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Mechanical Properties of High Strength Concrete

Propriétés mécaniques du béton à haute résistance

Mechanische Eigenschaften vom hochfesten Beton

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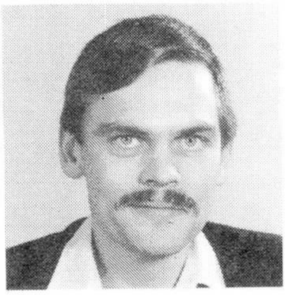

SUMMARY
This report deals with experimental data on high strength concrete. Compressive stress-strain relationship, ductility, lap splice strength, and fire resistance are discussed.

RÉSUMÉ
Des résultats de quelques essais sur béton à haute résistance sont présentés. Les relations contrainte de compression / déformation, ductilité, résistance des recouvrements d'acier et résistance au feu sont discutés.

ZUSAMMENFASSUNG
Ergebnisse von Versuchen mit hochfestem Beton werden vorgestellt. Das Spannungs-Dehnungsverhalten die Duktilität, die notwendigen Ueberdeckungslängen bei Bewehrungsstössen und der Feuerwiderstand werden diskutiert.

1. STRESS-STRAIN RELATIONSHIP IN UNIAXIAL COMPRESSION

It is generally recognized that for high strength concrete the shape of the ascending part of the stress-strain curve is more linear and steeper, the strain at maximum stress is slightly higher, and the slope of the descending part is steeper than for normal strength concrete.

Extremes of the stress-strain curves were obtained by Tomaszewicz [2] and by Wang et al [1]. Tomaszewicz investigated high strength concrete made with silica fume as additive. The descending part of the stress-strain curve was obtained by using a closed-loop testing machine so that the specimen could be loaded to a constant rate of strain increase avoiding unstable failure. Tomaszewicz represented the stress-strain curves mathematically as:

$$\sigma = f_c \cdot \frac{\varepsilon}{\varepsilon_{co}} \cdot \frac{n}{n - 1 + (\frac{\varepsilon}{\varepsilon_{co}})^{k \cdot n}}$$

$$n = \frac{8.32}{8.32 - f_c^{0.475}}$$

$$k = \begin{cases} \frac{f_c}{20} & \varepsilon > \varepsilon_{co} \\ 1 & 0 \leq \varepsilon \leq \varepsilon_{co} \end{cases}$$

$$\varepsilon_{co} = 0.0007 \cdot f_c^{0.31}$$

in which f_c is the compressive strength in MPa and ε_{co} is the strain at peak stress. Wang et al [1] used a simple method of obtaining a stable descending part of the stress-strain curve by loading the concrete cylinders in parallel with a concentrically placed large diameter, hardened steel tube with such a wall thickness that the total load exerted by the testing machine always increased. Wang et al represented the stress-strain curve mathematically by the equation

$$\sigma = f_c \cdot \frac{A \cdot (\frac{\varepsilon}{\varepsilon_{co}}) + B \cdot (\frac{\varepsilon}{\varepsilon_{co}})^2}{1 + C \cdot (\frac{\varepsilon}{\varepsilon_{co}}) + D \cdot (\frac{\varepsilon}{\varepsilon_{co}})^2}$$

in which f_c is the compressive strength in MPa, ε_{co} is the strain at peak stress, and A, B, C, and D are constants.

Two different sets of constants were used for the ascending and the descending parts of the curve. From Wang et al [1] details of the constants and of ε_{co} can be found.

Fig. 1 shows the test results obtained by Tomaszewicz and Wang et al. It can be seen that the slope of the curve in the post maximum stress range becomes steeper as the compressive strength of the concrete increases. For the same peak stress the shape of the ascending and especially the descending part of the curves from Tomaszewicz's investigation are steeper than those of Wang et al's investigations.

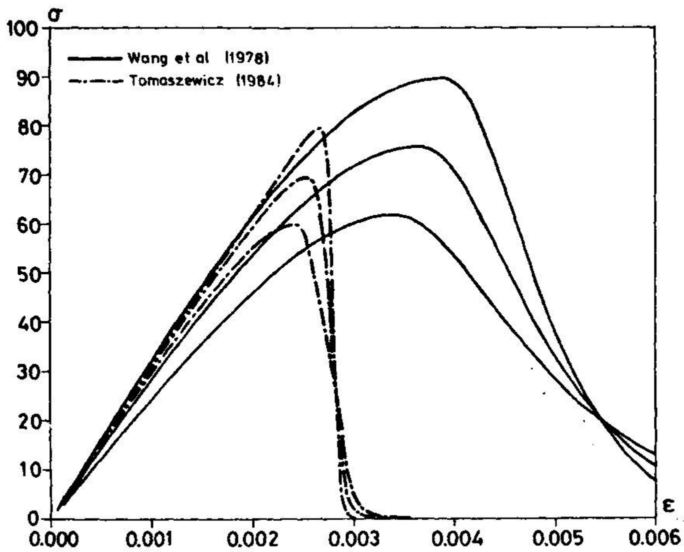

Fig. 1: Stress-strain curves from uniaxial compression tests.

2. DUCTILITY

High strength concrete is less ductile than normal strength concrete. It is not possible to express the relative ductility (or brittleness) in a quantitative manner, since no rational standard method of measuring this quantity currently exists. Attempts using nonlinear fracture mechanics to define fracture toughness are being made.

Ductility can be quantitatively expressed by the slope of the post-peak response of concrete subjected to uniaxial compression. If this slope is zero for instance, then the material is perfectly plastic, while for perfectly brittle material, the slope is infinite. Fig. 1 shows that the slope increases with increasing concrete strength, especially the types of high strength concrete reported by Tomaszewicz [2].

According to the above definition, high strength concrete is more brittle than normal strength concrete; however the same is not necessarily true for reinforced high strength concrete as compared to reinforced normal strength concrete.

The deflection ductility index for reinforced concrete beams will be defined as:

$$\mu = \Delta_u/\Delta_y$$

where

Δ_u = mid-span beam deflection at failure load

Δ_y = mid-span beam deflection at the local load producing yield of the tensile reinforcement.

This ratio depends not only on the compressive stress-strain curve of the concrete but also on the amount of longitudinal reinforcement, the shape of the beam cross section, the loading conditions and other factors.

The effect of the concrete compressive strength on the deflection ductility of a reinforced concrete beam under third-point loading was theoretically calculated by Ahmed and Shah [3] for three reinforcement ratios and five compressive strength levels. The amount of tensile reinforcement was varied so that the ratio between the actual steel content, ρ, and the balanced steel content, ρ_b (defined and calculated according to the ACI

Code [5]) remained essentially the same for the beams with the five different concrete strengths.

Ahmad and Shah [3] compared the theoretically calculated deflection ductility with experimental research results conducted at Cornell University [4]. They found that the theoretical prediction was close to the experimentally observed values.

Fig. 2. shows the theoretically calculated deflection ductility values [3] and the experimentally determined values [6]. The experimentally determined values are for high strength concrete containing silica fume (Si/C < 0.15). These beams were third point loaded and included compressive reinforcement and lateral confinement steel in the form of closed stirrups.

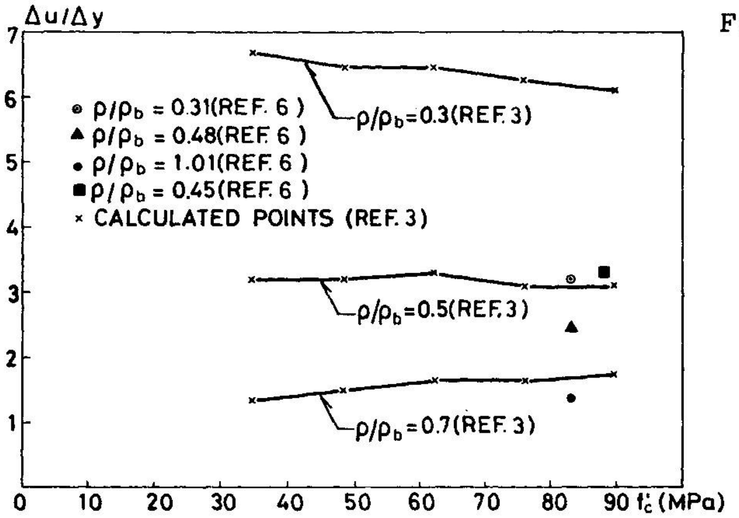

Fig. 2: Relationship between deflection ductility and compressive concrete strength.

3. SPLICES

Although some information regarding development length and anchorage of tensile steel has recently become available for high strength concrete, not enough data have been reported at the moment.

Tepfers [7] has investigated the effect of concrete strength on the lap splice strength. Fig. 3 shows the measured relationship between concrete compressive cube strength, σ_{cube}, and the splice strength represented by the ultimate tensile stress, σ_{su}, in the reinforcement just outside the splice. The tensile reinforcement used was Swedish deformed bars, ø 16 mm with yield stresses of 60 and 90 MPa and a splice length of 520 mm. The concrete cover in the vertical direction was 16-24 mm and in the horizontal direction 26-37 mm. No stirrups were used.

Fig. 3 shows that the splice strength increases with increasing concrete strength up to $\sigma_{cube} \sim 70$ MPa. For larger values of the concrete strength the opposite is the case. Tepfers explains this by the shrinkage of the concrete. The shrinkage creates concrete tensile stresses (hoop stresses) around the reinforcing bars. These stresses increase the tendency to splitting of the concrete. Shrinkage increases with increasing amount of cement. Tepfers's concrete with $\sigma_{cube} \sim 110$ MPa contained 1693 kg cement per m^3 concrete.

Tepfers's tests suggest that the high strength should preferably be obtained - not by a high cement content - but by other means, for instance, by use of silica fume, fly ash and/or superplasticizers.

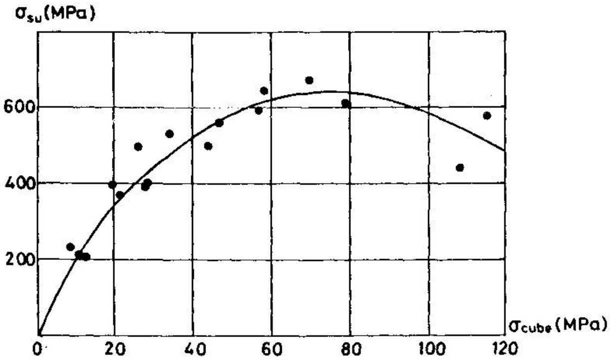

Fig. 3: Relationship between compressive concrete strength and splice strength represented by σ_{su}.

4. FIRE RESISTANCE

When producing high strength concrete by using superplasticizers and silica fume the concrete gets a very low permability. Due to the dense microstructure high strength concrete is far more resistant to many physical and chemical influences than normal strength concrete. However, damage may occur from the internal steam pressure build up when the high strength concrete is heated during a fire.

Hertz [8] investigated the lack of fire resistance by heating (in an electrical oven) concrete cylinders with a compressive strength level of 150-170 MPa. He concluded that high strength concrete possesses a high risk of damage due to steam pressure and the low permability, even at a low heating rate of 1° C per minute. The damage ratio was 67% and the silica fume content was 20% of the cement by weight. Cement content was 500 kg per m^3 concrete.

Recently high strength concrete cylinders were tested at the Technical University of Denmark in order to study the lack of fire resistance for concretes with a lower strength than those tested by Hertz.

Three series of ø 100 mm by 200 mm cylinders were made with intended compressive strengths of 50, 70 and 90 MPa. Cement content was 250 kg, 300 kg and 350 kg, respectively, and the silica fume content was 10% of the cement by weight. The cylinders were cured in two different ways: a) 7 days in water and then 21 days in the laboratory atmosphere (20° C and 60% RH), b) 7 days in water and then sealed for 21 days with plastic-aluminum foil.

All test pieces were heated in an electrical oven at a rate of 2.5° C per minute to a temperature of 600° C, which was maintained for 2 hours. They were then cooled down at a rate of maximum 1° C per minute. Figs. 4a and 4b show the measured compressive strength and the damage percentage for cylinders cured under condition a and b, respectively. Each point in the figures represents the average of three cylinders. (Damaged cylinders had totally lost their integrety).

It appears from figs 4a and 4b that although the heating rate was higher than in Hertz's experiments, the tendency to damage is moderate especially for the cylinders cured under condition a. (It must be emphasized that the total number of cylinders tested was only 36).

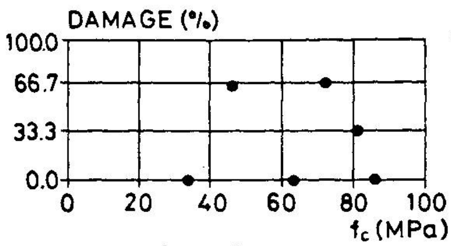

Fig. 4a.

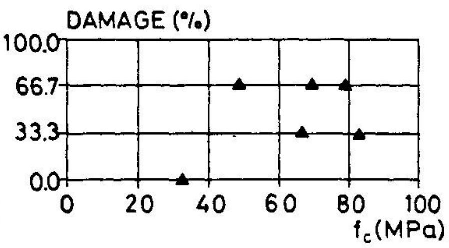

Fig. 4b.

Fig. 4a: Damage percentage for cylinders cured under condition a

Fig. 4b: Damage percentage for cylinders cured under condition b

5. CONCLUSIONS

On the basis of this work the following conclusions can be drawn:

There are significant differences in the shape of the compressive stress-strain curves from normal and high strength concrete, especially high strength concrete containing silica fume. The curve for higher strength concrete is much more linear to a much higher fraction of the compressive strength. The slope of the post peak range increases as the strength increases.

High strength concrete is less ductile than normal strength concrete. For reinforced concrete beams, the deflection ductility is independent of the concrete compressive strength if the ratio ρ/ρ_b is kept constant.

Only little information is reported regarding bond and anchorage of reinforcement in high strength concrete. Investigation conducted by Tepfers showed that the splice strength increased with increasing concrete strength up to $\sigma_{cube} \sim 70$ MPa. For larger values of the concrete strength the opposite is the case. Further investigations are needed in order to study anchorage problems in high strength concrete.

From investigation at the Department of Structural Engineering at the Technical University of Denmark, high strength concrete damage percentage during fire heating appears moderate. Further investigations are needed on this subject.

It is the author's opinion that more information is needed regarding shrinkage and creep and regarding the durability of high strength concrete.

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