

Advanced civil infrastructure materials

Related titles:

The deformation and processing of structural materials

(ISBN-13: 978-1-85573-738-9; ISBN-10:1-85573-738-8)

This new study focuses on the latest research in the performance of a wide range of materials used in the construction of structures, particularly structural steels. It considers each material's processing and its deformation behaviour in structural applications. This book will help engineers by providing them with a better understanding of the performance of the major structural materials (especially metals) under different conditions in order to select the right type of material for a job and for setting design specifications. It also shows how the microstructural composition of materials is affected by processing and what influence this has on its subsequent *in situ* performance. This book will be the first to give such comprehensive coverage to the deformation and processing of all types of structural materials and will be a valuable resource for researchers in mechanical, civil and structural engineering.

Analysis and design of plated structures, Volume 1: Stability

(ISBN-13: 978-1-85573-967-3; ISBN-10: 1-85573-967-4)

Steel plated structures are used in a variety of marine and land-based applications, such as ships, off-shore platforms, power and chemical plants, box-girder cranes and bridges. The basic strength members in steel plated structures include support members, plates, stiffened panels and girders. During their lifetime structures constructed using these members are subjected to various types of loading. For example, stiffened panels are prone to buckling, resulting in progressive collapse and failure. For more effective service life it is essential to predict the behaviour and ultimate load-bearing capacity of these structures. This major new book will provide the first authoritative survey on the stability, analysis and design of plated structures particularly laminated plates, tapered steel members, concrete filled tubular columns, and stiffened composite structures. It will be a valuable source of reference for all those in mechanical, civil and structural engineering.

Inspection and monitoring techniques for bridges and civil structures

(ISBN-13: 978-1-85573-939-0; ISBN-10: 1-85573-939-9)

With the current emphasis on infrastructure rehabilitation and renewal, advanced techniques for bridge monitoring and assessment are of great interest to civil engineers and those researchers involved in the testing, inspection, management, planning, design, construction, maintenance and life extension of civil structures. The integration of these techniques can lead towards more realistic predictions of the time-dependent performance of bridges and civil structures. The potential penalties for ineffective inspection can be catastrophic. The overall emphasis now is on a life extension approach which requires the effective use of NDE techniques and reliability monitoring. This comprehensive new book discusses those techniques requiring physical measurement for inspection and/or monitoring of structures.

Details of these and other Woodhead Publishing materials books and journals, as well as materials books from Maney Publishing, can be obtained by:

- visiting www.woodheadpublishing.com
- contacting Customer Services (e-mail: sales@woodhead-publishing.com;
fax: +44 (0) 1223 893694; tel.: +44 (0) 1223 891358 ext. 30; address: Woodhead
Publishing Ltd, Abington Hall, Abington, Cambridge CB1 6AH, England)

If you would like to receive information on forthcoming titles, please send your address details to: Francis Dodds (address, tel. and fax as above; email: francisdd@woodhead-publishing.com). Please confirm which subject areas you are interested in.

Maney currently publishes 16 peer-reviewed materials science and engineering journals. For further information visit www.maney.co.uk/journals.

Advanced civil infrastructure materials

Edited by
Hwai Chung Wu

**Woodhead Publishing and Maney Publishing
on behalf of
The Institute of Materials, Minerals & Mining**

**CRC Press
Boca Raton Boston New York Washington, DC**

WOODHEAD PUBLISHING LIMITED
Cambridge England

Woodhead Publishing Limited and Maney Publishing Limited on behalf of
The Institute of Materials, Minerals & Mining

Published by Woodhead Publishing Limited, Abington Hall, Abington,
Cambridge CB1 6AH, England
www.woodheadpublishing.com

Published in North America by CRC Press LLC, 6000 Broken Sound Parkway, NW,
Suite 300, Boca Raton, FL 33487, USA

First published 2006, Woodhead Publishing Limited and CRC Press LLC

© Woodhead Publishing Limited, 2006

The authors have asserted their moral rights.

This book contains information obtained from authentic and highly regarded sources. Reprinted material is quoted with permission, and sources are indicated. Reasonable efforts have been made to publish reliable data and information, but the authors and the publishers cannot assume responsibility for the validity of all materials. Neither the authors nor the publishers, nor anyone else associated with this publication, shall be liable for any loss, damage or liability directly or indirectly caused or alleged to be caused by this book.

Neither this book nor any part may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, microfilming and recording, or by any information storage or retrieval system, without permission in writing from Woodhead Publishing Limited.

The consent of Woodhead Publishing Limited does not extend to copying for general distribution, for promotion, for creating new works, or for resale. Specific permission must be obtained in writing from Woodhead Publishing Limited for such copying.

Trademark notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation, without intent to infringe.

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library.

Library of Congress Cataloging in Publication Data

A catalog record for this book is available from the Library of Congress.

Woodhead Publishing Limited ISBN-13: 978-1-85573-943-7 (book)

Woodhead Publishing Limited ISBN-10: 1-85573-943-7 (book)

Woodhead Publishing Limited ISBN-13: 978-1-84569-117-2 (e-book)

Woodhead Publishing Limited ISBN-10: 1-84569-117-2 (e-book)

CRC Press ISBN-10: 0-8493-3477-2

CRC Press order number: WP3477

The publishers' policy is to use permanent paper from mills that operate a sustainable forestry policy, and which has been manufactured from pulp which is processed using acid-free and elementary chlorine-free practices. Furthermore, the publishers ensure that the text paper and cover board used have met acceptable environmental accreditation standards.

Project managed by Macfarlane Production Services, Dunstable, Bedfordshire, England (macfarl@aol.com)

Typeset by Replika Press Pvt Ltd, India

Printed by TJ International, Padstow, Cornwall, England

Contributor contact details

(* = main contact)

Chapter 1

Sidney Mindess
Department of Civil Engineering
University of British Columbia
6250 Applied Science Lane
Vancouver, British Columbia
V6T 1Z4
Canada

E-mail: smindess@civil.ubc.ca

Chapter 2

Professor Charles W. Roeder*
Department of Civil Engineering
University of Washington
Seattle
WA 98195-2700
USA

E-mail: croeder@u.washington.edu

Professor Masayoshi Nakashima
Disaster Prevention Research Institute
Kyoto University
Gokasho
Uji
Kyoto 611-0011
Japan

Chapter 3

Professor Hwai-Chung Wu
Department of Civil and
Environmental Engineering
Wayne State University
5050 Anthony Wayne Drive
Detroit
MI 48202
USA

Fax: 00 1 313 577 3881

E-mail: hcwu@eng.wayne.edu

Chapter 4

Dr Julio F. Davalos
Department of Civil and
Environmental Engineering
West Virginia University
Morgantown
WV 26506-6103
USA

Tel: (304) 293-3031, Ext. 2632

Fax: (304) 293-7109

E-mail: Julio.Davalos@mail.wvu.edu

Dr Pizhong Qiao*
Department of Civil Engineering
The University of Akron
Akron
OH 44325-3905
USA

Tel: (330) 972-5226
Fax: (330) 972-6020
E-mail: qiao@uakron.edu

Luyang Shan
Department of Civil Engineering
The University of Akron
Akron
OH 44325-3905
USA

Tel: (330) 972-5226
Fax: (330) 972-6020
E-mail: ls30@uakron.edu

Chapter 5

Vistasp M. Karbhari
Department of Structural
Engineering and Materials Science
and Engineering Program
University of California, San Diego
La Jolla
CA 92093-0085
USA

Tel: 858-534-6470
Fax: 858-534-6373
E-mail: vkarbhari@ucsd.edu

Chapter 6

Professor Habib J. Dagher
Director, AEWCCenter
5793 AEWCC Building
University of Maine
Orono
ME 04469-5793
USA

Tel: (207) 581-2138
E-mail: hd@umit.maine.edu

Chapter 7

John Harrison
TecEco Pty Ltd
Tec-Cement Pty Ltd (Sales)
497 Main Road
Glenorchy TAS 7010
Australia

Tel: 61 3 62497868 (a.m., weekends)
Tel: 61 3 62713000 (p.m., weekdays)
E-mail: john.harrison@tececo.com

Preface

Concrete and steel are by far the most widely used man-made construction materials in the world. Despite numerous successful constructions of worldwide infrastructures, many of these infrastructures are now rapidly deteriorating. It has been estimated that infrastructure rehabilitation costs, in the US alone, will reach into trillions of dollars over the next twenty years. One of the primary causes for the decay of our infrastructures is the deterioration of the materials used in the construction and repair of these structures. Intrinsically, concrete is brittle hence vulnerable to cracking, whereas structural steel is heavy and prone to corrosion. These alarming infrastructural problems indicate an urgent need for more durable construction materials ultimately to replace conventional concrete and steel, and most likely to supplement these popular materials in the near future.

In recent decades, material development in response to the call for more durable infrastructures has led to many exciting advancements, especially the paradigm design example of Fiber Reinforced Plastics Composites which enjoys tremendous success in the aerospace and automotive industries. It has inspired many composite designs involving concrete and wood. These fiber reinforced composites, with unique properties, are now being explored in many infrastructural applications. Even concrete and steel are being steadily improved to have better properties and durability. Such advancement also makes it possible to use advanced concrete or steel in an unprecedented way.

The purpose of this book is to provide an up-to-date review of several emerging construction materials that may have a significant impact on repairs of existing infrastructures and/or new constructions. Two areas take high priority in this book. First, we emphasize the materials design concept which leads to the creation of advanced composites by synergistically combining two or more constituents. Such design methodology is made possible by several key advancements in materials science and mechanics. Second, we conclude each chapter with selective examples of real-world applications using such advanced materials. This includes relevant structural design guidelines and mechanics to assist readers in comprehending the uses of these advanced materials.

Selected authors who are recognized for their expertise in each field have each contributed to certain chapters. It is hoped that this book will be of value both to graduate and undergraduate students of civil engineering, materials science, architecture and construction engineering, and will serve as a useful reference guide for researchers and practitioners in the construction industry.

H C Wu
Detroit, Michigan

1.1 Introduction

Cementitious materials are certainly the oldest manufactured materials of construction, and today are the predominant construction materials worldwide, their production far outstripping those of steel, timber, asphalt and other building materials. Their use goes back at least 9000 years, as in a mortar floor discovered in Israel (Malinowski and Garfinkel 1991; Bentur 2002). Similar lime mortars, prepared by calcining limestone, were used throughout the Middle East. Gypsum-based mortars were later used in Egypt, for example in the construction of the Pyramid of Cheops (~3000 B.C.); these were prepared by calcining impure gypsum. However, neither of these cementing materials is hydraulic; that is, they will not harden under water.

Later, the Greeks and the Romans were able to produce hydraulic lime mortars, mixed with finely ground volcanic ash. In particular, the Romans used a material called *pozzolana*, found in the vicinity of the village of Pozzuoli, near Mt Vesuvius. This material is described by Vitruvius* writing in about 27 B.C.:

There is also a kind of powder which from natural causes produces astonishing results. It is found in the neighborhood of Baiea and in the country belonging to the towns round about Mt Vesuvius. This substance, when mixed with lime and rubble, not only lends strength to buildings of other kinds, but even when piers of it are constructed in the sea, they set hard under water.

Materials such as these were used extensively in hydraulic structures, such as piers and sea walls. They were also used to make a form of concrete. Probably the best preserved Roman structure, the Pantheon, dating from the

*Vitruvius, *The Ten Books of Architecture*, Bk II, Ch. VI (New York, Dover, 1960), pp. 46–7.

second half of the second century A.D. was built largely of concrete. The 44 m diameter dome was constructed by pouring concrete into ribbed sections and letting it harden. In addition, to reduce the weight, a lightweight aggregate (pumice) derived by crushing a porous volcanic rock was used.

Though the quality of cementing materials declined through the Middle Ages, high quality mortars were later rediscovered after the 14th century A.D., and by the middle of the 18th century, research began which led to the development of 'modern' Portland cements. John Smeaton, who in 1756 had been commissioned to rebuild the Eddystone Lighthouse off the coast of Cornwall, England, carried out a series of experiments with different limes and pozzolans, and discovered that the best limestones for this purpose were those containing high proportions of clayey material. While this was still not quite Portland cement, it represented a distinct improvement over the slaked limes then in use.

Other developments followed rapidly. James Parker in England patented (1796) a natural hydraulic cement, produced by calcining nodules of impure limestone containing clay. In France, Louis-Joseph Vicat (1813) prepared artificial hydraulic lime by calcining synthetic mixtures of limestone and clay. Finally, in 1824, Joseph Aspdin, a Leeds builder, took out a patent on 'portland' cement (so named because of a real or fancied resemblance of the hardened cement to a naturally occurring limestone quarried on the Isle of Portland, which was then a popularly used material in buildings). This cement was prepared by calcining finely ground limestone, mixing this with finely divided clay, calcining the mixture again in a kiln, and then finely grinding the resulting clinker. This patent was followed by work in many countries, leading to improved kiln designs and methods of proportioning the raw materials.

However, work on the chemistry of Portland cement really began only late in the 19th century, with the publication in 1887 of the doctoral thesis of Henri Le Chatelier in France. He established that the main cementing phase in the cement was tricalcium silicate ($3\text{CaO}\cdot\text{SiO}_2$), and identified some of the other phases as well. Subsequent work by many others finally resulted in the high quality Portland cements that we use today. Finally, in the 1930s, a systematic study was begun on the role of chemical admixtures in Portland cement concrete. (This technology was not entirely new; the Romans had used animal fat, blood and milk in some of their concretes, probably to improve the workability.) Air entraining agents, water reducers, superplasticizers, set retarders and accelerators, corrosion inhibitors, and various other admixtures make possible the high performance concretes that can now be produced.

Still, to the lay person, concrete is a deceptively simple material: You mix together cement, water and aggregates, and it gets hard – what else is there to know? Indeed, it is this apparent simplicity that has helped to make

concrete such a widely used material. The reality, of course, is very different. Modern concretes, despite the popular prejudice to the contrary, are truly 'high-tech' materials. We can produce concretes for virtually any purpose. However, our ability to produce advanced concretes, with controlled rheological properties, compressive strengths of several hundred MPa, tensile strength of over 50 MPa, high toughness, and excellent long-term durability, depends upon our understanding of the fundamental mechanisms governing the chemical and mechanical properties of the concrete, and our ability to manipulate the microstructure (and sometimes even the nanostructure) of the material. Without this understanding, concrete structures such as the 452 meters tall Petronas Towers in Kuala Lumpur would not have been possible. In the remainder of this chapter, some of the recent developments in the production and use of modern advanced concrete will be described.

1.2 What is modern advanced concrete?

Advanced concrete, more commonly referred to as 'high-performance concrete', may be defined as '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' (Russell 1999). In other words, advanced concrete is simply concrete that is significantly better in some respects than the concrete that we usually make. Clearly, the above definition is, like concrete itself, highly time-dependent; what might have seemed like very advanced concrete 100 years ago would look very ordinary today, just as today's 'advanced' concretes will seem quite primitive 100 years from now.

1.3 Materials

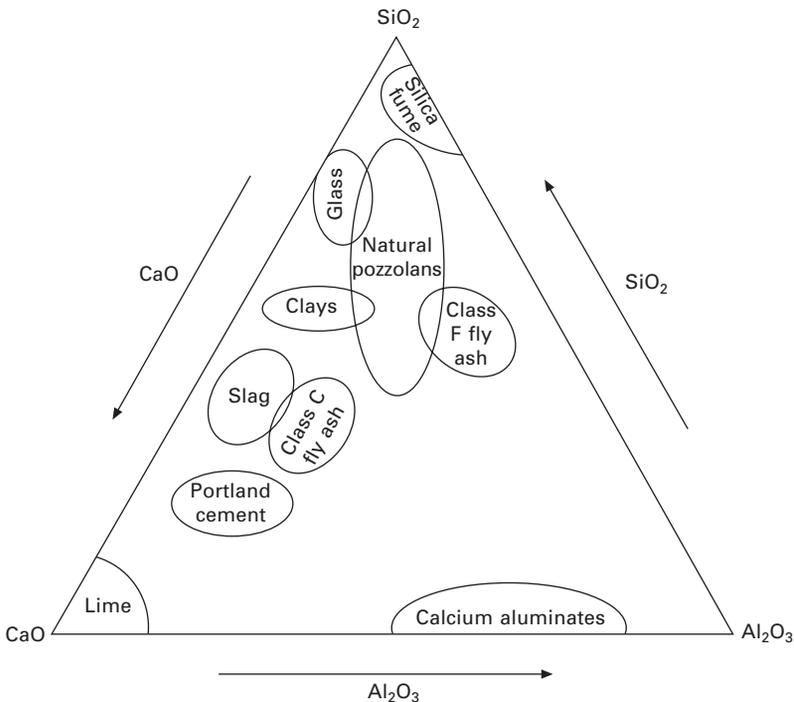
Before discussing the properties of some of the advanced concretes available today, it is necessary first to say a few words about the materials that are currently available. It must be emphasized that, in order to produce truly high performance concretes, it is essential that the composition and properties of *all* of the components of the concrete be carefully considered: cement chemistry and particle size distribution, the chemistry and size distribution of the supplementary cementing materials, the chemistry of the admixtures and their possible reactions with the cementing materials, and the physical, chemical and mechanical properties of the aggregates. In addition, there must be strict quality control governing every phase of the concrete-making process; the design engineer(s), the cement producer, the concrete supplier and the contractor must all work together to ensure the quality of the final product. Even with the best choice of materials, if the concrete is not placed, finished and cured properly, the result will be a substandard material.

1.3.1 Portland cements

The basic raw materials for Portland cement production are limestone (the major source of CaO) and clays or shales containing about 55 to 60% SiO₂, 15 to 25% Al₂O₃ and 5 to 10% Fe₂O₃. The production technology depends upon high-temperature chemistry. Based on the work of Taylor (1997), the high temperature reactions for the formation of cement clinker have been described as follows (Bentur 2002):

1. Decomposition of the clay minerals (~500 to 800 °C)
2. Decomposition of the calcite (~700 to 900 °C)
3. Reactions of the calcite (or lime formed from it), SiO₂ and the decomposed clays to form 2CaO·SiO₂ (~1000 to 1300 °C)
4. Clinkering reactions at about 1300 to 1450 °C to form 3CaO·SiO₂. A melt of aluminates and ferrite is formed to act as a flux to facilitate the formation of 3CaO·SiO₂ by the reaction between CaO and 2CaO·SiO₂
5. Cooling back to ambient temperature, during which time the melt crystallizes to form the ferrite and aluminates phases.

The resulting clinker is then interground with gypsum (to control the setting behavior of the cement). The ternary phase diagram of the CaO-Al₂O₃-SiO₂ system into which the various cementitious materials fit is shown in Fig. 1.1.



1.1 Ternary phase diagram of the CaO-Al₂O₃-SiO₂ system (after Bentur, 2002).

While this helps enormously in our understanding of clinker chemistry, it remains a considerable simplification of the true state of affairs, in that it overlooks several important factors:

1. The presence of the roughly 5 to 8% of impurities present in the clinker, the exact type and amount of which depend on the particular raw material sources. These impurities include alkalis (sodium and potassium), sulfates, magnesium, manganese, iron, potassium, titanium, and perhaps others as well.
2. The fact that the mineral phases formed are not pure, but are 'doped' with various other ions, depending on the exact chemistry of the raw feed.
3. The different mineral phases are not in the form of separate grains; each cement particle will generally contain several phases.

These simplifications are not particularly important for 'ordinary' concretes, whose properties (in both the fresh and hardened states) can be predicted reasonably well based on the aggregate grading, the cement content, and the water/cement (w/c) ratio. The strength and other concrete properties are largely independent of the details of the cement chemistry. However, for high performance concretes, these details can be of vital importance, since such concretes will invariably contain both mineral admixtures and chemical admixtures, and in particular superplasticizers (also known as high range water reducers). The behavior of these much more complex mixtures can be greatly affected by the 'minor' components of the cement, and by the cement mineralogy and composition. The problems of cement-superplasticizer incompatibility and other adverse admixture interactions can create difficulties in finding satisfactory mix designs for concretes for some special applications.

It should also be noted that some of the cements produced today lead, on the whole, to less durable concretes than the 'old' (pre-1960) concretes. This has been driven largely by the demands of the construction industry for higher rates of strength gain, since these permit more rapid form removal and lead to economies in construction costs. The higher rate of strength gain has been achieved primarily by grinding the cement more finely and increasing the tricalcium silicate content; unfortunately, both measures lead to higher heats of hydration and a greater possibility of thermal cracking. Modern concretes also appear to be somewhat more brittle than their older counterparts.

1.3.2 Aggregates

As is the case with cements, ordinary concrete is quite insensitive to the aggregate properties, as long as the aggregates fall within the normal range of particle size distributions, and are not chemically reactive with the cement (as in alkali-aggregate or alkali-carbonate reactions). Even aggregates that

do not meet the specified grading limits may often be used to make satisfactory concretes, albeit at additional cost. However, for advanced concretes, the aggregate properties become increasingly important. Obviously, for the very high strength concretes which will be described later, the aggregates must be strong enough and stiff enough so that they do not become the strength limiting factor. For the new generation of self compacting concretes (SCC) which will also be described later, the aggregate grading must be very tightly controlled to achieve the appropriate rheological properties. It may also be necessary to ‘engineer’ in some way the interfacial region at the cement-aggregate interface, as this is often the ‘weak link’ in the system. Unfortunately, most concrete research over the past few decades has focused on the binder system; it is now becoming necessary to focus equal attention on the aggregates which, after all, make up 70 to 80% by volume of the concrete.

1.3.3 Chemical admixtures

For the purposes of the present discussion, only superplasticizers amongst the various chemical admixtures will be discussed here, since they are essential for the production of most advanced concretes. These types of admixtures were first developed in the 1960s. They are synthetic, high molecular weight, water soluble polymers, that adsorb onto the surfaces of the cement (and supplementary cementitious) particles and are very effective in dispersing these particles. They can permit very large reductions in the amount of water required for adequate workability through three mechanisms:

1. They build up a negative charge on the particle surfaces sufficient to cause repulsion amongst them.
2. They increase the affinity between the particles and the liquid phase.
3. Steric hindrance, which occurs when the adsorbed polymers are oriented in such a way as to weaken interparticle attraction (Haneharo and Yamada, 1999).

There are four main types of superplasticizers currently available (Aitcin 1998; Sakai *et al.* 2003). Melamine superplasticizers (polycondensates of formaldehyde and melamine sulfonate) were the first superplasticizers to be used commercially, and are still widely used in both North America and Europe, and are considered to be very reliable in terms of quality and performance. Naphthalene superplasticizers (polycondensates of formaldehyde and naphthalene sulfonate) are available as either sodium or calcium salts. While the sodium salt version is more commonly used because it is less expensive, the calcium salt version, which does not contain any chlorides, is required for nuclear applications of reinforced or prestressed concrete, to protect the steel from chloride-induced corrosion. In general, these superplasticizers tend to be less expensive than melamine superplasticizers.

Lignosulfonate-based superplasticizers are, by themselves, less effective than the other two, and are not commonly used in conjunction with either of the other two. Recently, a new family of superplasticizers, the polycarboxylates (Sakai *et al.* 2003) have been developed (sometimes referred to as ‘comb-type’ superplasticizers) These superplasticizers maintain the fluidity of the concrete much longer than the naphthalene and melamine superplasticizers but without excessively retarding the concrete mix. They appear to be particularly effective for producing self-compacting concretes (see section 1.4.4).

Unfortunately, not all superplasticizers interact in the same way with all cements (in large part because different cements contain different impurities), and there is no way yet of predicting which combination of cement and superplasticizer will give the best results. Unless there is prior information available, concrete producers may have to resort to a ‘trial and error’ procedure to find the best combination.

1.3.4 Mineral admixtures

Most concretes produced today contain one or more mineral admixtures; it would be unusual to find a pure Portland cement concrete (Malhotra, 1987). As mentioned above, this is particularly true of advanced concretes, for which not only the strength, but also the rheological properties and the durability must be tightly controlled. The mineral admixtures (also known as ‘supplementary cementing materials’), are either preblended with the cement (more common in Europe), or added separately at the batching plant (more common in North America). The three most common such materials are fly ash, granulated blast furnace slag and silica fume. In ordinary concrete, fly ash or blast furnace slag are used primarily for economic reasons, as they are cheaper than the Portland cement that they replace; silica fume, being more expensive than cement, is not used. However, for very high strength, low permeability materials, the use of silica fume, commonly in conjunction with one or sometimes both of the other two materials, is essential. The physical properties of some common supplementary cementing materials are given in Table 1.1; their particle size distributions are shown in Fig. 1.2.

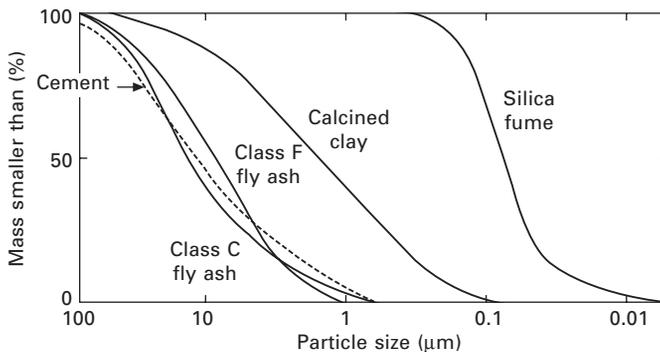
Silica fume

Silica fume is a waste by-product of the production of silicon and silicon alloys, and is most commonly used to make high strength concretes. It is essential for concretes with compressive strengths greater than 100 MPa, and makes it easier to produce high strength concretes in the 60 to 100 MPa range. It is best used at addition rates of about 8 to 10% by weight of cement.

Table 1.1 Physical characteristics of some supplementary cementing materials

Material	Mean size (μm)	Surface area (m^2/g)	Particle shape	Specific gravity
Portland cement	10–15	<1	Angular, irregular	~3.2
Natural pozzolans	10–15**	<1	Angular, irregular	Variable
Fly ash (F and C)	10–15	1–2	Mostly spherical	2.2–2.4
Silica fume	0.1–0.3	15–25	Spherical	2.2
Rice husk ash	10–20**	50–100	Cellular, irregular	<2.0
Calcined clay (metakaolin)	1–2	~15	Platy	2.4

** After grinding



1.2 Particle size distributions of some supplementary cementing materials.

It affects concrete properties by a number of different mechanisms (Mindess *et al.* 2003):

1. It eliminates the growth of calcium hydroxide at the cement-aggregate interface, or transforms the calcium hydroxide to calcium silicate hydrate by the pozzolanic reaction between silica and lime.
2. It eliminates many of the large pores at the cement-aggregate interface, making it denser.
3. It modifies the rheological properties of the fresh concrete, in such a way that internal bleeding is reduced, and less superplasticizer is required to achieve a particular workability.
4. Because of its very fine particle size (about 1/100 the mean size of cement grains), silica fume has a marked filler effect; that is, it is able to pack between the cement grains, lowering the mean size of the capillary pores, and increasing the density of the material.

Fly ash

Fly ash is the inorganic, noncombustible residue of powdered coal after burning in power plants. While it is used in concrete (at typical replacement rates of about 15% by weight of cement) primarily because it is cheaper than cement, it also has the beneficial effect of reacting with the lime produced during cement hydration to produce more calcium silicate hydrate (i.e. the same pozzolanic reaction that silica fume undergoes). This will generally increase the long-term strength and improve the durability of the concrete. By itself, fly ash cannot be used to achieve concrete strengths higher than about 100 MPa; for higher strengths, it must be used in conjunction with silica fume.

Blast furnace slag

Granulated blast furnace slags are the ground residue from metallurgical processes, either from the production of metals from ore or from the refinement of impure metals. They are rich in lime, silica and alumina (and are thus somewhat similar to Portland cements). Pure slag cements react only very slowly, and so commercially they must be activated, most commonly by Portland cement. Typical dosage rates of slag are in the range of 15 to 39% by weight of cement, though much higher dosages are sometimes used. As with fly ash, for compressive strengths in excess of about 100 MPa, they must be used in conjunction with silica fume.

1.4 Modern advanced concretes

In the remainder of this chapter, a number of the principal advanced, or high performance, concretes that are used today will be described. The choice is an arbitrary one, and is not intended to be an exhaustive list of all advanced concretes. Rather, it is intended to describe some of the basic principles, and to illustrate the range of possibilities.

1.4.1 High strength concretes

For most brittle materials, strength is inversely proportional to porosity. A typical expression for this empirical observation is

$$f_c = f_{c0}e^{-kp} \quad 1.1$$

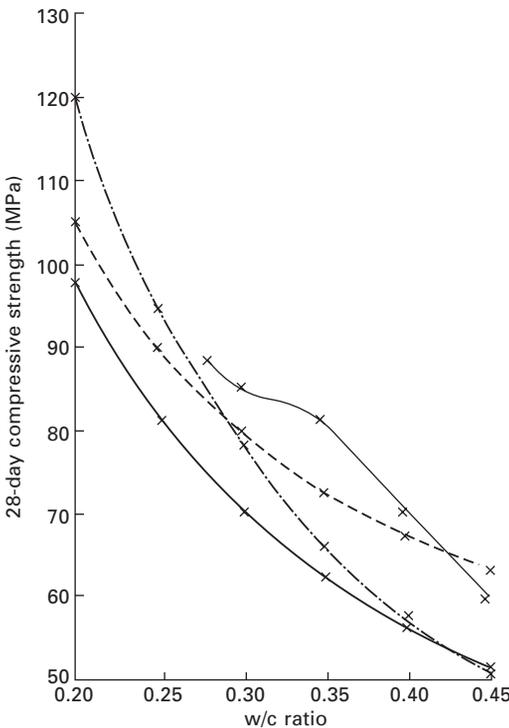
where f_c is the strength, f_{c0} is the strength at zero porosity (sometimes referred to as the 'intrinsic' strength), p is the porosity, and k is a constant that depends on the particular system. Expressions of this form are also applicable to concrete, for which the porosity is largely determined by the w/c ratio.

The w/c ratio ‘law’ enunciated by Duff Abrams in 1918 states that ‘For given materials, the strength depends only on one factor – the ratio of water to cement.’ This can be expressed as

$$f_c = (A/B)^{(w/c)} \tag{1.2}$$

where A and B are constants which depend on the cement properties, age, curing conditions, and so on. This works reasonably well for ordinary concretes, and even up to strengths of about 120 MPa as shown in Fig. 1.3; indeed, it forms the basis for most mix design procedures.

However, as the w/c ratio decreases, particularly below about 0.3, this relationship becomes increasingly unreliable. The constant ‘A’ is frequently taken to be 96.5 MPa (14,000 psi), implying a maximum strength of 96.5 MPa, but we know that it is possible to make concretes with strengths well in excess of 600 MPa. Thus, simple reliance on the w/c ratio law does not work for ultra-high-strength concretes. This should come as no surprise, since Abram’s law was formulated long before the advent of superplasticizers and supplementary cementing materials. Clearly, though, something besides



1.3 Compressive strength vs. w/c ratio for different concretes.

w/c ratio (or porosity) must play a large part in determining the strength of very low w/c ratio concretes. Unfortunately, we do not yet know what these additional factors are, though they may be related to an improved cement-aggregate bond, or to stronger bonds within the hydrated cement paste system. Table 1.2 shows some mix proportions and properties of some commercially available high strength concretes in North America (Burg and Ost 1994). These are empirically arrived at mix designs, since there are as yet no generally accepted procedures for a more rational design of such mixes.

Table 1.2 Mix proportions and properties of some commercially available high strength concretes (after Burg and Ost, 1994)

Units per m ³	Mix number					
	1	2	3	4	5	6
Cement, Type 1, kg	564	475	487	564	475	327
Silica fume, kg	–	24	47	89	74	27
Fly ash, kg	–	59	–	–	104	87
Coarse aggregate SSD (14 mm crushed limestone), kg	1068	1068	1068	1068	1068	1121
Fine aggregate SSD, kg	647	659	676	593	593	742
HRWR Type F, litres	11.6	11.6	11.22	20.11	16.44	6.3
HRWR Type G, litres	–	–	–	–	–	3.24
Retarder, Type D, litres	1.12	1.05	0.97	1.46	1.5	–
Water to cementing materials ratio	0.28	0.29	0.29	0.22	0.23	0.32
Fresh concrete properties						
Slump, mm	197	248	216	254	235	203
Density, kg/m ³	2451	2453	2433	2486	2459	2454
Air content, %	1.6	0.7	1.3	1.1	1.4	1.2
Compressive strength, 100 × 200-mm moist-cured cylinders						
3 days, MPa	57	54	55	72	53	43
7 days, MPa	67	71	71	92	77	63
28 days, MPa	79	92	90	117	100	85
56 days, MPa	84	94	95	122	116	–
91 days, MPa	88	105	96	124	120	–
182 days, MPa	97	105	97	128	120	–
426 days, MPa	103	118	100	133	119	–
1085 days, MPa	115	122	115	150	132	–
Modulus of elasticity in compression, 100 × 200-mm moist-cured cylinders						
91 days, GPa	50.6	49.9	50.1	56.5	53.4	47.9

1.4.2 Ultra-high-strength concretes

While high-strength concretes in the range of about 100 to 125 MPa are now readily available, at least in some regions, there is another class of concretes that may be referred to as ultra-high-strength. They are also sometimes referred to as ‘reactive powder (RPC) concretes’. With concretes of this type, compressive strengths of over 600 MPa and flexural strengths approaching 100 MPa have been achieved.

RPC was developed in France in the early 1990s (Richard and Cheyrezy 1994; Richard 1996). The quite remarkable properties of this material were achieved by careful control of the concrete mixture, in particular the particle size distribution of *all* of the solid materials. Optimization of the particle size distribution leads to a mix approaching optimum density. RPC contains no coarse aggregate; indeed, the maximum aggregate size is 0.3 mm! This permits production of a more homogeneous material. For purposes of ductility, up to 5% by volume of steel fibers are added to the mix. Typical mix proportions and mechanical properties of two different strength levels of RPC are given in Table 1.3. It must be noted, however, that to achieve the higher strength levels some degree of heat treatment may be required. RPC was used to build a pedestrian walkway at the University of Sherbrooke, Quebec, Canada, using conventional concreting equipment and techniques, as a demonstration of using this apparently exotic material in the field.

A commercial development of RPC is now being marketed under the name of DUCTAL[®]. For some applications heat treatment (90 °C steam for 48 hours) is applied to improve the dimensional stability and durability. With steel fibers, compressive strengths are of the order of 150 to 180 MPa, with flexural strengths of about 32 MPa. These strengths are reduced by about 25% when polypropylene fibers are used. This material was used

Table 1.3 Typical composition and properties of RPC (adapted from Richard and Cheyrezy, 1994)

	RPC 200	RPC 800
Type V Portland cement	955 kg/m ³	1000 kg/m ³
Fine sand (150–400 µm)	1051 kg/m ³	500 kg/m ³
Silica fume	229 kg/m ³	230 kg/m ³
Precipitated silica (35 m ² /g)	10 kg/m ³	–
Ground quartz (µm)	–	390 kg/m ³
Superplasticizer	13 kg/m ³	18 kg/m ³
Steel fibers (12.5 × 180 µm)	191 kg/m ³	–
Steel microfibers (< 3 mm long)	–	630 kg/m ³
Total water	153 l/m ³	180 l/m ³
f'c (compressive strength)	170–230 MPa	490–680 MPa
E	54–60 GPa	65–75 GPa
Flexural strength	25–60 MPa	45–102 MPa