CONDITION ASSESSMENT and Repair

An Existing Composite Concrete Slab and Steel Beam Framed Parking Structure
Part 2

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In the fall of 2010, a property management company retained Pennoni Associates Inc. to conduct a condition assessment of a large sub-grade parking garage and loading dock located in Center City, Philadelphia. Constructed during the 1980s, the structure was exhibiting signs of significant deterioration of the wearing surface and the supporting composite metal deck. Establishing the extent and cause of the deterioration, and identifying appropriate repairs, required a thorough condition assessment of all of the sub-grade loading docks, parking areas and ramps. The following article is a continuation of one that appeared in the April 2012 issue of STRUCTURE. It presents a discussion and assessment of the observations and material testing described in Part 1.

Petrographic Analysis Summary

Core No.	Coarse Aggregate	Percent Entrained Air	Atypical Features
1	½-inch diameter lightweight expanded clay	None	Non air entrained
2	0.6-inch diameter lightweight expanded clay	5%	Large water voids
3	½-inch diameter lightweight expanded clay	3% – 6%	No epoxy sealer. Paste to aggregate ratio poor.
4	½-inch diameter regular weight limestone	4%	No lightweight course aggregate. Unusual water voids. Clay particles detected in paste matrix.
5	0.6-inch diameter lightweight expanded clay	4%	Numerous water voids
6	0.40-inch diameter lightweight expanded clay	4%	Large water voids

Physical Condition

The surface spalling and subsurface delamination observed at both levels of the garage and loading dock areas, and most of the cracking observed at the upper level, resulted from corrosion of the internal reinforcement and other embedded and exposed steel. Corrosion is an electrochemical process that requires an anode, a cathode and an electrolyte. For the existing structure, the moist concrete provided the electrolyte and the reinforcement, and other steel provided the anode and cathode. Water and oxygen must be present for any corrosion to take place, and in good-quality concrete the high alkalinity slows the corrosion process. However, if the concrete alkalinity is lowered (due to carbonization) or if corrosive chemicals (like chlorides) are present, the corrosion process will accelerate.

The electrical current that flows between the cathode and anode results in an increase in metallic volume at the anode as iron is oxidized and precipitates as rust. As the layer of rust increases due to the ongoing corrosion process, tensile forces generated by the expansion of the corrosion byproduct cause the surrounding concrete to crack, delaminate and ultimately spall. As the surface of the concrete degrades, the corrosion process accelerates because internal areas of the reinforcing that were previously protected by the concrete cover are exposed to moisture and road salts transported into the garage on vehicles. In addition, abrasion of the exposed concrete surface due to vehicular wheel traffic further damages the exposed concrete and internal reinforcement. Eventually, if left unchecked, the corrosion process will result in the complete destruction of the concrete slab.

In the case of the exposed metal deck, the corrosion process had resulted in damage and destruction even though the material was originally galvanized. The most significant aspect of this deterioration involves the deck's contribution to the structural capacity of the concrete slab above. Composite metal deck provides two important functions: it acts as a stay-in-place formwork that supports the dead weight of the concrete until it has achieved adequate compressive strength; and, it serves as the flexural reinforcement for the composite, one-way slab section that spans between supporting steel beams.

The composite action between the metal deck and concrete slab is made possible by two factors. First, deformations located along the entire length of the fluted deck allow the concrete and metal deck to bond mechanically. Second, the location of the metal deck at the bottom of the slab, where the maximum positive flexural tensile stresses occur, enables the steel to contribute more efficiently to the composite section, while the concrete resists the maximum compressive flexural stresses located at the top of the slab.

Additional internal reinforcement within the concrete slab provides resistance to other stresses besides those induced by positive flexural bending. Welded wire reinforcement helps to prevent cracking that can result from induced thermal and shrinkage stresses. Supplemental bars located in the top of the slab over the primary beams help to resist negative flexural bending tensile stresses. However, in the absence of the positive flexural capacity provided by the composite metal deck, the ability of the concrete slab to support the imposed vehicular live loads is significantly

Image from Petrographic Analysis.

impaired, even though the welded wire reinforcement (via catenary action) and the top bars (by limiting moment redistribution) provide some additional capacity.

Material Testing

Petrographic Analysis

With the exception of some atypical features noted in the report, in general, the results of the petrographic analysis of the six core samples indicated that the concrete appeared to be of good quality. It was not clear, however, why entrained air content was not detected in core sample #1. Normally, concrete contains anywhere from 1% to 2% entrapped air; a value above 3% is indicative of the use of an air entrainment admixture. This admixture is typically recommended in concrete that will be exposed to exterior conditions because it greatly improves the ability of the concrete to resist damage that can result from freeze-thaw cycles.

The concrete in the garage is not exposed to the exterior environment, and therefore not ordinarily susceptible to freeze-thaw cycles. However, the concrete may have been placed during winter conditions when the slab was temporarily exposed to cold weather and freezing temperatures. As indicated below, the water-soluble chloride tests suggested that this was, in fact, the case.

Water-Soluble Chloride Tests

In order to prevent the corrosion of internal reinforcing steel and the subsequent deterioration of the surrounding concrete, the American Concrete Institute (ACI) recommends that the ratio of water-soluble chlorides to weight of cement not exceed 0.10% for conventionally reinforced concrete structures in a moist environment that is exposed to chlorides. Although the existing garage and loading dock are in an enclosed building, moisture is still brought into the garage via any wet vehicles that enter the facility on a rainy or snowy day. Also, as the garage entrances are open to the exterior atmosphere, the environmental humidity within the garage and loading dock is likely to be very similar to the external conditions.

In addition, during the winter months deicing salts (a source of chlorides) are brought in and deposited on the garage surface from any wet vehicles that have been driving on the outdoor road surfaces. Therefore, the parking garage and loading dock should comply with the chloride limitations recommended by ACI to mitigate potential deterioration of the slab, embedded steel and metal deck.

The results of the chloride powder sample tests indicated that the actual chloride content per mass of concrete (modified by a factor of 5 to approximate the equivalent cement content) was 25 times greater than the recommended limit of 0.10%. In addition, the chloride content at the base of the concrete where it is in contact with the metal deck and protected from exposure to deicing salts was as high as 8.5 times greater than the 0.10% limit.

Some of the chloride content in the samples taken from the top surface of the concrete likely resulted from deicing salts that were brought into the garage by vehicles that had just driven on wet and icy roadways during the winter months. However, the magnitude of chloride content at the exposed slab surface and the presence of elevated chloride content at the base of the slab, in particular at an area where the exposed wear surface had been painted, indicated that there was probably a secondary source of chlorides in the concrete.

The most plausible explanation for the elevated chloride content in the concrete slab is that a chloride-based set accelerator was used as a chemical admixture in the original concrete mix. Set accelerators are typically only employed during winter concreting operations when there is a desire for the concrete to set more quickly than normal, in order to avoid freezing of the mix water before complete hydration occurs. Therefore, it is very likely that the concrete for the garage was placed during winter conditions when the slab was temporarily exposed to cold weather and freezing temperatures.

Carbonation

The high alkalinity of concrete protects any internal reinforcing from corrosion by creating a layer of passivity around the embedded steel. When concrete is exposed to carbon dioxide from the combustion exhaust of vehicles and the surrounding polluted atmosphere, the gases are absorbed by the concrete and react with any dissolved calcium hydroxide associated with the free moisture located in the pores of the concrete. As a result of this reaction, the alkalinity of the concrete is reduced from its normal pH level of approximately 12.5. Once the pH level reaches approximately 9, the layer of passivity is lost and the internal steel is no longer protected from corrosion.

Phenolphthalein is a substance that is used to detect the effects of carbonation by reacting with the surface of the concrete if the alkalinity is above a pH of 9. If the concrete has a pH higher than 9, then the phenolphthalein reacts and turns reddish in color. If there is no reaction due to low alkalinity in the concrete, the phenolphthalein remains colorless.

The results of the phenolphthalein tests of both surface spalls and core samples indicated that only the exposed concrete surfaces, to a depth of no more than 1/8 inch, have been carbonized in the upper parking garage and loading dock areas. As there was no embedded reinforcing in the top 1/8 inch of the concrete, the presence of the carbonated concrete was therefore not contributing to the loss of any corrosion resistance of the internal steel.▪

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Part 3 of this article will appear in a future issue of STRUCTURE magazine, and will present a description of the repairs developed as a result of the condition assessment and analysis of the physical observations and material testing discussed in Parts 1 and 2.