Processing of HPC

by Chiara F. Ferraris and Colin L. Lobo

High-performance concrete (HPC) has been used more widely in recent years due to the increasing demand for durable concrete in an attempt to extend the service life and reduce maintenance costs of concrete structures. To identify the type of problems related to production of HPC encountered in the field, the National Ready-Mixed Concrete Association (NRMCA) conducted a survey of ready-mixed concrete producers. The National Institute of Standards and Technology (NIST) assisted in the analysis of the responses and in conducting a literature review. In this article, the results obtained from the survey and the findings from the literature review are presented. Recommendations are drawn from the results. Research needs are also presented.

The definition of HPC is not standardized, nevertheless a commonly used definition is given by Zia: "A concrete that meets special performance and uniformity requirements that can not always be obtained using conventional ingredients, normal mixing procedures, and typical curing practices."[1]

The definition we used in the survey was relative to a job specification and was based on one suggested by the Federal Highway Administration (FHWA).[2] This concrete specification requires one or more of the following: a minimum compressive strength of 41 MPa (6000 psi), a water-cement ratio (*w/c*) less than 0.40 and chloride ion permeability less than 3000 Coulombs as measured by ASTM C 1202.[2,3] These specifications can only be achieved by closely monitoring the properties and uniformity of concrete ingredients and the production process. The critical stages for HPC use are: flowing, transporting, placing, finishing and curing.

Ready-mixed concrete industry survey

Two surveys were conducted by NRMCA. The first survey was a short questionnaire attempting to identify companies involved with producing HPC and those who would be willing to answer more detailed questions on the processing of HPC. The second questionnaire was more elaborate and asked detailed questions about the job specifications, type of structure, materials used, and processing of HPC, as well as mix design, quality control, and observations about handling, placing, curing and testing concrete. Besides being sent to the previous respondents, this questionnaire was mailed to a wider pool of producers. Overall, the surveys did not generate a significant number of responses.

The first survey triggered 48 responses and a description of 108 jobs. A summary of the types of concrete specifications is given in Table 1. All concretes but one corresponded to the definition of HPC given previously. Only 24 percent of the jobs had a specification requirement for the measurement of chloride ion permeability. The general comment was that it was difficult to meet the specification for chloride ion permeability. This is due primarily to the significant variability in the test results and because there is no adequate guidance in designing concrete mixtures and modifying the production process to obtain the specified value.

The second questionnaire yielded 24 responses from 17 companies. A summary of the concrete specifications is given in Table 2. The general conclusions are:

The chloride ion penetration test was generally not specified except for parking garages or bridge deck concretes. Companies reported no problems conforming to the *w/c* and the compressive strength specification.

All HPC mixtures contained both mineral and chemical admixtures. In many cases the concrete mixtures contained more than one supplementary cementitious material, i.e., fly ash and silica fume.

The production technique was almost evenly divided between central-mixed and truck-mixed concrete.

This second, more extensive questionnaire, was divided into three main sections: workability, finishability and curing. This article will examine these three properties in detail, combining findings from the survey and the literature.

The specification issue

Ideally, specification formats should follow either a prescriptive approach or

Table 1 — First survey results

Compressive strength MPa (ksi)				Chloride penetration 10^3 Coulombs			*w/c*			
41 - 55 (6 - 8)	55 - 69 (8 - 10)	69 - 97 (10 - 14)	> 97 (> 14)	3 - 2	2 - 0.8	< 0.8	**1**	**2**	**3**	**4**
Percent of responses										
49	23	14	1	1	12	11	39	29	7	3

The total number of responses were 108 from 48 companies. Seven participants stated that they did not deliver HPC.

The responses were classified for strength and chloride ion permeability as described on the table in reference 2. The ***w/c*** were divided in 4 categories:

1 = 0.40 - 0.35
2 = 0.35 - 0.30
3 = 0.30 - 0.27
4 = < 0.27

Most of the concretes were defined either by the compressive strength (22 percent) or by the *w/c* (16 percent), or both (63 percent). Therefore, it can be deduced that the only test of durability that was considered is not always performed and that the two parameters recorded are strength and *w/c*.

Table 2 — Second survey results

Compressive strength MPa (ksi)				Chloride penetration 10^3 Coulombs			*w/c**			
41 - 55 (6 - 8)	55 - 69 (8 - 10)	69 - 97 (10 - 14)	> 97 (> 14)	3 - 2	2 - 0.8	< 0.8	**1**	**2**	**3**	**4**
Percent of responses										
59	32	9	0	0	18	4	59	23	4	14

There were 24 responses from17 companies. The same classification was adopted for the second survey as for the first.

Some other characteristics are:

- All participants reported the concrete test results, but it should be noted that only 5 (22 percent) reported the results of the chloride ion permeability test.
- All concretes were specified by strength, *w/c*, and slump.
- Some (68 percent) reported the air content, although it was specified for only 59 percent of the concretes.
- Almost all concretes (90 percent) contained mineral admixtures.
- High-range water-reducing admixtures were used in all concretes but one. The time of addition was regular for 32 percent and delayed for 67 percent of the cases.
- Air entrained admixtures were used in 32 percent of the concretes.
- 45 percent of the responses indicated that concrete was truck-mixed while 54 percent used central mixers.
- 50 percent of the responses indicated that the mixture tended to be sticky and caused build-up in the truck and/or mixer.
- 77 percent of the responses indicated that the concrete was hard to finish.

*See Table 1 for ***w/c*** categories.

a performance approach and not a mixture of the two. In the prescriptive format the concrete producer is told how to design the mixture with parameters such as a minimum cement content, maximum *w/c*, admixtures quantities, or in some cases batch quantities of concrete ingredients. The performance approach, on the other hand, would require attributes such as strength, workability and permeability.

An interesting exercise is to evaluate the specification formats from the first survey. Overall, for the 108 job specifications, 80 percent had a strength requirement, 73 percent had a specified *w/c* and 24 percent had a requirement for chloride ion. Only 13 percent followed a strictly prescriptive format by specifying only a *w/c* ratio. A strictly performance format was used in 28 percent of the specifications where strength and/or permeability were specified. Illustrative of the mixing of specification formats, 72 percent of the jobs prescribing strength and 84 percent of the jobs prescribing chloride ion permeability, also specified a maximum *w/c*.

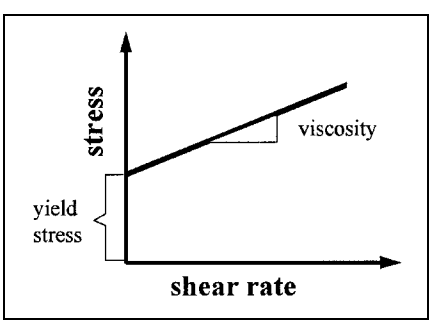

Fig. 1 — Definition of a Bingham fluid.

Workability

Workability or placeability is usually defined by concrete slump, or, in some parts of Europe, as the spread of the concrete after a kind of slump cone test, DIN 1045.[4] On the other hand, workability is often intuitively defined as the ease of handling, placing and finishing. The premature loss of workability of HPC is often reported as a major problem. Operators quantify this phenomenon as a slump loss. Survey responses indicated that complying with a target slump range was difficult to achieve. Most of the producers from the survey controlled the workability by either delayed addition of a specified amount of high-range water-reducing admixture (HRWRA) or by the adjustment of the admixtures dosage at the job site. The literature reports the same tendency in other countries,[5, 6, 7] while small changes in the water content can be also a means of controlling the workability of HPC.[8]

Survey responses indicated that more than half considered the slump test to be adequate to characterize workability but a better test was needed. In the literature, the same problems and needs are reported.[5, 9, 10, 11] It is generally recognized that the slump test does not fully quantify the workability of HPC, but no other currently available test is as easy to conduct.

The reason for the discrepancy often encountered between the slump test results and the perceived workability or pumpability of a given concrete is that the concrete behaves like Bingham fluid (Fig. 1). Concrete rheology is characterized by two parameters: the yield stress and the plastic viscosity. The yield stress is the stress needed to initiate movement and the plastic viscosity is the slope of the stress versus the shear rate after the stress exceeds the yield stress.

The yield stress can be related to the measurement of the slump. Viscosity measurements are more sophisticated, because the measurements must be done while the concrete is moving. Only a few instruments exist that can measure either the viscosity directly or a value related to the viscosity.[12]

The importance of distinguishing between the two factors, yield stress and

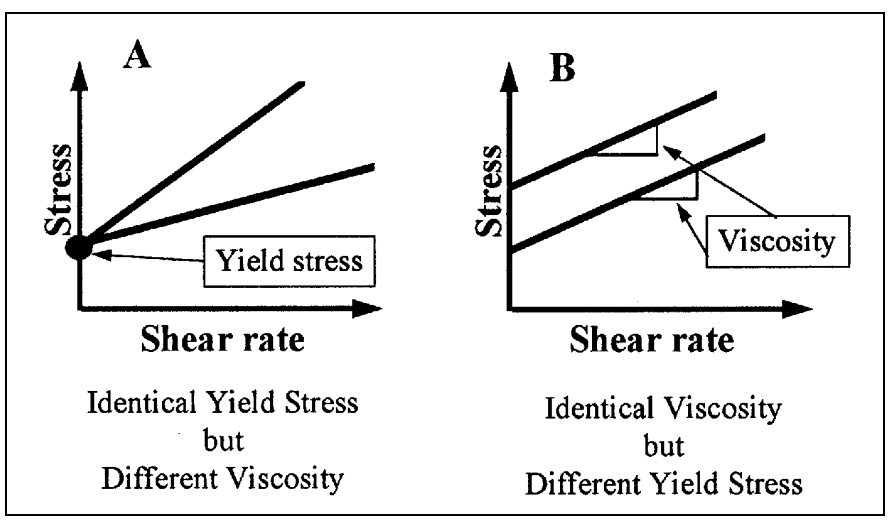

Fig. 2 — Concrete rheology.

viscosity, is illustrated in Fig 2. The difference in the rheological characteristics of two concrete mixtures can be differentiated only if both parameters are measured. A study by Punkki et al.[13] showed that, depending on time of addition and dosage of the chemical and mineral admixtures, yield stress and viscosity are modified in different ways. More precisely, the slump loss phenomenon generally corresponds to an increase of the yield stress, while the plastic viscosity only displays minor changes.[14]

Another problem related to the rheological properties of concrete is segregation. While HPC is generally cohesive and holds together well, slight changes in the material characteristics can result in segregation, such as aggregate grading or moisture content. The survey indicated that segregation could be avoided if the concrete slump was maintained at a 76 to 127 mm (3 to 5 in.) range. Vibration can increase the segregation if improperly performed. On the other hand, adjusting the viscosity of cement paste can prevent the problem. Unfortunately, as only the slump is measured, the difference in viscosity is only perceived by comparison between mixes, not by actual measurement. Therefore, the prediction of segregation is not possible from the tests routinely performed at the job site. The laboratory mixing method is not identical to the one used in the field. Therefore, laboratory trial batches can be quite different from field production batches.

Finishability

The finishability of a concrete depends on the relative perception of the person on the job, and it is more critical for some types of structures, such as slabs and bridge decks. No standard test characterizing finishability exists. HPC is almost always reported as being hard to finish with descriptions like "sticky" or "rocky." Factors such as high cementitious materials content, large doses of chemical admixtures and air entrainment contribute to the difficulty in finishing these concretes. Rostam[9] reported that HPC has a tendency to stick to everything, including reinforcing steel and finishing trowels. In the survey, 75 percent of the responses reported that the concrete mixtures were sticky. In fact, some contractors[15] do not use HPC for slabs that must be trowelled for smoothness because of the stickiness problem. Malier et al.[10] suggested that the concrete should be finished less than 30 min. after placement to prevent such difficulties.

The stickiness of HPC is related to its high cohesiveness, the viscosity of the mix and lack of bleeding due to the increased amount of fine particles, and the low *w/c* ratio. HPC is different from regular concrete and finishers should recognize the need for a different sequence of operations. Due to the lack of bleeding, a crust will form relatively quickly preventing the finishing tool from operating correctly. The crust formation can lead to other problems such as cracking and difficulties in blending two successive layers of concrete. Great attention to timing of finishing operations is recommended.

The fact is that the stickiness is related to the viscosity of the outer layer of the concrete, i.e., mortar with fine sand or cement paste, makes the slump test inadequate to determine the finishability. A test method to predict the finishability of HPC is needed.

Curing

HPC is characterized by a lack of bleeding due to the low *w/c* ratio and a high heat of hydration, a result of the high cementitious factors used. The lack of bleeding results in a quick drying at the surface, if it is left unprotected and bleed water does not readily move to the surface.[16] The surface dries out relative to the interior which leads to plastic shrinkage cracking. These cracks are either parallel or in a mesh form and they appear in the first 10 hours after placement,[16] sometimes as early as 30 min. after casting.

To prevent this type of cracking it is important to follow proper curing practices that are correctly timed. The three methods adopted are wet burlap or similar fabric, curing compounds, and fog sprays. In extreme cases, more than one method is used simultaneously. The timing of application is critical to avoid plastic shrinkage cracking. Rostam[9] recommends that all free surfaces must be protected before 0.5 kg/m^2 (0.1 lb/ft^2) of water has evaporated. He suggests that the rate of evaporation should not exceed 0.3 kg/m^2/hr (0.06 lb/ft^2/hr). ACI recommends that protective measures be used when the evaporation rate exceeds 0.5 kg/m^2/hr, which might not be sufficient precaution for some HPC concrete mixtures, especially with those mixtures incorporating silica fume.

In the survey, 62 percent of the contractors used a water mist or wet burlap, while 16 percent used a curing compound. Only less than 1 percent reported that nothing was used to protect the concrete during the first 24 hours. The duration of the curing also varied from 24 hours (16 percent) to 7 days (20 percent) while 1 percent protected the structure to about 14 days. HPC typically uses high dosages of HRWRA that retard the setting time and the development of early age strength. Therefore, often a longer curing time is necessary to obtain the high strength specified.

The other type of cracks that are likely to appear are thermal cracks, due to the high heat of hydration associated with HPC mixtures. Thermal cracking is due to the thermal gradient within the concrete mass or between a previously cast portion and the newly placed concrete. To prevent thermal cracks, the solution depends on the case. In the first case, a temperature gradient between the interior of the concrete and the ambient atmosphere should be avoided. Many authors[17-21] advise that the temperature should be closely controlled and that the concrete surface be insulated with a blanket or foam during the setting and hardening period, as it can take up to 5 days for the concrete to equilibrate with ambient temperature.[16] In the second case, the remedy is to lower the temperature rise of the newly cast concrete as much as possible, e.g., by lowering the as-placed concrete temperature, by replacing the cement by supplementary cementitious materials or by cooling the structure by passing water through embedded pipes.

It might be worth using finite element calculations for a better control of the temperature related cracking.[8] Tanigawa[20] showed that compressive strength of concrete in the center of a structure decreases with higher temperature. He recommends the use of low heat cements and emphasizes proper curing of the structure. On the other hand it seems that the final strength of HPC is less sensitive to high temperature, relative to conventional concrete. In our survey, only one contractor for one job indicated that the temperature was maintained below maximum of 50 C (122 F).

From the survey, only 17 percent reported problems with plastic shrinkage or drying shrinkage cracking. Most of the reported cracks were due to plastic shrinkage. This finding is quite surprising because the literature reports crack-

ing to be a real problem, where it seems that no large job is totally immune from cracks.

In addition to plastic shrinkage and thermal shrinkage, another type of cracking at very early age has been reported,[22] which is due to the autogenous shrinkage of concrete. HPC displays a rather high autogenous shrinkage due to its low water-binder ratio.[23] Unlike conventional concrete, HPC autogenous shrinkage is high enough to provoke cracking when fully restrained.

Finally some cracking phenomenon has been reported in HPC bridge decks, although the concrete was properly cured and still in the dormant period.[24] It is believed that the chemical shrinkage could be the main cause.

Recommendation and conclusions

From this survey and the literature search conducted, the three most important factors that must be controlled to obtain good high-performance concrete are: the selection and control of the ingredient materials, the batching sequence, mixing efficiency of the equipment, and the curing method. It was seen that the mix design needs carefully planned trial batches to determine the compatibility of the materials, such as cement and chemical admixtures, to avoid segregation, and to achieve a desired workability and compliance with specification requirements. The need for further research was indicated in two main areas: workability, which includes finishability, and curing.

The workability is usually determined by a slump test, but this test does not measure a very important rheological parameter, the plastic viscosity. The plastic viscosity of the mortar forming the skin of the concrete determines the stickiness and the finishability. Also, the plastic viscosity of the cement paste or mortar influences the segregation of the mix, by preventing aggregates from settling.

The concrete plastic viscosity is a major parameter governing the concrete flowability and pumpability.[6] After the concrete is placed into the forms, the plastic viscosity controls the ease of placement. Therefore, there is a need for a new simple test to be used in the field to measure the plastic viscosity in conjunction with yield stress.

The prediction of the concrete workability from the mix design as well as the prediction of the effect of vibration on segregation is necessary. Further research is needed to obtain a complete prediction model that includes the influence of vibration.

Curing, which includes moisture and temperature control, must be optimized to avoid cracks. Further research is needed to be able to establish guidelines for concrete curing depending on the mix composition and ambient conditions.

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