Concrete Mix Design:
Key to Excellence in Performance of New Concrete Structures

By Jose M. Izquierdo-Encarnacion

Synopsis: In honor of Dov Kaminetzky, two case stories are discussed; one to reflect his passion for the correct usage and design for concrete and the other his other great passion, the forensic and technical evaluation of existing structures.

Keywords: Concrete Mix-Design; failure; forensic; quality control; ACI318 Code; investigation

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TOURISM PIERS#4 - OLD SAN JUAN, PUERTO RICO

Pier #4 was constructed in the 80's. There have been several piers constructed in the city during the twentieth century. Pier #4 was built to handle the operation of a new class of big cruise ships for the Caribbean Sea and was structurally designed to resist the docking forces of a 76,000 ton ship (nearly as heavy as the Navy ship, the Nimitz). Compared to modern cruise ships of 180,000 tons, this is now a comparatively small displacement tonnage.

Several new technologies were used for the design of Pier#4, but in particular was a new bumper system that dramatically absorbed up to 90% of the docking forces. The architectural designs for the roof of the building consisted of twenty four (24) concrete shells, each 94 ft (28.66m) in span and 6 in (150mm) thick. This building, compared to those used for modern cruise ships now looks quite small.

Figure 1 - East view of Pier#4

Back to the early 80's in Puerto Rico, there was a problem with concrete construction of the marine piers. The piers would promptly corrode reducing the life cycle of the infrastructure. Dov Kaminetzky enjoyed the networking that ACI provided, and through the Institute he provided a great wealth of knowledge to many professionals. For this project many professionals helped develop the proper criteria for the final material and structural design. In addition to ACI documents and publications, the best design manual used was from NAVFAC.

In terms of cement, Puerto Rico had a bigger problem because only a single Type-I cement was available on the island because of the local cement producers' control. Although other types of cement were available in the USA, they were not economically available in Puerto Rico due to transportation costs. It was decided to use a modified Type I cement. Although the local cement producer could produce Type II cement, the manufacturer did not want to disclose that they were actually producing Type II cement. Cement chemical composition affects the behavior of concrete. The most important component in cement for reducing reinforcement corrosion is the C_3A content.according to Verbeck 1968. The higher the C_3A, the more chloride can be bound as chloro-aluminate complexes—and thereby be unavailable for catalysis of the corrosion process. Where chloride is encountered along with sulphates in soil or groundwater, ordinary portland cement with a C_3A content from 5 to 8 per cent is desirable to be used in concrete rather than sulfate resisting cement. Figure 2 describes the effects of cement composition on durability properties of concrete.

Cement Property	**Cement Effects**
Placeability	Cement amount, fineness, setting characteristics
Strength	Cement composition (C_3S, C_2S and C_3A), loss on ignition, fineness
Drying Shrinkage	SO_3 content, cement composition
Permeability	Cement composition, fineness
Resistance to sulfate	C_3A content
Alkali Silica Reactivity	Alkali content
Corrosion of embedded steel	Cement Composition (esp. C_3A content)

Figure 2 – Effects of chemical components in Cement Properties

During the 60's and 70's one of the largest problems in the U.S. and several other countries was a by-product from the use of admixtures. With the explosion of their use, concrete mixes started yielding higher compressive strength which then allowed the use of higher levels of water cement ratio. For example, concrete mixes of 3,000 psi compressive strength were produced with up to 0.80 water cement ratios. This sort of design yielded a concrete with high permeability and very low durability. As a consequence, engineers started specifying minimum water cement ratio. ACI 318 Code, Table 4.2.2 details requirements for special exposure conditions (Figure 3).

TABLE 4.2.2—REQUIREMENTS FOR SPECIAL EXPOSURE CONDITIONS

Exposure condition	Maximum water-cementitious materials ratio*, by weight, normalweight aggregate concrete	Minimum f_c', normal-weight and light-weight aggregate concrete, psi*
Concrete intended to have low permeability when exposed to water	0.50	4000
Concrete exposed to freezing and thawing in a moist condition or to deicing chemicals	0.45	4500
For corrosion protection of reinforcement in concrete exposed to chlorides from deicing chemicals, salt, salt water, brackish water, seawater, or spray from these sources.	0.40	5000

* When both Table 4.3.1 and Table 4.2.2 are considered, the lowest applicable maximum *w/cm* and highest applicable minimum f_c' shall be used.

Figure 3 - ACI 318 requirements for special exposure conditions

Corrosion inhibitors had started to be available at that time such as DCI from W.R. Grace. In terms of the concrete mix design, the specifications were:

- a modified cement with C_3A less than 8%,
- a compressive strength of 5,000 psi,
- DCI as corrosion inhibitors and
- a 0.4 water cement ratio.

In addition, the US Army Corp-of- Engineers had started to extensively use epoxy coated reinforcement bars in their projects. Therefore, there was a big push from the Port Authority to use epoxy coated reinforcement. In terms of project cost epoxy coated reinforcement is expensive compared to the better alternative of producing a concrete with low permeability. Finally, the Port Authority was convinced to use the epoxy bars only selectively on the stirrups and the sidebars.

During the construction additional quality and assurance programs were established consisting of:

1. Regular testing of the cement used by the Ready Mix producer to verify the C_3A content.
2. Modulus of elasticity of concrete for removing the roof shells formwork at 24 hours.

Carefully planning the project requirements, combined with the evaluation of local materials with a cost effective solution yielded a structure that has been in use for over 25 years without corrosion.

PCC PAVEMENT RESTORATION PR-22, PUERTO RICO

PR-22 is a 51-mile (83-km) long toll road in the north coast of Puerto Rico that connects the cities of San Juan and Hatillo. The road is also known as the José de Diego Expressway. It is a 4-lane road for much of its length, but expands to up to 12 lanes in the San Juan metro area. The road is frequently congested, particularly during rush hour due to heavy commuter traffic; handling an average of 140,000 vehicles per/day.

Over the years the pavement deteriorated in some areas. Puerto Rico Highway and Transportation Authority requested bids for the repair of several segments as shown in Figure 4.

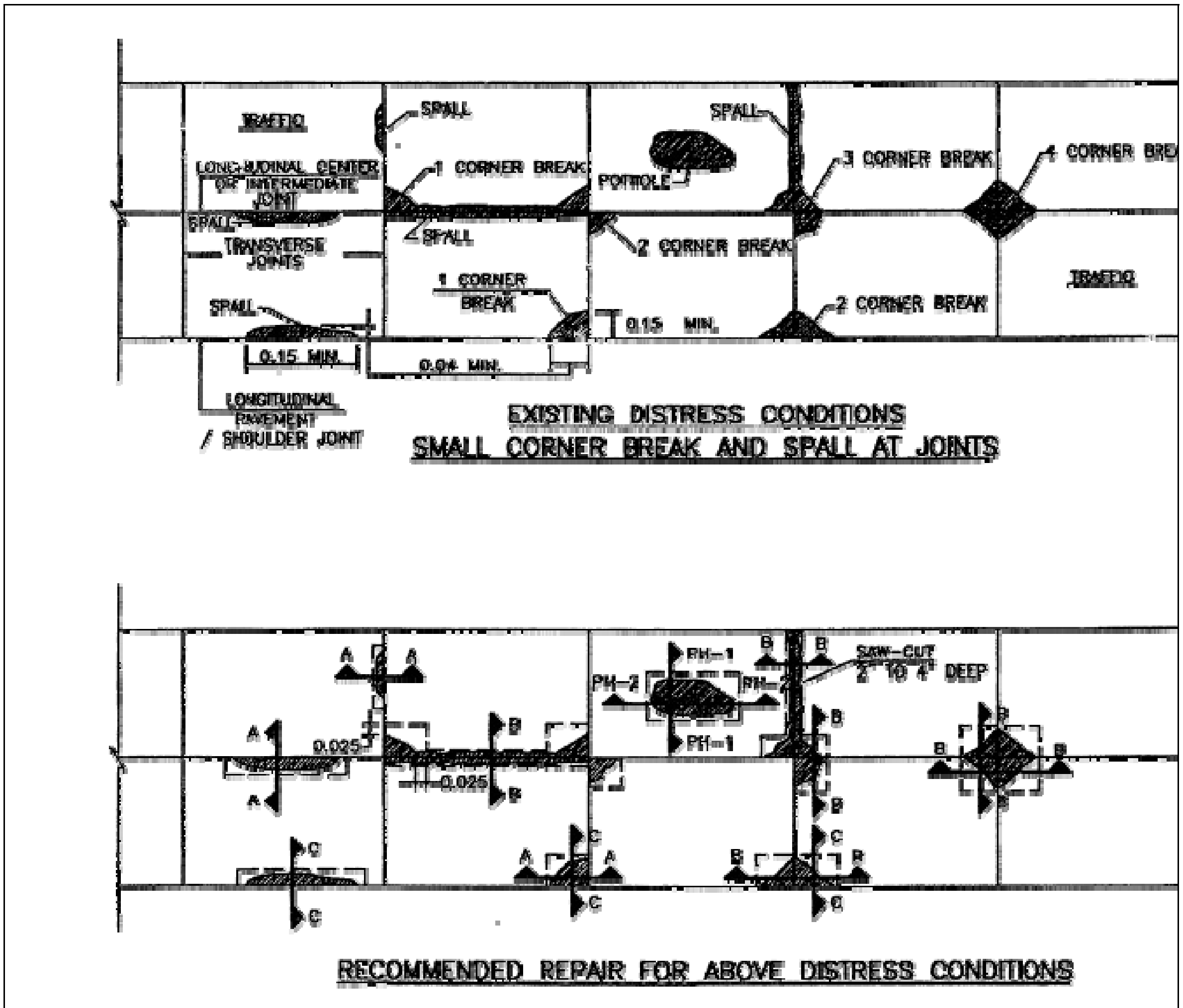


Figure 4 – Typical recommended repair

Due to the heavy traffic, special conditions were imposed on the contractor:

1. On Friday at 10:00 PM, the highway would be closed to traffic.
2. On Monday at 4:00 AM. The highway would be reopened to traffic
3. The performance specification required concrete with f'_c = 3,000 psi (20.6 MPa) at 5 days.

Due to the construction time restraints, demolition occurred through Friday night and preparation was finished during early morning Saturday. The concrete was poured beginning on Saturday morning up to 3:00 pm. Because the highway would be opened to traffic at 4:00 AM Monday rapid concrete strength development was needed within 40 hours after placement.

The approved mix design had very high cement content (846 lbs) in order to achieve the specified concrete compressive strength at 5 days. This solution yielded a concrete that will continue to increase strength for several weeks. Since the traffic would be opened before the recommended curing period, traffic would remove the curing compound, un-protecting the pavement.

Figure 5 – Plastic shrinkage cracks

After a few months of operation the pavement showed cracks on several of the repaired segments. Some of the cracks were superficial and some were full depth.

Several possibilities were considered to determine the probable cause of the cracking and possible alternatives to improve the new repairs of the pavement slabs. In addition to the construction procedures, the mix design and the repair design were evaluated.

Core samples were taken on several pavement slabs. All slabs were inspected to observe the type of distress shown. Combining the inspection with the study of the core samples, the slab segments were separated in groups indicating the type of damage. The evaluation was separated into:

1. Superficial cracks
2. Visible full depth cracks
3. Structural cracks due to cutting
4. Damaged joints
5. Excessive cutting

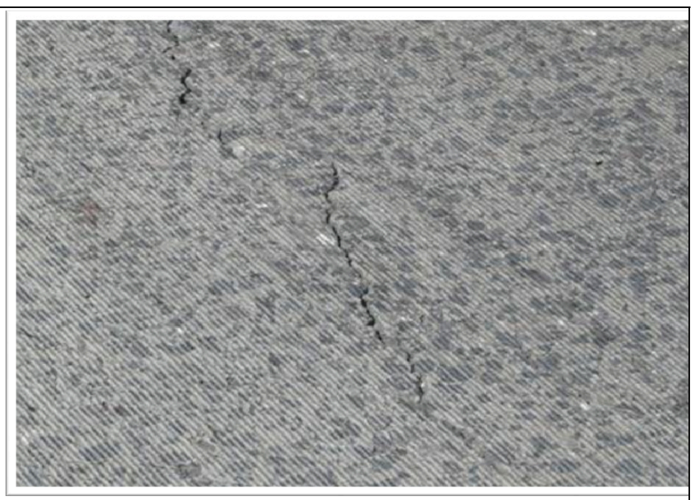


Figure 6 – Full depth cracks

As a reaction to the cracks, the curing process was improved by combining the use of curing compound and burlap cure. This action improved the performance, but did not solve the cracking problem.

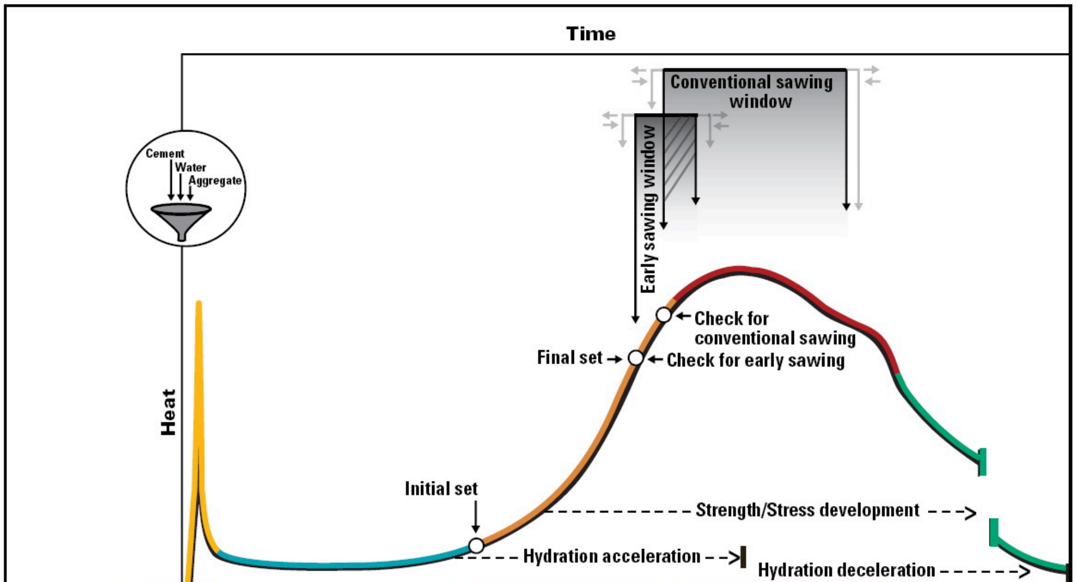
Other areas of potential problems were identified:

1. The project specified a reinforced concrete replacement slab, while the original one was unreinforced.
2. As shown in Figure 4, the plans show cutting segments within a slab to be cut out. This action would cause corner cracking of the remaining slab.
3. The new segment inside an existing slab would be connected by dowels on all sides, thus preventing temperature movement with the original slab.

The Federal Highway administration has developed a great publication for pavements, which includes pavement repair: <u>Integrated Materials and Construction practices for concrete pavements</u> (IMCPCP). It provides guidance in all areas of pavement design, construction and repair. In addition it covers cement and concrete for educational purposes. In addition it is very illustrative of the concrete hardening process (Figure 7).

In terms of the construction practice the IMCPCP manual gives three valuable recommendations:

a. After sawing joints, insulate the pavement if air temperatures are expected to drop rapidly and significantly. (If the pavement surface cools too quickly, the slab may crack.)
b. Keep traffic and construction equipment off the pavement as long as possible (preferably, at least 72 hours) to protect the curing compound. Curing compound reduces moisture loss from the concrete and thus enables continued hydration, increasing concrete strength and reducing *its* permeability.
c. Tying a new concrete pavement to an existing pavement can result in significant stress on the new slab from restraint. This can be especially true if the new slab is placed on a warm sunny day following a cool night, as may occur in the fall. In the morning the existing slab is cool. As the day becomes sunny and warm, the existing slab warms and expands. If new concrete is placed and tied to the existing slab in the morning, it will reach the cooling stage of hydration and begin to shrink during the warmest part of day, when the existing slab's expansion is peaking. Because they are tied together, each slab's movement is restrained by the other's. The new, weaker pavement is likely to crack.



	Stage 1 Mixing	Stage 2 Dormancy	Stage 3 Hardening	Stage 4 Cooling	Stage 5 Densification
	Lasts about 15 minutes	Lasts about 2–4 hours	Lasts about 2–4 hours		Continues for years
Characteristics of concrete mixture	High heat is generated immediately, followed by rapid cooling.	Mixture is plastic, workable, and not generating significant heat.	• Hydration generates significant heat. • Mixture sets, begins to harden, and gains strength. • Stress begins developing in the concrete.	Stress development will exceed strength development if stress is not relieved.	Slab continues to become stronger and less permeable.
What engineers, supervisors, and workers must do to ensure durable pavement	Ensure adequate mixing.	Transport, place, and finish the concrete while plastic and workable.	• Begin curing as soon as possible. • Thoroughly apply curing compound.	Saw joints to relieve stress and control cracking.	• Insulate the slab if the air temperature is expected to cool rapidly and significantly. • Protect curing compound as long as possible.

Figure 4-13. Concrete characteristics, and implications for workers, during stages of hydration

Figure 7 – Concrete Characteristics during stages of hydration (IMCPCP).

Several tests were performed for a new concrete mix design in order to develop a high early strength mix that would not continue to increase its strength significantly after five days. In addition tests were made considering the use of steel fibers instead of reinforcing bars. Based on the testing the final recommendations were:

1. Change the Concrete Mix Design to produce a concrete suitable at 36 hours without high volumes of cement.
2. Study alternative concrete mix designs with more compatibility with the existing pavement:
3. Eliminate reinforcement to match substrate properties.
4. Integrate partial slabs with repair materials and not dowels.
5. Change the shape of the cut sections for replacement, eliminating the creation of corners.
6. Schedule concrete placement to 4:00 am Saturday to force compatibility of expansion between existing concrete and new concrete.
7. Replace fully cracked slabs
8. Repair slabs with surface cracks with a High Molecular Weight Methacrylate (HMWM)

REFERENCES

1. ASCE Manual of Practice No. 73, 2000**, "**Quality in the Constructed Project: A Guide for Owners, Designers, and Constructors**,"** 2nd Edition, American Society of Civil engineers, Reston, VA, 266 p.

2. Carino, N.J. Lew, H.S., and Stone, W.C., 1984, "Investigation of East Chicago Ramp Collapse," *ASCE Journal of Construction Engineering and Management*, vol. 110, No. 1, March 1984, pp 1-18

3. Carino, N.J. Lew, H.S., Stone, W.C., Chung, R.M. and Hoblitzell, J.R., 1982, "Investigation of Construction Failure of the Riley Road Interchange Ramp, East Chicago, Indiana," Report NBSIR 82-2593, National Bureau of Standards, Washington, D.C., October, 213 p.