Properties and performance of high-strength concrete

Autor(en): **Nilson, Arthur H.**

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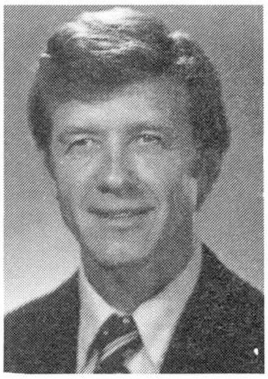
Properties and Performance of High-Strength Concrete

Propriétés et performances du béton à haute résistance

Eigenschaften und Verhalten von hochfestem Beton

Arthur H. NILSON
Prof. of Struct. Eng.
Cornell University
Ithaca, NY, USA



The author received his BS degree from Stanford University, MS from Cornell, and PhD from the University of California. Prior to joining the faculty at Cornell he was engaged in professional practice. He is the author of two texts on concrete design, as well as numerous technical papers.

SUMMARY

This paper is a summary of certain results from a 10-year program of research on high-strength concrete which had the following objectives : to establish the fundamental nature of the material ; to establish its engineering properties and to relate these to differences in internal response ; and to study the behavior of structural members made using high-strength concrete.

RÉSUMÉ

Cet exposé résume certains résultats d'un programme de dix ans de recherche sur le béton à haute résistance dont les objectifs étaient : d'établir la nature fondamentale du matériau ; d'établir les propriétés mécaniques et d'établir le rapport entre les différentes réponses intérieures ; et d'étudier le comportement des éléments en béton à haute résistance.

ZUSAMMENFASSUNG

Der Beitrag gibt eine Uebersicht über die Ergebnisse aus einem zehnjährigen Forschungsprogramm über hochfesten Beton, welches folgende Zielsetzungen hatte : die Erforschung der fundamentalen Beschaffenheit des Materials, das Feststellen der mechanischen Eigenschaften hochfester Betone und das Studium des Verhaltens von Stahlbetonbauteilen aus hochfestem Beton. Es werden vor allem die ersten beiden Aspekten, welche die Materialeigenschaften behandeln, besprochen.

1. INTRODUCTION

The past decade has seen a rapid growth of interest in high-strength concrete, with compressive strength in the range from about 40 to 85 MPa. Concretes in this strength range can be produced economically using carefully selected, but commonly available, cement, sand, and stone, through use of very low water-cement ratios and careful production control. Workability is achieved by high-range water-reducing admixtures, the so-called super-plasticizers.

Remarkably, use of high-strength concrete has preceded full knowledge of its properties, or of the behavior of structural members made using it. Much of our design methodology, including many design equations, is based on tests of members for which the material strengths were less than about 40 MPa.

In an effort to provide the data needed for design, an intensive program of research was initiated at Cornell University with three objectives: (a) to establish the fundamental nature of the material, (b) to establish the engineering properties, and (c) to study the behavior of reinforced and prestressed concrete members using high-strength concrete. Results summarized in this paper relate mainly to parts (a) and (b) of the investigation.

2. INTERNAL RESPONSE TO LOADS

2.1 Microcracking Under Short-Term Compression

It is generally recognized that many characteristics of concrete can be explained by progressive internal microcracking that occurs as load is gradually increased. Microcracking results mainly from the differences in stiffness and strength between the mortar and the stone. Bond cracks start on the interface between the mortar and aggregate. As load is increased, cracking spreads through the mortar, leading to an interconnected network of cracks, discontinuity of the material and, eventually, failure.

Significant differences were found between low- and high-strength concrete [1]. Microcracking starts at about 35 percent of ultimate load for low-strength concrete, and, at loads above about 65 percent, the interconnected crack pattern is well established. For high-strength concrete, there is little or no microcracking at low loads. Bond cracks start between about 65 and 80 percent, and even at 90 percent of ultimate load the bond cracks are mostly isolated, not interconnected.

A typical fracture surface of a compression cylinder of low strength concrete is rough and rugged. Cracks follow around the stone inclusions, then branch through the mortar. There is substantial energy dissipation associated with development of such a surface. For high-strength concrete, the typical failure surface is a clean fracture plane, as in Fig. 1. with cracks passing through stone and mortar without bias.

2.2 Microcracking Under Sustained Compression

Other studies have shown that sustained load behavior can also be related to differences in internal microcracking [2]. Sustained-load compression tests were of two types: (a) creep tests at loads from 40 to 80 percent of the short-term failure load, and (b) time-dependent failure tests at loads from 75 to 95 percent of short-term strength.

For sustained loading, three distinct stages of microcrack development were identified, associated with: (1) Linear creep, for which creep strain is proportional to stress and elastic strain; this is the range for which the usual creep coefficient applies; (2) Nonlinear creep, for which creep strains are disproportionately larger than creep coefficient times elastic strain, the ratio increasing with increasing load; and (3) Failure under high sustained load less than the short-term strength. Differences between low-strength and high-strength concrete behavior under sustained load are summarized in Table 1 [3].

Stage	Stress as Percent of Short-Term Strength		Microcracking
	Low-strength	High strength	
Linear creep	to 45%	to 65%	Some increase in bond cracks for low-strength; negligible for high
Nonlinear creep	to 75%	to 85%	Bond cracking increases for both
Failure	above 75%	above 85%	Bond cracks, mortar cracks, and combined cracks increase sharply

Table 1 Sustained load microcracking

3. ENGINEERING PROPERTIES

3.1 Compressive Stress-Strain Curve

Compressive stress-strain curves are shown in Fig. 2. The range of approximately linear elastic behavior is extended to 80 to 90 percent of maximum stress. Strain at maximum stress is about 0.002 for normal concrete, but increases to about 0.003 for high-strength specimens. The maximum strain reached is less [4]. While the shape of the compressive stress-strain curve after the peak stress is reached is highly dependent on testing methods, typically, for high strength concrete, there is a rapid dropoff of stress after the peak. The long descending branch displayed for normal concrete, corresponding to the gradual development and spread of microcracking, is absent.

3.2 Static Modulus of Elasticity

It was found that the ACI Code equation for elastic modulus E_c overestimated by as much as 20 percent. Modified predictor equations were established for both normal-weight and lightweight concrete [4,5].

3.3 Poisson's Ratio

Poisson's ratio in compression ranged from 0.15 to 0.26. The average value was essentially 0.20 regardless of compressive strength, curing conditions, or test age [4,5].

3.4 Tensile Strength

The two measures of tensile strength used in U.S. design practice are modulus of rupture f_r and the split cylinder strength f_{ct}. Data was obtained for each, for both normal and lightweight concrete, and is summarized in Table 2 [4,5]. Values stated in the ACI Code are shown for comparison.

Type of Concrete	Predicted Values of f_r		Predicted Values of f_{ct}	
	Cornell	ACI	Cornell	ACI
Normal-weight moist cured	$0.90\sqrt{f'_c}$	$0.63\sqrt{f'_c}$	$0.68\sqrt{f'_c}$	$0.54\sqrt{f'_c}$
Sand-lightweight	---	$0.53\sqrt{f'_c}$	---	$0.48\sqrt{f'_c}$
All lightweight moist cured	$0.66\sqrt{f'_c}$	$0.47\sqrt{f'_c}$	$0.51\sqrt{f'_c}$	$0.42\sqrt{f'_c}$
All lightweight dry cured	$0.36\sqrt{f'_c}$	$0.47\sqrt{f'_c}$	$0.42\sqrt{f'_c}$	$0.42\sqrt{f'_c}$

Table 2 Modulus of rupture f_r and split cylinder strength f_{ct} (all units MPa)

3.5 Creep Coefficient

One of the most significant differences between normal-strength and high-strength concrete is the greatly reduced creep coefficient, C_{cu}. Coefficients given for high strength concrete in Table 3 were obtained by extrapolating from tests of 6 month duration or less [3,6], but appear reasonable as an extension of 5 year data for lower strengths.

Material	f'_c MPa	C_{cu}	$C_{cu}/C_{cu,low}$
Low-strength concrete	21	3.1	1.00
Medium-strength concrete	28	2.9	0.94
" " "	41	2.4	0.77
High-strength concrete	55	2.0	0.65
" " "	69	1.6	0.52

Table 3 Creep Coefficients (adapted from Ref. 2 and 3)

3.6 Sustained Load Strength

It is well known that the strength of concrete under sustained loading is less than that determined by short-time loading. Based on earlier studies, the load that will produce failure if sustained over a period of time was thought to be related to the discontinuity stress. Because this is higher for high-strength concrete, it was expected that the sustained load strength would be higher.

This is true as illustrated by Fig. 4. For low-strength concrete, loads below about 75 percent of short-term strength could be sustained without failure, while loads above that level produced failure. For high-strength concrete, loads as high as 85 percent of short-term strength could be sustained at least for 60 days [3].

4. MEMBER BEHAVIOR

With differences in material behavior that were very significant in some respects, it was expected that there would be important differences in the behavior of members made using high-strength concrete. Some matters of particular concern included: (1) Differences in shape of the compressive stress-strain curve brought into question the validity of the equivalent rectangular stress block used for beam and column strength calculations; (2) The smaller compressive strain limit in axial compression tests required investigation of the validity of the assumption of ultimate flexural strain of 0.003 normally used in U.S. design; (3) Beam deflection ductility could be significantly less because of the more brittle nature of high-strength concrete; (4) Short-term beam deflections would be incorrectly predicted unless a more accurate equation for E_c were used; (5) Time-dependent beam deflections would be greatly over-predicted by present design methods that do not recognize the much lower creep coeffcients; (6) Predictions of beam shear strength might be unsafe for high-strength concrete beams because of the lack of aggregate interlock across diagonal cracks, a result of the typically smooth fracture surfaces.

These concerns led to the third stage of the investigation, involving tests of flexure-critical and shear-critical reinforced concrete beams [7,8], shear-critical prestressed concrete beams [9], reinforced concrete beams under sustained loading [10], and axially loaded columns [11]. A summary review of design implications is presented in Ref. 12.

5. CONCLUSION

The essential fact that has become clear is that high strength concrete is in many respects a new material, in most ways greatly superior to normal concrete, but with special characteristics that require careful consideration. Extrapolation of empirically-based design equations such as are found in all national codes cannot be considered safe practice. A thorough review of these codes, in the light of newly-available information, is essential.

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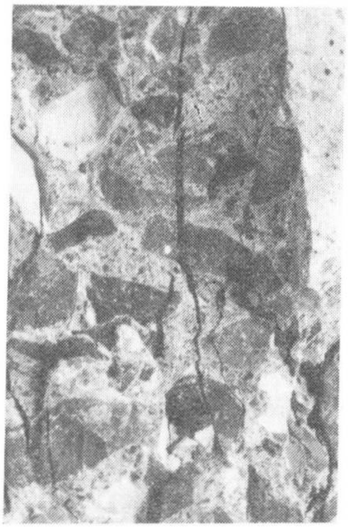

F' Path of cracks

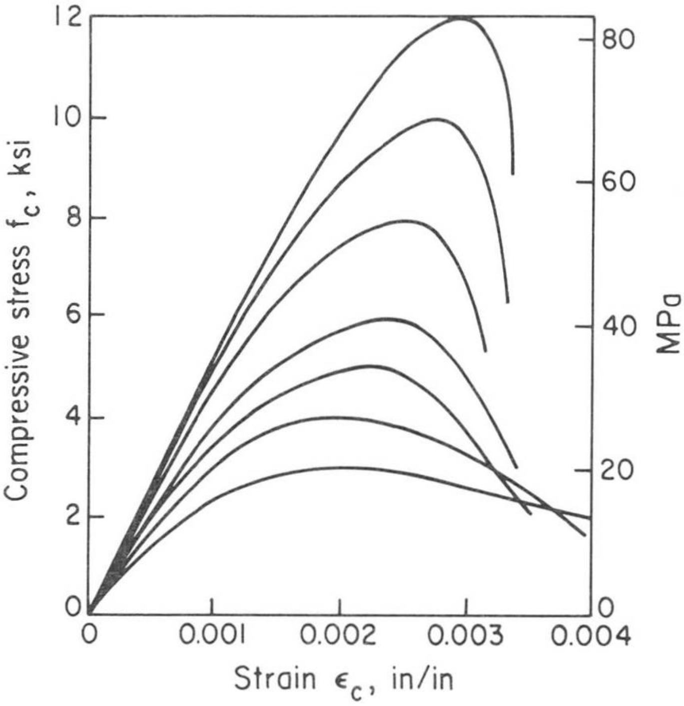

Fig. 2 Typical compressive stress-strain curves

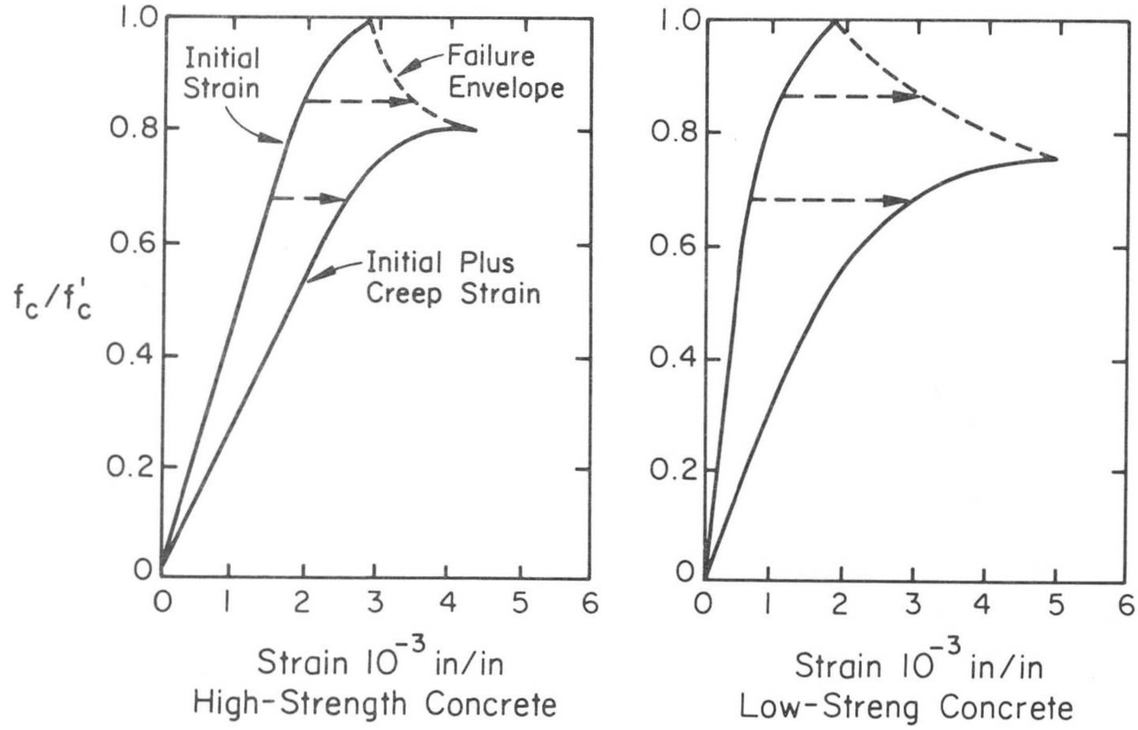

Fig. 3 Sustained load stress strain curves