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Project Spotlight

Twintec China

Concrete crack formation in elevated slab forensic analysis

Twintec China was appointed as an industry expert to analyse the causes of crack formation in an elevated concrete slab in Southern China. As part of the investigation to understand the potential contributing cause(s) of the cracking, Twintec used petrographic examination in addition to site visits, mix design analysis, crack mapping and execution photo and video review.

Background

The slab was presented as being heavily reinforced with diameter 10@ 150 double layer rebar. The concreting for the cast-in-place structure was done without weather protection in the open air during July and August, and cracking was observed as early as November.

The approved concrete mix design was provided as follows:

- Water-to-cementitious materials (w/cm) ratio 0.40
- Slag cement 20% and fly ash 18% of total cementitious materials by weight (395 kg/m3 in total excluding an expansive component, see below)
- Expansive agent 8% (32 kg/m3) of total cementitious materials by weight (material identity unknown)
- Granite coarse aggregate, max size 25 mm
- Slump 180 mm
- Predicted compressive strength of 44.3 MPa at 28 days

Field photos showing cracks and slump testing results were provided and reviewed.

Typical cracking parallel to beam (90%)

Oblique cracking (5%)

Core Samples

Cores were extracted from areas where the cracking ran parallel to monolithically cast beams. Six cores were taken and three were sent for analysis.

The cores were labeled with the marking "TCN" followed by "Core 4", "Core 5" and "Core 6". (Figure 1 to Figure 3). Core 4 was used as a control sample and did not contain macrocracking (cracks that can be seen with the unaided eye). Cores 5 and 6 contain full-depth cracks.

The cores were 100 mm diameter and ranged in length from 150 mm to 190 mm. All cores represent the full slab depth with a formed bottom surface and a finished top surface.

Cores 5 and 6 contained a very well adhered thin plastic membrane on the top surface, but a small portion was able to be peeled off to reveal the surface.

The cores were sent to Wiss, Janney, Elstner Associates, a top tier structural & materials company where petrographic analysis was conducted in accordance with ASTM C856, "Standard Practice for Petrographic Examination of Hardened Concrete."

- Photographs of all as-received cores were taken before any sample preparation.
- Each core was cut in half longitudinally (in a direction perpendicular to the major crack, when present) using a water-cooled, continuous-rim, diamond saw blade.
- One resulting sawed surface of each core was lapped using progressively finer abrasives to achieve a fine, matte finish suitable for examination with a stereomicroscope. Lapping exposes textural features such that characteristics of the paste and aggregate, including cracking, can be more easily observed microscopically.
- The opposing half of each core was allowed to dry, then immediately sprayed with pH-indicating phenolphthalein solution.
- Fresh fractured surfaces were also prepared to study the characteristics of the concrete.
- A thin section was prepared from a selected region of Cores to further assess paste characteristics and potential deterioration.
- Powder mount examinations were made on the cementitious pate of the Core.

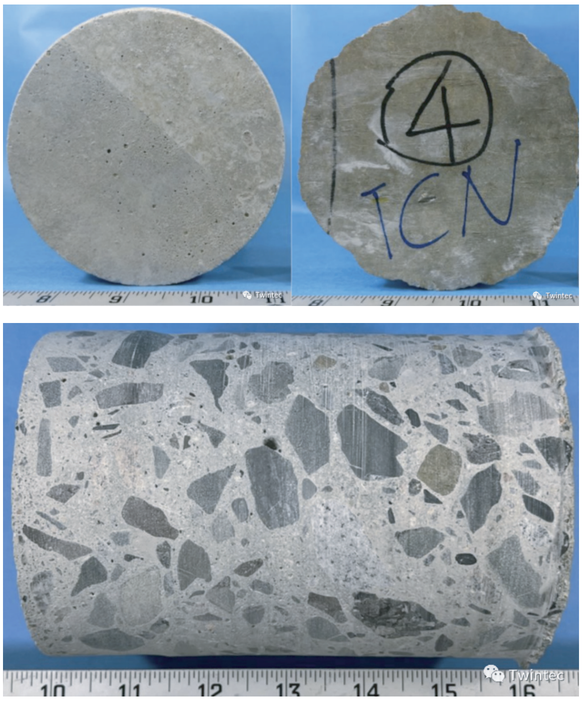

Figure 1. Core 4. Images of the core as received. The top left image shows the top surface, top right shows the bottom surface, and the bottom image shows a longitudinal view with the top surface to the left.

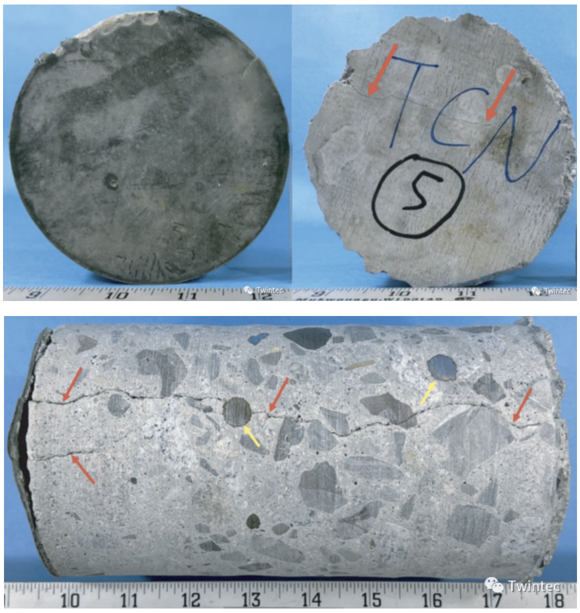

Figure 2 and 3. Core 5. Images of the core as received. The top left image shows the top surface, top right shows the bottom surface, and the bottom image shows a longitudinal view with the top surface to the left. Red arrows indicate partial and full-depth cracking visible along the side and bottom surface. Yellow arrows indicate rebar.

Results

The following observations were obtained from the examinations detailed above in order to present conclusions on cracking of the slab.

Reinforcement

On examination, rebar and/or hollow plastic tubes were located roughly parallel to the top and bottom surfaces at the following cover depths from the top surface of each core:

Core Nr	Reinforcement Observed
4	10 mm bar at 35 mm (only one end present, terminates within core) 10 mm bar roughly perpendicular to surfaces from 95 to 135 mm
5	10 mm bar at 69 mm 5 mm wire at 72 mm 5 mm wire at 80 mm 10 mm bar at 143 mm 10 mm bar at 153 mm
6	10 mm rebar at 38 mm 10 mm rebar at 49 mm 10 mm rebar at 55 mm 20 mm outer diameter hollow pipe at 106 mm 20 mm outer diameter hollow pipe at nominally 125 mm 20 mm outer diameter hollow pipe at nominally 130 mm.

Conclusion

It was concluded that the approved design was followed within the floor slab construction, however it was observed that there were some pipes and other wires within the slab.

Concrete

Observations and findings are detailed as follows (applying to all three cores unless stated otherwise):

1. The cores indicate that the concrete is well consolidated and distribution of paste and aggregate is uniform (Figure 4 through Figure 10), however, variations in composition of coarse aggregate and cementitious materials were observed among the cores.
2. A thin, weak, absorptive top layer was observed along the top region of Cores 5 and 6 but not Core 4.
3. The petrographic analysis shows that the paste of each core is composed of ordinary portland cement and slag cement (Figure 11). Slag cement was estimated to be 20-30% of total cementitious materials by weight based on thin section examinations of Core 4 and 5.
4. Cementitious particles, suspected to be non-portland cements, were also observed in the concrete. These particles and small globules of calcium hydroxide were likely ingredients of the expansive agent.
5. Trace amounts of fly ash were observed in the thin section examination of Cores 4 and 5, but not observed in the powder-mount examinations of Core 6. Note: the provided mix design specified 18% replacement of portland cement with fly ash, however, microscopic observations suggest that this rate of replacement was not met, but rather that fly ash was likely a contaminant and did not appear to be a purposely-batched constituent due to its trace occurrences.
6. The paste was moderately hard (2.5 to 3.0 Mohs hardness) and moderately absorptive to water on a fresh fracture surface. Paste-aggregate bond was moderately tight; fractures created during the laboratory examinations propagated both through and around coarse aggregate particles in approximately equal amounts. It is likely that w/cm in the concrete was higher than the specified 0.40 based on the physical characteristics and paste-aggregate bond strength.
7. Concrete in each core contains many small spherical air voids (Figure 6 to Figure 9), likely caused by chemical admixtures (not necessarily air-entraining agents). Total air content was estimated at 2-4% in Cores 4 and 6, and 4-5% in Core 5.
8. Coarse aggregate in Core 6 is composed of granite and is considered to be consistent with the mix specification. Coarse aggregate in Core 4 is composed mainly of crushed sandstone/ siltstone/mudrock and their low metamorphic counterparts (meta-sandstone/ siltstone/ mudrock as defined in ASTM C294, Standard Descriptive Nomenclature for Constituents of Concrete Aggregates), with small amounts of crushed granite. The crushed granite is estimated to be less than 25% of total coarse aggregate. Core 5 contains roughly equal amounts of crushed granite and sandstone/siltstone. The mix design specifies solely granite as coarse aggregate.
9. The depth of carbonation was less than 0.5 mm in Core 4 and 2-4 mm in Cores 5 and 6 (Figure 5). The carbonated top layer in Cores 5 and 6 was weaker and more absorptive to water droplets than the concrete below the top layer. The carbonated, weak layer appeared to have been caused by elevated w/cm, inadequate curing, or a combination thereof. Elevated water could be due to minor bleeding/segregation or water addition during finishing. No weak layer was observed in Core 4.
10. No evidence of materials-related distress involving paste or aggregate, such as alkali-silica reaction (ASR) or delayed ettringite formation (DEF) was observed. Microcracks were rare in Core 4 overall and in areas away from the major cracks in Cores 5 and 6.

Conclusion

Based on the findings of the petrographic examination it is possible to verify the composition of the actual supplied concrete against the intended concrete mix. Considering the lack of significant amounts of fly ash in all three cores, potentially higher w/cm, and substantial amounts of non-granite coarse aggregate in Cores 4 and 5, the concretes in the three cores are interpreted to be inconsistent with the reviewed mixture design and inconsistent between samples.

Cracking

Observation of the core samples shows that Core 4 does not contain major cracks (Figure 1, 4, 5), but Cores 5 and 6 contain a full-depth crack (Figure 2-5, Figure 7-10).

Crack widths on Cores 5 and 6 were measured along the side of the samples in the as-received condition. The main full-depth crack in Core 5 measured approximately 1 mm near the top and narrowed slightly with depth to an average of 0.7mm near the bottom. The full-depth crack in Core 6 was slightly narrower than that in Core 5, measuring on average 0.7 mm near the top and tapering slightly near the bottom. The cracks in both cores were measured on two sides of each core, and measurements were not identical in both locations; the values listed above are approximate averages of both sides.

Both cracks intersected rebar and the crack in Core 6 also intersected a plastic tube. Due to raveling, abrading, and relaxation from coring operation, true crack widths in the field are likely less than those measured in the laboratory examinations.

On lapped faces and opened crack interfaces, cracks extended through a few coarse aggregate particles, including at least one coarse aggregate particle in the top 1 inch in Cores 5 and 6.

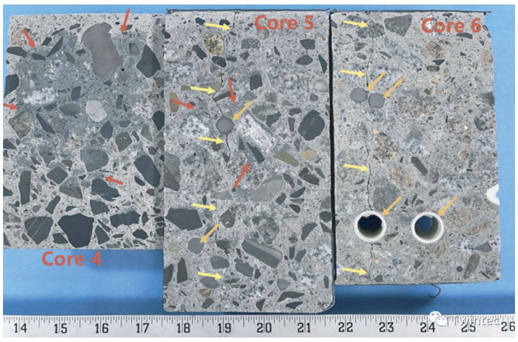

Figure 4. Cores 4, 5 and 6, as marked. Image of the full-depth lapped cross section of each core. Note the bluish color paste near the upper center of Core 4 (red arrows), minor mottled bluish color in Core 5, and minimal blue paste in Core 6, which are all due to presence of slag cement. Yellow arrows indicate full-depth cracking in Cores 5 and 6. Orange arrows indicate embedded steel or plastic tubes.

Conclusion

The observations suggest that the cracks were not plastic cracks but formed after the concrete developed significant strength.

Cracks naturally propagate along weak areas of concrete, and may initiate at the reinforcement or tubes and follow the embedded items in space, since the interface between concrete and embedded items is generally the weakest area. Cores 5 and 6 contained as many as 6 bars and/or tubes.

No evidence of rebar or tube movement during the concrete's plastic state was observed, which could cause plastic or subsidence cracks. Imprints of deformed rebars were sharp and well defined.

No evidence of deleterious chemical reactions such as ASR or DEF was observed.

Summary

Petrographic examination was conducted on three cores to determine the possible contributing cause(s) of cracking. The cause of the cracking cannot be attributed to any material related defect, such as ASR, DEF, etc.

a. The concrete is composed of crushed rock coarse aggregate and siliceous sand fine aggregate dispersed within Portland cement and slag cement paste. The concrete is well consolidated and distribution of paste and aggregate is overall uniform.
b. Trace to no fly ash was observed in the concrete. Absence of fly ash and potentially elevated w/cm in all three cores and presence of significant non-granite composition coarse aggregate in Cores 4 and 5 are not consistent with the stated (required) mixture design.
c. Cracks in Cores 5 and 6 are consistent with restrained volumetric changes due to drying shrinkage and/or thermal-related volumetric changes. The cracks are not related to deleterious chemical reactions such as ASR or DEF.
d. Cores 5 and 6 contain a roughly 3 mm (1/8 inch) thick, weaker layer than the body concrete along the top surface. The weak layer was likely caused by elevated w/cm and/or inadequate curing. No weak layer was observed in Core 4.

There are differences in the concrete represented by Cores 4 and 5 compared to the stated concrete mixture proportions: elevated water to cementitious ratio, observed differences in aggregate composition, and absence of fly ash. These factors contributed to the cracking of the slab.

Based on review of provided photographs & documents; crack characteristics and experience on similar projects, the cracking in Cores 5 and 6 is likely caused by restraint of drying shrinkage and/or thermal-related volumetric changes.

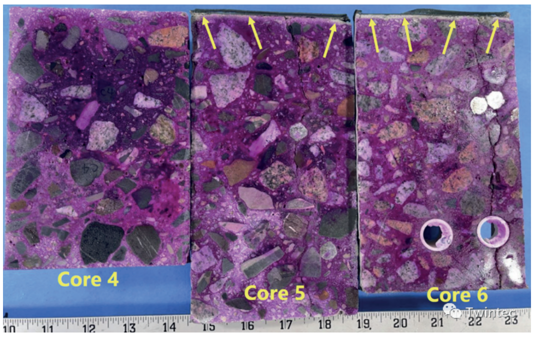

Figure 5. Cores 4, 5, and 6, as marked. Image of freshly sawn full-depth cross sections of each core shortly after being sprayed with pH-indicating phenolphthalein solution. Note the thin layer of carbonated paste along the top surface of Cores 5 and 6 (yellow arrows), and no visible carbonation on the surface of Core 4.

Appendix

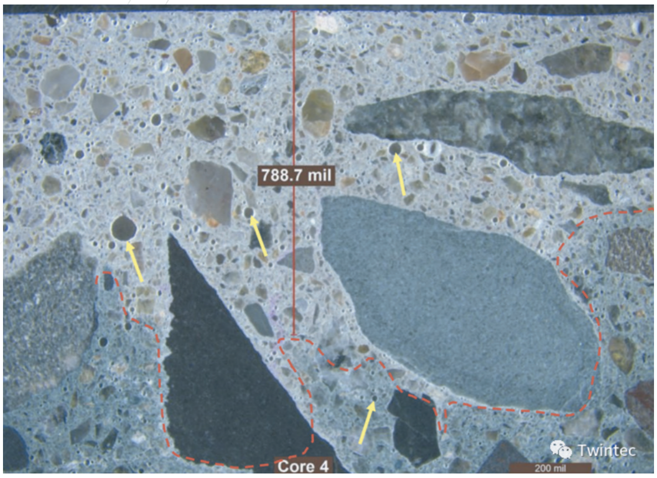

Figure 6. Core 4. Close-up image of the top surface region. The measurement in the center of the image indicates the typical depth at which bluish color paste is present (approximately 788 mils or 20 mm). The bluish paste can be seen in the bottom half of the image (below red dashed lines). The concrete contains many small spherical air voids (yellow arrows).

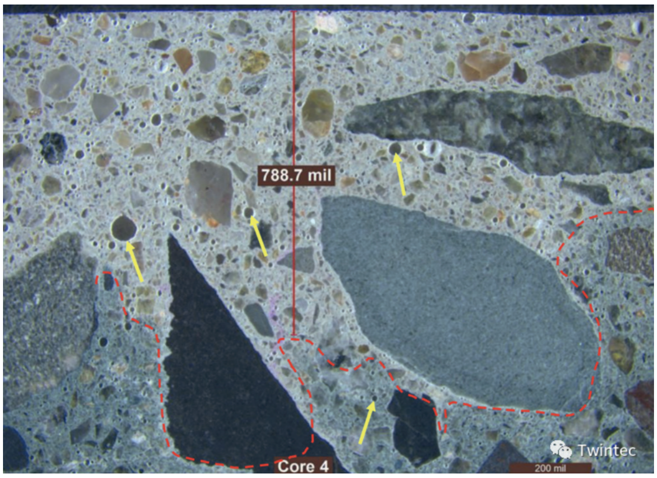

Figure 7. Core 5. Close-up image of the top surface region. The measurement near the top of the image indicates typical depth of slightly lighter and weaker paste, approximately 105 mils (2.6 mm), which roughly corresponds to depth of carbonation. Red arrows indicate interconnected cracking, which extends the full depth of the sample. Cracks appear to propagate around aggregate in this region. The concrete contains many small spherical air voids (yellow arrows).

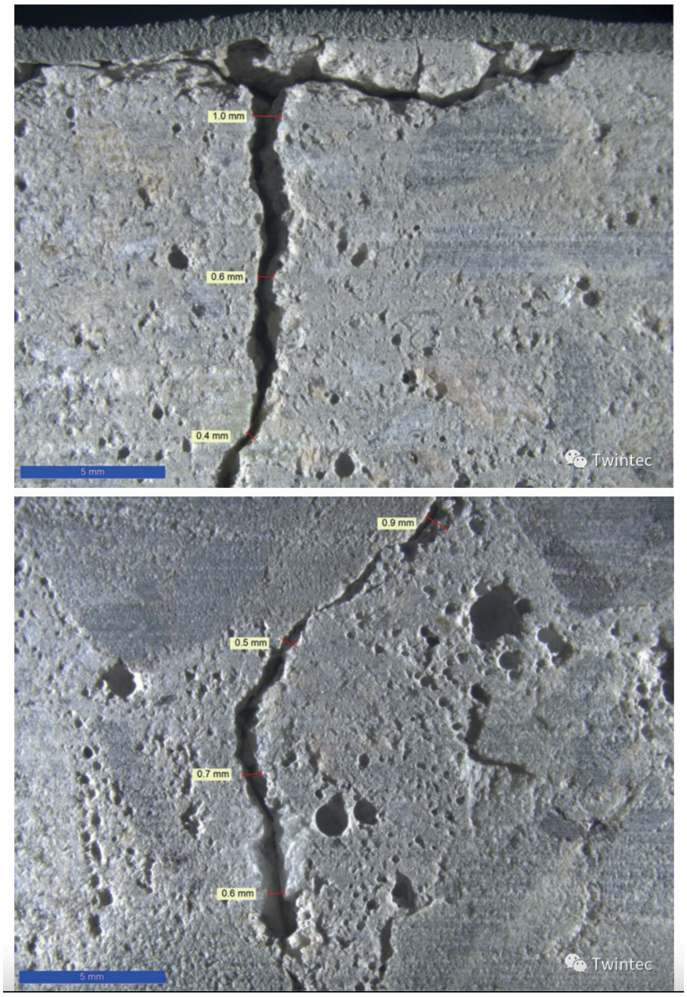

Figure 8. Core 5. Close-up images of the full-depth crack along the as-received core side surface, showing crack width measurements at the top (top image) and bottom (bottom image) of the core. Note that the crack width does not vary much, averaging 0.9 to 1 mm. Due to raveling/abrasing from coring operation, true crack with is likely less than the measured.

Figure 9. Core 6. Close-up image of the top surface region. The measurement near the center of the image indicates typical crack width along the lapped surface within the top region. Red arrows indicate cracking, which extends the full depth of the sample. The crack propagates through two coarse aggregate particles in this region.

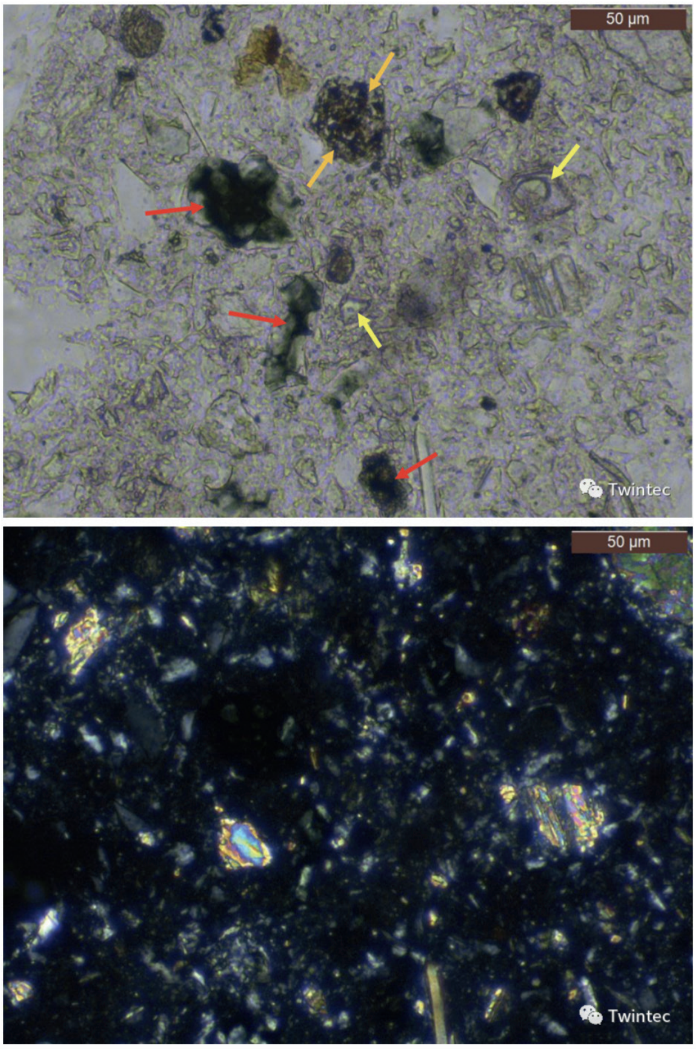

Figure 10 and 11. Core 4. Photographs of paste show Portland cement (red arrows), slag cement (yellow arrows) and suspected specialty cement of the expansive agent (orange arrows). Trace amounts of fly ash were observed (not shown). Note Portland cement was stained green due to presence of slag cement, contributing to the observed blue-green color of the paste. Top image: plane-polarized light. Bottom: cross-polarized light.

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