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Project: Muckelshoot Indian Casino Parking Structure, Auburn, Washington
Subject: Concrete Parking Garage Condensation and Crack Problems

BACKGROUND:

Mr. Len Holm of Holm Construction Services has asked me to evaluate the concrete parking structure at the Muckelshoot Indian Casino in Auburn, Washington. I was told that condensation had occurred on all levels of the parking structure, and was asked to investigate how this had happened. Also there were many visible cracks on the top floor, which is addressed in this document.

CONDENSATION PROBLEM:

On Wednesday, January 19, 2005, the newly constructed concrete parking garage at Muckelshoot Indian Casino experienced condensation problems throughout the entire structure. In an email exchange between two employees the following was mentioned:

> "The entire garage has been like a sweat box. Elevator 4 was shut down because of the extreme high moisture affecting the brakes. The electrical closet has potential of being damaged because of the high moisture on the panels. It could also damage the fire alarm system components. Why is so much water penetrating a deck crack in front of the utility/electrical/computer rooms? Is this an unusual event due to the recent temperature extremes?" And:

> "This appears to be a design oversight. It appears that there should have been some air moving through the garage, if it is condensation that we are seeing. What is being done about the elevator and the electrical room?"

On Wednesday, January 19, 2005, the high temperature at Seattle-Tacoma International Airport was 62ºF, breaking a record for the date of 60 degrees, set in 1961. On Tuesday, January 18 a record 60ºF at the airport topped the 1981 record of 59ºF. The unusually high temperatures in conjunction with a 2-inch rain event produced a 100% humidity condition, which is probably responsible for the ensuing condensation and "sweat box" effect in the parking structure.

Condensation is the process of changing from a gas or vapor to a liquid, the process by which water in air changes from a vapor to a liquid due to a change in temperature or pressure. It occurs when water vapor reaches its dew point (condensation point).

All concrete surfaces at the parking structure are painted. This impervious paint layer acts like an impervious membrane coating the concrete surface[1,2]. Concrete surface can absorb some moisture upon rewetting, or in this case as the vapor changes to liquid. This phenomenon is shown in Figure 1[3].

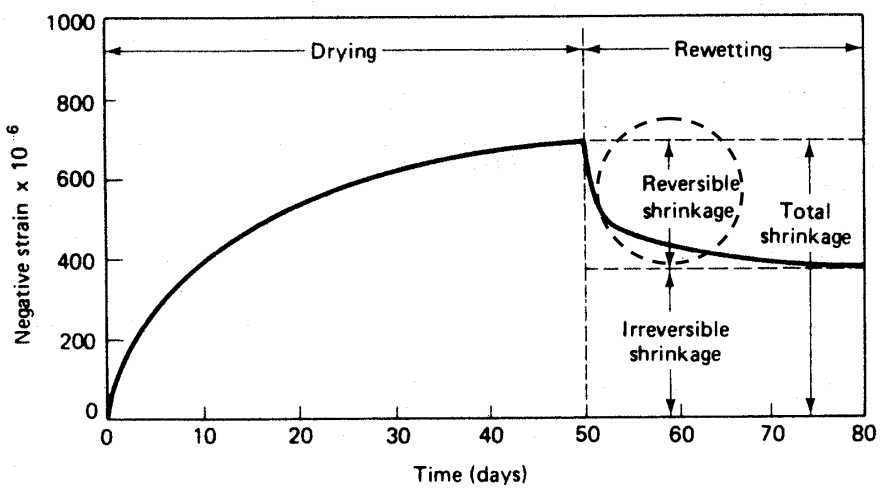

Figure 1: Reversibility of drying shrinkage

However, when concrete surface is coated with an impervious membrane, i.e., oil-based paint, this absorption cannot take place, and hence condensation occurs. This is probably the most reasonable explanation for what happened on January 19, 2005.

In order to prevent future condensation problems in the future, should favorable atmospheric conditions prevail, additional H.V.A.C. measures should be considered, to ensure proper air circulation throughout the entire parking structure. However, the frequency of such conditions to induced condensation are not such that make such a decision an emergency.

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[1] Hokoi, S. and Matsumoto, M. "Condensation process in external concrete walls under random fluctuation of outdoor temperature - fundamental study on heat and moisture behavior by Fokker-Planck equation," *HVAC&R Research*, v 2, n 4, pp. 337-353, October 1996.

[2] Hens, Hugo "Condensation in Concrete Flat Roofs, *Batiment International/Building Research & Practice*, v 6, n 5, pp. 292-309Sep-October 1978.

[3] Mehta, P.K. and Monteiro, P.J.M. "Concrete: Structure, Properties, and Materials," Second Edition, Prentice Hall, 1993.

<u>CONCRETE CRACK PROBLEMS:</u>

When I inspected the parking structure on Wednesday, February 9, 2005, I noticed unusual amount of visible cracking on the roof of the parking structure as shown in Figure 2.

Figure 2: Cracks on the top floor of the parking structure

Looking on the bottom of the same slab, cracks revealed themselves at almost the same location on the opposite side of the slab (Figure 3), suggesting that they might be through cracks.

Figure 3: Cracks on the bottom of the same slab

It appears that these cracks were generated as the result of improper curing or no curing at all, when the concrete was placed. It also appears that instead of repairing the cracks structurally, only water sealant or caulk were applied to the cracked areas. While water sealants prevent moisture and debris from getting into the cracks, it does not help the structure compensate from the lack of continuity in the material itself. This may lead to improper load transfer and cause undesirable stress concentration in other parts of the structure.

Cracks and crack patterns have different characteristics depending on the underlying cause. For example plastic shrinkage cracks tend to form in an irregular pattern over the structure while cracks due to reinforcement corrosion will follow the line of reinforcement.

Different types of cracks occur at different times in the life of a concrete element. So as well as crack patterns, knowledge of when the cracks first appeared is helpful in diagnosing the cause of cracking. Cracks can influence the behavior and durability of a concrete element. They can reduce the shear capacity of a section or provide a path for moisture, oxygen, carbon dioxide and chlorides to penetrate into the concrete surrounding the reinforcement, and in time this may result in reinforcement corrosion.

Plastic Shrinkage Cracks

Figure 4 shows typical plastic shrinkage cracking in concrete[4].

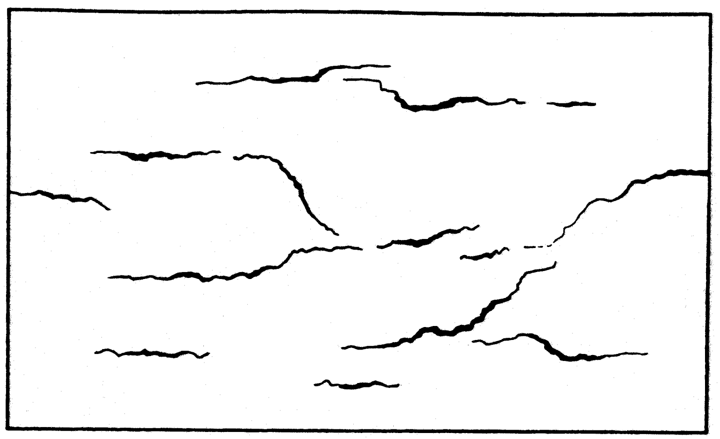

Figure 4: Typical plastic shrinkage cracking

For the first few hours, concrete is plastic and has little strength. Water can move relatively freely in what is still a mixture of cement, aggregate, and water. The least dense components of the mixture, air and water, tend to move upwards towards the top surface as the heavier materials move down due to gravity during compaction. The upward movement of water is known as “bleeding” and water that reaches the surface evaporates. The evaporation is more rapid at high temperatures and/or low humidity, particularly in windy conditions. If water evaporates from the surface faster than it bleeds, there is a net loss of water from the surface of concrete, leading to a net reduction in volume. The surface of concrete tries to shrink, but is restrained by underlying layers which have not lost moisture to the same extent. The result of the restraint is that tensile stresses develop in the surface. As the concrete is still in the plastic state and has very

[4] Price, Walter H. “ Control of Cracking During Construction,” *Concrete International: Design and Construction*, V. 4, No. 1, pp. 40-43, January 1982.

low strength, irregular cracks develop. The process is illustrated in Figure 5, the upper part showing initiation and the lower the condition after a few hours.

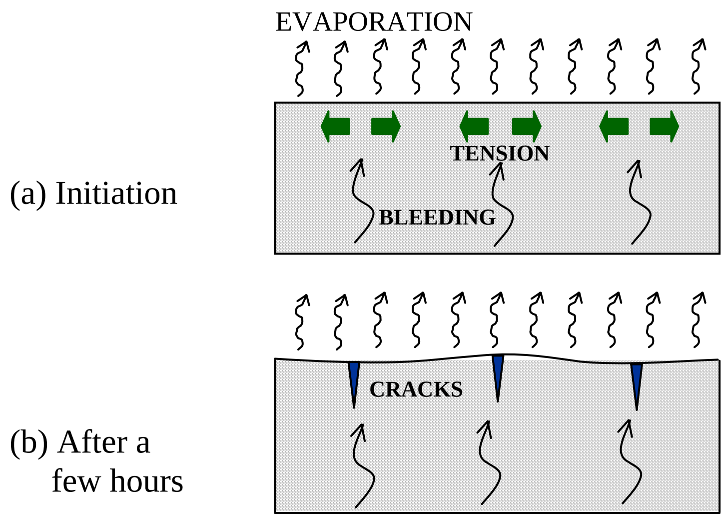

Figure 5: Formation of plastic shrinkage cracks

The only certain way to avoid plastic shrinkage cracks is to reduce the rate of evaporation from the surface of fresh concrete by early curing.

Characteristic defects

Plastic shrinkage cracks tend to be 1-2 mm wide, 300-500 mm long, and 20-50 mm deep, though, in some circumstances, they may extend through the full depth of a member. The pattern of cracks is usually random but may be influenced by the direction in which finishing operation has been carried out. As the cracks form in concrete when the paste is still in a plastic state, they run through the paste rather than through pieces of aggregate. Plastic shrinkage cracks can form in both reinforced and unreinforced concrete.

Cracking of Hardened Concrete

A common cause of cracking is restrained drying shrinkage. Drying shrinkage is caused by the loss of moisture from the cement paste constituent, which can shrink by as much as 1 percent. Fortunately aggregate provides internal restraint that reduces the magnitude of this volume change to about 0.06 percent. On wetting, concrete tends to expand.

These moisture-induced volume changes are characteristics of concrete. If shrinkage of concrete could take place without restraint, the concrete would not crack. It is combination of shrinkage and restraint (usually provided by another parts of the structure or by the subgrade) that causes tensile stresses to develop. When the tensile strength of concrete is exceeded, it will crack. Cracks may propagate at much lower stresses than are required to cause crack initiation.

In massive concrete elements, tensile stresses are caused by differential shrinkage between the surface and the interior concrete. The larger shrinkage at the surface causes cracks to develop that may, with time, penetrate deeper into the concrete.

Evaluation of Cracking

When anticipating repair of cracks in concrete, it is important to first identify the location and the extent of cracking. It should be determined weather the observed cracks are indicative of current or future structural problems. The cause of cracking should be established before repairs are specified. Cracks need to be repaired if they reduce the strength, stiffness, or durability of the structure to an unacceptable level, or if the function of the structure is seriously impaired.

Methods of Crack Repair

Following the evaluation of the cracked structure, a suitable repair procedure can be selected. Successful repair procedures take into account the cause(s) of the cracking. If cracking is primarily due to drying shrinkage, then it is likely that after a period of time the cracks will stabilized.

Epoxy injection

Cracks as narrow as 0.002 inches can be bonded by injection of epoxy. The technique generally consists of establishing entering and venting ports at close intervals along the cracks, sealing the crack on exposed surfaces, and injecting epoxy under pressure. Epoxy injection has been successfully used in the repair of cracks in buildings, bridges, dams and other types of concrete structures (ACI 503R[5]). Epoxy materials used for structural repairs should conform to ASTM C 881[6] (Type IV). With the exception of certain moisture tolerant epoxies, this technique is not applicable if the cracks are actively leaking and cannot be dried out. Wet cracks can be injected using moisture tolerant materials, but contaminants in the cracks (including silt and water) can reduce the effectiveness of the epoxy to structurally repair the cracks.

The use of low-modulus, flexible adhesive in a crack will not allow significant movement of the concrete structure. The effective modulus of elasticity of a flexible adhesive in a crack is substantially the same as that of a rigid adhesive[7]because of the thin layer of material and high lateral restraint imposed by the surrounding concrete.

Epoxy injection requires a high degree of skill for satisfactory execution, and application of the technique may be limited by the ambient temperature. The general procedures involved in epoxy injection are as follows (ACI 503R):

- Clean the cracks. The first step is to clean the cracks that have been contaminated, to the extent this is possible and practical. Contaminants such as oil, grease, dirt, or fine particles of concrete prevent epoxy penetration and bonding, and reduce the effectiveness of repairs.
- Seal the surfaces. Surface cracks should be sealed to keep the epoxy from leaking out before it has gelled.

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[5] American Concrete Institute (ACI) code 503R: Use of Epoxy Compounds with Concrete.
[6] American Society of Testing and Materials ASTM C 881: Standard Specification for Epoxy-Resin-Base Bonding Systems for Concrete.
[7] Adams, Robert D. and Wake, William C. "*Structural Adhesive Joints in Engineering*," Elsevier Applied Science Publishers, Ltd., Essex, England, pp. 121-125, 1984.

- Mix the epoxy. This is done either by a batch or continuous methods. In batch mixing, the adhesive components are premixed according to the manufacturer's instructions. In the continuous mixing system, the two liquid adhesive components pass through metering and driving pumps prior to passing through an automatic mixing head. The continuous mixing system allows the use of fast setting adhesives that have a short working life.
- Inject the epoxy. Hydraulic pumps, paint pressure pots, or air-actuated caulking guns may be used. The pressure used for injection must be selected carefully. Increased pressure often does little to accelerate the rate of injection. In fact the use of excessive pressure can propagate the existing cracks, causing additional damage.
- Remove the surface seal. After the injected epoxy has cured, the surface seal should be removed by grinding or other means as appropriate.

Another method recently being used is a vacuum or vacuum assist method. There are two techniques: one is to entirely enclose the cracked member with a bag and introduce the liquid adhesive at the bottom and to apply a vacuum at the top. The other technique is to inject the crack from one side and pull a vacuum from the other. Typically, epoxies are used; however, acrylics and polyesters have proven successful.

Success of the repair depends on the absence of bond-inhibiting contaminants from the crack plane.

In conclusion, the presence of such major cracks in a concrete slab is not structurally acceptable, and in extreme cases the structural integrity of the concrete may be seriously affected. Application of the water sealant that is in place now, is not a structural solution and all it does is to prevent water and deleterious substances from getting into the cracks. In order to ensure proper load transfer within the slab, a structural repair, such as epoxy injection, is recommended.

If there are any questions, please feel free to contact me. I would be willing to meet with Mr. Holm, the client, or the structural engineer if need be.

Sincerely yours,

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