고성능 콘크리트 공학

High Performance Concrete Engineering

문주혁 조교수
Assistant Prof. Juhyuk Moon

Introduction

Purpose of Course:

Concrete is a versatile manufactured material. Among different types of concrete products, this lecture will focus on various aspects of high performance concrete, which is actively being implemented in modern infrastructure, including chemistry of cement and concrete, manufacturing technology, material characteristics, and relevant design codes.

There will be two exams (midterm and final), ~~one project,~~ and four homework assignments.

The lecture is designed for graduate students who do not have background on concrete materials.

Evaluation Method:

Attendance: 10 %
Task: 20 % (4~5 homework 4~5%/each HW, ~~1 project 10%~~)
Midterm exam: 30 %
Final exam: 40 %

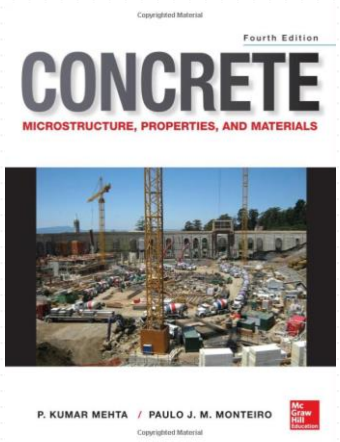
Big Picture

Week	고성능 콘크리트 공학 (High performance concrete eng.)	고급건설재료학 (Advanced construction materials)	통계역학해석?
1–2	Introduction (cement chemistry)	Bond, Crystals	Stat. Mechanics
3	Admixture, aggregate, water	Steel (phase diagram, compositions, ultimate strength under various loadings)	
4	Fresh and hardened properties	Cement chemistry	
5–6	Durability (chemistry, corrosion)	Admixture, aggregate, water	
7	Mix design	Fresh and hardened properties	
8–9	UHPC	Crystal theory	
10		XRD application	
11–12	Time-dependent behavior	XRF, TGA, SEM, MIP, NMR theory and application	Molecular Dynamics
13–15		Smart & Sustainable Civil Materials	

Introduction

Materials and Reference

(Metha and Monteiro 2006)



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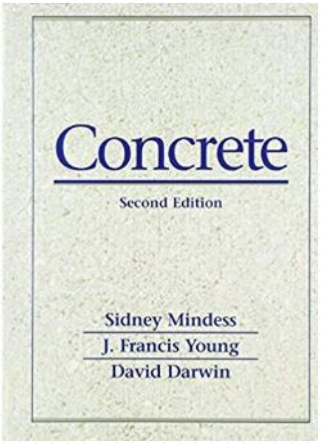
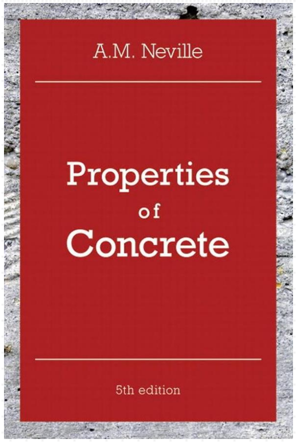


(Adam Neville 2002)



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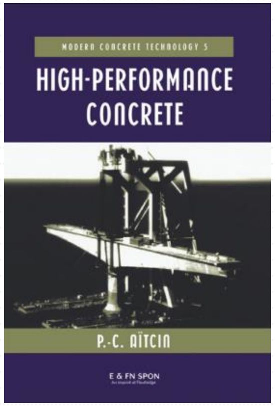
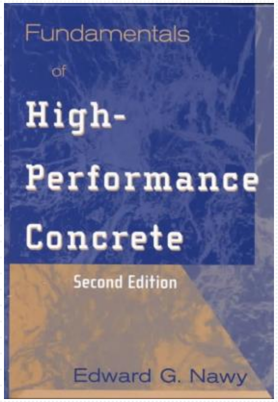
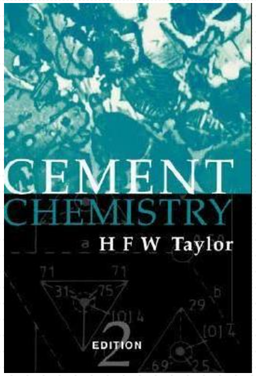


(Nawy 1996)

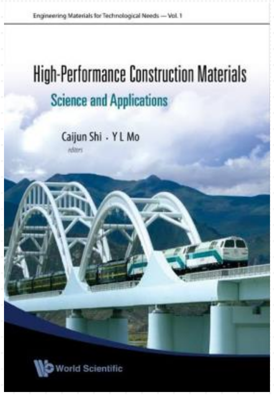


(M. Cardarone 2009)

(Taylor 1990)

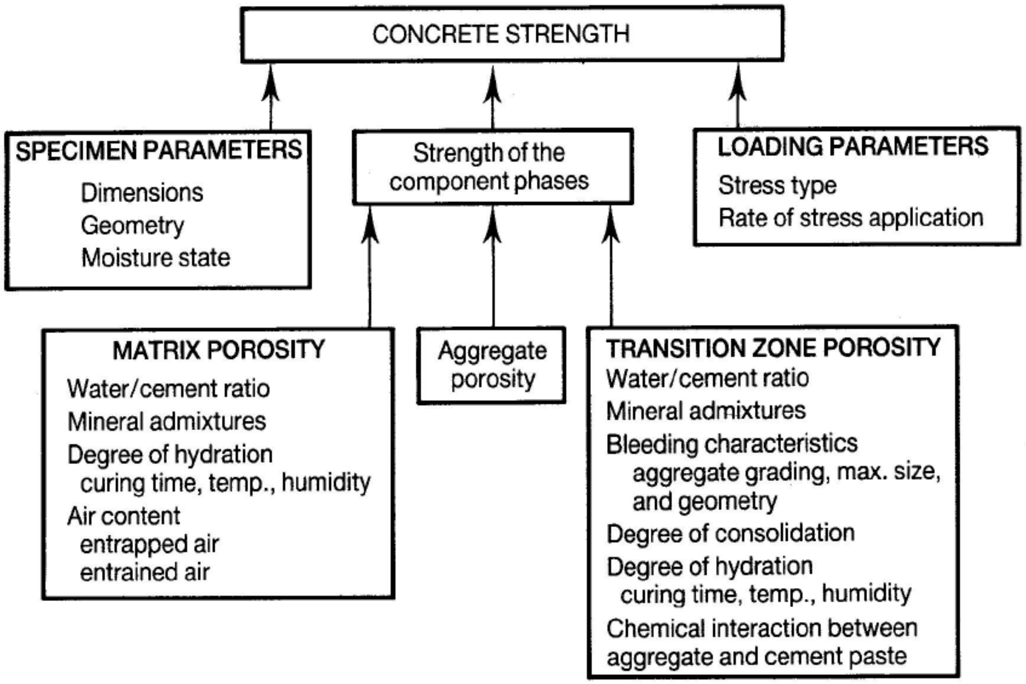


(Shi and Mo 2008)

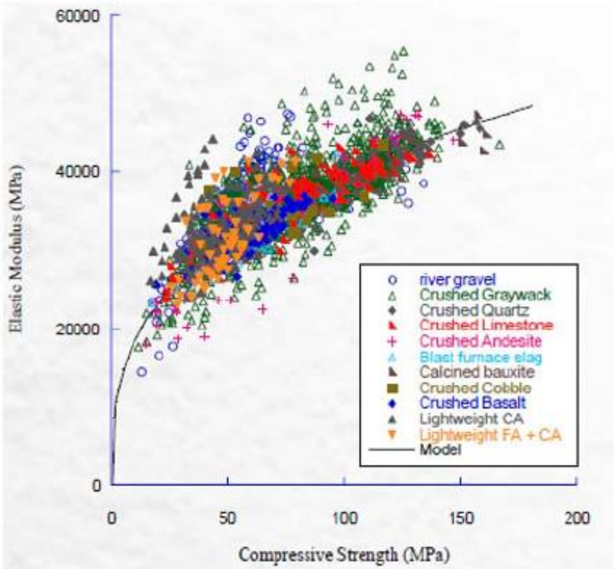


Why concrete is difficult?

Various factors affecting the strength of concrete



$$E_c = w_c^{1.5} \times 0.043 f_c^{'0.5}$$

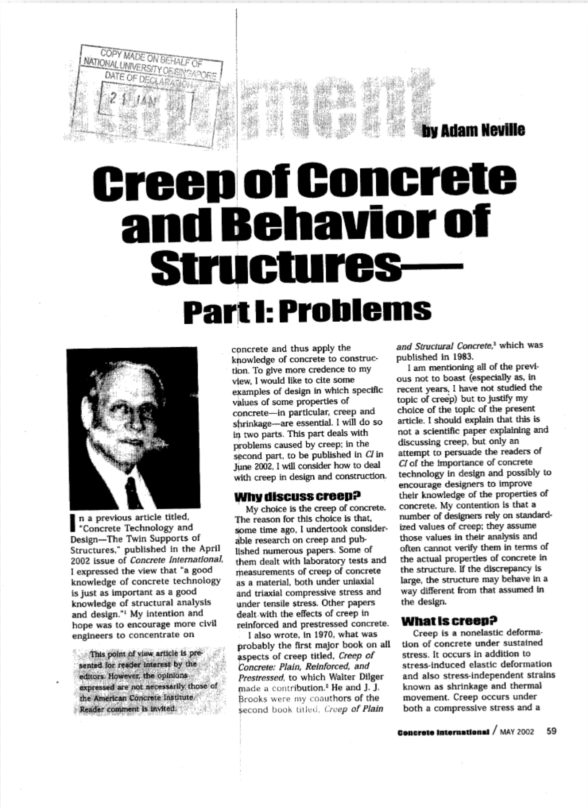


(Data from Tomosawa and Noguchi)

(Shi 2008)

Introduction

Why concrete is difficult?



by Adam Neville

Creep of Concrete and Behavior of Structures— Part I: Problems

In a previous article titled, "Concrete Technology and Design—The Twin Supports of Structures," published in the April 2002 issue of *Concrete International*, I expressed the view that "a good knowledge of concrete technology is just as important as a good knowledge of structural analysis and design."[1] My intention and hope was to encourage more civil engineers to concentrate on concrete and thus apply the knowledge of concrete to construction. To give more credence to my view, I would like to cite some examples of design in which specific values of some properties of concrete—in particular, creep and shrinkage—are essential. I will do so in two parts. This part deals with problems caused by creep; in the second part, to be published in *CI* in June 2002, I will consider how to deal with creep in design and construction.

This point of view article is presented for reader interest by the editors. However, the opinions expressed are not necessarily those of the American Concrete Institute. Reader comment is invited.

Why discuss creep?

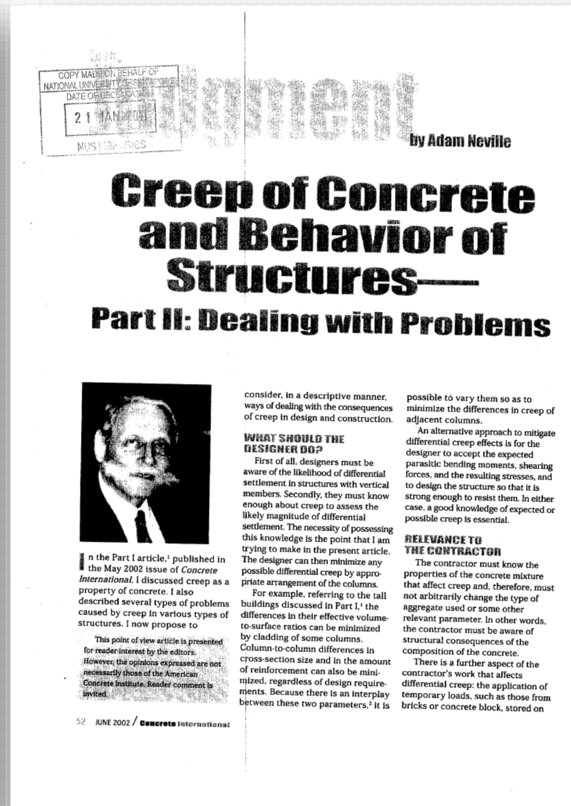
My choice is the creep of concrete. The reason for this choice is that, some time ago, I undertook considerable research on creep and published numerous papers. Some of them dealt with laboratory tests and measurements of creep of concrete as a material, both under uniaxial and triaxial compressive stress and under tensile stress. Other papers dealt with the effects of creep in reinforced and prestressed concrete.

I also wrote, in 1970, what was probably the first major book on all aspects of creep titled, *Creep of Concrete: Plain, Reinforced, and Prestressed*, to which Walter Dilger made a contribution.[2] He and J. J. Brooks were my coauthors of the second book titled, *Creep of Plain and Structural Concrete*,[3] which was published in 1983.

I am mentioning all of the previous not to boast (especially as, in recent years, I have not studied the topic of creep) but to justify my choice of the topic of the present article. I should explain that this is not a scientific paper explaining and discussing creep, but only an attempt to persuade the readers of *CI* of the importance of concrete technology in design and possibly to encourage designers to improve their knowledge of the properties of concrete. My contention is that a number of designers rely on standardized values of creep; they assume those values in their analysis and often cannot verify them in terms of the actual properties of concrete in the structure. If the discrepancy is large, the structure may behave in a way different from that assumed in the design.

What is creep?

Creep is a nonelastic deformation of concrete under sustained stress. It occurs in addition to stress-induced elastic deformation and also stress-independent strains known as shrinkage and thermal movement. Creep occurs under both a compressive stress and a



by Adam Neville

Creep of Concrete and Behavior of Structures— Part II: Dealing with Problems

In the Part I article,[1] published in the May 2002 issue of *Concrete International*, I discussed creep as a property of concrete. I also described several types of problems caused by creep in various types of structures. I now propose to consider, in a descriptive manner, ways of dealing with the consequences of creep in design and construction.

This point of view article is presented for reader interest by the editors. However, the opinions expressed are not necessarily those of the American Concrete Institute. Reader comment is invited.

WHAT SHOULD THE DESIGNER DO?

First of all, designers must be aware of the likelihood of differential settlement in structures with vertical members. Secondly, they must know enough about creep to assess the likely magnitude of differential settlement. The necessity of possessing this knowledge is the point that I am trying to make in the present article. The designer can then minimize any possible differential creep by appropriate arrangement of the columns.

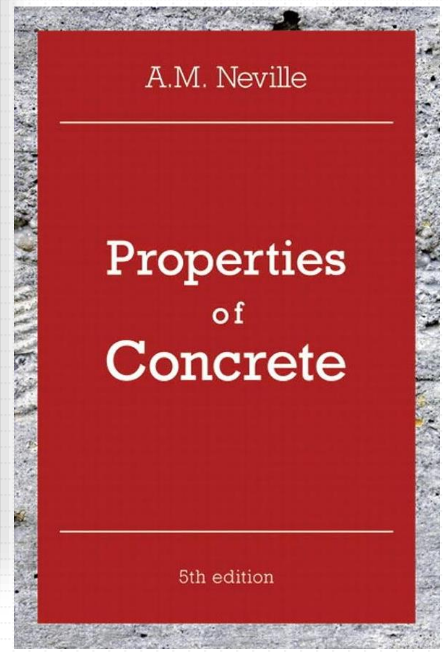
For example, referring to the tall buildings discussed in Part I,[1] the differences in their effective volume-to-surface ratios can be minimized by cladding of some columns. Column-to-column differences in cross-section size and in the amount of reinforcement can also be minimized, regardless of design requirements. Because there is an interplay between these two parameters,[2] it is possible to vary them so as to minimize the differences in creep of adjacent columns.

An alternative approach to mitigate differential creep effects is for the designer to accept the expected parasitic bending moments, shearing forces, and the resulting stresses, and to design the structure so that it is strong enough to resist them. In either case, a good knowledge of expected or possible creep is essential.

RELEVANCE TO THE CONTRACTOR

The contractor must know the properties of the concrete mixture that affect creep and, therefore, must not arbitrarily change the type of aggregate used or some other relevant parameter. In other words, the contractor must be aware of structural consequences of the composition of the concrete.

There is a further aspect of the contractor's work that affects differential creep: the application of temporary loads, such as those from bricks or concrete block, stored on



(Adam Neville 2002)

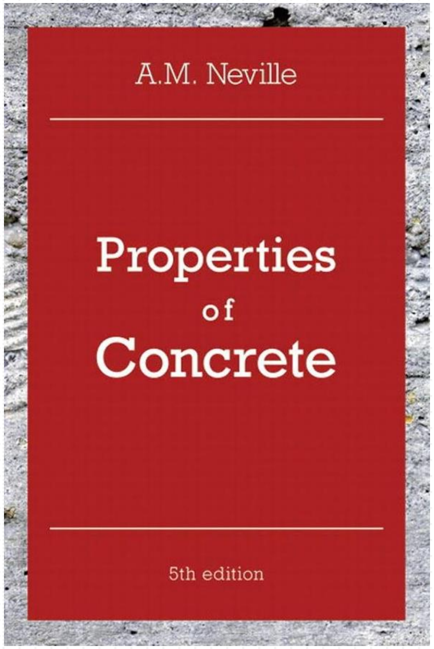
Introduction

Why concrete is difficult?

From "creep of concrete and behavior of structures

"Although creep is proportional to the applied stress, it is a function of numerous variables, which can be expressed in a variety of ways. Different researchers choose different groups of parameters, and different codes give standard values of creep characteristics in terms of different factors. To give an example, creep may be considered as a function of the w/c ratio or of the strength of concrete at the time of application of the sustained stress. Other features of the concrete mixture that influence creep relate to the aggregate: its type and density, its volume per cubic meter of concrete, and its modulus of elasticity. The age of the concrete when the sustained load is applied is also a factor. It is worth remembering that only sustained loads induce creep, and such loads may begin and cease to act at various ages. So overall, the situation is complicated."

"In addition to intrinsic factors in the concrete itself, creep is affected by extrinsic factors such as the relative humidity of the ambient medium and the temperature
of the concrete."

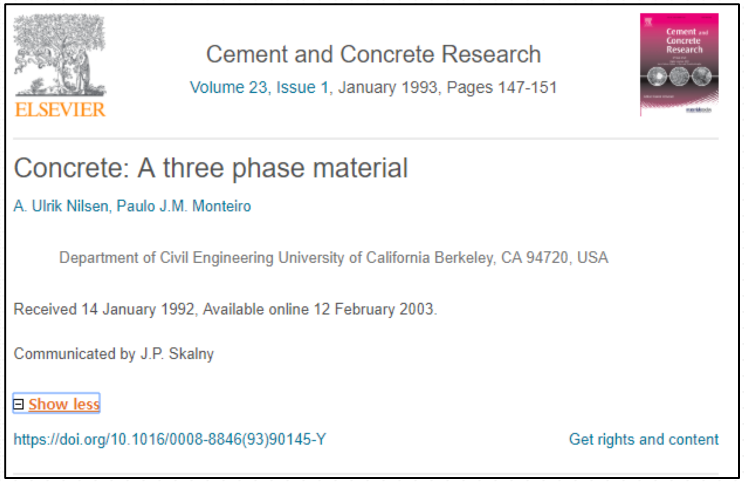


(Adam Neville 2002)

Why concrete is difficult?

Concrete does not consist of a single constituent.
Most of mechanical properties of concrete is relative characteristics.
So, the simplest form of microstructure of concrete is the Three-Phase-Materials

Is it true for high-strength concrete or high-performance concrete?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Cement and Concrete Research
Volume 23, Issue 1, January 1993, Pages 147-151

Concrete: A three phase material

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Department of Civil Engineering University of California Berkeley, CA 94720, USA

Received 14 January 1992, Available online 12 February 2003.
Communicated by J.P. Skalny

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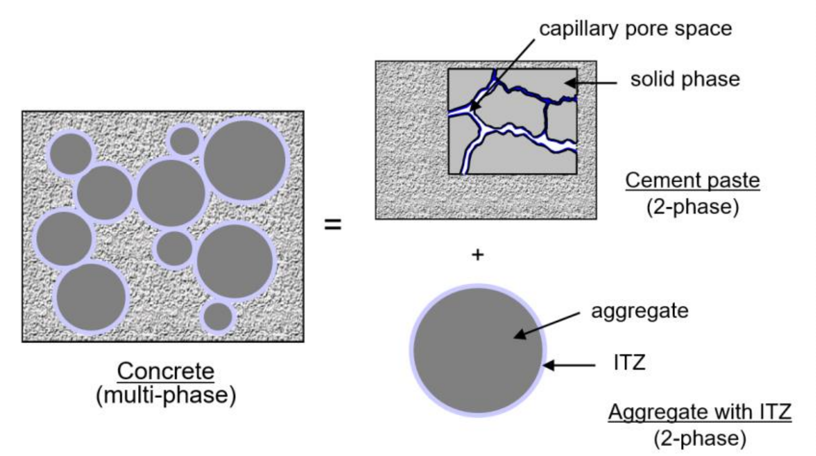
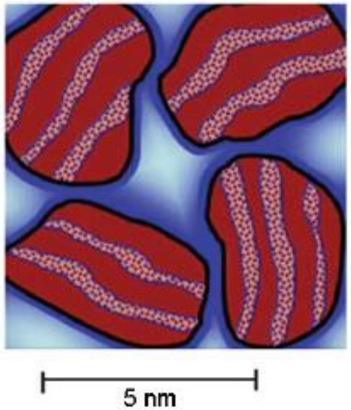


Introduction

Why concrete is difficult?

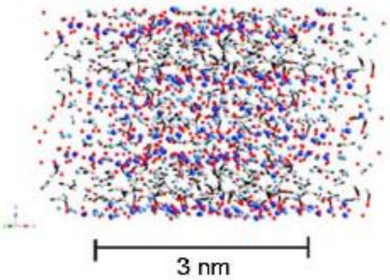
The most important hydration product in cement paste is Calcium-Silicate-Hydrates

<u>Is it true for high-strength concrete or high-performance concrete?</u>



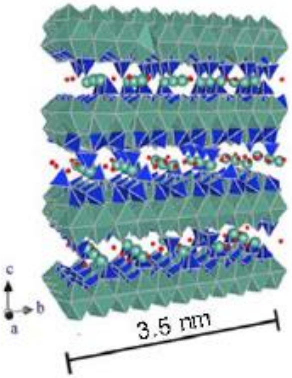
C-S-H nano-particle

(Image from Allen et al. Nature Material, 2008)



Molecular model of C-S-H

(Image reproduced from Pellenq et al. PNAS, 2009)



Refined C-S-H by PDF

(Image from Skinner et al. PRL, 2010)

In many cases, multiple engineering performance requirements need to be met simultaneously. The production of concrete is more of an art than a science, although the basic principle is simple.

Introduction

High-strength Concrete

In the early 1970s, it was predicted that the practical limit of ready mixed concrete would be unlikely to exceed a compressive strength greater than 43 MPa.

For example, in 1962, high-strength concrete with a design compressive strength of 42 MPa (6000 psi) was supplied to Chicago's 40-story Outer Drive East high-rise condominium project.

Over the past two decades, the development of high-strength concrete has enabled to produce very high strength concrete. Such as two buildings in Seattle, Washington contain concrete with a compressive strength of 130 MPa

1989, commercially available concrete with a design strength of 96 MPa (14,000 psi) was supplied for six stories of columns along with one 117 MPa (17,000 psi) experimental column at the 225 W. Wacker project.

(M. Cardarone 2009)

Concrete materials in general

It is only natural that hydraulic cement concrete would be viewed as a single material, but in reality, concrete is much better understood when viewed as a composite material comprised of two fundamentally different materials – filler (i.e. aggregate) and binder (i.e. paste).

Material properties, principally those mechanical in nature are fundamentally derived from the relative similarities (or differences) in the properties of the aggregate and paste. For this reason, the laws governing the selection of materials and proportions of concrete are by no means static.

The most influential factor affecting the strength and largely influencing the durability of concrete is the water-binder (water-cement) ratio.

(M. Cardarone 2009)

Concrete materials in general

There are extraordinary differences when comparing the properties of a very high-strength concrete having a compressive strength of 140 MPa to that of a conventional-strength structural concrete with a compressive strength of 30 MPa.

When considering the adjustments to the principles of mix proportioning necessary in order to satisfy mixture performance requirements, it is interesting to note that no abrupt change in material technology occurs at any one particular level of strength, or at a particular water-binder (W/B) ratio. Rather, the changes that occur when progressing up the strength ladder are quite subtle with each advancing step.

(M. Cardarone 2009)

Subtle terminology: Admixture vs Additive

In US, the term “admixture” refers to a material other than water, aggregates, hydraulic cementitious material, and fiber reinforcement that is used as an ingredient of a cementitious mixture to modify its freshly mixed, setting, or hardened properties and that is added to the batch before or during its mixing.

In UK, “admixture” is used to mean a material added during the mixing process of concrete in small quantities related to the mass of cement to modify the properties of fresh or hardened concrete. When a powdered admixture is added to factory-made cement during its production, it is called an “additive” and not an admixture.

For example, in the US, “slag cement” is one of several terms used for the material mostly accurately described as “ground granulated blast-furnace slag”. However, in other parts of the world, “slag cement” can refer to blended hydraulic cement containing ground granulated blast-furnace slag as a major constituent

(M. Cardarone 2009)

Subtle terminology: Water-binder ratio (W/B)

Water-to-cement ratio (W/C)

Water-cement plus pozzolan ratio (W/(C+P))

Water-cementitious materials ratio (W/CM)

Water-binder ratio (W/B)

Strength

If a concrete mix was only proportioned to achieve a median average level of strength at which the structure has been designed, the statistical probability that the results of a compression test would be below design strength would be 50 percent. It is important for users of concrete, particularly specifying authorities, to understand that even under the most stringent production and testing processes, there will always exist a statistical probability that the result of a material test will fall below a required level.

Strength is not an intrinsic property of concrete. It is a relative property that depends on numerous factors. Primary factors influencing the measured strength of concrete include specimen geometry, size, age, and curing history; testing equipment parameters, such as loading capacity, lateral and longitudinal stiffness, and the loading rate and uniformity of load distribution.

(M. Cardarone 2009)

Strength

Target strength simply refers to a desired level of measured strength at a given age, usually when evaluated under a standardized method of testing. It is important to recognize that target strength and design strength are unrelated terms.

Specified strength (f'c) refers to a defined level of concrete compressive strength chosen by a code-recognized authority in the design of structures, when tested at a designated acceptance age, under standard testing conditions, and evaluated in accordance with the acceptance criteria of a legally adopted design code, such as ACI 318-05.

Required average strength (f'cr) is the average compressive strength used as the basis for the selection of concrete proportions necessary to comply with the strength acceptance criteria of a legally adopted design code such as ACI 318-05. If the measured strength of concrete equals or exceeds f'cr, there is a statistical probability of only about 1 in 100 that the concrete fails to comply with the following strength acceptance criteria:

Every arithmetic average of any three consecutive strength tests equals or exceeds the specified compressive strength (f'c). No individual strength test (average of two cylinders) falls below fc' by more than 0.1 fc'.

(M. Cardarone 2009)

Normal Strength Concrete (NSC)

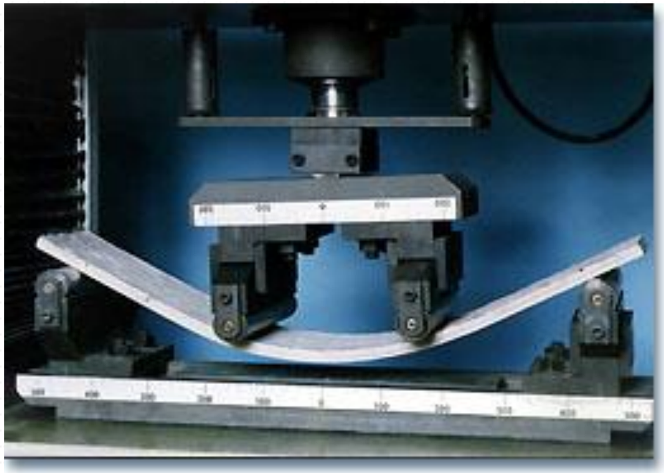
High Strength Concrete (HSC)

High Performance Concrete (HPC)

Ultra-High Performance Concrete (UHPC)

(M. Cardarone 2009)

And others?



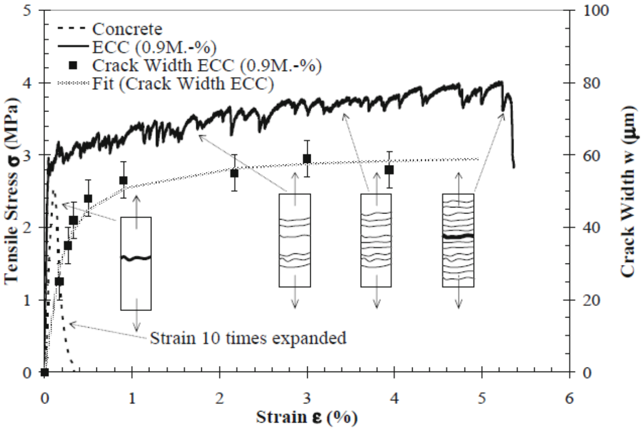
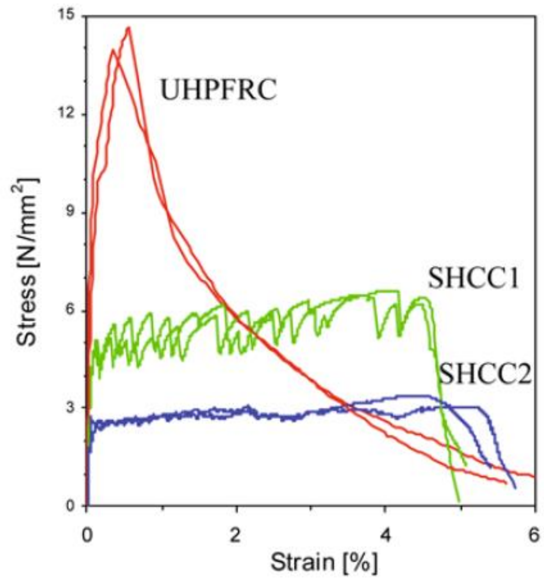
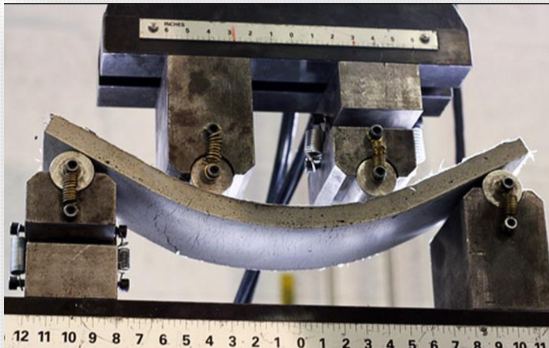


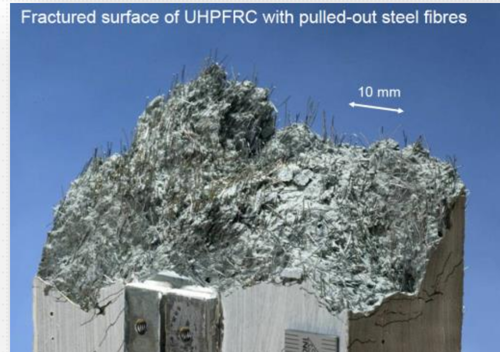
Fig. 1.1 Direct tensile stress-strain response of SHCC showing crack control to less than 65 μm (Weimann and Li, 2003).

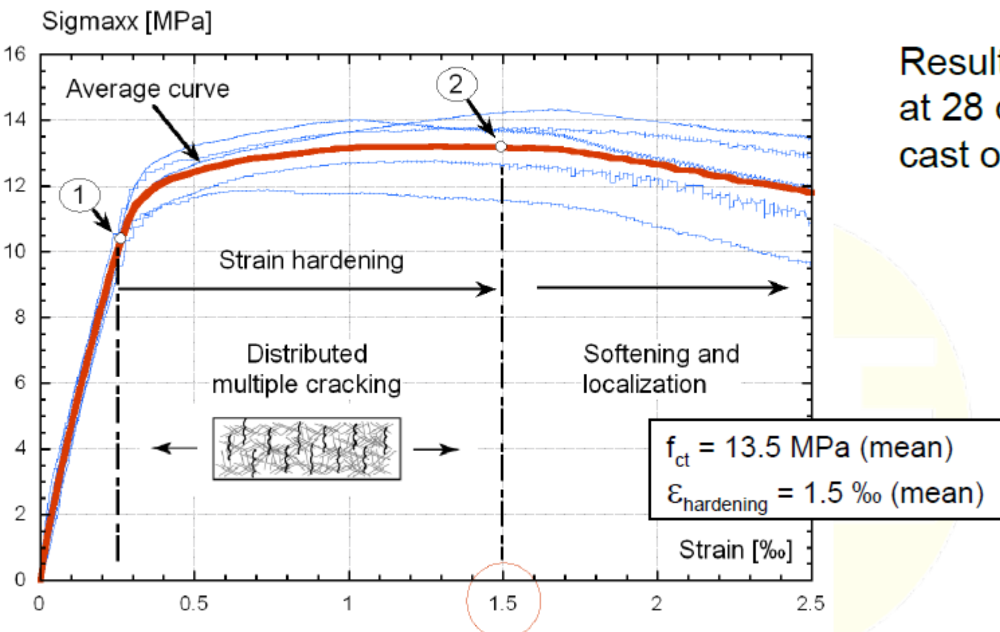


Uniaxial tensile behaviour of classes of HPFRCC (van Zijl, 2008).

And others?







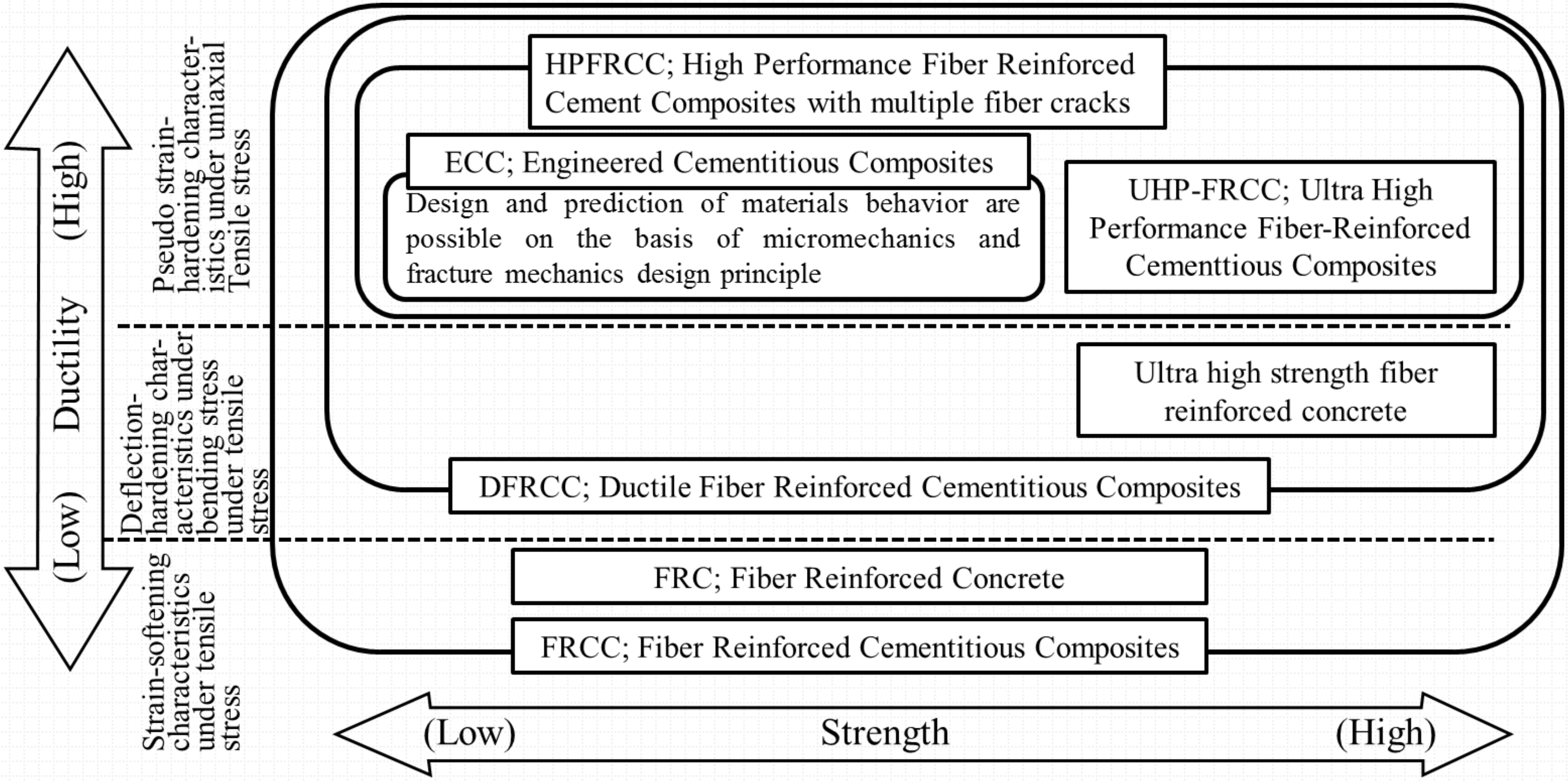
Results on 5 specimens,
at 28 days, Mix CM23,
cast on site

➔ Modulus of elasticity 30 % higher than normal concrete

(Image from Ecole Polytechnique)

Introduction

Classification of fiber reinforced cementitious composites partially revised from figure of JSCE 2008



High Strength Concrete (HSC)

In the 1984 version of ACI Committee Report 363R-92, 41 MPa was selected as a lower limit for high-strength concrete.

In the course of revising the 1992 version of the State-of-the-Art of High-Strength Concrete report, Committee 363 defined high-strength concrete as having a specified compressive strength for design of 55 MPa or grater.

Advancements in chemical admixture technology;
Increased availability of mineral admixtures (supplementary cementing materials)
Increased knowledge of the principles governing higher strength concretes

(M. Cardarone 2009)

High Performance Concrete (HPC)

In the Strategic Highway Research Program (SHRP in FHWA), HPC was initially defined by three requirements:

Maximum water-cementitious material ratio of 0.35
Minimum durability factor of 80%, as determined by ASTM C 666 Method A
Minimum compressive strength of either:
(a) 21 MPa within 4 hours after placement;
(b) 34 MPa within 24 hours;
(c) 69 MPa within 28 days.

In response to FHWA's call for a clear definition of HPC based on long-term performance criteria, Goodspeed et al. proposed a definition, consisting of four durability and four strength parameters, each one being supported by performance criteria, performance testing procedures, and recommendations to allow performance to be accurately related to specific adverse field conditions. The eight performance criteria are freeze/thaw durability, scaling resistance, abrasion, chloride penetration, strength, elasticity, shrinkage, and creep.

(Shi 2008)

High Performance Concrete (HPC)

ACI definition: Concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices.

Examples of characteristics that may be considered critical for an application are:

Ease of placement
Compaction without segregation
Early age strength
Long-term mechanical properties
Permeability
Density
Heat of hydration
Toughness
Volume stability
Long life in severe environments

High workability concrete
Self consolidating concrete (SCC)
High strength concrete
Lightweight concrete
Heavyweight concrete
Pervious (no fines concrete)
Low permeability concrete
Shrinkage compensating concrete
Sprayed concrete

(Russell, 1999)

Introduction

So, questions that you can handle at the end of this semester:

What kinds of properties we have to look at if measured strength of concrete is different from designed strength?

What kinds of actions need to be done if gypsum content in cement is too low or too high?

What kinds of actions need to be done if coarse aggregate contains too much water?

What is the manufacturing strategy to produce high-performance concrete?

How to design concrete for extreme condition?

Can we predict the strength of concrete by looking at its failure surface?

Can we make cementless high-performance concrete?

How can we model time-dependent behavior of concrete such as creep and shrinkage?

Etc.