DESIGN AND IMPLEMENTATION OF HIGH PERFORMANCE CONCRETE FOR LONG-TERM DURABILITY

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ABSTRACT

A high performance concrete (HPC) was used in the Wacker Drive reconstruction in downtown Chicago, IL to produce a structure with a projected design life of 75 years. While HPC can be designed for strength, for this application durability was considered paramount. Using the Wacker Drive project as an example, this paper discusses the recommended process in the implementation of HPC. This is summarized as follows: 1) targeted performance must be identified, in terms of general objectives and in terms of quantifiable measures 2) the best available raw-materials must be selected 3) trial batches of concrete must be produced both in the laboratory and with candidate ready-mix producers and tested for long term durability and 4) construction practices and the concrete itself must be carefully monitored through trial placements and during construction by means of a comprehensive QA/QC program. An up-front commitment to an in-depth implementation process for HPC such as outlined here is required to achieve the full long-term benefits possible with this material.

Keywords: high performance concrete, durability, Wacker Drive, chloride permeability

INTRODUCTION

High performance concrete (HPC), as defined by ACI, is "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"[1]. Long-term durability of a bridge structure is perhaps the most common performance requirement to which HPC is targeted. While there may be similarities between HPC for durability and high strength concrete, such as the use of relatively high cement contents, supplementary cementitious materials and low water-to-cementitious materials ratios (w/cm), experience over the past 20 years has shown that high strength concrete is not likely to be as durable as concrete in which long-term performance has been optimized and may introduce additional construction challenges that limit its durability. As the definition of HPC suggests, meeting increased durability requirements requires a non-standard effort beyond that for "normal” concrete. This requires a deeper commitment by all parties involved to optimizing the performance of the concrete at various levels from the beginning to the end of the project, from the material selection through to the construction process.

The bridge designer must be willing to commit additional time and resources to the development and utilization of HPC. The effectiveness of an HPC development program is dependant on the effort put into it. This effort is justified only if the time and costs saved in terms of future repair or reconstruction are significant enough to balance the initial outlay. A half-hearted attempt in choosing an HPC mix and overseeing its implementation may result in construction challenges and poor performance that outweigh the potential benefits. Therefore, a significant upfront commitment is required early in the mobilization phase of the project, but it will pay long-term dividends in the future durability of the structure.

Design and implementation of an HPC for durability poses some specific challenges since optimizing HPC for durability typically requires the use of two or three supplementary cementitious materials. Not only does the number of materials involved increase the complexity of the final concrete, but since some of these materials are byproducts of other industries, there is inherent variability in their properties resulting from the limited quality control effort involved in their production. Since generalizations about the best combination of SCMs cannot be made and for each application, the appropriate solution must be determined separately based on locally available materials.

The process of designing to maximize performance of the HPC is slow and painstaking since characterizing the ability of candidate concrete mixtures to withstand long-term environmental stresses must take the form of long-term and comprehensive testing. Some of the potentially harmful effects of inferior raw materials, such as aggregate susceptible to ASR, are only revealed slowly over time and require time-intensive test procedures to identify. In some cases, this process can take up to two years to complete.

A high performance concrete was used in the Wacker Drive Reconstruction project in downtown Chicago, IL to produce a structure with a projected design life of 75 years. The high sensitivity of the area where construction occurred and the severe environment to which the structure will be subjected provided the stimulus for the commitment to HPC for durability for this project. Using the Wacker Drive project, in which the authors assisted the Chicago Department of Transportation, as an example, this paper recommends a process for the implementation of HPC for durability.

The individual steps that make up this process are as follows: 1) define project objectives in general and as can be quantified using accepted test procedures, 2) evaluate the available raw materials, 3) develop mixture proportions based on the available materials and expected application, 4) develop effective construction practices for HPC, including a comprehensive QC/QA program. These steps will be outlined in this paper.

PERFORMANCE OBJECTIVES

The first step in the implementation of any HPC is defining the target performance. This must include an evaluation of the various mechanisms expected to cause deterioration of the bridge structure. The mechanism most responsible for deterioration of concrete bridges in northern climates has been spalling and delamination caused by reinforcing steel corrosion initiated by the presence of chloride from deicing salts. Concrete deterioration may also result from freezing and thawing, salt scaling, abrasion, alkali-silica reaction (ASR), alkali-aggregate reaction (AAR), sulfate attack, and from cracking occurring during construction or due to external and internal loads placed on the concrete such as plastic shrinkage, drying shrinkage, or thermal expansion and contraction.

At this stage of the process, the designer must identify which of these causes for deterioration are most significant based on local conditions and the intended function of the structure. Then properties of the concrete that will provide resistance to or circumvent the likely deterioration mechanisms must be identified. While SCMs are typically a part of achieving the desired properties, it should be recognized that the current understanding of the interactions between the cementitious materials is still incomplete and direct testing of the proposed materials is required to optimize performance. To do this, test methods to evaluate concrete performance relative to desired properties must be chosen. To appropriately interpret the results that are obtained, the advantages and disadvantages of various testing procedures must be identified relative to the actual mechanisms the tests are intended to simulate.

For each anticipated deterioration mechanism, concrete properties that provide resistance to deterioration must be identified and a test procedure to evaluate whether the appropriate properties are achieved in the concrete must be selected. The most significant potential cause of future deterioration in the concrete bridge deck installed at Wacker Drive is expected to be corrosion of the reinforcing steel. The process of defining the performance objective to resist the corrosion mechanism will be discussed.

The mechanism of corrosion deterioration is summarized as follows: the products of the corrosion process occupy a larger volume than the original steel which generates internal forces that lead to cracking and spalling. In freshly placed concrete, reinforcing steel is protected from corrosion by the formation of a passive oxide layer on the surface of the steel that develops in the highly alkaline environment produced by portland cement. This passive layer can be broken down through carbonation of the cement paste, or as is most common in bridge decks, by the presence of chloride ions.

Since this process is driven by water-borne chloride ions, limiting their access to the concrete interior was among the most important steps taken in producing effective HPC for Wacker Drive. Concrete that is less permeable is less likely to experience corrosion-related damage, or be affected by other deterioration mechanisms such as alkali-silica reaction (ASR), sulfate attack and freezing and thawing distress. All of these mechanisms require the ingress of water or aggressive water-borne agents into the concrete. Air and water permeability directly influence these deterioration mechanisms and can be measured. However, if corrosion is of prime concern testing of chloride permeability is most appropriate. This property of the concrete is commonly measured using two test procedures: the rapid chloride permeability (RCP) test, standardized as AASHTO T277, and the chloride ponding test, which is standardized as AASHTO T259 but rarely run exactly as specified.

Many variations of chloride ponding tests can be found in the literature since the standard 90-day test duration using 3% sodium chloride solution may not be severe enough to reliably differentiate between many HPC mixes that designed for low permeability. Instead, long ponding times, such as six months or a year, are often necessary. Because of the different rates at which hydration occurs, the limited amount of curing performed before ponding is usually applied may result in cement-only concretes performing better relative to concretes containing pozzolanic SCMs. This is generally not the case if the ponding is applied to specimens of greater age, e.g. at 56 days instead of 28 days.

The relative simplicity and short duration of the RCP test has resulted in its widespread adoption for measuring chloride permeability in lieu of ponding testing. For the same reasons, the RCP test is also commonly used for quality control purposes. However, many researchers and engineers have criticized the use of the RCP value as an oversimplified approximation of permeability and as misleading for certain concretes, particularly when SCMs are present as is commonly the case with HPC. Despite the relationship between permeability and RCP test results presented in tabular form in the standard, correlations between these two test methods should be established for the specific material combinations before making comparisons between concretes consisting of differing cementitious materials[2]. In other words, a concrete containing silica fume that exhibits a certain RCP value may not exhibit the same chloride permeability measured with a ponding test as a cement-only mix giving the same RCP test value. The charge passed measured using this test overestimates the actual chloride permeability since the movement of hydroxyl ions as well as chloride ions is measured[3]. SCMs may react with hydroxyl ions preventing their movement and making concretes containing these materials appear to have a lower permeability than is actually the case.

For the concrete design phase of the Wacker Drive project, it was decided that the best method to evaluate the chloride permeability of concrete mixes is with ponding testing as laid out in the AASHTO T 259 test method since that more realistically simulates the permeation mechanisms of chlorides in concrete. However, the long-term nature of the test required waiting for 180 days of ponding before decisions about the best performing concrete could be made. RCP testing is a less precise predictor of actual performance but was conducted to obtain additional information about the concrete mixes and to provide a basis for the quality control and assurance program during construction. The performance requirements chosen for the chloride ponding testing were chloride contents of samples taken between 0.5 and 1 in. of less than 0.03% and 0.07 % at 90 days and 6 months, respectively. The RCP specification called for a charge passed of less than 2000 coulombs at 28 days.

Freezing and thawing resistance, scaling resistance and susceptibility to cracking caused by drying shrinkage or thermal effects were also considered for the design of the HPC used in Wacker Drive. For each objective, a corresponding performance requirement was specified as a means to ensure that the concrete would meet the anticipated durability demands. For example, the objective of freezing and thawing resistance led to the specification of air void system parameters in hardened concrete, such as maximum air void spacing factor of 0.010 in. and a minimum air void specific surface area of 500 in^{-1}. Based on an understanding of property to be tested and the test procedures used to evaluate it, rational performance requirements can be specified to meet the durability objectives for the HPC. Candidate raw materials and mix designs that are expected to meet these objectives may be selected for evaluation.

RAW MATERIALS EVALUATION

A wealth of literature exists regarding the influence of various kinds of cements, SCMs, aggregates and other potential components of HPCs that can be used as guidance in making choices regarding the materials to be used in the HPC for a specific project. However, given the complexity of HPC, which can contain up to four cementitious materials and various chemical admixtures as well as the coarse and fine aggregate, this guidance is only a first step in selecting the raw materials to be used. There is likely to be large variability within the raw materials as well as the potential for interaction between these materials when combined that will influence the short-term properties and long-term durability of the concrete. Specifying a mix design or a concrete with certain properties without evaluating the specific, locally-available materials to be used on the job will not produce the best possible concrete. To achieve that goal, testing of concretes produced with local materials must be done. An understanding of the relationships between certain raw material properties and potential deterioration mechanisms may permit limiting the candidate materials to those which can be described as "high-performance" raw materials that are likely to produce high-performance concrete.

For a specific set of project objectives, this understanding can be translated into additional raw materials requirements beyond those given in typical state DOT and ASTM materials specifications. Depending on the objectives, specifications may be developed that apply to the cement, aggregate, SCMs and admixtures.

Limits on the chemistry of the cement may be set to control various chemical reactions that have implications for the long term durability of the concrete. The deterioration mechanisms influenced by the cement chemistry include ASR, delayed ettringite formation (DEF), internal sulfate attack, unsoundness and cracking related to heat of hydration. For Wacker Drive, restrictions were placed on the sulfate content, alkali content, fineness, and tendency for early stiffening. Cement fineness influences the rate of hydration which was limited to 400 m^2/kg Blaine to minimize the potential for thermal cracking. A limit was placed on total sulfate (less than 3.5%) and on water-soluble sulfate (0.5 g/L as measured by ASTM C265) since excess sulfate can increase the likelihood of DEF and internal sulfate attack. DEF, which is related to heat curing of concrete, is not normally a concern for cast-in-place bridge decks, but the design for Wacker Drive originally called for precast segments, although that requirement was later changed. The amount of alkali present in the cement is significant since it plays a role in determining the likelihood of alkali-silica reaction (ASR) that occurs between alkali in cement and reactive silica that may be present in the aggregate. The product of this reaction, ASR gel, is expansive when wet and can cause damage to the concrete over time. This reaction requires both cement of sufficient alkalinity and aggregate that is reactive and can be avoided if either of these conditions is not met. The significance of the cement alkalinity should be assessed based on concurrent testing of the candidate aggregates. For Wacker Drive, the total alkali content (Na_2O equivalent) was limited to 0.6%.

Aggregate specifications targeted at increasing durability may deal with ASR, freezing and thawing performance, scaling resistance, and chloride content. The Wacker Drive specifications for the aggregates called for high quality materials meeting the most demanding category or class requirements for the respective materials, which was a limited chloride content and additional requirements to limit the potential for ASR. The water-soluble chloride content of both coarse and fine aggregates was limited to a 0.04% to limit aggregate contributions to corrosion producing chloride contents. The aggregate was specified to be non-reactive per ASTM C33 Appendix and C295, C289, C227 and C1260, though certain exceptions could be made for the fine aggregate (if potentially deleterious per C289 and possibly deleterious per C1260, a limited amount reactive particles or control of reactivity using low alkali cement and Class F fly ash had to be demonstrated).

Additional limits on the fly ash were also specified for Wacker Drive to eliminate harmful long-term reactions. The fly ash was specified to be Class F and have a limited sulfate content (less than 3.5%), available alkali content (less than 1.5 %) and loss on ignition (less than 4.0%). The motivations behind these requirements were DEF, ASR and consistent performance in combination with air-entraining agents, respectively. Class F fly ash was chosen since it is more effective at mitigating ASR than Class C fly ash. Aggregate testing indicated that for some sources ASR was a potential problem. The fly ash was also subjected to an autoclave soundness test in combination with the job cement. The slag and silica fume were required to meet the standard AASHTO requirements.

EVALUATION OF MIX PROPORTIONS

Once performance objectives and the most likely raw materials have been selected, HPC mix designs may be proposed that are expected to meet those objectives based on past experience or available literature. Ideally, testing of proposed mixture proportions is a two phase process that should include both laboratory testing and trial batches conducted with potential suppliers. Laboratory testing allows the greatest amount of flexibility and control over the concrete proportioning and testing. New materials and or combinations can be evaluated at that time and comparisons can be made based on carefully controlled experiments involving the minimum amount of cost necessary. An NCHRP-funded project is currently being conducted by the authors to develop a mix design methodology using a statistically-based experimental design approach to assist in this process. A second phase of testing involving the suppliers in the trial batching process is then desirable since concrete produced according to the same mix design may vary widely from one supplier to the next. This also confirms that material combinations produced in the lab can be feasibly reproduced for a full scale application.

For Wacker Drive, raw materials that met most of the specifications previously outlined were used for HPC mix testing. The suppliers were given the option of producing two pre-defined mixes and/or a mix of their own design that they felt would meet the performance requirements. The pre-defined mixes were established based on experimental trials and the experience and expertise of the designers. These were included to ensure that at least some of the mixes produced in the trial batching phase would be capable of meeting the performance requirements. A total of 14 mixes were produced by six suppliers, and a test program was initiated that measured the following properties for each of these mixes: compressive strength, modulus of elasticity, air void parameters in hardened concrete, freezing and thawing resistance, RCP, chloride ponding, salt scaling resistance and shrinkage. A wide range of test results were obtained and compared to the performance specifications. The final HPC was chosen from those meeting the performance requirements based on cost and other considerations. The mixture proportions used during construction were as follows: Type I/II cement at 525 lbs./yd.^{3}, water at 30.5 gal./ yd.^{3}, Class F fly ash at 53 lbs./yd.^{3}, silica fume at 27 lbs./yd.^{3}, GGBFS at 79 lbs./yd.^{3}, fine aggregate (natural sand) at 1140 lbs./yd.^{3} and coarse aggregate (3/4-in. max. limestone) at 1800 lbs./yd.^{3}

It is important to evaluate the results of the testing relative to the project objectives and the test methods used to quantify the performance. Resistance to corrosion and freezing and thawing distress were driving forces in the HPC design process, and significant weight was placed on test results that most accurately evaluate these properties.

CONSTRUCTION PRACTICES

Once material performance has been optimized, implementation of the HPC places additional demands on the concrete supplier and contractor beyond those of conventional concrete. Production of HPC requires effort by the supplier to deal with the multiple materials and their inherent variability and to meet batching tolerances on smaller amounts of SCMs. HPC behaves somewhat differently from conventional concrete in the plastic state, exhibiting varied workability and finishing characteristics depending on its makeup that require the contractor to modify normal construction procedures. During the construction phase, a trial placement, increased curing requirements and a rigorous quality control programs are recommended to ensure that high performance in-place concrete is achieved.

To give the concrete supplier and contractor some experience with the HPC chosen, a trial placement or pre-construction mock-up is useful. An understanding of the influence of placement procedures on the concrete can be gained. For example, pumping can affect the air content and other concrete properties. The timing of finishing and curing operations for HPC, which may differ from conventional concretes, can also be estimated. This is especially important for HPC containing silica fume, which tends to experience less bleed water than other concretes and is more susceptible to plastic shrinkage cracking.

During the Wacker Drive trial placement, which utilized a concrete pump, losses in air content from 1 to 4 % were measured depending on the pump configuration and other considerations. Cylinders were cast to assess the relationship between the air contents of the plastic and hardened concrete. During the trial placement, it was found that the air content of the hardened concrete was measured to be about 1.5 % less than in the plastic concrete. In practice, the loss through the pump or conveyor and the difference between plastic and hardened air contents varied throughout the project. However, the trial gave the contractor some basis to determine target air contents for the concrete delivered to the site for the remainder of the work.

HPC containing SCMs requires more careful attention to protection and curing than conventional concrete[4]. Because of the limited amount of bleeding that typically occurs in HPC with SCMs, fogging may be necessary to prevent plastic shrinkage. The hydration reaction of fly ash, slag and silica fume occurs more slowly than in portland cement. Therefore prolonged wet curing is necessary. For Wacker drive, fogging was required if the evaporation rate exceeded 0.1 lbs./sq.ft./hr. The concrete surface was covered immediately after texturing with cotton mats which were then soaked. These mats were kept wet using soaker hoses for seven days.

The quality control effort required to assure optimum performance for HPC is also somewhat greater than conventional concrete. The quality of the raw materials, plastic concrete and hardened concrete as sampled must be evaluated. The Wacker Drive Quality Control (QC) / Quality Assurance (QA) program was written into the project specifications. The concrete supplier submitted materials for use in the final construction that were evaluated relative to the raw materials specifications discussed above. The contractor shouldered the QC responsibilities during batching and in the field, while QA testing was conducted at a frequency of 10 % of that performed by the contractor. Testing was also conducted on aggregates (gradation, moisture, absorption, petrography, water-soluble chloride), cement (early stiffening, water-soluble sulfate, total alkali), fly ash (available alkali, loss on ignition, sulfate content), plastic concrete (slump, air content, temperature, unit weight) and hardened concrete (compressive strength, air void parameters, rapid chloride permeability).

CONCLUSIONS

To maximize the durability-related performance of the concrete the following tasks must be completed: the project objectives based on the desired function of the structure must be defined in a manner that can be quantified, the highest quality raw materials must be selected, trial batches using the local materials and production procedures must be conducted, and proper construction practices must be employed. HPC, designed for durability, requires a commitment from all parties involved to meet the increased design, production, construction and quality control requirements. It must be recognized that this requires both additional time, in some cases up to two years to develop the mix and conduct the durability testing, and additional expense. However, the additional effort pays dividends in the form of durable structures that like Wacker drive can reasonably expected to live up to a projected design life of 75 years.

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