waves

No other similar studies on the dynamic behavior of concrete have been performed to date and to be able to apply this equation, a correlation factor "d" was introduced, being equal to the ratio between the maximum compressive and tensile stresses; in order to have it as a nondimensional expression it was divided by the quasi-static strength of the material and the resulting equation reads as follows:

$$\frac{\sigma_I}{\sigma_E} = \frac{1}{d\sigma_E}\left[\left(\frac{9\pi}{16}\,\frac{E\,K_{IC}^2}{C}\right)\dot{\varepsilon}\right]^{1/3} \qquad (3)$$

The magnitude of the critical factor of stress intensity can be evaluated for the hydraulic concrete in terms of experimental tests results obtained for the same material [15] and for the polymer concrete with a semi-empirical approach [1].

Hybrid model

The combined effect of the two phenomena described above have been taken into consideration, i.e. the thermal activation energy and the microstructural inertia; from equations 1 and 3 the following expression is obtained:

$$\frac{\sigma_I}{\sigma_E} = \left(\frac{\sigma_I}{\sigma_E}\right)_{\text{Ener. Act.}} + \left(\frac{\sigma_I}{\sigma_E}\right)_{\text{Iner. Micr.}} - 1 \qquad (4)$$

For the case of the hydraulic concrete, the best fitting physical model is the second one, where the microstructural inertial is taken into account. For the case of polymer concrete the best approach corresponds to the hybrid model (Figs. 3 and 4).

CONCLUSIONS

The loading rate and the amount of applied energy alter appreciably the deformation response of the materials. The study has shown that the behavioral laws of concrete vary in terms of the loading conditions and of the intrinsic properties of the material such as the type of binder and the microfissuring mechanisms occurring during the overall elastic behavior stage. These mechanisms play a leading role since they make it possible to explain the significant increase of strength under impact loads. The fissuring process of the polymer concrete is governed by the viscoelastic properties of the resin used.

REFERENCES

[1] D. Muriá Vila, Contribution a l'étude du comportement au choc des bétons. Doctoral thesis, INSA de Lyon (1986).

[2] L.I. Knab, Polyester concrete: Load rate variance. Highway Research Board, H.R. Record, No 287 (1969).

[3] J. Bhargava and A. Rehnström, Dynamic strength of polymer modified and fiber reinforced concrete. Cement and Concrete Research 7, 199-208 (1977).

[4] H.W. Reinhardt, Concrete under impact loading tensile strength and bond, HERON 27, 3-48, (1982).

[5] D. Muriá Vila and P. Hamelin, Comportement au choc des bétons et mortiers a matrices hydraulique. Proceeding of the First International RILEM Congress "From materials science to construction materials engineering" 2, 725-732, France (1987).

[6] G. Dreux, Noveau guide du béton. Editions Eyrolles (1981).

[7] D. Prin, Béton de résine polyester: Application au domaine du génie civil. DDI Thesis, INSA de Lyon (1972).

[8] H. Kormeling, A model for concrete under impact tensile loading. Proc. of Interassociation Symposium of RILEM, CEB IABSE/ASS, Berlin West (1982).

[9] U.F. Wittman, Kriechmessungen an zementstein. Rheological Acta, Band 6, Heft 4, (1967).

[10] R. Boutemeur, Etude de la sensibilité á la vitesse de déformaction du mortier sollicité en compression. Thesis DDI, Ecole Nationale Supérieure de Mécanique, (1986).

[11] J.C. Polet and S.J. Burns, Thermally activated crack propagation-theory. Int. Journal of Fracture, 13, 5, 667-679 (1977).

[12] U.S. Lindholm, L.M. Yeakley and A. Nagy, The dynamic strength and fracture properties of dresser basalt. Int. J. Rock Mech. Min. Sci. & Geomech. 11, 181-191 (1984).

[13] M.E. Kipp, D.E. Grady and E.P. Chen, Strain rate dependent fracture initiation, Int. J. of Fracture 16, 5, 471-478 (1980).

[14] D.E. Grady and M.E. Kipp, The micromechanics of impact fracture of rock, Int. J. Rock Mech. Min. Sci. & Geomech. 16, 293-302 (1979).

[15] B. Khaleghi, G. Debicki and P. Hamelin, Analyse de la fissuration des bétons. Journées Universitaires de Génie Civil, (1984).