HPC ~ NEW HAMPSHIRE'S BRIDGE TO CONCRETE STRUCTURES

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ABSTRACT

Ten years ago New Hampshire would have been considered an unlikely candidate to become involved in High Performance Concrete (HPC). Traditionally a "steel" state, New Hampshire's exposure to concrete for superstructures was mostly limited to concrete decks. That all changed as NH became involved in the SHRP initiative for HPC.

Beginning in 1996, NH built a succession of three HPC bridges. NH's philosophy was to start simple and work towards more complex projects. The successful construction and excellent performance of these structures has convinced NH of the benefits of HPC which has now been incorporated into NH's standard practice. NH's evolution to a performance based specification, highlights the critical performance factors, with particular emphasis on deck cracking, concrete curing issues and lessons learned.

Key Words: New Hampshire, High Performance, Concrete, HPC, SHRP, Cracks, Decks, Curing, Finishing, Specifications

INTRODUCTION

In 1996 the NHDOT Bridge Design office was issued a challenge. What were we doing to address the fact that the costs of NH bridges were continuing to spiral upward at levels significantly exceeding the average bridge costs throughout the rest of the nation; also, why were large sums of money being spent on repairing, and sometimes replacing, cracked or deteriorated bridge decks that were only 15 to 20 years old. Explanations that contractors were being pressured to build bridges quicker and that increasing salt usage (due to the State's "bare roads" policy, accommodating the tourism industry) was leading to premature concrete deterioration, answered these questions in only a very limited fashion. Subsequently NH embarked on a two-fold initiative to address these concerns.

NH's first point of attack was to introduce more competition into the local bridge market. Up to that point in time NH had been primarily a "steel" state, with almost exclusive use of steel girders in structures longer than 50-70'. A concerted change in philosophy was adopted in an attempt to introduce more competition to the steel market by including prestressed concrete girders in the type selection process. There were also some concerns within the DOT that perhaps the bridge deck cracking problem could be partially attributed to the more flexible steel girder bridges. Girders had become shallower over the 15 to 20 years prior to the early 90's with the shift from Grade 36 to Grade 50 steels.

The issue of early age cracking in NH's concrete bridge decks was a matter of great concern in the 1990's. This problem was occurring with increasing regularity and therefore, as High Performance Concrete (HPC) came on to the national scene, this was seen as an opportunity to change the way NH conducted business. If top dollar was going to be paid for concrete bridge decks, NH wanted to make sure it received top quality concrete. The HPC effort became interwoven with an initiative to use a performance based (QC/QA) specification which rewarded, or penalized, contractors depending on their ability to consistently achieve performance objectives. NH's efforts in the development and refinement of these specifications evolved through a series of three bridges, highlighting NH's active involvement in the HPC initiative and the improvements in concrete performance which have been seen as a result.

NH was one of the original six lead states that became involved in HPC as part of FHWA's HPC Bridge Showcase efforts. NH's goal in becoming involved in the use of HPC was to reduce the maintenance and repairs required during the life of structures while also increasing the overall life span of structures. NH's rapid growth and the increasing demands on the transportation system were placing a greater emphasis on minimizing disruptions to traffic and reducing life cycle costs. Primarily, the major benefit of HPC for concrete decks was not the additional strength, though this was an added side benefit which could be used to economic advantage; it was more importantly an issue of concrete durability and long-term performance. Therefore, as HPC relates to deck concrete, it was of primary importance that the deck have low permeability, that it be free of the extensive cracking that was occurring with current deck construction techniques, and that it address freeze-thaw resistance and wear resistance due to the harsh winter environment and frequent snow plowing.

As NH became involved in HPC, it was not without a good deal of caution. There was much that needed to be learned. A significant investigative effort was undertaken to begin laying the groundwork for the new specifications. In addition, a parallel effort involving research of the different design considerations and the application of the AASHTO specifications to HPC was pursued. At that time, the concrete industry in the Northeast was only marginally ahead of NHDOT concerning HPC issues and they were a limited resource for answering the many materials questions that were in peoples' minds. NH sought out answers beyond the Northeast, consulting with experts from around the country using both their professional literature as well as person to person contact at the HPC showcases. The HPC showcases were very beneficial as they brought together designers, materials engineers, construction/fabricators and researchers from academia. However, this didn't always make decisions easier. Advice from experts was at times contradictory. Differences in opinions had to be weighed, and there was some frustration as decisions made early in the design process often had to be revisited later on. Expectations that this was a new technology that would immediately solve all the problems, quickly yielded to the reality that HPC needed to be approached with a diligent, thoughtful, evaluation of all the available research. It would have been extremely difficult for NH, on its own, to have gathered all the available information and bring coherence to the various research efforts scattered around the country. What the HPC showcase effort provided was a very effective means of establishing both a focus and a forum for attacking the various problem areas.

NH'S FIRST HPC BRIDGE – BRISTOL 1

The selection of NH's first HPC bridge was made with two criteria in mind: 1) Of primary importance was to select a bridge that would be a basic straightforward structure. 2) Select a bridge that could have a similar structure built having approximately the same span and traffic conditions. This other bridge would serve as an "experimental control" and would be built using NH's typical specifications of that time period. This bridge was to become the so-called Normal Performance Concrete (NPC) bridge. The NPC bridge was actually never built as such; this will be discussed later.

Two bridges in Bristol, NH, both in need of immediate repair, fit the requirements of the two criteria. NH's first HPC bridge is called Bristol 1 and it carries NH Route 104 over the Newfound River. It is a 65' single span structure consisting of 5 precast, prestressed AASHTO Type 3 girders spaced at 12'-6" on center. The 9" thick monolithic concrete deck was cast-in-place with transverse grooves sawn in the hardened concrete deck. Performance criteria and actual mixes for the deck concrete for Bristol 1 are shown in Tables 1, 2, and 3.

Table 1 ~ Deck Concrete Specification - Bristol 1

	Specification
Cement	Type II
Silica Fume	7.5%
w/cm	.38 (max)
Air Content	6-9%
28 d Strength	7,200 psi
Permeability 56 d	1000 C. (max)
Corrosion Inhibitor	4 gal/yd^3
Curing	4 day wet cure with cotton mats

The basic mix design specified for the concrete bridge deck was a prescriptive specification developed as part of a testing program performed by the University of New Hampshire (UNH)[1]. The concrete supplier further refined the deck mix through several trial batches. A 5 cubic yard test placement prior to the deck placement was required and this gave the Contractor and Producer the opportunity to refine their mix and placement techniques. Simulating the conditions anticipated during the actual deck placement was very important. Several changes were subsequently made to the mix: Additional superplasticizer was added to obtain better workability and an error in calculating the amount of water added to the mix was corrected. The approved deck mix is shown in Table 2.

Table 2 ~ Approved deck mix proportions - Bristol 1

Component	Product	Proportion
Cement	Ciment Quebec – SF (≈ 8%)	660 lb
Fine aggregate	Sand	1190 lb
Coarse aggregate	No. 67 Stone	1815 lb
Water	30 gal	253 lb
Air entrainment	Daravair – 1000	5 oz
Water reducer	WRDA w/ hycol	20 oz
*Superplasticizer	Daracem –100	158 oz
Corrosion inhibitor	DCI-S	4 gal
w/cm		0.384

* Added at the site

Table 3 ~ Deck concrete test results - Bristol 1

Test	Target	Results	Test Method
Slump	5 to 7 in	3 to 5 in	AASHTO T119
Unit weight	--	144 to 147 lb	AASHTO T121
Air content	6 to 9%	4.0 to 5.8%	AASHTO T152
w/cm	0.38	0.39	**
28-day cylinder strength f'_c	7200 psi	8163 to 9614 psi	AASHTO T22
*Modulus of elasticity, E	4.4×10^6 psi	4.2 to 4.3×10^6 psi	ASTM C 469
Chloride ion permeability	1000 coulombs	609 to 896 coulombs	AASHTO T277
Freeze-thaw durability	80%	96 to 99%	AASHTO T161
*Scaling	--	0 to 1	ASTM C 672

*Results determined by UNH graduate student Cheryl Wilson[2]
** Results determined by NHDOT microwave oven drying test

Concrete was placed by pumping, with care taken to position the hose horizontally to minimize the loss of air. The surface was finished using a self-propelled finishing machine followed by a vibrating finishing pan and wet burlap drag directly behind the pan. Additional superplasticizer, over and above the extra required by the trial placement, had to be added to provide the workability needed to finish the concrete. The supplier also had difficulty maintaining the required air content but the additional super appeared to stabilize this problem. Freeze-thaw durability tests performed on prisms provided evidence of excellent freeze-thaw durability. Concrete strength and permeability results were excellent; significantly better than required by specification. It was interesting to see the comparison with the approach slabs which were placed using the same mix as the deck, only without the DCI corrosion inhibitor. Less super was required for the approach slabs and they were still more workable with higher air contents than the deck. However, the DCI did appear to positively effect the strength gain with strengths for the deck averaging 8500 psi vs. 6850 psi for the approach slabs.

Proper finishing and curing of the deck concrete on Bristol 1 was considered a high priority. NH had been experiencing numerous problems with deck cracking, and the work with HPC was considered as an opportunity to implement some improved curing practices emphasizing strict enforcement of the specifications. Within 10 minutes after a portion of the deck had received the burlap drag it was required that it be covered with dry cotton mats, which are made with burlap stitched together with cotton bat filling. The cotton mats were then immediately wetted down and kept continuously wet for 4 days using sprinklers, prior to their removal from the deck surface. Weather during the deck pour was ideal as a fine mist provided conditions that easily met the requirements of the evaporation rates specified by the

ACI evaporation chart. Specific instructions were given not to bullfloat or over-finish the concrete surface, a common practice with conventional deck mixes. The final surface was noticeably rougher than NH's typical surface required for membrane placement but it was precisely what was desired per the specifications.

The final surface finish on the deck was achieved by transversely saw cutting the hardened deck concrete. 1/8" grooves, 1.5" apart and 1/4" deep, were sawn regularly into the deck. Due to low traffic speed over the bridge, random spacing of the grooves was not considered necessary. There were no visible cracks found in the deck during field reviews conducted over the next several years, other than microscopic longitudinal flexural cracks which were discovered over the girders during a "wet" study of the concrete surface.

With respect to girder requirements for Bristol 1, NH decided to take a slightly conservative approach. The specified girder concrete strengths of 9400 psi (actual design value of 8000 psi) were not as high as what other states were targeting, but still substantially more than NH's typical design values of 5000 psi at that time. NH felt it was wise to work up gradually to the higher strength values, and in line with the philosophy of incremental improvements, aim for strengths that could comfortably be obtained, and then build on the anticipated success.

This proved to be a wise course of action as these strengths were not as readily achieved during production as some thought they would be. During the design phase several mixes from potential fabricators were evaluated to confirm that the specified strength could reasonably be obtained. However, with little to no history using mixes that achieved the required design strength of 8,000 psi, the NH specification required the fabricator to follow the requirements of ACI Building Code, Chapter 5 on Concrete Quality, Mixing and Placing. This necessitated that they demonstrate with their trial mixes the ability to achieve an average 28 day compressive strength of 9,400 psi. Trial mixes by the supplier, Unistress Corporation of Pittsfield Massachusetts, demonstrated that these strengths could be readily achieved. However, it was discovered during production of the first girder, that use of the approved mix design resulted in the girder occupying significant time in the casting bed before the release strength of 6,500 psi could be obtained. After Girder 1 had been in the bed 5 days, the Fabricator decided to discard the beam. Subsequently, Unistress began making adjustments to the mix, changing to a Type 3 cement and increasing the amount of cement (See Table 4) while reducing the amount of silica fume.

Table 4 ~ Girder Concrete - Bristol 1

	Girder 1 Mix Design	Revised Mix Design
Cement Type II	752 lbs	777 lbs (Type III)
Silica Fume	75 lbs	50 lbs
Fine Aggregate	1075 lbs	1075 lbs
Coarse Aggregate	1850 lbs	1850 lbs
Water	273 lbs	273 lbs
Air Entrainment	10 oz	10 oz
High Range Water Reducer	206 oz	206 oz
Retarder	14 oz	14 oz
Corrosion Inhibitor	4 gal	4 gal
w/cm	0.35	0.35

Ultimately this mix could not achieve the required 28 day strength. Further adjustments were made during production. The supplier gradually reduced the amount of air which resulted in improved strength values, with the exception that girder 5 strengths were very low. A decision was made to core three of the girders (2 cores/girder) which revealed that girder 5 was definitely below strength (See Table 5).

Table 5 ~ Girder Strengths

Girder	NH DOT	Unistress	Cores
1	6862	8250	8233
2	7425	7780	8209
3	8780	8500	---
4	8640	8375	---
5	7070	7550	7791

A significant amount of discussion ensued as to the proper disposition of Girder 5. Alternatives ranged from outright rejection of the girder to complete acceptance of the girder as is. One of the over-riding concerns was that too harsh a penalty would send a message, effectively discouraging innovation by placing the risk of using innovative materials and engineering practices, all on the Fabricator/Contractor. The primary concern of NHDOT was the structural adequacy of the girder. Therefore, a design analysis was conducted using the reduced strength which assured the DOT that the measured strength was adequate for all design loadings. Ultimately girder 5 was accepted for use with a slight monetary penalty.

The girders were steam cured and two of the girders were instrumented to monitor strain and internal temperature throughout the different stages of construction. Just prior to being opened to traffic a load test of the structure was conducted which highlighted the significant stiffness and strength of the bridge. (Specifications for the girders are shown in Table 8).

Lessons Learned-Bristol 1

There were a number of important lessons learned from the Bristol 1 experience.

1. The decision to start simple was confirmed; setting sights on even higher concrete strengths would likely have accentuated the problems that were experienced. Those new to HPC should anticipate a learning curve; increased testing, trial batching, and stricter quality control was necessary.
2. Even though close communications and up front preparation was encouraged prior to production, in retrospect there was too much of a “hands-off” approach by the NHDOT in working with the supplier; the industry was not quite as well prepared as was believed. The post bid meeting should be mandatory. Development of the HPC mix was time consuming and allowing time to develop and test mixes must be considered in the project schedule. For those new to HPC there is a significant cost associated with developing the new mix. Cooperative involvement of all parties became a focus on the succeeding HPC projects.
3. The air requirement for the girders was given a closer look and revised for future projects. It was believed that the air requirement of 5-8% was a significant reason that the higher strengths were difficult to obtain for the girders. Percentage of air entrainment for the girders was adjusted down to a target value of 5% with an absolute minimum of 3.5% on future projects. Research has supported the freeze thaw durability of concrete with air entrainment values as low as 3 percent.[3] Additional justification for this change was that the girder would not be subjected to wetting from melting snow laden with deicing salts. Lowering the air requirements may not be appropriate in other applications, such as where the ends of girders could be exposed to leaking expansion joints.
4. Due to the wider girder spacings of 12'-6", the typical wooden falsework system could not be used, resulting in expensive special formwork at an estimated increased cost of 75%.
5. The trial use of match curing was very successful. Match curing provided both the DOT and the fabricator with a very reliable, non-destructive means of determining the compressive strength of concrete within the girder. It was agreed that this method of curing cylinders was preferable to either curing cylinders with the girders or curing in a curing chamber. These latter methods tended to show lower early strengths but higher later strengths.
6. The emphasis placed on the importance of curing was very successful in achieving positive results. Deck cracking in the near-term was basically eliminated and today, 7 years later, there are still no visible cracks either on or below the deck surface (though the curbs and sidewalk have exhibited some regular cracking).
7. Bagged (biodegradable bags) silica fume should not be used. The bags did not fully disintegrate in the mixing process. Pieces of the bags were found along the failure plane of several test cylinders. In addition, there were questions about whether the silica fume had been adequately dispersed throughout the mix or whether clumping had occurred.

8. Specify only what is needed-the target permeability value for the girders was set too low at less than 1000 coulombs. Research indicated that target values could comfortably be increased to 1500 coulombs.

BRISTOL 2

The initial design work on the Bristol 2 project, which carries NH Route 3A over the Newfound River, had commenced while Bristol 1 was still under construction. As previously mentioned, during NH's early involvement in HPC it was planned to make the second Bristol project serve as an experimental control to the Bristol 1 bridge. However, soon after completion of Bristol 1, the NHDOT determined it would be better to look forward rather than revert to the conventional deck and girder concrete construction. Therefore, the goal was to build on the results of Bristol 1, making adjustments where problems had occurred and solidifying where successes had been achieved. A thorough update of the HPC deck and prestressed specifications was undertaken at the completion of Bristol 1 to address the issues previously discussed.

The second Bristol bridge is a 60' long simple span structure that is 30' from curb to curb with one 5' wide sidewalk. The superstructure consists of 3 1/2" thick precast concrete deck panels with a 5 1/2" thick cast-in-place (CIP) concrete deck overlay, and four precast, prestressed concrete New England bulb-tee (NEBT) 1000 HPC girders.

The advantages of using HPC with the NEBT girders became apparent during the design process. The NEBT is a very efficient section which allowed a straight strand pattern, as well as a design with zero tension in the bottom flange at final service loads. Girder spacings were increased to 11'-6" on center. This reduced the number of girders from five to four. The NEBT was also 5 1/2" shallower than the AASHTO/PCI Type III girders, providing additional vertical clearance over the design flood elevation. The same girder concrete design compressive strength of 8000 psi used on Bristol 1 was specified for use on Bristol 2. As previously mentioned, a more proactive approach was taken in pursuing the necessary trial batching for developing an acceptable concrete mix design. The precaster, Northeast Concrete Products of Plainfield, Mass., aggressively supported a cooperative effort and trial batches consistently achieved strengths required by the specification. In addition, a 10' long test placement of the actual girder section was successfully performed using the proposed concrete placement and curing methods. This test placement provided the precaster an excellent opportunity to try out the match cure system. Match cured cylinders achieved the required release strength of 5500 psi in 28 hours and compressive strength of 9500 psi at 28 days.

A big asset to the contractor in pursuing a condensed construction schedule was the use of partial depth precast, prestressed concrete deck panels. The use of deck panels as stay-in-place forms on Bristol 2 helped to reduce the costs associated with difficult access under the bridge and special deck falsework needed for the wider girder spacings. The deck panels, as well as the cast in place overlay, were specified as 6000 psi concrete.

Average 28-day compressive strengths of 9000 psi were obtained in the field for the CIP deck concrete along with chloride permeabilities well below the specification goal of 1000 coulombs at 56 days. The proper finishing and curing of the deck was crucial in order to achieve an excellent and durable concrete surface. Using a work bridge behind the screed machine, the dry cotton mats were spread out on the deck and most were wetted within 10 minutes after the screeding operations. Inspections to date have revealed an excellent surface with only four visible hairline cracks. The completed bridge was opened to traffic in June 1999.

Several deck placement issues during construction are worthy of note. The Contractor requested that the trial deck placement requirement be waived; assurances were given to the State that the Contractor had worked with similar concrete mixes. While the Contractor was indeed experienced, the State insisted that the trial deck placement be conducted as required by the Specifications. During the test placement, the Contractor found that the proposed deck mix was difficult to finish properly. The proposed geotextile fabric drag resulted in the tearing of stones out of the surface. Subsequently, the Contractor experimented with several other finishing methods prior to settling on using just a pan finish. The deck was placed using a crane and a 2 cubic yard bucket. The Contractor/Supplier controlled slump very well. Conditions for deck placement were once again very good with an early morning placement, temperatures in the 70's, high humidity and no wind. Conditions changed significantly towards the end of the placement at 9:00 am as the sun came out. Just as the weather was changing, delays occurred in getting the deck finished and properly covered as the Contractor's attention turned to clean-up of the finishing machine. Portions of the last quarter of the deck went half an hour prior to being covered with the cotton mats. A seven day wet cure using the cotton mats was specified. The Contractor was concerned with the length of time and the large volume of water that was needed to initially soak the mats after they were placed on the deck. Applying too much water too soon to the cotton mats was causing puddling of water below the mats which could possibly damage or weaken the concrete deck surface. To facilitate the mats soaking up water, it was determined that they should be "conditioned" by soaking and drying several times before actual use. In ensuing discussions some contractors expressed reservations about going through this conditioning process, and consequently the specification for future decks was changed to also allow dampened burlap as an alternative to cotton mats.

This bridge was NH's first use of the NEBT as well as the first use of .6" diameter prestressing strand. Similar to Bristol 1, two girders were instrumented on Bristol 2, monitoring for both temperature and strain. Epoxy coated rebar was used in the deck as is typical with NH construction but black bar was used in the approach slabs for comparison. To date there has not been any differences in performance. Both deck and approach slabs used DCI and will be tested in future years to determine the effectiveness of the DCI.

Lessons Learned ~ Bristol 2

1. The importance of proper preparation and research was confirmed, i.e. Trial batching, placing the Girder Test Section, and the test deck placement, all helped the actual placement during production proceed smoothly.
2. The revised permeability limits and less stringent air requirements facilitated the achieving of the required girder strength. Only ask for what you need!
3. Once again, the use of the match cure system was very successful and it was agreed that it should be required on all future projects in NH with prestressed concrete products.
4. Use of the deck panels was welcomed by the Contractor as a much quicker, as well as less expensive, means of forming the deck. Each of the 8’ wide panels was placed in 15-20 minutes.

The performance of Bristol 2, in both the near term and up to this time four years later, has been excellent. The only deck cracking which has been observable to the naked eye are four very fine, short cracks towards one end of the deck. Reflective cracking at deck panel edges has not been experienced at all and NH has become increasingly comfortable with the use of the panels as an alternative to the traditional temporary timber falsework. NH has emphasized the importance of a two-step grouting system in order to establish proper support for the panels prior to placing the concrete overpour.

ROLLINSFORD

NH's third HPC project was constructed in Rollinsford, NH on a replacement bridge carrying Rollins Road over Main Street and the B&M RR. This bridge, completed in 2000, is a 110' simple span, using 5 NEBT 1400 girders at a spacing of 7'-5". This narrow girder spacing was proposed in order to minimize increases in the profile grade while obtaining clearance over the Railroad. This project received Innovative Bridge and Research Construction funding and, to NH's knowledge, was the first example of a concrete deck reinforced entirely without steel. The deck is reinforced with two mats of carbon fiber reinforced plastic grid called NEFMAC. The Contractor was very enthusiastic about the use of this material which was easily and rapidly placed in approximately two days.

Once again the trial deck placement highlighted the difficulties associated with achieving a good deck finish. An astroturf drag tore the surface and the Contractor decided to go with just the pan finish following the screed machine. The mix design was altered after the pre-placement meeting by substituting flyash for slag. The Contractor was uncomfortable with the slag mix due to some difficulties he encountered with finishing on a prior project. (These difficulties may have been associated with the high cement factor used on that project’s bridge deck. NH is now successfully using slag mixes in decks on a routine basis.) This deck has also performed extremely well with no visible cracks to date. Coordination between the Contractor, Fabricator, and State was excellent, resulting in a smoothly run project. There was a noticeable delay in achieving the specified deck concrete strengths but this was immediately recognized as being the result of the combination of the flyash and the unseasonably cool weather during the initial curing period.

Lessons Learned – Rollinsford

1. The plans called for a sawn grooved deck finish but the Contractor and the DOT construction representative suggested that this was an unnecessary expense. It was agreed that since this was a low speed, low volume road with good drainage off the bridge, that a sufficiently rough surface could be achieved with just a broomed finish.
2. This was the first NH project with Alkali Silica Reactivity (ASR) language introduced into the specification. The addition of slag/flyash to control ASR introduced several noticeable changes in the characteristics of the mix. The ability to isolate the reasons for changes highlights the benefit of instituting changes in a step-wise fashion; on this project it made it much easier to pinpoint the reasons for changes in the performance.

Summary of Current Practice

The Rollinsford project was NH's last use of the specified HPC deck mix designs. Since that time NH has moved exclusively to a QC/QA performance specification. The mix designs being supplied for the QC/QA projects since 1999 had become very similar to the specification mix design, evidence that HPC had now become NPC. QC/QA is a performance based specification that had its beginning in the late 1980's but it began achieving a much better focus and success as HPC came to the forefront. This specification provides incentive for contractors and suppliers who can achieve consistency in obtaining results within given target ranges for the following parameters:

- cover
- air content
- w/c ratio
- strength (disincentive only)
- permeability

This specification has undergone numerous changes through the years, most significantly in the area of the permeability limits. With significant pay incentives for permeability (maximum of an additional 10% of the bid price) the Contractors pushed very high cementitious content in the mixes to lower the permeability values as much as possible. This practice resulted in substantial positive pay adjustments to the contractors. However, the result was more deck cracking. After several years of seeing this aggravated deck cracking problem, the correlation with the high cement factors, which at times were over 800 lbs/cy, convinced the DOT to make a change and increase the permeability target range to 1500 – 2500 coulombs. The maximum pay factor was set such that values outside this range, either higher or lower, resulted in a decreasing amount of incentive pay. This was admittedly a backdoor attempt to reduce cementitious content in the mixes. Preferably, testing of the mix designs for shrinkage would have been conducted, but the DOT did not have any shrinkage testing equipment or any guidelines as to acceptable shrinkage limits. As soon as suppliers began using the revised permeability guidelines/specifications there was an immediate improvement in the deck cracking problem. These changes, coupled with more stringent curing specifications, have led to a dramatic decrease in the number of decks exhibiting cracking. The importance of attention to curing cannot be overstated. Both cotton mats and burlap are now allowed as curing blankets; they need to be on the deck and wet within a maximum of 30 minutes.

NH's specifications continue to require test sections (both girders and decks) for contractors and/or suppliers who lack proven experience with HPC mixes. It has been well documented throughout NH's HPC projects that this heads off problems which could subsequently lead to compromises in quality during construction of the final product.

Match curing of cylinders is now required for all prestressed members. The match curing system cures cylinders at the same internal temperature as the girder, using temperature controlled cylinder molds. Cylinders cured in a curing chamber may indicate strengths up to 30% higher than match cured cylinders.[4] Match cured cylinders generally exhibit higher compressive strengths at an earlier age and lower long-term strengths when compared to conventionally cured cylinders. This provides an incentive to fabricators who are looking to turn over their casting beds as quickly as possible and it provides the owner with the best non-destructive estimate of the actual concrete strength within the girder. Consequently, fabricators have embraced the use of match curing.

Tables 6, 7, 8 and 9 provide a good summary of where NH started before its involvement with HPC 10 years ago, and the changes and improvements that have been made up to today.

Table 6 ~ Specification Requirements - Deck

	Pre-HPC	**Bristol 1**	**Bristol 2**	**Rollinsford**	**QC/QA**
Cement	658 lb/yd^3 (Type II)	658 lb/yd^3	658 lb/yd^3	658 lb/yd^3	Type II, IP
Silica Fume	--	7.5%	7.5%	5%	--
Flyash/Slag	--	--	--	--	--
W/cm	.44	.38 max	.38 max	.38 max	.44 max
Air Content	6-9%	6-9%	5-9%	5-9%	5-9%
Strength (28 d) psi	4000	7200	7200	6000	4000
Permeability (56 d)	--	1000 C.	1000 C.	1000 C.	1500-2500 C. Target
Corrosion Inhibitor	--	4 gal/yd^3	4 gal/yd^3	--	As specified
Curing	3 day wet	4 day wet	7 day wet	7 day wet	7 day wet

Table 7 ~ Approved mix designs - Deck

	Early QC/QA (Typical Mix)	**Bristol 1**	**Bristol 2**	**Rollinsford**	**QC/QA (Typical Mix Today)**
Cement	370 lb/yd^3 (Type II)	660 lb/yd^3 (Type II) Blended	660 lb/yd^3 (Type II) Blended	528 lb/yd^3 (Type II) Blended	329 lb/yd^3
Silica Fume	--	8%	7.5%	6.5%	--
Flyash/Slag	370 lb/yd^3 slag	--	--	132 lb/yd^3 flyash	329 lb/yd^3 slag
Fine Aggregate	1050 lb	1190 lb	1190 lb	1205	1215
Coarse Aggregate	1850 lb	1815 lb	1815 lb	1805	1725
Water	290 lb	253 lb	253 lb	253 lb	286 lb
Air Entrainment	5-9 oz	6 oz	5 oz	1.5 oz	4 oz
Water Reducer	30 oz	20 oz	20 oz	18 oz	
High Range Water Reducer	103 oz	158 oz	106 oz	101 oz	38 oz
Corrosion Inhibitor	--	4 gal/yd^3	4 gal/yd^3	--	--
W/cm	.38	.38	.38	.38	.42

Table 8 ~ Specification Requirements - Girder

	Pre – HPC	Bristol 1	Bristol 2	Rollinsford	QC/QA
Cement	752 lb/yd^3	Type II or III	Type II or III	Type II or III	*PAMD
Silica Fume	--	--	--	--	PAMD
Flyash/Slag	--	--	200 lb/yd^3 (NewCem)	--	PAMD
w/cm	.33	--	--	--	PAMD
Air content	5-8%	5-8%	5% (3.5% min)	5% (3.5% min)	5% (3.5% min)
Permeability (Coulombs at 56 d)	--	1000	1500	>3500 reject ≤ 1500 positive pay 1500 – 3500 negative pay	<2500
Corrosion Inhibitor	4 gal/yd^3	4 gal/yd^3	4 gal/yd^3	Not Required	Not Required
Slump		5-7"	5-7"	5-7"	5-7"
Prestressing Strand (Grade 270 low-relax)	.5"∅	.5"∅	.6"∅	.6"∅	.6"∅
Test Section	--	Not Required	Required (30 d prior to fab)	Exempt with proven experience (30 d prior)	Exempt with proven experience (30 d prior)
Match Cure	--	Not Required	Required	Required	Required
Pre-placement Meeting	--	Not Required	Required (45 d prior to fab)	Required (45 d)	Required (45 d)
Release Strength (psi)	4000	6500	5500	5700	As Required
Design Strength (psi)	5000	8000	8000	8000	As Required

*PAMD- Per Approved Mix Design

Table 9 ~ Approved Mix Design - Girder

	Pre – HPC	Bristol 1	Bristol 2	Rollinsford	QC/QA
Cement	752 lb/yd^3	777 lb/yd^3 (Type III)	550 lb/yd^3 (Type II)	800 lbs/yd^3 (Type II)	*PAMD
Silica Fume	--	50 lb/yd^3	50 lb/yd^3	56 lb/yd^3	PAMD
Flyash / Slag	--	--	200 lb/yd^3 (NewCem)	--	PAMD
w/cm	.33	.33	.30	.29	PAMD
Corrosion Inhibitor	4 gal/yd^3	4 gal/yd^3	4 gal/yd^3	4 gal/yd^3	PAMD
Slump		5-7"	5-7"	5-7"	5-7"
Required Strength (psi)	5000	9400	9400	9400	As Required
Water (lb)	250	273	242	253	PAMD
Fine Aggregate (lb)	1275	1075	1200	940	PAMD Test for ASR
Coarse Aggregate (lb)	1625	1850	1750	1850	PAMD
WRA	72-210 oz	14 oz	--	52 oz	PAMD
HRWR	--	206 oz	80 oz	52 oz	PAMD
Air	9 oz	10 oz	5 oz	3 oz	PAMD

*PAMD- Per Approved Mix Design

Future Areas of Study

There continue to be areas where NH is not satisfied with the specifications, as well as areas that need to receive more study. Continued refinement of the deck permeability requirements has been an on-going effort. ASR has been an increasing concern as revealed in some NH research. The addition of supplementary cementing material (SCM) is now required in all ready-mix concrete to mitigate for ASR. NH's efforts in this area are still in the first stages of implementation and evaluation.

Issues relative to girder transportation and erection have been of greater concern more recently as longer spans and heavier girder weights become more common. Specifications need to be clear in order to prevent damage during handling as witnessed during several recent NH projects. Finally, NH continues to work on the curing of girders and especially concrete decks. Specifications that would provide incentives for proper curing are being investigated.

CONCLUSIONS

Four additional HPC bridges (girder specifications) have been advertised for construction since the completion of Rollinsford. All are nearing their successful completion and should be opened to traffic by the fall of 2003. However, in the future you will likely not see the term HPC used in any NH specifications. This is because the overall HPC philosophy of designing the concrete to meet the specific needs of an application has been incorporated into NH's Standard Specifications and everyday practice. All of NH's concrete decks have been QC/QA since 1999, now totaling over 100, and use of this specification will continue at least into the foreseeable future. Similarly, all concrete girders have been HPC since 2001 as each project is evaluated for specific strength and permeability requirements. HPC has been a major success story for NH. NH is no longer exclusively a steel state as we make better use of concrete in superstructures. NH received the 2000 PCI award for Bristol 2 as the best bridge with a span less than 65' and Bristol 1 received the 1998 PCI award for the best structure in Heavy Construction. However, if these structures were not performing well today the significance of these awards would be greatly diminished. NH's embracing and promotion of HPC has everything to do with achieving top quality. NH enthusiastically encourages the use of HPC and wants to make others aware of the excellent performance of the HPC structures that have been built. Changes made in the past 8 years to NH's design and construction practices have been very successful in moving NH towards its goals of more durable and thus cost-effective, structures. For those who haven't tried HPC – start slow, learn from your mistakes on small projects, and build on your successes … but get started.

Figure 1 ~ Bristol 2 - 2000 PCI Award Best Bridge Span less than 65'

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