Studies Offer Proof Of Precast's Durability

Survey of parking garages offers tips on design and maintenance, while chloride-permeability tests show existing standards are confusing

Creating a precast structure that will retain its durability and aesthetic appeal over time remains a key concern of owners and designers. Although first costs always are among owners' top priorities, life-cycle and long-term maintenance expenses can eliminate any initial savings. Recently, two detailed studies of precast components sponsored by the Precast/Prestressed Concrete Institute (PCI) were released that can help owners and designers balance these needs.

"Durability of Precast Prestressed Concrete Structures" reports on the long-term durability of parking structures nationwide. The study was conducted by The Consulting Engineers Group Inc. (CEG) of San Antonio. The report summarizes a survey undertaken by CEG of 62 parking structures. The firm evaluated various performance characteristics and inspected several sites to determine what methods and design criteria work best in various situations.

In general, the study found that precast parking garages perform extremely well over time and those that are well-maintained and regularly inspected perform best. It also offers a host of suggestions on how to achieve these ends through design, construction, and on-going inspection plans.

The second report, "Durability Aspects of Precast Concrete, Parts I and II, Historical Review and Chloride Permeability Study," was conducted by the engineering firm of Wiss, Janney, Elstner Associates Inc. (WJE) of Northbrook, Ill. The one-year experimental study was designed to answer questions relating to chloride permeability, water-absorption rates, and other durability considerations. Among its findings was that in many cases, accepted tests for determining the durability of concrete needed for a project may be overstated, costing owners money by making them pay for methods and materials that aren't necessary.

Parking Maintenance

CEG's study of parking garages found that "the overall performance of precast prestressed concrete parking structures can be rated as very good, with the general performance rated as 84 percent out of 100 percent." The primary areas of concern if problems were to arise, it notes, are derived from field-placed toppings, excessive leaking, poor drainage-system design, and cracking in precast spandrels. This latter rating area was due primarily to hairline cracks, the study says. Even so, it notes, "The performance of the precast products was excellent," and these problems seldom arose.

However, it found that maintenance efforts average just 5.76 on the 10 scale. This represents a major concern, as lack of maintenance often lies at the heart of any problems that do arise with precast garages, it notes.

The examined structures ranged in age from two to 24 years and were located in 17 states across the country. The dimensions were representative of typical structures, the study says, with a

Durability in parking structures can be enhanced with a lower water/cement ratio and a long-term maintenance plan. Photo: Hedrich-Blessing

minimum width of 105 feet, a maximum length of 1,200 feet, and up to 12 levels of parking. About 65 percent of the structures were located in regions where salt was applied, with 69 percent in regions where freeze-thaw conditions were a consideration. Some 41 percent of the structures also featured warped double tees, which remains a key focus for design considerations. Concrete strength averaged 5,878 psi and ranged from 5,000 to 7,000 psi.

These key areas were spotlighted.

Proper Drainage A Must

"Poor drainage was found to be one of the principle culprits in the deterioration of [the studied] parking structures," the study reports. In the few cases where it occurred, the study says, poor drainage allows water to collect on the deck's surface, creating ponds that allow road salt to concentrate and attack the concrete. This in turn lets chloride ions penetrate the concrete. Ponding also can create a safety problem, particularly when it freezes.

Good drainage includes five key components, the study reports: primary span floor slope, cross slope, drain location, drain size, and joint sealing.

'Poor drainage was found to be one of the principle culprits in the deterioration of parking structures.'

Excessive slopes can lead to warping problems, minimized headroom, or safety issues, the study says. The goal should be to create a minimum slope that still drains water efficiently. The survey found that in most cases, the desired slope ran between 1.5 percent and two percent for the primary long-span slope and 0.5 percent to one percent for the beam lines that create crickets that direct water to the drains. This, in fact, was achieved for most of the garages studied.

Drains located as close to the column grid lines as possible minimize local ponding, while drains measuring at least 11 inches in diameter perform the best, the study reports. Trench drains are used at the bottom of the roof-level ramp. They tend to be spaced so they don't interrupt the floor-framing system, rather than being used continuously.

Sealants Make A Difference

Sealants play a critical role in maintenance programs, the study found. "The structures that performed the best were sealed at all circumstances where precast members come together," it says. This includes joints connecting flange to flange, tee to beam and spandrel, tee and beam to wall panels, and all those around columns. If these were properly sealed, the study says, across the board "the deck had very few

if any leaks." Urethane was the most typical sealant used, the study adds. "Properly installed urethane appears to have an effective life of seven to 10 years, with touch-up maintenance when and where required."

Joints should be prepared properly prior to sealing them, the study stresses. In topped systems the topping should be tooled (not sawn) to a depth of 1/2 inch and all scales or latence removed by grinding. Flange joints in pretopped systems should be ground or stoned to remove sharp edges and loose material.

Flange Cracking

Strains caused by shrinkage create most of the cracking in double tee flanges that occurs, the study reports, emphasizing that such cracking is not typical. These cracks most often develop during the production and curing cycles, and they build up in the flange regions between the stems. During the curing process, the stem concrete is held rigidly by the steel forms. This restrains the flange's ability to shrink between the stems as it cures, occasionally producing a crack in the flange adjacent to the inside corner of the juncture between the stem and the flange. "These cracks can be minimized by proper curing techniques that retain moisture," the report says.

'Flange cracking, unless severe, seldom leads to poor performance of the double tee.'

Cracking also can occur during the stripping process, it notes, when one end of the stem is elevated higher, putting more stress on the other end. It also can result from excessive wracking of the tee as it is transported to the jobsite. Although none of these occur often, they are the key areas to focus on to prevent any cracking that may arise.

Even then, the report team's inspections showed that "flange cracking, unless severe, seldom leads to poor performance of the double tee." Small cracks (those less than 0.004 inch in width) "typically are not through cracks and seldom affect the performance of the member," the report says. "Therefore, nothing typically is done to such flange cracks if a field-placed topping is to be applied." If the system is pretopped, however, even small cracks should be sealed to ensure water and water-borne chlorides do not attack the underlying system.

Any cracks in pretopped systems, should they arise, as well as larger cracks in field-topped decks, typically are sealed by a surface application of a clear, low-viscosity epoxy, the report adds. Working cracks are best treated with a sealant such as urethane. It also says that cracks larger than 0.0010 inch should be examined by an experienced engineer. Silane sealants have also proven to be effective for small cracks (less than 0.0005 inch).

Although no type appeared in the surveyed garages with regularity, spandrel cracking was reported to be the most prevalent type, the report says. Such cracking typically is observed as a diagonal torsion crack, particularly in L-beam spandrels or cracks radiating from the bearing or connections. To alleviate this, connections should be used that allow spandrels to relieve temperature strains, the report suggests. "Bolted connections have proven to perform quite well," it notes. In addition, "Fiber-reinforced bearing pads at least one-half-inch thick also were observed to perform better than plain bearing pads."

Admixtures Can Help

"Certain admixtures are fairly universally employed by precast concrete producers to greatly enhance the durability of precast concrete products," the study reports. The two most common are air-entraining agents used in freeze/thaw regions and super plasticizers that reduce the amount of water needed to produce a workable concrete mix, thereby lowering the water/cement (w/c) ratio.

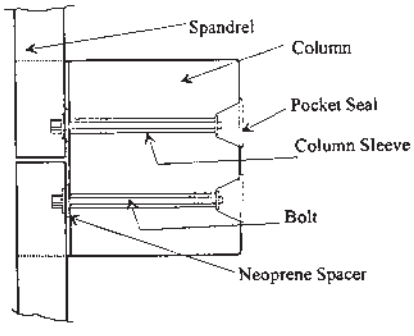
The report refers to the tests and experiments run in the WJE study, adding that its own survey bears out the findings that reducing the w/c ratio to within the range of 0.35 to 0.40 greatly reduces the ability of chloride ions to penetrate the concrete. "Concrete with this w/c ratio has proven to be nearly impervious, and the additions of other admixtures such as silica fume provide little substantial benefit." It also notes that 57 percent of respondents said they employed w/c ratios of this range in their projects already.

"The most durable structures would be ones that minimize field-placed concretes which typically have high w/c ratios," the report summarizes. "The pretopped double tee system would produce the most durable concrete at the riding surface as well as throughout the structure. If field-placed topping is employed, then a w/c ratio of no more than 0.45 is recommended." In fact, PCI recommends that field-placed topping should offer a w/c ratio as low as possible, preferably 0.40 or lower.

Steel embeds often are left exposed to the elements in a precast structure, the study observes, and these usually consist of precast-member bearing plates and connection plates between precast members in welded connections. These can be subjected to water from leaks or harsh climates and should be protected. In regions where road salt isn't used, only a shop paint rust preventative coat is needed to ensure smooth operation, it reports. In regions where salt is used, the embeds should be galvanized or protected with zinc or epoxy paint. It also points out that regular maintenance of the structure will provide additional protection by ensuring caulks and sealers are working properly.

Shear Walls Predominate

The predominant lateral-load system used by the studied garages consisted of a shear wall system. Some 89 percent of the structures examined used this approach, while 10 percent used moment frames and one percent used only stair and elevator shafts. However, examination of the systems showed there is no need to isolate stair and elevator shafts away from the structure, the study found. "If appropriate connections are



This diagram of a typical ductile bolted connection shows the voids in the sleeve surrounding the bolt permit lateral movement without impairing performance. In not one case in the study where such a connection was inspected was cracking at the connection observed.

employed, such shafts can be included in the lateral-load system."

The most effective connection system appeared to be one using bolted connections between the spandrel and the columns, with those connections relieving thermal stresses. The predominant connection type between the shear walls themselves was a welded connection in a recessed pocket.

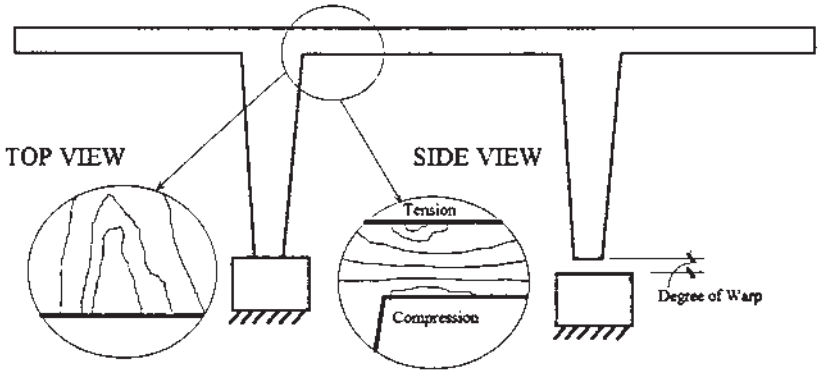
Maximum Warping Analyzed

Double tees at times are warped deliberately in a parking garage project when drainage plans provide different slopes for the bearings at each end of the double tee floor member. Although this presents no problems in general and can be accomplished routinely, the report says, large warps may result in some cracking in the double tee flange. To measure the extent of this at different amounts of warping, the survey team ran a finite-element analysis. The result showed that maximum tensile stresses occur in the top of the flange near the unwarped stem. This follows classical bending-stress distribution patterns, except the top surface of the flange exhibits a stress distribution similar to a concentrated load-stress distribution. The results of the finite-element analysis were supported by an actual test of durable tees with various degrees of warping.

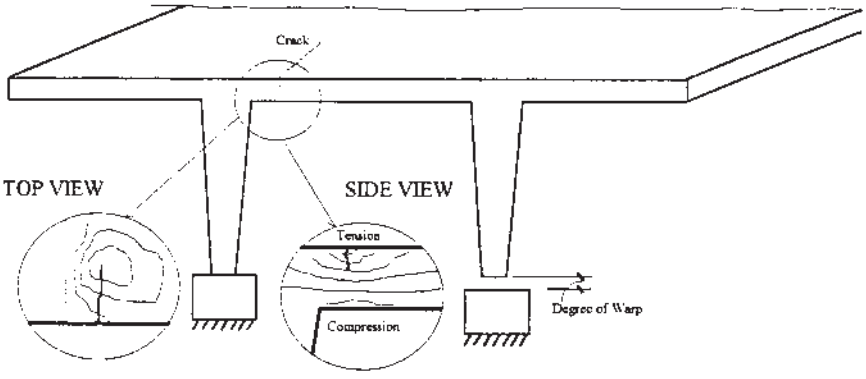
The study says that double tees can be warped safely to the amount of 3/4 of an inch between stems and 1.5 inches for a full tee width. In general, it adds, "The stresses caused by a moderate warp are generally not critical. The cracks resulting from a service warp are generally longitudinal and do not penetrate through the flange."

'The overall performance of precast prestressed concrete parking structures can be rated as very good.'

Despite its focus on key areas of concern that arise with precast construction, the report emphasizes that this approach should not be construed to mean that precast garages offer many difficulties. In fact, it stresses that just the opposite was the case. "It should be



This side view of a stress pattern in a warped double tee from CEG's durability study shows the patterns of compression. The maximum tensile stresses occur in the top of the flange near the unwarped stem, the survey found.



This diagram shows the stress pattern that develops in a warped double tee that cracked. The study found that the crack will propagate along the flange rather than through it, supporting the theory that most through-flange cracking is created by handling of the warped tee rather than the actual warping process.

Changes Suggested For AASHTO Standards

In its findings, the WJE study suggests several key changes to the existing AASHTO standards for curing and ponding tests.

"The current AASHTO moist- and heat- or steam-curing specifications [in Section 8.11] need to be revised," it says. "There are numerous technical reasons for requiring moist-cured field concrete that will see chloride exposure in its lifetime to have moist curing beyond the age when the concrete reaches 70 percent of the design strength." The present provision allows these field concretes to receive as little as one to three days of moist curing with existing low w/c ratios and cements.

It also suggests revisions to the T 259 Ponding Test. These include:

- A "more realistic" curing period, halving the current 14-day period.
- Use of a 15-percent chloride concentration solution for the ponding solution. The existing three-percent NaCl solution represents sea water, not current deicing salt solutions used in northern regions that are more concentrated and harmful.
- Increased ponding periods from 90 days to 365. Since ponding tests require little supervision, this should add little impact to its cost, the study points out.
- Doubled chloride samples, from two to four, as two data points are "totally insufficient to determine diffusion coefficients."
- Use of core rather than drilled samples, which can be contaminated and erroneous and provide inaccurate drilling depths.

noted," the report says in its summary, "that all structures surveyed or inspected were in serviceable condition even when over 25 years old and in severe corrosion exposure and subjected to poor maintenance." Even with its focus on finding where problems arise and how they can be eliminated, "The typical good performance of precast parking structures of all kinds in all ranges of exposure was apparent."

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Chloride Ion Tests

The ability to achieve high durability through various curing methods was enhanced by the findings of the study performed by WJE. It examined various durability properties when cured in different ways and when created with different w/c ratios. The study was conducted by WJE engineers for PCI and featured several formats. Each tested concrete sample was cured in a water tank, under wetted burlap or through heat-curing. Concretes incorporating admixtures of silica fume were cured under wetted burlap only.

Three w/c ratios were produced, at 0.46, 0.37 and 0.32. These represented the two ends of the range typically found in precast products (0.37 to 0.32), plus one considerably higher in w/c, which is typical of 0.45 AASHTO-grade concrete. Samples using silica-fume additions of 5.0 percent and 7.5 percent by weight of cement also were tested under wetted burlap, while standard precast concrete type mixes made with each of the three w/c ratios were tested under each of the three types of curing. This resulted in 15 different test samples. The results for each sample are shown in Table 1.

All 15 mixtures were tested according to standards set by the American Society of Testing Materials (ASTM) to check for permeable voids. The three heat-cured mixtures of conventional concrete were found to have the lowest volume of permeable voids. Adding silica fume increased the number of voids by 100 percent for the five-percent mixture and 50 percent for the 7.5-percent version.

The study also tested the coulomb rating of each sample. The rating expresses the amount of electrical charge that passes through the concrete in a set period of time and is measured in coulombs. The ratings are supposed to allow designers and owners to specify the level of permeability they desire by using the mixture's coulomb rating as a delineator. However, the study found that ASTM's existing coulomb ratings for concrete cured in each type of system do not correspond well to the actual permeability that can be seen in practice.

"Using coulomb ratings as an indicator of durability will be misleading and will add cost to a project," says Donald W. Pfeifer, project manager at WJE. This can be critical, because specifying concrete to meet the set coulomb ratings can be more expensive than using other concretes that are less costly.

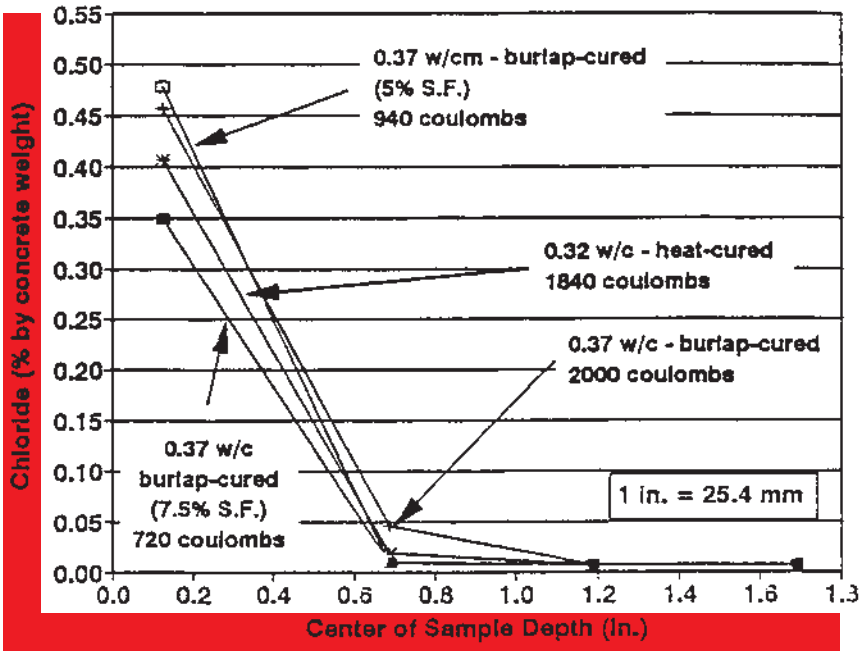
"The concrete w/c ratio is the dominant factor in reducing chloride permeability," the study says. The report found that the concrete with a 0.37 w/c ratio had reduced its chloride ingress by about 80 percent over the concrete with a 0.46 w/c ratio. Further, the concrete with a 0.32 w/c ratio had reduced penetration of 95 percent. It pointed out that this evidence confirmed a three-year corrosion study performed by the Federal Highway

Mix	Cure	Fume content (%)	w/cm	Chloride after 1-yr ponding (percent by weight of concrete)			D_{as} mm^2/s	C_o (%)	AASHTO T277 coulomb	Years to corrosion for different cover depths		28-day strength (MPa)	Volume of permeable voids (%)
				0 to 6 mm	13 to 22 mm	25 to 35 mm				50 mm	75 mm		
1	Tank	0	0.31	0.476	0.009	<0.007	7.69×10^{-7}	0.734	1431	11	26	48.0	8.5
2		0	0.37	0.469	0.099	<0.007	2.51×10^{-6}	0.586	2004	4	9	45.0	8.9
3		0	0.46	0.377	0.277	0.082	1.09×10^{-5}	0.444	2909	1	2	35.6	9.9
4	Burlap	5.5	0.33	0.422	<0.007	<0.007	7.41×10^{-7}	0.657	637	12	28	50.2	12.5
5		5.5	0.38	0.478	0.009	<0.007	7.70×10^{-7}	0.737	943	11	25	37.0	14.4
6		5.5	0.46	0.436	0.058	<0.007	1.81×10^{-6}	0.569	1484	5	12	36.2	14.7
7		7.5	0.33	0.355	<0.007	<0.007	5.55×10^{-7}	0.600	678	17	38	55.6	9.6
8		7.5	0.37	0.349	0.010	<0.007	8.79×10^{-7}	0.521	726	11	25	49.6	9.9
9		7.5	0.46	0.430	0.052	<0.007	1.69×10^{-6}	0.567	1696	6	13	36.3	11.7
10		0	0.32	0.506	0.019	<0.007	9.69×10^{-7}	0.739	1411	9	20	47.4	9.3
11		0	0.37	0.457	0.046	<0.007	1.52×10^{-6}	0.613	1965	6	14	48.0	9.8
12		0	0.46	0.419	0.253	0.088	8.79×10^{-6}	0.483	3041	1	3	37.2	10.7
13	Heat	0	0.32	0.407	0.019	<0.007	1.06×10^{-6}	0.583	1841	9	20	45.2 (46.3)*	5.8
14		0	0.37	0.364	0.063	<0.007	2.15×10^{-6}	0.464	2794	5	11	45.2 (43.1)*	6.8
15		0	0.46	0.287	0.130	0.039	6.19×10^{-6}	0.331	3410	2	4	38.5 (39.0)*	8.0

*Strength determined from heat-cured cylinders.

Chloride ingress, calculated diffusion coefficient and surface chloride and calculated times to corrosion for the 15 mixtures

Table 1, produced by WJE for its chloride-permeability study, summarizes the key findings of the tests. Among other things, it indicates that lower water/cement ratio of any concrete sample correlated better with resisting chloride penetration than the AASHTO T277 coulomb ratings.



This diagram from WJE's chloride-permeability study shows that four different concretes offering a wide range of coulomb ratings performed quite similarly during actual tests.

Complete Studies Available

"Durability of Precast Prestressed Concrete Structures" was conducted by Thomas J. D'Arcy, Walter J. Korkosz and Larbi Sennour of the Consulting Engineers Group Inc. of San Antonio. Copies are available from the company at 2455 N.E. Loop 410, Suite 125, San Antonio TX 78217; 210/637-0977.

The Chloride Permeability study was conducted by Matthew Sherman, David McDonald and Donald Pfeifer of Wiss, Janney, Elstner Associates Inc. of Northbrook, Ill. Copies are available from PCI. (See the in-depth story in the *PCI JOURNAL* July/August '96.)

Both reports can be obtained from PCI, the sponsoring association, at 175 W. Jackson Blvd., Suite 1859, Chicago IL 60604; 312/786-0300; e-mail, info@pci.org.

Administration in 1987. "The correlation between long-term chloride permeability and the coulomb test recommended in the ASTM C1202 test appears to be highly variable," the study says, "and requires individual correlation between these two types of tests for every concrete mixture."

'Using coulomb ratings as an indicator of durability will be misleading and will add cost to a project.'

Heat-Cured Performs Well

Heat-cured concrete had the lowest water absorption and volume of permeable voids at the tested date of 42 curing days, the report says. The 365-day, long-term ponding tests also showed that heat-cured slabs generally had the lowest near-surface chloride concentrations compared to the average of the other types.

The silica-fume mixtures produced 28- and 180-day compressive strengths equal to the strengths of conventional concretes with equal w/c ratio, either burlap- or tank-cured, the study reports. The five-percent burlap-cured silica fume mixture with a w/c ratio of 0.46 had an estimated time-to-corrosion rate essentially equal to that of 0.37 w/c conventional heat-cured concrete, while the 7.5-percent burlap-cured mixture with a w/c ratio of 0.37 corresponded to the heat-cured conventional concrete of 0.32 w/c ratio.

This shows two different approaches to achieving the same durability, as measured by a w/c ratio. However, the use of silica fume changes the overall characteristics, the study stresses. "The addition of silica fume to concrete caused a significant increase in the water absorption and volume of permeable voids in moist-cured concrete at all w/c levels," it says. Similarly, heat-curing dramatically decreased the absorption and volume of permeable voids in conventional concrete at all w/c levels. "The reasons for and the implications of these findings merit further research."

No Strength Loss

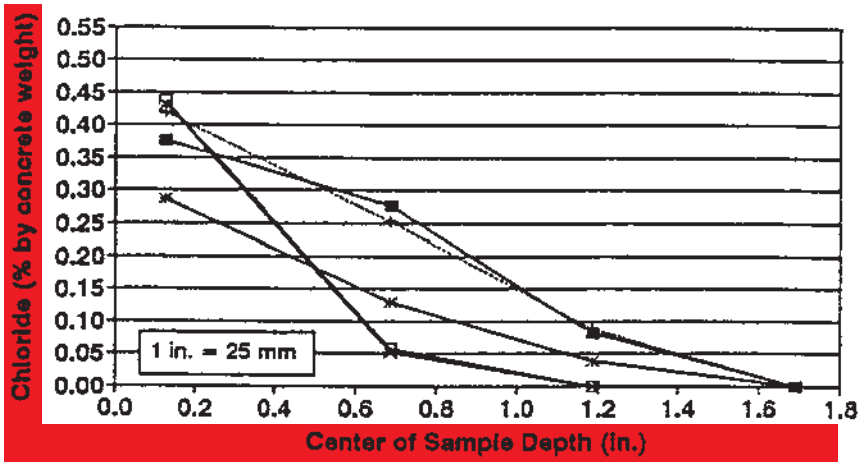
The study also reports that "Proper heat-curing created no significant strength loss at 28 days at all three w/c levels." This could be seen in the fact that 28-day strength of the material that received no supplemental moist-curing after heat-curing averaged 90 percent of the companion 28-day, water tank-cured samples for all three w/c levels.

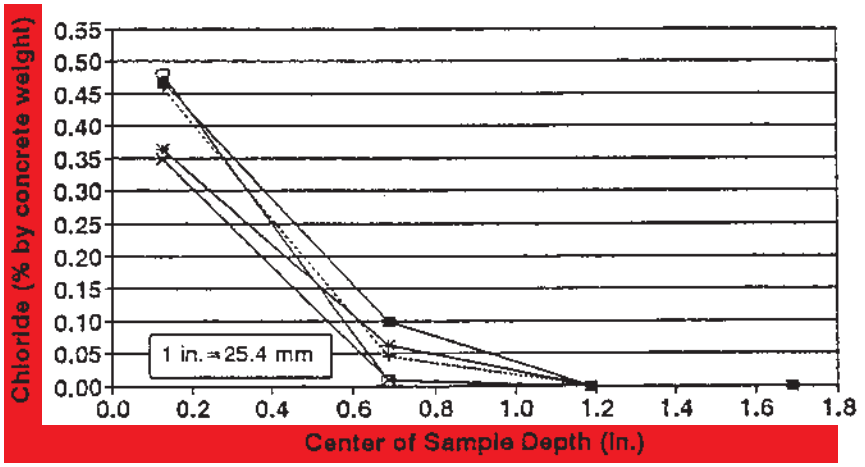
In addition, the study says, "The surface chloride concentrations for the heat-cured concretes are significantly

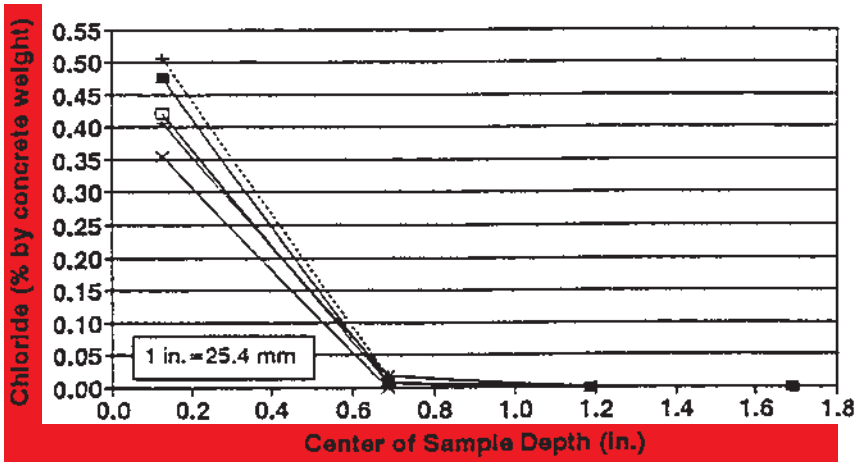
Changes Suggested For ASTM Standards

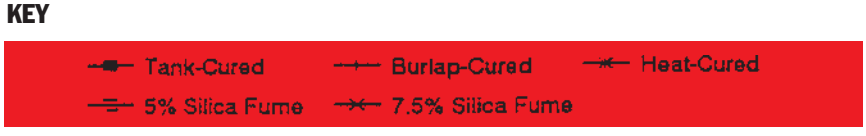
The WJE study team suggests five key changes to the ASTM C1202 coulomb-testing standards:

- The age of the concrete should be specified when laboratory-produced mixtures are being evaluated and correlated to long-term ponding tests.
- All laboratory-produced specimens for coulomb and ponding testing should be moist-cured for no more than seven days. Moist curing to ages or 28 or 90 days should be prohibited as unrealistic.
- Long-term ponding tests should be specified to mean at least 365 days.
- Salt-water solutions in long-term ponding tests should be increased to 15 percent salt from the current three percent.
- The existing tables showing correlations between coulomb ratings and permeability should be eliminated totally.









These three diagrams from WJE's chloride-permeability study compare permeability levels of various curing methods for concretes with water/cement ratios of 0.46 (top), 0.37 (middle) and 0.32 (bottom). They show that no matter the curing method used, durability improved as the w/c ratio was lowered.

lower than that assumed in other published corrosion research for long-term life estimates." The heat-cured concrete surface concentrations were between 18 percent and 36 percent lower than the surface concentrations for the overall average of the burlap- and water tank-cured concretes with and without silica fume, at all w/c levels.

Overall, the study states, "The best way to improve current concrete is to tighten specifications to require the use of lower w/c concretes. Concrete should be specified to have a low chloride-diffusion coefficient as determined by long-term ponding tests." Use of the ASTM standards that provide only coulomb values should not be used to specify concrete mixtures because they do not apply uniformly across all variables that can be used to reach the same durability, including different

'The best way to improve current concrete is to tighten specifications to require the use of lower w/c concretes.'

aggregates, admixtures, and curing procedures. "The tests must be used only when proper correlations between coulomb values and long-term ponding test results have been established for the individual concretes under test, as already required in the 1991 ASTM C 1202."

The study suggests that the precast industry should carry out long-term ponding tests, of at least one year in duration, to prove the performance of the material to all purchasers. "Taking a long-term view of concrete performance can increase the durability of all structures, lessening the need for repair and maintaining concrete as a state-of-the-art building material of choice for the transportation and construction industry."

These two studies provide owners and designers with more insight into how to create their precast concrete structures—and how to avoid costly mistakes. Everyone benefits when those involved in design, construction, and maintenance are aware of the material's design properties and how long-term care combine to keep costs to a minimum. ■

— Craig A. Shutt