

High performance concrete: recent developments in material design

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*You mix together cement, water and aggregate, and it gets hard.
What else is there to know about concrete?*

– Anonymous

The use of high strength concrete ($f'_c > 70$ MPa) is becoming increasingly common. However, when we use the phrase “high performance concrete”, other properties of the concrete are also taken into consideration, such as the rheology of the fresh concrete or the durability of the hardened concrete. With the advent of a new generation of admixtures, combined with a much better understanding of the fundamental mechanisms governing rheology, strength, cracking and durability, we can now largely “tailor-make” concretes to provide the precise properties required for a particular project. Unfortunately, while the knowledge certainly exists to permit the production of concretes with a wide variety of properties, there continue to be a distressing number of concrete failures, due largely to a poor transfer of the existing technology from the laboratory to the field. This is evidenced by the explosive growth in construction-related litigation. At least in North America, one unfortunate consequence has been a concerted attempt to water down existing codes and standards, rather than to base our material designs on the underlying science.

In this lecture, the issues governing the design of some of the different types of high performance concretes will be discussed, in terms of the fundamental principles underlying the selection of the materials. (Inevitably, given the background of the author, this will be largely from a North American perspective). As will become apparent, the science is largely understood – it is the practice that needs most of our attention!

1. Introduction

High performance concrete has been defined as “concrete meeting special combinations of performance and uniformity requirements that cannot



FIGURE 1. Abandoned cement silo in the town of Concrete, Washington, U.S.A.

always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices" [1]. In more colloquial language, it is simply concrete that is better in one or more respects than the concrete that we usually make. Clearly, like concrete itself, this definition is highly time-dependent. What might have been considered a high performance concrete 100 years ago would probably look very ordinary today. In its commentary to this definition, ACI goes on to state [1] that

"A high performance concrete is a concrete in which certain characteristics are developed for a particular application and environment.

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.”

It is interesting to contrast this definition with an earlier one developed by the Strategic Highway Research Program SHRP-C-205 on High Performance Concrete [2], which defined high performance concrete rather differently:

- It shall have one of the following strength characteristics:
 - 4-hour compressive strength ≥ 17.5 MPa,
 - 24-hour compressive strength ≥ 35 MPa, or
 - 28-day compressive strength ≥ 70 MPa.
- It shall have a durability factor greater than 80% after 300 cycles of freezing and thawing, following ASTM C666 Method A.
- It shall have a water – cementitious materials ratio $[w/cm] \leq 0.35$.

Eventually, under the SHRP program, four types of high performance concrete were developed [3], all to have a durability factor greater than 80% as defined above:

- Very Early Strength (VES): 6-hour compressive strength ≥ 14 MPa, $w/cm \leq 0.40$.
- High Early Strength (HES): 24-hour compressive strength ≥ 34 MPa, $w/cm \leq 0.35$.
- Very High Strength (VHS): 28-day compressive strength ≥ 69 MPa, $w/cm \leq 0.35$.
- Fiber Reinforced: HES + (steel or polypropylene fibers), $w/cm \leq 0.35$.

These are much more restrictive than the ACI definition [1], and are therefore less helpful, since they focus almost entirely on strength.

After over 100 years of serious concrete research, and the publication of literally hundreds of thousands of reports, books and research papers, one would be forgiven for thinking that virtually all of the concrete problems listed above have by now been solved. We can now commercially produce a remarkable range of concrete products, all of which may be classified as *high performance concretes*:

- High strength concretes, with compressive strengths of up to 600 MPa; compressive strengths > 100 MPa are becoming commonplace;
- Controlled low strength concretes, with compressive strengths of only a few MPa;
- Self-compacting (or flowing) concretes;

- Corrosion inhibiting concretes;
- “Tough” concretes (through the addition of fibres and/or polymers);
- Durable concretes.

In fact, we can now largely “tailor-make” concretes for virtually any project. Why, then, do we still so frequently encounter concrete durability problems, severely cracked or spalled concrete, an environmentally unfriendly material, and failures of concrete structures? Why, in North America at least, is construction litigation such a growing industry?

2. Current issues

Traditionally, concrete structures have been designed primarily on the basis of the strength of the concrete. It was (and all too often still is) assumed that if the concrete were strong enough to carry the design loads, it would also behave satisfactorily in all other respects: “Strength (compressive or flexural) is the most universally used measure for concrete quality” [4]. While modern design codes (e.g., [4]-[6]) do, of course, include provisions for durability, it remains the case that the only criterion now used for judging the adequacy of the concrete in a structure is its compressive strength (f'_c). For new construction, the acceptance criterion is that the average compressive strength, f'_{cr} , exceeds f'_c by a statistical factor that takes into account the variability in the test data. For *in situ* concrete that is suspected of having suffered damage, the acceptance criterion [4]-[6] is that the average compressive strength of drilled cores shall be $\geq 0.85f'_c$.

Unfortunately, this approach to design and quality control has not always served us well, in part because it does not explicitly deal with the issue of durability. Concrete is an inherently durable material, as long as it is designed, placed and maintained properly. However, many modern concrete structures have not performed satisfactorily. For instance, it has been estimated that the annual cost of the repair of concrete structures in Europe is of the order of five billion U.S. dollars. In the United States, about one-third of the concrete highway bridges are in need of repair, and there are similar durability problems world wide. Much of this is due to improper choice of materials, and/or poor construction practices, due to the inattention paid to durability by many design engineers. It is *not* due to a lack of knowledge of the factors that go into making durable concrete, since there is a huge volume of literature on this topic (e.g., Refs. [7]-[10]).

As stated above, we have made enormous advances in the types of concrete that we can now produce. However, in our approach to mixture proportioning, we still rely largely on *prescriptive* specifications, including re-

quirements such as maximum water-cement (w/c) ratios, minimum cement contents, cement types, and so on. While prescriptive specifications have served us reasonably well in the past, they have also had the unintended consequence of inhibiting the most efficient use of the materials now available to make up a concrete mixture. It is perhaps time to consider a much more extensive use of *performance based* specifications. Properly devised, these could permit concrete producers to be more imaginative and innovative in their use of supplementary cementing materials, admixture, blended cements, fibres, polymers, and so on. One major problem inhibiting the move to performance based specifications is the lack of quick and reliable *tests* of concrete properties, which would have to go far beyond our reliance on f'_c as the sole arbiter of concrete quality. In particular, we would need to establish tests for those durability concerns (e.g., sulfate resistance, freeze-thaw resistance, alkali-aggregate reactivity, marine exposure, corrosion resistance, scaling, and so on) that may be germane to any particular project.

A related problem is that of *assigning responsibility* for proper concrete design. If we do move towards performance based specifications, there must be some way of giving the consumers (buyers) of the concrete confidence that the concrete is indeed suitable for its intended purpose. This would require a clear definition of exactly who is responsible for ensuring concrete quality, and clearly defined procedures to deal with those (hopefully infrequent) cases in which the concrete does not meet its performance requirements. Currently, this responsibility appears to be rather diffusely shared amongst the geotechnical engineer, the structural engineer, the cement producer, the concrete supplier, the contractor, the developer, and perhaps others as well. Given the cost and complexity of construction litigation, this is not a situation to inspire confidence in the ultimate owner of the concrete structure.

The final issue to be addressed here is that of *sustainability*, or to use the popular term, "*green concrete*". According to Mehta [11], the concrete industry is the largest user of natural resources in the world, and thus has a considerable environmental impact; each tonne of Portland cement requires about 1.5 tonnes of raw materials for its production. This industry is not only energy intensive (requiring about 4000-7500 MJ of energy to produce each tonne of cement), but is also a major contributor of greenhouse gases, in the form of CO_2 . Each tonne of Portland cement clinker that is produced involves the release into the atmosphere of about one tonne of CO_2 . Indeed, the cement industry is responsible for about 7% of global CO_2 emissions [12]. Thus, if the concrete industry is itself to remain "sustainable", the way in which we specify, produce, use and recycle concrete must undergo significant changes [13]-[16].

3. Design of high performance concrete mixes

As has been noted by Aitcin and Mindess [17], “ordinary” concrete is a relatively forgiving material. Its strength is assumed to be governed primarily by the w/c ratio, and aggregate properties are not generally considered (except for those properties required for mix design). However, for high performance concretes, it is essential that the properties of *all* of the concrete components be carefully considered: cement, supplementary cementing materials, admixtures, and aggregates. In some applications, the cement-aggregate interface also plays an important role. As well, there must be strict quality control governing every phase of the concrete-making process. This means that the design engineer(s), the concrete producer, and the contractor must all work together to ensure the quality of the final product.

In what follows, the principles and the issues underlying the design of some of the major classes of high performance concrete are discussed.

3.1. High strength concrete

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

$$f_c = f_{c0} e^{-kp} \quad (3.1)$$

where f_c is the strength, f_{c0} is the strength at zero porosity (i.e., the “intrinsic” strength), p is the porosity, and k is a constant which depends on the particular system. This expression is also applicable to cementitious materials, for which p is largely determined by the w/c ratio. Hence, for concrete, the w/c ratio “law” enunciated by Duff Abrams in 1919 states that “For given materials, the strength depends only on one factor – the ratio of water to cement.” This can be expressed as

$$f_c = A/B^{(w/c)} \quad (3.2)$$

where A and B are constants which depend on the cement properties, age, curing conditions and so on. For ordinary concretes, the w/c ratio works well for any given set of materials, and indeed forms the basis for most common methods of mix design. However, this relationship becomes increasingly unreliable as the w/c ratio decreases, particularly when $w/c \leq$ about 0.3. For these low w/c ratios, the scatter in the results becomes increasingly large [17], as may be shown in Fig. 2. As well, the constant A in Eq. (3.2) is frequently taken to be 96.5 MPa (14 000 psi), implying an upper limit for f_c of 96.5 MPa, while we know that it is possible to make concretes with $f_c > 600$ MPa. Thus,

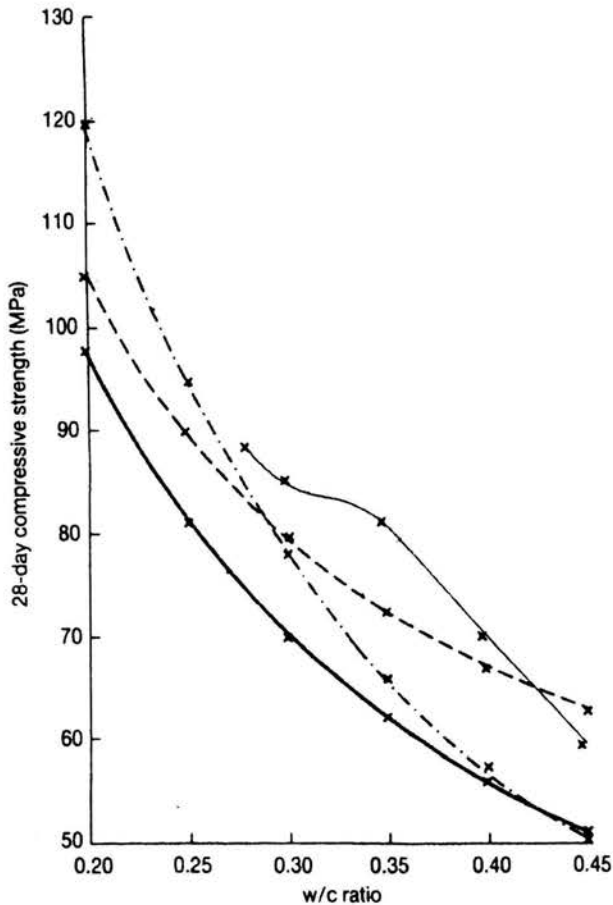


FIGURE 2. Compressive strength vs. w/c ratio relationships.

even if the concrete can be *fully compacted* using the appropriate workability aids and an optimum particle size distribution of all of the solid materials, simple reliance on some form of the w/c ratio law does not work for very high strength concretes.

In addition, Abram's law was originally formulated for cements that were quite different from modern Portland cements: they were much more coarsely ground, and had significantly lower tricalcium silicate (C_3S) contents. Moreover, it was formulated before the advent of today's supplementary cementing materials and superplasticizing admixtures. It is thus not surprising that it does not properly describe modern high strength concretes, for which the use of these materials is essential. Clearly, something else in addition to porosity must play a large part in determining the strength of very low w/c ratio

mixtures. For instance, Aitcin and Neville have recently suggested [18] that an improved cement paste-aggregate bond, and better bonding within the hydrated cement paste system generally, may be largely responsible for the much higher strengths that can now be obtained; they were unable, unfortunately, to define the nature of these bonds.

It is worth noting that since the w/c ratio controls the porosity of the hydrated cement paste, it also therefore controls the *permeability* of the concrete, and thus plays a major role in determining the *durability* of the concrete. However, there are still no empirical relationships (of the form of Eq. (3.1) or (3.2)), which can be used to relate the permeability of concrete to the w/c ratio.

Aitcin [19] has provided a detailed account of the considerations that should go into the materials selection for high strength concretes. It must be noted that high strength concretes can be made with a large variety of materials, though as the required strength increases, the materials selection criteria become increasingly stringent.

Portland cement. Cement for use in high strength concrete not only must develop the appropriate strength, but also must exhibit the appropriate rheological behaviour. Many different cements have been used successfully to produce high strength concrete. However, most cement specifications (such as ASTM C150 – Standard Specification for Portland Cement) are quite imprecise in their chemical and physical requirements. Hence cements of nominally the same type can have quite different strength and other characteristics, particularly when used in conjunction with superplasticizers and supplementary cementing materials. Therefore, when choosing cement for use in high strength concrete, both its fineness and its chemistry must be examined carefully.

Increasing the *fineness* of cement will increase the rate of early strength gain, but may also lead to rheological problems, since the greater amount of reaction at early ages (in particular the formation of ettringite), will increase the rate of slump loss. It may also lead to somewhat lower strengths at much later ages. It is now recommended that the cement should have a Blaine fineness in the range of that of ASTM Type I (ordinary) cement, 300 to 400 m²/kg [20]. In terms of the *chemical composition* [19], the cement should contain as little C₃A as possible (for reasons of rheology control), and what C₃A there is should be primarily cubic in form (rather than orthorhombic). The cement should contain the right amount of *soluble* sulfates to control the ettringite formation. It should also contain somewhere in the range of 50-55% C₃S.

Unfortunately, the cements produced today lead, on the whole, to concretes that are generally less durable than the "old" (pre-1960) concretes. This has been driven largely by the demands of the construction industry for higher rates of strength gain (and by our obsession with 28-day compressive strengths). Higher early strengths permit more rapid form removal, and thus lead to economies in construction costs. This higher rate of strength gain has been achieved primarily by increasing the C_3S content and the fineness of the cement, but at the "cost" of higher heats of hydration and a greater possibility of thermal cracking. Modern concretes also appear to be somewhat more brittle than their older counterparts. So, in the end, this has led to concretes with inferior long-term properties.

Supplementary cementing materials. Most modern high strength concretes contain at least one supplementary cementing material: fly ash, blast-

TABLE 1. Physical characteristics of selected supplementary cementing materials.

<i>Material</i>	<i>Mean size</i> [μm]	<i>Surface area</i> [m^2/g]	<i>Particle shape</i>	<i>Specific gravity</i>
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	platey	2.4

* after grinding

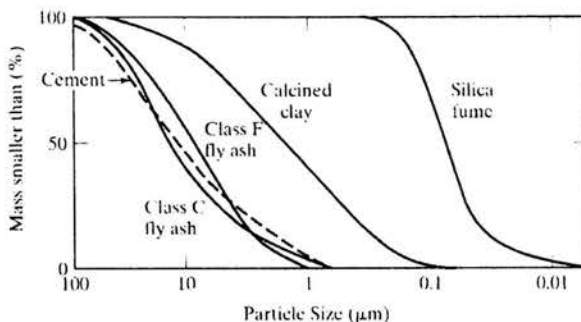


FIGURE 3. Particle size distributions for some supplementary cementing materials.

furnace slag, or silica fume [21]. Very often, silica fume is used in combination with one of the other two materials, as so-called *ternary* cement blends are becoming more common [22, 23]. The physical properties of some supplementary cementing materials are given in Table 1; their particle size distributions are shown in Fig. 3.

Silica fume: It is possible to make concretes with compressive strengths of up to about 100 MPa without the use of silica fume, though it is always easier to make such high strength concretes with the use of silica fume than without it. Above 100 MPa, the use of silica fume is essential. In addition, for very low water/binder ratios, about 10% silica fume will greatly reduce the amount of superplasticizer required for a given workability; silica fume can thus act as an efficient fluidifier [24].

Since silica fume is a waste by-product of the production of silicon and silicon alloys, its quality is rather variable. It is therefore necessary to characterize any new source of this material. While there is as yet no ASTM standard specification for silica, there are various other national standards. For instance, the Canadian Standards Association [25] has quite specific requirements, as shown in Table 2. The American Concrete Institute [26] has also provided very useful guidelines for silica fume quality. Silica fume is available in various forms: bulk (200-250 kg/m³); densified (400-500 kg/m³); in slurry form (with a solids content of about 50%); and in some places already blended with Portland cement. In any one location, though, the choice may be much more limited.

TABLE 2. Some Canadian specifications for silica fume (taken from CSA Standard A23.5 [25]).

<i>Chemical requirements</i>	
SiO ₂ , min. (%)	85
SO ₃ , max. (%)	1.0
Loss in ignition, max. (%)	6.0
<i>Physical requirements</i>	
Accelerated pozzolanic activity index, min. (%) of control	85
Fineness, max. (%) retained on 45 μm sieve	10
Soundness - autoclave expansion or contraction (%)	0.2
Relative density, max. variation from average (%)	5
Fineness, max. variation from average (%)	5
<i>Optional physical requirements</i>	
Increase of drying shrinkage, max. (%) of control	0.03
Reactivity with cement alkalis: min reduction (%)	80

There are a number of different mechanisms by which silica fume affects concrete properties [27]:

- It eliminates the growth of calcium hydroxide, particularly at the cement-aggregate interface, or transforms the calcium hydroxide to C-S-H by the *pozzolanic reaction*.
- It eliminates many of the larger pores at the cement-aggregate interface, making it more homogeneous and denser.
- It modifies the rheological properties of the fresh concrete in such a way as to reduce internal bleeding.
- 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 reducing water requirements.

Empirically, silica fume seems to work “best” at addition rates of about 8-10% by mass of cement [19]. However, it must be emphasized that its effectiveness is strongly dependent upon how well the silica fume is dispersed in the concrete. This generally requires the use of superplasticizers and thorough mixing.

Fly Ash: Fly ash has, of course, been used extensively in concrete for many years [15, 16, 25]. Indeed, in some areas, it is difficult to find ready-mixed concrete that does not contain fly ash. Fly ashes that work well in ordinary concrete will also work well in high strength concrete. By itself, fly ash will not generally lead to strengths greater than 100 MPa; for higher strengths, it must be used in conjunction with silica fume.

Fly ash is a highly variable material in both its physical and chemical characteristics. Therefore, for its use in high strength concrete, quality control is of the utmost importance. In addition to the Blaine fineness, the contents of SiO_2 , Al_2O_3 , Fe_2O_3 , CaO , alkalis, carbon and sulfates should be determined. The degree of crystallinity is also important; the more glassy the fly ash, the better.

Fly ash is generally used at dosages of about 15% by mass of cement in high strength concrete, but this number can vary considerably, depending on the other details of the mix. (See discussion below regarding high volume fly ash concretes.)

Blast Furnace Slag: As with fly ash, slags that perform well in ordinary concrete would also be expected to perform well in high strength concrete, at typical dosage rates of about 15 to 30%. Again, to achieve strengths in excess of about 100 MPa, slags must be used in conjunction with silica fume.

Because slag compositions do not vary much, quality control is generally limited to measurements of Blaine fineness, and X-ray diffraction studies to ensure that the degree of crystallinity is low.

Ternary Blends: As indicated above, ternary blends of cement, silica fume and other mineral fillers are becoming more common. Properly designed, these may improve both the rheological properties of the concrete and the strength (particularly the early age strength). An example of the effects of such blends on strength is shown in Table 3 [28].

TABLE 3. Effects of some ternary blends on the strength of high performance concrete [28].

(a) Microfiller particle sizes

<i>Microfiller</i>	<i>Surface area</i> [m ² /kg]	<i>Average</i> <i>particle size</i> [μm]
Ordinary Portland cement (OPC)	350	25.6
Silica fume (SF)	18 000	0.26
Limestone filler 1 (LF1)	2 300	2.90
Limestone filler 2 (LF2)	10 000	0.70
Ground silica (GS)	1 250	13.8

(b) Microfiller effect on 28-day compressive strength ($w/b = 0.25$)

<i>Microfiller blend</i>	<i>28-day compressive</i> <i>strength</i> [MPa]
OPC	92
OPC + 15% GS	87
OPC + 15% LF1	95
OPC + 15% LF2	102
OPC + 15% SF	116
OPC + 10% LF2 + 10% SF	115
OPC + 15% LF	114

Aggregates. The compressive strengths and elastic moduli of aggregates vary enormously (Table 4), depending upon the geologic history of any particular aggregate source, and the nature and degree of weathering. For ordinary concretes, the aggregate strength is rarely a consideration, since it is assumed (correctly) that almost all common aggregates are stronger than the cement paste matrix. Kaplan [29] used several different aggregates to make concrete and concluded that there was no relationship between aggregate strength

TABLE 4. Strength and elastic modulus of some common aggregates.

<i>Aggregate</i>	<i>Compressive strength [MPa]</i>	<i>Elastic modulus [GPa]</i>
Granite	35-450	15-60
Limestone	90-270	10-80
Sandstone	35-240	5-50
Quartzite	110-470	~ 80
Marble	50-240	20-65
Gneiss	95-235	25-70
Schist	90-290	~ 50

and concrete strength, though he went on to say that weak aggregates could affect concrete strength. The data in the literature indicate that, for ordinary concretes, it is necessary only that the aggregate strength be *similar* to the design concrete strength. However, for high strength concretes, the aggregate itself may become the strength limiting factor. Therefore, the coarse aggregate particles must be strong. A number of different aggregate types have been found to be suitable (limestone, granite, diabase, and so on), so at least in principle suitable aggregates should be fairly widespread in the world.

Any discussion of aggregates for high performance concrete must also include a discussion of the cement-aggregate interface (generally referred to as the *interfacial transition zone*, *ITZ*). In the ITZ, the volume fractions of the phases constituting the microstructure are significantly different from those in the "bulk" hydrated paste:

- Less unhydrated cement,
- Higher porosity, with generally larger pores,
- Less C-S-H,
- Large oriented crystals of calcium hydroxide,
- Greater concentration of ettringite.

Because of this particular microstructure, it is often suggested that the ITZ is the strength limiting factor for ordinary concretes. In high strength concretes, however, the combined use of a low w/c ratio, superplasticizers, and very fine supplementary cementing materials such as silica fume or metakaolin essentially densifies the ITZ or eliminates it entirely, thus removing this "weak link" in the concrete structure.

The elastic modulus of the concrete cannot simply be related to that of the aggregate. However, it would appear that, in general, a higher elastic modulus of the aggregate will lead to a higher concrete elastic modulus.

The coarse aggregate particles should, of course, be clean, roughly equidimensional, and not prone to any chemical reactions (e.g., alkali-silica reaction) with the cement paste. It is helpful if the aggregate surfaces are rather rough, rather than smoothly polished, as this will improve the cement-aggregate bond. It is often assumed that the coarse aggregate should have a relatively small maximum size (in the range of 10-15 mm), but this is not necessarily true, since perfectly good high strength concretes have been made with aggregate sizes up to 25 mm.

The fine aggregate should, ideally, consist of smooth, rounded particles, to reduce the water demand. Gradings should be on the coarse side (fineness modulus > 3), both to improve workability of high paste content mixes, and to decrease the amount of water required for adequate workability.

Superplasticizers. Superplasticizers (high range water reducers) are an essential component of modern high strength concrete mixes. A number of different superplasticizers are commercially available. While the exact formulations are generally closely guarded industrial secrets, the most common types are:

- Pure bases,
- Sodium or calcium salts of polynaphthalene sulfonate,
- Sodium salt of polymelamine sulfonate,
- Sodium lignosulfonate,
- Polyacrylate.

For a detailed account of the various ways in which superplasticizers act in concrete, the reader should consult [19]. Suffice it to say that all of them might be found suitable in some applications, but no one type will always work.

The issue is one of *cement-superplasticizer compatibility*. The ability of any superplasticizer to work effectively depends not only on the composition of the superplasticizer itself, but also on the chemistry of the cementitious phase (including supplementary cementing materials), and on the presence of other chemical admixtures (air entraining agents, retarders, corrosion inhibitors, etc.). Different superplasticizers will have differing degrees of effectiveness in different systems, and there is no easy way to predict what will happen for any particular combination of materials. So, one is inevitably left with a “trial and error” situation, in which different brands of superplasticizer might be combined with different cement brands and supplementary cementing materials to find the combination that is most effective. Similarly, there is no way to predict *a priori* the required *superplasticizer dosage* – it too must be determined experimentally.

3.2. Mix design for high strength concrete

Finally, it must be pointed out that there are no well-accepted methods of designing a very high strength concrete mix, since as pointed out earlier the usual w/c vs. strength relationships are rather unreliable for very low w/c ratios. The variety of high strength mixes shown in Table 5 [30] might, however, provide at least a starting point for what must still be an empirical mix design procedure.

TABLE 5. Mixture proportions and properties of commercially available high-strength concrete (after Burg and Ost [30]).

Component	Units	Mix number					
		1	2	3	4	5	6
Cement, Type 1	kg/m ³	564	475	487	564	475	327
Silica fume	kg/m ³	–	24	47	89	74	27
Fly ash	kg/m ³	–	59	–	–	104	87
Course aggregate SSD (14 mm crushed limestone)	kg/m ³	1068	1068	1068	1068	1068	1121
Fine aggregate SSD	kg/m ³	647	659	676	593	593	742
HRWR Type F	litres/m ³	11.6	11.6	11.22	20.11	16.44	6.3
HRWR Type G	litres/m ³	–	–	–	–	–	3.24
Retarder, Type D	litres/m ³	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
<i>Fresh concrete properties</i>							
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
<i>Compressive strength, 100 × 200 mm moist-cured cylinders</i>							
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	–
<i>Modulus of elasticity in compression, 100 × 200 mm moist-cured cylinders</i>							
91 days	GPa	50.6	49.9	50.1	56.5	53.4	47.9

3.3. High volume fly ash concrete

As already indicated above, fly ash is currently used mostly at addition rates of about 15% by mass of cement. However, because of the issue of sustainable development discussed earlier, it is desirable both for economic and for environmental reasons to use a much higher proportion of fly ash (or slag) in our concretes. Thus there is currently a great deal of development in what are referred to as *high performance, high-volume fly ash concrete* [15, 16]. Such concretes may be defined as:

- Containing at least 50% fly ash by mass of the cementing materials,
- Having a Portland cement content of less than 200 kg/m³,
- Having a water content of less than 130 kg/m³,
- Having a water/cementing materials ratio of less than 0.35.

Because of their high pozzolanic content, these concretes reach their full strength potential rather more slowly than conventional concretes. For instance, the 91-day and 365 day strengths of such concretes may be 20% and 40%, respectively, higher than the 28-day strength [15], thus providing a considerable benefit for the durability of the concrete. It appears to make no particular difference whether the fly ash is added at the batching plant, or is preblended with the cement. It is not clear what maximum strength can be attained with these concretes, but 28-day compressive strengths in excess of 40 MPa have certainly been obtained.

TABLE 6. Comparison of mixture proportions for 25 MPa concrete (adapted from [11]).

	<i>Conventional concrete</i>		<i>HVFA concrete</i>	
	by mass [kg/m ³]	by volume [m ³]	by mass [kg/m ³]	by volume [m ³]
Cement	307	0.097	154	0.049
Fly ash	–	–	154	0.063
Water	178	0.178	120	0.120
Entrapped air (2%)	–	0.020	–	0.020
Coarse aggregate	1040	0.305	1210	0.449
Fine aggregate	825	0.322	775	0.299
Total	2350	1.000	2413	1.000
w/cm	0.58	–	0.38	–
Paste – volume:	–	0.226	–	0.192
– percent:	–	29.6%	–	25.0%

Properly produced high volume fly ash concretes have a low permeability, and thus are highly durable. They are also more resistant to cracking than ordinary concretes of the same strength. The reasons for this may be explained by comparing the two typical mixes shown in Table 6 [11].

As may be seen, the high volume fly ash mix has both a lower water to cementitious materials ratio, and a substantially lower paste volume, though both mixes have about the same 125-150 mm slump. For both of these reasons, the drying shrinkage and the heat of hydration are substantially reduced, leading to less likelihood of cracking for the fly ash concrete.

However, it must be emphasized that even more than for ordinary concretes, proper curing is essential. It is recommended [16] that there be at least 7 days of moist curing, at temperatures in excess of 10°C, for high volume fly ash concrete to achieve its full potential.

3.4. High durability concrete

For many engineers, unfortunately, the concepts of “high strength” and “high durability” are synonymous. Of course, these are in fact quite separate concepts. There is far more concrete distress due to poor durability than there is due to low strength. Thus, in designing high performance (or any other concrete), it would be more sensible to focus first on the environmental conditions to which the concrete will be exposed, and only then to worry about strength. Fortunately, many modern design codes are beginning to encourage such an approach. For instance, The ACI Building Code [6] is now formatted to indicate that durability requirements shall take precedence over strength requirements. (On the other hand, the mix design procedures outlined in ACI 211 [31] are less clear in this regard, and remain focused more on strength, though if they are read and followed carefully the durability requirements should also be properly taken care of. The mix design procedures recommended in Refs. 4 and 6 are much clearer with regard to durability).

The first line of defence against any form of external chemical attack (e.g., due to sulfate attack, de-icing chemicals, seawater, industrial waste water, agricultural wastes, and so on) is to produce a concrete with a low water/cementitious materials (w/cm) ratio [32]. (Some codes do indeed specify *maximum* w/cm ratios of 0.40 for the most severe freeze-thaw or sulfate conditions). This reduces the porosity and permeability of the concrete, making the ingress of aggressive chemicals much more difficult. Thus, it is worth emphasizing again that ***it is the w/cm ratio, and not the strength, that governs the permeability, and hence the durability, of concrete.*** The lower w/cm ratio is also likely to lead to higher strengths, perhaps higher than are absolutely “necessary” for the structure in question, but it is the

durability requirements that must prevail. (Presumably, a skilled structural designer will be able to make good use of this “extra” strength).

Of course, permeability is not the only factor that controls durability. We must not forget the other well-known durability requirements: air entrainment for freeze-thaw exposures, sulfate resistant cements, low alkali cements when the aggregates are susceptible to the alkali-silica reaction, and so on. However, even in these cases, a low w/cm ratio will be of great assistance in mitigating the severity of the attack.

Since most high performance concretes contain some supplementary cementing materials, the reaction between the calcium hydroxide and the pozzolanic material, which effectively reduces the amount of $\text{Ca}(\text{OH})_2$ and increases the amount of C-S-H, also leads to reduced permeability, particularly when silica fume is used.

We must also recognize that the concrete “skin” (the outermost 5-10 mm of the concrete surface) generally has rather different properties than the “bulk” concrete in the interior of a structural member. Because of the so-called *wall effect*, aggregate particles are less densely packed at the concrete surface, and so this region tends to be rich in cement paste. If the concrete is not cured properly, this can increase the possibility and the severity of surface cracking due to differential drying shrinkage.

Abrasion resistance. The abrasion resistance of concrete is an important parameter in highway pavements, dam spillways and stilling basins, and so on. In some areas, abrasion due to ice is also of importance. Abrasion resistance is one of the few durability parameters that is in fact almost entirely proportional to the strength of the concrete, though the coarse aggregate properties and volume concentration are also of importance. Thus, high strength concretes, particularly those made with the incorporation of silica fume, are particularly abrasion resistant. It has also been suggested that the incorporation of steel fibres into a low w/c ratio mix can improve the abrasion resistance, but there have been mixed experiences using this technique.

It has been found that at compressive strengths of about 120-150 MPa, concrete has about the same abrasion resistance as granite. In general, it is found that, for the same water/binder ratios, the coarse aggregate properties are the determining factor in abrasion resistance. For instance, Laplante et al. [33] found that granitic aggregates led to a more abrasion resistant concrete than did dolomite or limestone aggregates. However, there is still no standard test that can be used to predict the abrasion resistance of any particular aggregate, though tests such as the Los Angeles abrasion test may be helpful at least for screening purposes.

Freeze-thaw resistance. It is sometimes suggested that, because of their low w/c ratios, very high strength concretes need not be air entrained in order to provide adequate resistance against repeated cycles of freezing and thawing. However, though the mechanisms of freezing and thawing in concrete are now pretty well understood [34], this remains an open question, and the experimental studies to date have shown mixed performance. Some low w/c ratio mixes perform well under freeze-thaw cycling, while others do not. In addition, there is an obvious contradiction in wanting to entrain air into high strength concretes, since every 1% of air entrainment will reduce the compressive strength by about 5% [27].

The experimental evidence on the necessity (or otherwise) of using air entrainment in high strength mixes has been summarized by Aitcin [19]. Basically, for concretes made with w/c ratios of *less than 0.25*, it would appear that air entrainment is not necessary [34]. For mixes with $w/c > 0.30$, air entrainment should be used as for ordinary concretes. In the intermediate range, the necessity of air entrainment will depend on the particular cement, the presence of supplementary cementing materials, and so on, and this can be determined only by carrying out the appropriate freeze-thaw tests. (What constitutes an "appropriate" freeze-thaw test is a matter of considerable controversy, and is outside the scope of the present discussion. Here, "appropriate" will be defined loosely as conforming to whatever national standards are currently in use). In the view of the author, it would be prudent to conduct the appropriate freeze-thaw tests on all high strength concretes, even those for which the $w/c < 0.25$.

Closely related to freeze-thaw resistance is the issue of *salt scaling*, that is, damage due to repeated applications of de-icing salts in freezing conditions. While the precise mechanisms underlying salt scaling are not understood, it is known that scaling is most likely to occur on surfaces that have been overvibrated, troweled too early and too long, subjected to plastic shrinkage, or where excessive bleeding has occurred. Clearly, then, the curing and finishing procedures will have a considerable influence on scaling resistance. Fortunately, care in this regard is always mandatory for high strength concretes, and so these are generally found to be highly resistant to scaling.

Scaling resistance is largely controlled by the w/c ratio, as is freeze-thaw resistance. However, it has been found [19] that it is generally easier to make a scaling resistant high strength concrete than one that is resistant to freezing and thawing.

Corrosion of steel in concrete. The corrosion of steel in concrete is probably the single most expensive durability problem facing our concrete infras-

structure. The mechanisms of steel corrosion in concrete are by now well known and understood (10, 35). Whether it occurs or not depends heavily on the quality of the concrete "skin" as discussed earlier, and on the thickness of the concrete cover. However, a number of different "materials" solutions to the problem of steel corrosion have been proposed over the years, all of which have both advantages and drawbacks.

Galvanized reinforcing bars have long been used to try to prevent steel corrosion. The zinc coating acts both as a barrier and as a sacrificial coating, as the zinc itself slowly oxidizes (corrodes). The effectiveness of the coating depends on its thickness, with its effective life expectancy being linearly proportional to its thickness. For instance, ASTM [36] specifies two types of coatings, with thicknesses of about 85 μm and 150 μm . Thicknesses greater than about 200 μm may decrease the bond between the concrete and the rebar.

While galvanizing is effective against corrosion induced by carbonation of the concrete cover, it is apparently less effective when the corrosion is induced by chlorides [35]. As well, if the coating is too thin, then it may break when the rebars are being bent or handled at the jobsite, which can lead to very rapid localized corrosion. Finally, galvanized steel cannot be welded. Nonetheless, despite their relatively high cost, galvanized rebars seem to find a ready market.

In *epoxy coated reinforcing bars*, the epoxy acts as a barrier to isolate the steel from an aggressive environment. Typically, the thickness of the epoxy coating is specified [37] to be in the range of 130 μm to 300 μm , with a specified maximum number of defects of various kinds. The epoxy must be flexible enough to permit the bar to be bent without rupturing. If the coating is ruptured, this can lead to severe localized corrosion and failure of the rebar. There have also been some instances of the epoxy coating de-bonding from the steel when used in warm marine environments. In addition to the high cost, the major problem with epoxy coating is that the bond between the concrete and the steel is substantially reduced, increasing the possibility of cracking, and requiring the use of larger anchorage and lap lengths.

Stainless steel reinforcing bars are occasionally used in extreme exposure conditions. While they are very effective in preventing corrosion, their high cost severely limits their use.

Corrosion inhibitors of various types are now becoming increasingly common. These act not as barriers to aggressive agents, but as chemicals that reduce the corrosion of the steel. There are two types of corrosion inhibitors: *Anodic* inhibitors stabilize and reinforce the passivating film which forms on the steel surface in the high pH environment of concrete. *Cathodic* inhibitors are adsorbed onto the steel surface, where they act as a barrier to the reduc-

tion of oxygen (which is the principal cathodic reaction for steel in concrete). However, it must be remembered that corrosion inhibitors are effective only if used in otherwise good concrete; they are not a panacea for corrosion in poorly designed or placed concrete.

The most common anodic corrosion inhibitor is currently calcium nitrite, which acts essentially by increasing the level of chloride necessary to initiate corrosion [38]. Cathodic inhibitors are less effective than anodic ones. They are primarily amines, phosphates, zincates and phosphonates, which have the unfortunate side effect of severe set retardation at the high dosages required for them to provide effective corrosion control.

The measures to prevent steel corrosion noted above (coatings, corrosion inhibitors) should really be seen not as absolute solutions, but as means of providing additional protection to otherwise good quality concrete. This brings us to perhaps the most sensible and efficient means of avoiding most corrosion problems: The use of the *high performance concretes* that are the subject of this discussion, that is, concretes with a low water/cementitious materials ratio, and perhaps incorporating supplementary cementing materials. The low permeability of such concretes should provide adequate corrosion protection.

In particular, for more extreme exposure to chlorides, a high performance silica fume concrete should provide good protection. There are two reasons for this. A low water/binder silica fume concrete has very low permeability, making the ingress of chloride ions difficult. As well, such concretes have high electrical resistivity (about an order of magnitude higher than that of ordinary concrete), which reduces the chloride diffusion rate. If necessary, the silica fume concrete can be combined with one of the other chemical or mechanical means of reducing corrosion described earlier.

3.5. Reactive Powder Concrete (RPC)

RPC is an ultra-high strength-concrete that was developed in France in the early 1990s [39, 40]. With this material, it is possible to achieve strengths of up to 800 MPa, combined with very considerable ductility, and flexural strengths of up to 100 MPa. These quite remarkable properties are achieved by very careful control of the concrete mixture, and particularly the particle size distribution of *all* of the solid ingredients. The material contains no coarse aggregate at all. Indeed, the maximum particle (aggregate) size is 300 microns (0.3 mm). In addition, very finely ground quartz (4 micron) and silica fume are added, along with a very high cement content. For ductility, up to about 5% of steel fibers are added. For workability, a substantial superplasticizer dosage must also be used. Typical mix proportions and mechanical

properties of two different strength levels of RPC are given in Table 7 [39]. It must be emphasized that in order to achieve these properties, some heat treatment may be required. For the lower strength RPC 200, heating to about 90°C at ambient pressure is recommended, while for the RPC 800, heat treatment at 250°C to 400°C is required. The properties can also be enhanced by applying pressure to the fresh concrete during setting.

TABLE 7. Typical compositions and properties of RPC (adapted from [39]).

<i>Component or property</i>	<i>RPC 200</i>	<i>RPC 800</i>
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 (4 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 litres/m ³	180 litres/m ³
f'_c	170-230 MPa	490-680 MPa
E	54-60 GPa	65-75 GPa
Flexural strength	25-60 MPa	45-102 MPa

There are a number of conditions to be satisfied for the production of RPC. Not using coarse aggregate particles permits production of a more homogeneous material. Optimization of the grain size distribution of the solids leads to a mix approaching optimum density. The microstructure of the hydrated cementitious materials is enhanced by heat treatment, accelerating the pozzolanic reaction, and in the case of RPC 800 leading to the formation of crystalline xonotlite. The fibers, of course, provide the ductility and the high fracture energies.

A commercial development of RPC is now being marketed under the name of DUCTAL[®] (a joint venture amongst Bouygues Construction, Lafarge Concrete and Rhodia). This material has the following typical mix proportions: 710 kg/m³ cement, 230 kg/m³ silica fume, 210 kg/m³ crushed quartz, 1020 kg/m³ sand, 13 kg/m³ superplasticizer, 140 kg/m³ total water, and 40-160 kg/m³ of either steel or synthetic fibers (13 mm × 0.20 mm). For some applications, primarily to further enhance durability and dimensional stability, heat treatment with 90°C steam is applied for 48 hours. This concrete is rather denser than ordinary concrete (2500 kg/m³ vs. 2320 kg/m³).

When using steel fibers, f'_c is in the range of 150-180 MPa, with a flexural strength of about 32 MPa and $E = 50$ GPa. Strength values with the synthetic fibers are about 25% lower. Because of the low water/binder ratio, and therefore low permeability, these materials also tend to be highly durable.

As these ultra-high-strength materials come into more common use it is likely that even higher compressive strengths will be achieved commercially, rather than just in the laboratory.

3.6. Self-Compacting Concrete (SCC)

Self-compacting concrete (SCC) is concrete that can flow on its own (i.e., without vibration) to fill the forms of virtually any shape, and to become fully compacted with no segregation or bleeding. These concretes will typically have free slump values in the range of 250-275 mm! This technology was first developed in Japan in the late 1980s, and is now gaining widespread acceptance, as it can be used to produce both "ordinary" concretes and high strength concretes. While from a material point of view SCC is certainly more expensive than ordinary concrete, this is compensated for by the much greater ease of placement.

Basically, SCC is obtained by increasing the volume of fine material in the concrete without particularly changing the amount of mixing water, combined with the use of superplasticizers. Typically, the ratio of fine to coarse aggregate in SCC is of the order of 1.0 to 1.3 (for normal concretes, it is approximately 0.75). As well, there must be a relatively high volume of material with particle sizes below 0.125 mm; this is often achieved by use of appropriate supplementary cementing materials.

The background for SCC and the current technology for its production are described in detail in [41, 42]. In particular, the fresh concrete must exhibit the following properties:

- Filling ability, or the ability of the concrete to flow into the formwork and around the reinforcing bars entirely under its own weight, and to fill the formwork completely.
- Passing ability, or the ability of the SCC to pass through narrow spaces in the formwork, or through and around the reinforcing bars, without either blocking or segregating.
- Segregation resistance, both while it is flowing, and after it has finally come to rest.

The way in which we select and proportion the concrete mix determines whether we can meet all of these objectives. The basic principles may be summarized as follows:

- The required high fluidity is achieved by severely limiting the coarse aggregate content, and by the use of superplasticizers.
- The use of superplasticizers also permits a reduced water/binder ratio.
- The resulting reduced water/binder ratio, combined with the limited coarse aggregate content, imparts a high segregation resistance to the concrete.
- The high fluidity, combined with the high segregation resistance, then make possible the production of SCC.

In order to achieve the appropriate *fresh* concrete properties, EFNARC [42] suggests the following mix proportions as a first estimate:

- Water/powder ratio (by volume) of 0.8 to 1.1,
- Total powder content of 400-600 g/m³,
- Coarse aggregate content of 28-35% of the mix volume,
- Water content less than 200 kg/m³,
- Fine aggregate content to make up the remainder of the volume.

Of course, these values may have to be modified to meet the strength and durability requirements of the *hardened* concrete for a particular project. If the specified fresh or hardened concrete properties can not be met, then the mix should be adjusted as appropriate, making use of different types or volumes of supplementary cementing materials or fine mineral fillers, using different superplasticizers, adding a viscosity modifying agent, changing the fine/coarse aggregate ratio, and so on.

At the moment, unfortunately, there are no well-defined or agreed upon procedures to determine the rheological properties of SCC (or of any other type of concrete). Thus, in the design of these concretes, and for quality control, one or more *ad hoc* or empirical tests are used. Typical tests, as described by EFNARC [42], include tests to assess horizontal free flow, to assess the ability of the concrete to pass through layers of steel reinforcement, to assess the “filling” ability of the concrete, or to assess its segregation resistance (or stability).

The durability and the strength of SCC are similar to those of ordinary concrete, since it is the *w/c* ratio that largely controls these properties.

3.7. Controlled low-strength materials

To emphasize the point that “high performance” is *not* synonymous with “high strength,” it is appropriate to end this discussion of high performance concretes with a description of a very different type of high performance material, namely *controlled low-strength material* (CLSM). CLSM may be

defined as “a self-compacted, cementitious material used primarily as a back-fill in place of compacted fill” [43]; it must have a compressive strength of *less* than 8.3 MPa. It is not generally considered merely to be a low-strength concrete – rather, it is used more specifically as backfill, structural fill, as a pavement base, and as a bedding material for pipes, conduits, and so on. It is also used for filling voids in abandoned tunnels, sewers or mines.

CLSM is made with essentially the same materials and admixtures as used in conventional concretes. As with many other types of concrete, mix proportioning is carried out empirically, depending on the particular application. Typically, cement contents are low (30-120 kg/m³), while fly ash contents, which help to determine the flowability of the material, can range as high as 1200 kg/m³. The aggregate consists most commonly of only fine aggregate, at contents of about 1500-1800 kg/m³. When coarse aggregates are used, they constitute about 50% of the total aggregate. For good flowability, relatively high water contents are used, ranging from about 200 to 350 kg/m³. Often, although these concretes are not designed to withstand freeze-thaw cycles, high volumes of air are incorporated to lower the unit weight of the CLSM. In some cases, pre-formed foams are used to achieve very low unit weights; densities as low as about 300 kg/m³ have been achieved, though the compressive strength of such a mix could be as low as 0.1 MPa.

4. Concluding remarks

The foregoing discussion has dealt with the properties (in terms of the raw materials) of some of the major classes of high performance concretes. The choice of which concretes to describe in some detail has been an arbitrary one, intended to describe some of the basic principles, and to illustrate the range of possibilities; it was not intended to be an exhaustive list of all of the concretes that can be considered to be “high performance”. In particular, fibre reinforced concretes and polymer concretes were not discussed. Clearly, with our understanding of basic principles, and with the materials and production technologies currently available, we can produce an enormous range of Portland cement-based materials. Indeed, we can now largely “tailor-make” concretes for virtually any application. The strength and durability levels that we can now achieve will almost certainly be surpassed in the future; *we are limited only by our imaginations*. The challenge for the future is to ensure that the way in which we educate civil engineers (and others involved in cement and concrete production and use) reflects the issues of innovation and sustainability, without which the industry will not continue to prosper.



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