Laboratory demonstration of advantages of performance specifications

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Performance specifications present an immense opportunity to optimise the design of concrete mixtures. The paper describes a laboratory study on concrete mixtures for bridge deck, optimised for better performance. The results of the comparative study show the advantages of concrete mixtures designed based on performance over that designed as per prescriptive specifications.

Keywords: *HPC bridge deck, mixture proportioning, durability tests, performance specifications.*

The National Ready Mixed Concrete Association (NRMCA) has an initiative to evolve specifications from prescriptive requirements to performance-based concepts for concrete mixtures. The prescription to performance (P2P) initiative has been identified by the concrete producers as one of the significant ways to raise the level of credibility and performance of the ready mixed concrete industry. It enables the concrete producer to have more control over his product to satisfy the needs of the owner.

One of the goals of the P2P initiative has been to develop technical data that demonstrate the benefits of performance-based specifications that could be used to support changes in codes and specifications. This study, conducted by the NRMCA Research Laboratory, is one attempt to quantify comparative properties of concrete mixtures optimised for performance that may not comply with typical prescriptive provisions in specifications for concrete construction[1]. The study was conducted to address the following three cases:

(*i*) concrete floor slab construction;

(*ii*) concrete bridge deck construction using high performance concrete (HPC);

(*iii*) an evaluation of the current prescriptive provisions for durability in ACI 318, *Building Code for Structural Concrete*[2].

Concrete mixtures were prepared according to the prescriptive provisions of these specifications and compared to mixtures that satisfy the intended performance attributes. Fresh and hardened concrete properties were measured and compared. This comparison demonstrated the benefits and optimisation of concrete mixtures for performance over prescriptive provisions. Funding for the study was provided by the RMC Research Foundation. This paper addresses only the part of study concerning the HPC bridge deck.

Experimental study

HPC bridge deck concrete specification

The main features of the HPC bridge deck specification used by one Department of Transportation included:

(*i*) specified 28-day compressive strength = 27.6 MPa (4000 psi); required average strength will be based on a historical test record in accordance with ACI 318 or ACI 301[2,3];

(*ii*) maximum water-to-cementitious ratio of 0.39;

(*iii*) total cementitious content = 418 kg/m^3 (705 lb/yd^3); cementitious composition should contain at least 15 percent fly ash and 7 to 8 percent silica fume

(*iv*) slump = 100-150 mm (4-6 inches);

(*v*) air entrainment of 4 to 8 percent required.

The performance criteria were established to target the following requirements:

(*i*) specified 28-day compressive strength = 27.6 MPa (4000 psi); required average strength based on ACI 318 or ACI 301 using past test records;

(*ii*) supplementary cementitious materials were allowed and their quantities would not exceed limits of ACI 318 to protect against deicer salt scaling;

(*iii*) Slump = 100-150 mm (4–6 in);

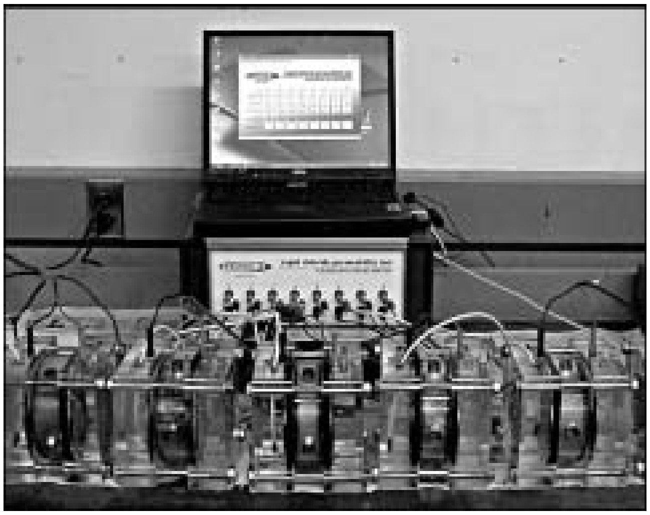

Fig 1 Rapid indication of chloride ion penetration (ASTM C 1202) test set up

(*iv*) Air entrainment of 4 to 8 percent required;

(*v*) rapid chloride ion permeability test (RCPT) = 1500 coulombs after 45 days of moist curing;

(*vi*) length change (drying shrinkage) < 0.04 percent at 28 days of drying after 7 days of moist curing.

Mixing concrete

A 0.1 m^3 (3.5 ft^3) revolving drum mixer was used to mix the concrete. Concrete batch was kept at 0.08 m^3 (2.9 ft^3) concrete was mixed in accordance with ASTM C 192[5]. Type A water reducing admixture was mixed with the water and batched with the coarse aggregate prior to adding the sand and cementitious materials. Air entraining admixture was added on top of the sand. The mixtures were mixed to a target w/cm ratio. Type F high range water reducer was added only after the concrete had mixed for about 2 minutes and a slump of about 13 mm (0.5 in) had been ascertained visually. Concrete was mixed for an additional 2 minutes over the 3-3-2 mixing cycle as per ASTM C 192. High-range water reducing (HRWR) admixture dosage was adjusted to achieve the desired slump.

Testing

All concrete batches were tested for slump, (ASTM C 143), air content, (C 231), density, (C 138) and temperature (C 1064)[6-9]. Compressive strength tests for concrete mixtures were conducted in accordance with ASTM C 39[10]. Specimen size used was 100 × 200 mm (4 × 8 in) cylindrical specimens. Test specimens were transferred to the 100 percent humidity room as soon as they were made and cured until the test age. Strength test results reported are the average of two test cylinders tested at the same age. Length change of concrete due to drying shrinkage was tested by ASTM C 157[11]. The shrinkage test specimens were moist cured for 7 days and after that they were stored in at 21°C (70°F) and a relative humidity of 50 percent. Length change measurements were obtained at various periods of air drying as indicated in the reported results. The length change reported is the average of two specimens.

The rapid indication of chloride ion penetrability, also known as rapid chloride permeability test (RCPT), was conducted in accordance with ASTM C 1202[4]. Two 100 × 200 mm (4 × 8 in) specimens were prepared for the C 1202 test. The specimens were cured in a moist room at 21°C (70°F) until the test age. The top 50 mm (2 in) portion of the test specimens as cast were used for the test. The test set up is shown in *Fig 1*.

The rapid migration test is a provisional AASHTO standard (2004), AASHTO TP 64[12]. This test is similar to ASTM C 1202 in that the chloride ions are driven into the concrete by an electric current. The depth of penetration of chloride ions is measured by spraying the fractured specimen with silver nitrate. The results are reported as rate of penetration which is calculated by dividing the depth of penetration, mm, by the product of applied voltage (V) and the test duration (h). The rapid migration test is considered by many as a more reliable indicator of the chloride penetrability of concrete than the RCP test. Two 100 × 200 mm (4 × 8 in) cylindrical specimens were cured in the moist room at 21°C (70°F) until the test age. The top 50 mm (2 in) of the cylinders were cut and used for the test. *Fig 2* shows the depth of penetration for a typical test specimen.

The sorptivity test was standardised as an ASTM test method, C 1585 in 2004[13]. In this test 50 mm (2 in) thick concrete slices from a cylinder are placed with the exposed surface immersed in water as shown in *Fig 3*. The other surfaces of the specimen are sealed with an epoxy. The increase in specimen mass with time due to moisture absorption is measured. The initial and secondary rate of water absorption is calculated in accordance with the test procedure. Sorptivity is not a direct measure of permeability but measures the rate of flow of fluid due to capillary suction. The sorptivity test specimens were moist cured for a period of 51 days. This was followed by a period of sample conditioning as required in ASTM C 1585. Two cylinders were tested for each mixture and the results averaged.

The bulk diffusion test, ASTM C 1556, is a new test standardised in 2003[14]. In this test, after 28 days of moist curing the top 76 mm (3 in) of the concrete cylinders are cut, sealed (except for the finished surface) and vacuum saturated in saturated calcium hydroxide solution. The saturated test specimen is immersed in a sodium chloride solution with one unsealed face exposed to the solution until the specimens attained an age of about 180 days. The specimen is then removed and ground in 2 mm thick layers from the exposed surface. The acid soluble (total) chloride content is measured

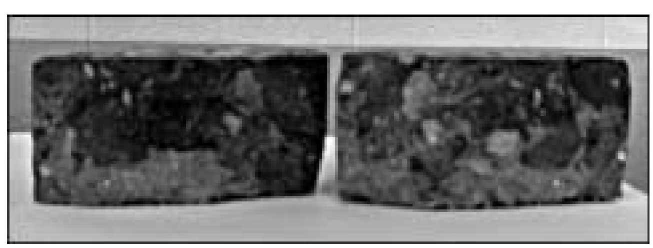

Fig 2 Rapid migration test (AASHTO TP 64) showing chloride penetration depths

at different depths from which an apparent chloride diffusion coefficient is calculated in accordance with ASTM C 1556. The apparent chloride diffusion coefficient is used in service life predictive models such as 'Life 365' to estimate the service life of concrete structures exposed to chlorides. This is a detailed test procedure requiring in excess of 10 hours/specimen. Duplicate specimens of two of the mixtures were tested to verify repeatability.

Table 1: Details of the HPC bridge deck mixtures

Product description	*Mixture*			
	BR-1	*BR-2*	*BR-3*	*BR-4*
Cement, kg/m^3 (lb/yd^3)	326 (550)	253 (426)	178 (300)	253 (426)
Fly ash, kg/m^3 (lb/yd^3)	62 (105)	89 (150)	(0)	89 (150)
Silica fume, kg/m^3 (lb/yd^3)	30 (50)	14 (24)	(0)	(0)
Slag, kg/m^3 (lb/yd^3)	(0)	(0)	178 (300)	(0)
UFFA, kg/m^3 (lb/yd^3)	(0)	(0)	(0)	20 (34)
Total cementitious content, kg/m^3 (lb/yd^3)	418 (705)	356 (600)	356 (600)	362 (610)
Coarse aggregate (#67), kg/m^3 (lb/yd^3)	1068 (1800)	1140 (1922)	1151 (1940)	1154 (1945)
Fine aggregate, lb/yd^3 (kg/m^3)	665 (1121)	711 (1199)	717 (1209)	720 (1214)
Water, lb/yd^3 (kg/m^3)	163(275)	139 (234)	139 (234)	129 (218)
w/cm	0.39	0.39	0.39	0.36
AEA, ml/kg (oz/cwt)	0.26 (0.40)	0.29 (0.45)	0.26 (0.40)	0.26 (0.40)
Type A WR, ml/kg (oz/cwt)	2.61 (4)	2.61 (4)	2.61 (4)	2.61 (4)
Type F HRWR, ml/kg (oz/cwt)	8.49 (13.0)	6.14 (9.4)	12.02 (18.4)	7.25 (11.1)
Fresh concrete properties				
Slump, mm (in)	102 (4.00)	127 (5.00)	127 (5.00)	146 (5.75)
Air, percent	4.6	7.2	4.7	7.6
Density, kg/m^3 (lb/ft^3)	2334 (145.7)	2308 (144.1)	2411 (150.5)	2283 (142.5)
Temperature, ^{o}C (^{o}F)	21 (69)	21 (69)	18 (65)	21(69)
Hardened concrete properties				
Compressive strength, MPa (lb/in^2)				
3-day	28.61 (4,150)	25.16 (3,650)	17.93 (2,600)	25.58 (3,710)
7-day	37.37 (5,420)	33.64 (4,880)	38.33 (5,560)	35.58 (5,160)
28-day	51.57 (7,480)	46.88 (6,800)	61.84 (8,970)	49.50 (7,180)
Length change (drying shrinkage), percent				
28-day	-0.037	-0.017	-0.021	-0.018
90-day	-0.045	-0.027	-0.029	-0.027
180-day	-0.043	-0.024	-0.025	-0.024
RCP, Coulombs				
45-day	1563	1257	1126	1244
110-day	541	434	541	479
180-day	327	275	375	242
Rate of penetration (RMT), mm/(V-h)				
60-day	0.019	0.018	n/a	0.023
120-day	0.0090	0.0070	0.0060	0.011
180-day	0.0058	0.0045	0.0054	0.0047
Rate of water absorption (Sorptivity), x10^{-4} mm/s$^{1/2}$ at 69 days				
Initial	6.19	7.37	8.89	15.20
Secondary	3.47	4.59	4.52	6.37
Diffusion coefficient, x10^{-13} m^2/s				
180 days	7.17	5.38	4.31	9.59
Surface chloride, percent by weight of concrete				
180-day	0.74	0.84	0.58	0.67

Notes: UFFA : Ultra-fine fly ash; AEA: Air-entraining agent; WR: Water-reducing admixture; HRWR: High-range water reducing admixture

Mixture proportions

Four concrete mixtures were cast. The mixture design and test results are provided in *Table* 1. All mixtures were designed for the slump and air requirement and contained a standard ASTM C 494 Type A water reducer dosage at 2.61 ml/kg (4 oz/cwt) and an ASTM C 494 Type F HRWR dosage sufficient to attain the desired slump.

Mixture BR-1 is the control mixture designed according to the prescriptive specification. The w/cm was 0.39 and the total cementitious content was 418 kg/m^3 (705 lb/yd^3) out of which 15 percent was Class F fly ash and 7 percent was silica fume. Mixtures BR-2 to BR-4 were designed to satisfy the performance-based criteria.

Mixture BR-2 had the same w/cm (0.39) as mixture BR-1 but had a much lower total cementitious content [356 kg/m^3 (600 lb/yd^3) as opposed to 418 kg/m^3 (705 lb/yd^3)]. The silica fume content was set at 4 percent and the quantity of Class F fly ash was increased to 25 percent by mass of cementitious materials.

Mixture BR-3 had the same w/cm (0.39) as mixture BR-1 but had a much lower total cementitious content [356 kg/m^3 (600 lb/yd^3) as opposed to 418 kg/m^3 (705 lb/yd^3)]. This mixture contained 50 percent slag by mass of cementitious materials without silica fume or fly ash.

Fig 3 Sorptivity test (ASTM C 1585) set up

Mixture BR-4 was similar to mixture BR-2, except that silica fume was replaced with ultra fine fly ash (UFFA). Based on supplier's recommendations the quantity of the UFFA was higher than that of silica fume [20 kg/m^3 (34 lb/yd^3) versus 14 kg/m^3 (24 lb/yd^3)] at the same cement and fly ash contents. The water content of this mixture was about 7 percent lower than mixture BR-2 for achieving the target slump. This reduced the w/cm of this mixture to 0.36.

Discussion of test results

From the test results provided in *Table 1*, it can be observed that the the slump of the four mixtures varied between 100 mm (4 in) and 146 mm (5.75 in). The air contents varied between 4.6 percent and 7.6 percent and the fresh concrete temperature varied between 18ºC (65ºF) and 21ºC (69ºF). The density of the concrete varied between 2308 kg/m^3 (144.1 lb/ft^3) and 2411 kg/m^3 (150.5 lb/ft^3). The required ASTM Type F HRWR dosage was about 27 percent lower for mixture BR-2 compared to mixture BR-1 even at a lower water content of the concrete by over 15 percent. This was because of the much lower silica fume content and higher fly ash content used in mixture BR-2. The HRWR dosage required for mixture BR-3 was about 40 percent higher than that of mixture BR-1. The required HRWR dosage was about 15 percent lower for mixture BR-4 as compared to mixture BR-1 even with a water content that was reduced by over 20 percent.

Compressive strength

The specified 28-day compressive strength of 27.6 MPa (4000 psi) was easily achieved and significantly exceeded by all the concrete mixtures.

Drying shrinkage

The specified length change (ASTM C 157) of 0.04 percent after 28 days of drying was satisfied by all the mixtures. The highest level of shrinkage (0.043 percent at 180 days) was observed for the mixture that complied with the prescriptive HPC bridge specification – BR-1. The length change value of all the performance mixtures (BR-2, BR-3, BR-4) was much lower at all ages, most likely because of the lower paste content (4.36 percent to 5.17 percent).

Durability tests have a high testing variability. These tests are therefore recommended for pre-qualifying mixtures and not for job-site testing and acceptance.

Rapid chloride permeability and rapid migration

The specified RCPT (ASTM C 1202) value of 1500 coulombs after 45 days of moist curing was met with by all the mixtures except the prescriptive BR-1 mixture which had a slightly higher value of 1563 coulombs. Note that this is still a low value of charge passed. The RCP test values after 180 days of moist curing varied between 242 and 375 coulombs which indicates a "very low" permeability for all mixtures according to Table 1 of ASTM C 1202.

The rapid migration test results show that the measured rate of penetration for the mixtures after 180 days of moist curing varied between 0.0045 mm/V-h and 0.0058 mm/V-h. These numbers indicate no significant differences between the concrete mixtures. The results comply with the performance requirements of FHWA's HPC Grade 3 (highest durability) according to AASHTO TP 64.

Sorptivity

The sorptivity test results show that the initial rate of water absorption varied between 6.19 × 10^{-4} mm/s$^{1/2}$ and 15.20 × 10^{-4} mm/s$^{1/2}$. The prescriptive mixture had the lowest initial rate of water absorption. The performance mixtures which contained lesser or no silica fume had higher initial rate of water absorption. The final rate of water absorption varied between 3.47 × 10^{-4} mm/s$^{1/2}$ and 6.37 × 10^{-4} mm/s$^{1/2}$. At this point it is not clear as to what criteria apply to these data in categorising the relative performance of the four mixtures evaluated. Clearly, one might surmise that mixtures that show a higher rate of water absorption will absorb salt solution at a faster rate. After the surface of the concrete has reached a saturated state, the ingress of chlorides will be controlled by diffusion. Bulk of the chloride penetration up to the rebar is due to diffusion and not due to absorption. The diffusion process is longer and controls the corrosion free service life of reinforced concrete exposed to chlorides.

Chloride diffusion

The chloride diffusion test results show that the apparent chloride diffusion coefficient after about 180 days of immersion in chloride solution varied between 4.31 × 10^{-13} m^2/s and 9.59 × 10^{-13} m^2/s. The mixture complying with the prescriptive bridge specification, BR-1, had an apparent chloride diffusion coefficient of 7.17 × 10^{-13} m^2/s. Mixture BR-1 was removed from the chloride solution at a slightly younger age (146 days) as opposed to the performance mixtures (168 to 188 days). It is clear that performance mixtures could be designed to attain lower apparent chloride diffusion coefficients. Regardless the difference in the measured chloride diffusion coefficients is still not very high and all four concrete mixtures can be classified as low permeability concrete mixtures. For example Life-365 computer program assumes an apparent chloride diffusion coefficient of 75 × 10^{-13} m^2/s for a plain portland cement only concrete mixture with about a w/cm of 0.39. These mixtures were about one order of magnitude lower than that value. The estimated surface chloride content at the termination of the exposure varied between 0.58 percent and 0.84 percent by weight of concrete. *Fig* 4 shows the chloride content measured as a function of specimen depth for two mixtures – BR-3, and 318-1 (a portland cement only mixture with w/cm = 0.42). It is clear that different mixtures differ in their ability to resist the ingress of chloride ions.

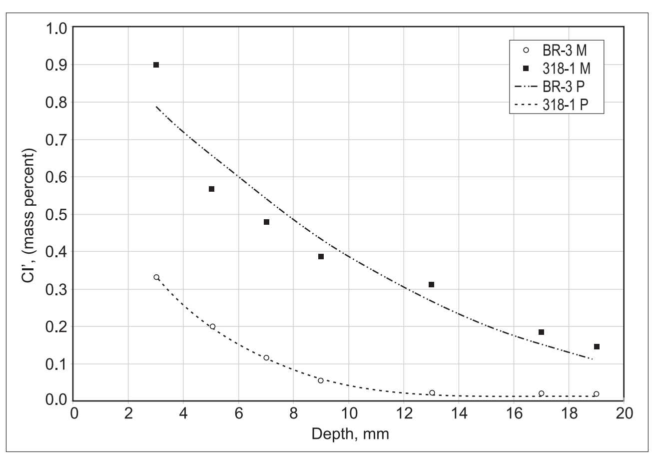

Fig 4 Chloride penetration into concrete exposed to sodium chloride solution

Summary

(*i*) Performance criteria in specifications for concrete will assure the owner that the performance objectives are achieved. Prescriptive specifications that imply performance do not assure much. In the HPC bridge deck application discussed in this paper targeting specific performance criteria resulted in equal or better performance (lower shrinkage, better workability/lower admixture dosage, lower chloride permeability etc.) as compared to prescriptive limitations in the specification. Along with improved performance, the mixtures evaluated in this study were achieved at a significantly lower material cost.

(*ii*) Performance specifications allow a great opportunity to optimise the concrete mixture designs. This ensures that different producers can compete based on their knowledge and resources and better serve the needs of the project.

As mentioned initially, the floor slab application and the ACI 318 study have not been reported in this paper. The floor slab study led to similar conclusions as the bridge deck study reported in this paper. The ACI 318 study suggested that w/cm limits that control intended durability need a fresh look as the test programme demonstrated that significant differences in performance related to permeability and shrinkage could be attained even at the same w/cm and similar strength.

In order to ensure durability engineers typically use prescriptive requirements such as minimum cementitious content, dosages of supplementary cementitious materials such as fly ash, slag, silica fume and maximum w/cm. These prescriptive requirements could be replaced by targeting specific performance levels to be attained with different durability test methods. The rapid chloride permeability, and rapid migration test could be specified in actual project applications. However, it should be noted that these durability tests have a high testing variability. Therefore they are not recommended for job site testing and concrete acceptance purposes. It is suggested these tests be conducted to pre qualify concrete mixtures. Some state highway departments in the USA are using the RCPT as a job site test.

In general, before requiring a test for concrete acceptance it is important to take into account the variability of the test that is specified. A test method that shows a high testing variability is most likely to show a high variability at the job site. This increases the risk of rejecting acceptable product, which impacts the concrete supplier. For this reason acceptance criteria established in specifications should take into consideration the precision of the test. It is well known that the acceptance criteria for strength requirements are based on a 1 percent probability of failure. The acceptance criteria for a durability test such as RCPT established on a similar basis could cause a significant shift in the designed mix to avoid the potential of a failure. For example, to achieve the specified RCPT value of 1000 coulombs the concrete producer would be forced to target a much lower average RCPT value which would lead to unrealistic and expensive concrete mixtures. A better approach would be to word the specification as "80 percent of the specimens should be below 1000 coulombs".

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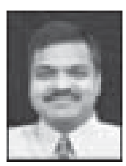

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