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The influence of concrete mixture composition on the risk of plastic shrinkage cracking

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ABSTRACT: Plastic shrinkage cracks form between the time of concrete placement and setting time. High temperatures, low relative humidity and high wind speeds in the first hours after placing accelerate evaporation from the fresh concrete surface and increase the cracking risk. However, the occurrence and the severity of plastic shrinkage cracking depend also on the mixture composition of the concrete. This study aims at assessing the influence of concrete mixture composition on the risk of plastic shrinkage cracking for a series of typical Swiss and European cements and concrete mixtures.

The risk of plastic shrinkage cracking appears to be a function of water-to-cement ratio, with the highest cracking risk observed for concrete with w/c 0.45 to 0.55. Since the capillary stresses are higher for small particles and at the same time bleeding is reduced, the risk of cracking increases with increasing fineness of the cements. The differences between cements of similar fineness but different mineralogical composition are limited.

1 INTRODUCTION

Cracking due to restrained volume changes may accelerate deterioration by facilitating the ingress of aggressive agents (e.g., chloride ions that induce corrosion of the reinforcement) and ultimately decrease the service life of concrete structures. Fresh concrete is susceptible to plastic shrinkage cracking, depending on weather conditions after concrete placement and before the time of setting (Powers 1968). Plastic shrinkage cracks appear especially in concrete floors and pavements exposed to strong evaporation (Fig. 1a). Since they occur when the strength is low and before any substantial bond between concrete and reinforcement has developed, plastic shrinkage cracks may not be arrested by the reinforcement and are able to penetrate through whole concrete slabs (Fig. 1a). The main driving force of plastic shrinkage cracking is evaporation of water that creates menisci and high tensile stresses in the capillary water near the surface (Lura et al. 2011, Lura et al. 2007). When the bleeding water on the surface of the concrete is consumed by evaporation, water menisci form (Fig. 1b). These menisci produce capillary stresses that put the whole concrete under compression and cause it to shrink (Lura et al. 2007). As long as the concrete remains plastic, the capillary stress manifests as settlement of the concrete. The settlement of the plastic concrete suddenly stops when a critical point is reached a couple of hours after casting; at this point, cracks may develop. The extent of plastic shrinkage cracking is closely related to the evaporation rate, to the settlement and to the magnitude of the developed negative pressure (Radocea 1994, Slowik et al. 2008).

A traditional method to reduce drying and capillary stresses is fogging/wetting of the concrete surface, which is however labor-intensive, expensive and unpractical (Slowik et al. 2008). Another solution is based on adding polypropylene fibers, which reduce the width of the cracks, but increase costs and worsen workability (Banthia & Gupta 2006).

This study addresses the effect of cement type, cement fineness, water-to-cement ratio (w/c) and cement paste content on the risk of plastic shrinkage cracking. The ultimate aim is identifying mixtures that require special care during curing and possibly developing concrete mixture compositions with reduced susceptibility to plastic shrinkage cracking.

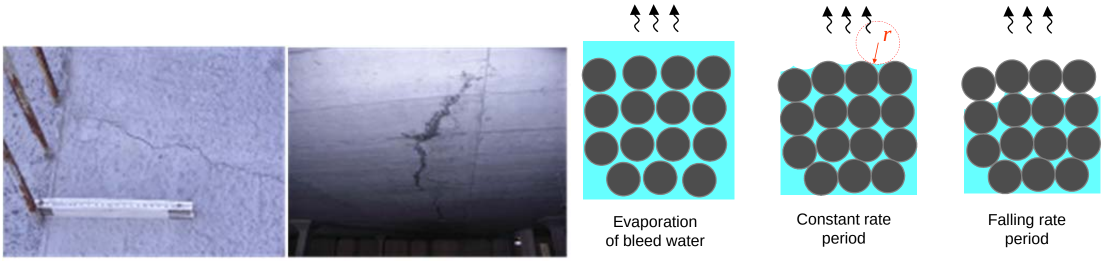

Figure 1. a) plastic shrinkage cracks through concrete slab (Lura et al. 2011) and b) phases of drying of fresh concrete (Lura et al. 2007).

2 MATERIALS

The mixture compositions and the fresh concrete properties are shown in the results and discussion section (see Tables 1-3). The w/c was varied between 0.40 and 0.60, with most concretes having w/c 0.50. The following types of cement were used: CEM I 42.5 N; CEM III / B 42.5 N HS; CEM I 32,5 N; CEM I 52.5 R; CEM II / A-LL 42.5 N; CEM II / B-M (V-LL) 32.5 R. Alluvial sand and gravel (0-1 mm: 31% by mass; 1-4 mm: 19% by mass; 4-8 mm: 20% by mass; 8-16 mm: 30% by mass) was used for all mixtures. A superplasticizer was added at different dosages. A volume of 60 litres was produced for each mixture in an Eirich mixer (the maximum batch size of the mixer was 80 litres). The temperature in the mixing room was 20±1.5°C.

3 METHODS

3.1 *Fresh concrete properties and bleeding*

Concrete flow was measured according to EN 12350-5 immediately after mixing. The density was measured according to EN 12350-6. Air content was measured according to EN 12350-7. Bleeding was measured according to EN 480-4 for 5 hours. Bleeding was measured on samples covered with a lid to prevent evaporation from the surface.

3.2 *Plastic shrinkage cracking*

Plastic shrinkage cracking according to ASTM C1579-06 was measured on two samples per mixture. Two moulds (355×560×100 mm^3), provided with steel inserts to initiate cracking, were filled with concrete and vibrated on a vibration table until compaction. The moulds were moved to a climate chamber with temperature 30±1°C and relative humidity (RH) 45±5%, provided with a wind tunnel. Temperature, RH and wind velocity (7±0.5 m/s) were monitored at the concrete surface by coupled temperature/RH sensors and by anemometers. This allowed verifying that the parameters governing evaporation rate from the fresh concrete remained constant throughout a test and comparable between different tests. The age at cracking was determined by visual inspection every 30 minutes. The crack width distribution was obtained from image analysis of the cracked concrete surface (Qi et al. 2003) at the end of the experiment, about 6 hours after casting. The crack width was measured using an automated image analysis approach, which retrieved the thickness of the whole plastic shrinkage crack (or the cumulated thickness of multiple, parallel cracks) along the path over the stress riser. The minimum detectable crack width was about 0.02 mm. The obtained crack-width distribution for two specimens was then averaged to obtain the distribution of a single mixture.

3.3 Rate of evaporation, settlement and pore pressure

Rate of evaporation, settlement and pore pressure were measured on the same samples used for plastic shrinkage cracking. One of the two moulds employed for the cracking test was placed on a balance equipped with automatic data logging. The evaporation from the concrete surface was obtained simply by dividing the mass loss by the surface exposed to evaporation.

Measurements of settlement of the fresh concrete surface were performed with non-contact lasers (Lura et al. 2007) on the surface of the plastic shrinkage cracking specimens. The vertical displacement of the surface was measured every 30 s from the time of finishing (about 15 min after water was added). The non-contact laser measurement devices consisted of a laser beam projected at a small angle from the vertical direction toward the specimen surface. The distance from the laser head to the surface is calculated by measuring the horizontal displacement of the reflected beam. Two measurements were taken on one mould and one on the second mould for each mixture. The settlement was measured far from the sides of the moulds or the stress risers.

Measurements of pore pressure were performed with tensiometers (Radocea 1994, Slowik et al. 2008, Lura et al. 2011), consisting of a pressure sensor connected to a metallic tube by a rubber hose. The sensor and the tube were filled carefully with degassed water to avoid the formation of air bubbles. The tubes were inserted before casting into the plastic shrinkage cracking moulds through holes in the mould. After casting, the pressure in the pore fluid of the concrete was transmitted by the water in the tubes to the pressure sensors.

4 RESULTS AND DISCUSSION

4.1 Influence of water-to-cement ratio and cement paste volume

Table 1 shows the composition of 5 different concrete mixtures, all with CEM I 42.5 N but with different w/c and cement paste volumes. Table 1 also shows the concrete flow, air content, bleeding after 6 hours measured at 30°C and the number of specimens that showed plastic shrinkage cracks. The mass change due to evaporation, the settlement (average value of three measurements), the capillary pressure in the pore fluid and the width distribution of the plastic shrinkage cracks are shown in Figure 2. In mixture B, the specimens were not cracked over the whole width, which results into a cumulative width distribution with maximum smaller than 1.

The first two mixtures (A and B) have high cement paste content and low w/c, resulting in little bleeding and early-age cracking (Figure 2). Mixtures C and E have high bleeding, resulting in small maximum pore pressures and no cracks. Mixture D (91% of paste volume respect to A) bleeds little, but shows also little setting, low pore pressures and no cracks. Apparently, particle-to-particle contacts are prevalent in these mixtures not only at the level of the aggregate, but also at the level of the cement. Accordingly, the pore pressures and the settlement are limited and no cracking occurs. Moreover, because of the small amount of bleeding water, menisci fall quickly under the concrete surface, whereby the stresses at the surface are likely to be small. This mechanism might also explain the reduced evaporation rate of D after a few hours (Fig. 2).

Table 1. Mixture composition and some properties of concrete with variable w/c and paste volume

Mixture identifier	A	B	C	D	E
Aggregate 0/16 mm [kg/m^3]	1855	1825	1900	1930	1765
CEM I 42.5 N [kg/m^3]	352	396	302	352	352
Superplasticizer [mass-% of cement]	0.2	0.4	0.1	2.4	-
Cement paste content [l/m^3]	**289**	**302**	**274**	**262**	**324**
w/c	**0.50**	**0.44**	**0.57**	**0.40**	**0.60**
Flow [cm]	40	47	38	40	59
Air content [volume-%]	3.9	3.8	3.6	3.4	1.1
Bleeding after 6 h [%]	2.00	1.25	3.58	0.15	6.26
Plastic shrinkage cracks	Yes, 2/2	Yes, 1/2	No, 0/2	No, 0/2	No, 0/2

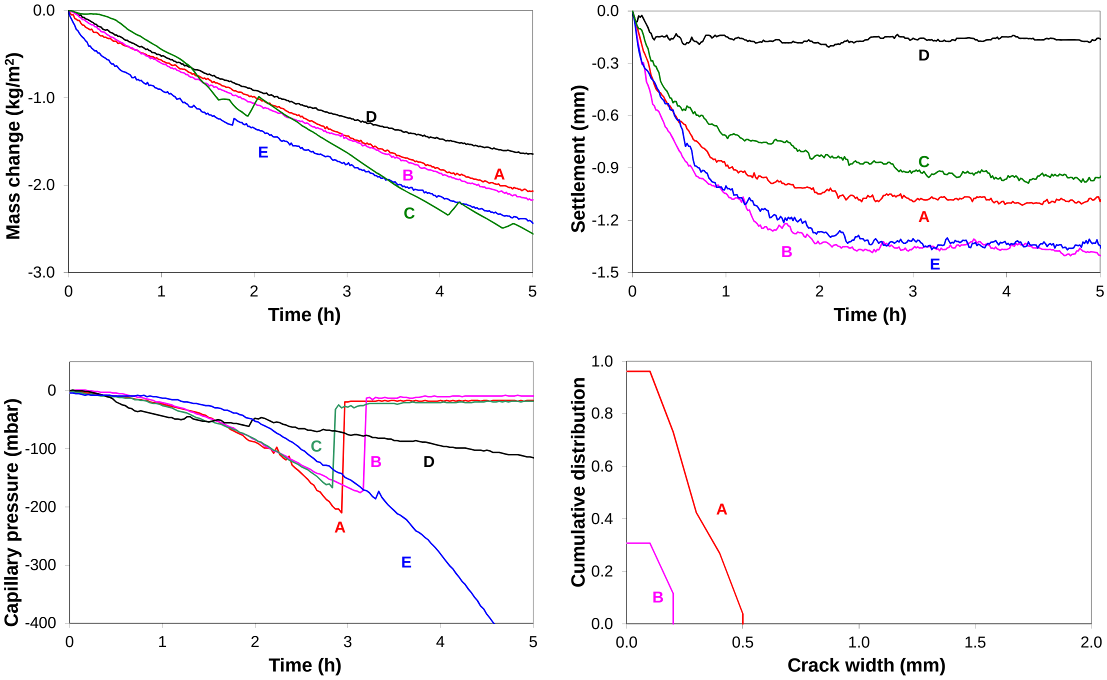

Figure 2. Mass change due to evaporation (upper left), settlement (upper right), capillary pressure (lower left) and cumulative crack width distribution for concrete mixtures (lower right) of concrete mixtures with variable w/c and paste volume.

Figure 3 shows a plot of w/c against volume of paste for concrete made with CEM I 42.5 N. It is noticed that in the original study on which this paper is based on, more mixtures with CEM I 42.5 N were tested than are shown in this paper. These additional mixtures are also plotted in Figure 3. Cracked mixtures are shown with red crosses in Figure 3. Within the limits of the available data (9 mixtures in all), it appears that there is a trend for mixtures with intermediate w/c and high cement paste volume to crack. On the other hand, less or no cracking is occurring when the w/c is low or high and when the cement paste volume is low.

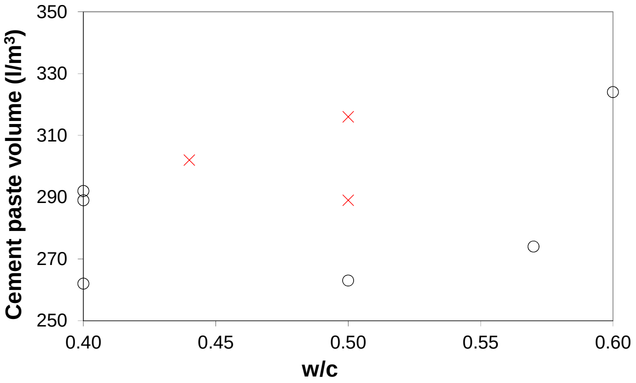

Figure 3: Plot of w/c against volume of paste for concrete made with CEM I 42.5 N. Cracked mixtures are shown with red crosses.

4.2 *Influence of cement fineness*

Three concrete mixtures with w/c 0.50 were produced (Table 2). The aggregate was about 71% by volume. The three mixtures differed for the Blaine fineness of the Portland cement: 2530 cm^2/g for CEM I 32.5 N, 3150 cm^2/g for CEM I 42.5 N and 4510 cm^2/g CEM I 52.5 R.

The fresh concrete properties are reported in Table 2. It is noticed that bleeding is inversely proportional to cement fineness. The mixture with CEM I 32.5 N bleeds about twice as much as the mixture with CEM I 42.5 N and about eight times more than the mixture with CEM I 52.5 R. This effect was expected, as finer cement particles tend to settle less in the mixture and in addition cement hydration, which binds part of the water, is accelerated with finer cements.

Table 2. Mixture composition and some properties of concrete with different cement fineness

Mixture identifier	F	A	G
Type of cement	**CEM I 32.5 N**	**CEM I 42.5 N**	**CEM I 52.5 R**
Blaine fineness of cement [cm^2/g]	**2530**	**3150**	**4510**
Aggregate 0/16 mm [kg/m^3]	1858	1858	1858
Cement content [kg/m^3]	352	352	352
w/c	0.50	0.50	0.50
Superplasticizer [mass-% of cement]	0.2	0.2	0.2
Air content [volume-%]	4.0/3.7	3.9	3.4/3.2
Flow [cm]	40/42	40	40/37
Bleeding after 6 h [%]	3.79	2.00	0.56
Plastic shrinkage cracks	No, 0/4	Yes, 2/2	Yes, 3/4

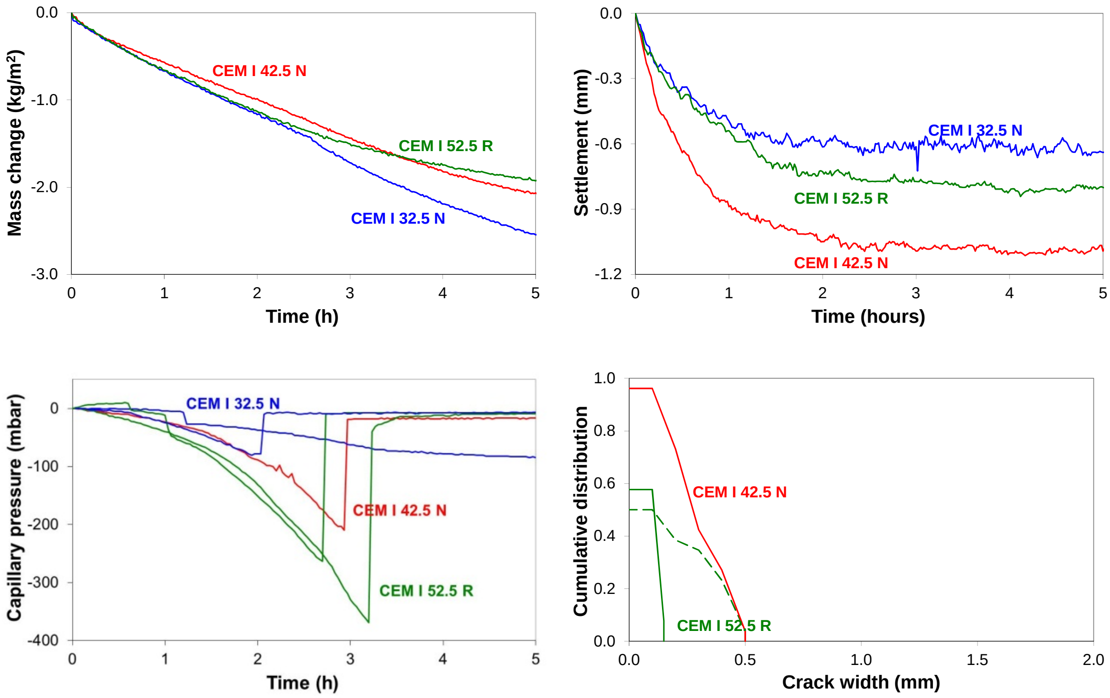

Figure 4. Mass change due to evaporation (upper left), settlement (upper right), capillary pressure (lower left) and cumulative crack width distribution for concrete mixtures (lower right) of concrete mixtures with w/c 0.5 differing in the cement fineness.

The evaporation rate (Figure 4, upper left) is similar in all mixtures in the first 2 hours, after which it decreases for the mixture with CEM I 52.5 R. The settlement of the fresh concrete (Figure 4, upper right) is highest for the mixture with CEM I 42.5 N and lowest for the mixture with CEM I 32.5 N. The underpressure in the pore fluid (Figure 4, lower left) is proportional to the fineness of the cement. This is due to the capillary forces in the fresh mixture being inversely proportional to the radius of the menisci that form between the cement particles (Lura et al. 2007). None of the four tested samples of the mixture with CEM I 32.5 N cracked. In the case of CEM I 42.5 N, 2 samples out of 2 cracked after 2.5 hours. 3 out of 4 samples showed plastic shrinkage cracks in the mixture with CEM I 52.5 R. The samples with CEM I 42.5 N had wider cracks than the samples with CEM I 52.5 R (Figure 4, lower right).

4.3 Influence of cement type

The concrete mixtures H, I and J were prepared with different types of cement (CEM III/B 42.5 N HS, CEM II/A-LL 42.5 N and CEM II/BM (V-LL) 32.5 R). The results were compared with those of concrete with CEM I 42.5 N (mixture A). The mixtures A and J show more bleeding and a higher evaporation rate than I and H (Table 3). The mixtures A, I and J have a similar settlement and comparable capillary pressure (Figure 5). H shows smaller settlement and no capillary pressure. All specimens of all mixtures showed plastic shrinkage cracks (Table 3). The cumulative crack width distribution was similar for all mixtures (Figure 5, lower right), with the smallest cracks in A and the largest occur in I. The four cements CEM I 42.5 N, CEM III/B 42.5 N HS, CEM II/A-LL 42.5 N and CEM II/BM (V-LL) 32.5 R therefore show no major differences in early-age behavior.

Table 3. Mixture composition and some properties of concrete with different cement types

Mixture identifier	A	H M7	I M12	J M13
Type of cement	**CEM I 42.5 N**	**CEM III/B 42.5 N HS**	**CEM II/A-LL 42.5 N**	**CEM II/B-M (V-LL) 32.5 R**
Blaine fineness [cm^2/g]	3150	4230	3130	4140
Agg. 0/16 mm [kg/m^3]	1858	1845	1853	1834
Cement content [kg/m^3]	352	352	352	352
w/c	0.50	0.50	0.50	0.50
Cement paste [l/m^3]	289	294	291	298
Superpl. [cem. mass-%]	0.2	0.2	0.2	0.2
Air content [volume-%]	3.9	3.7	4.1/4.2	45
Flow [cm]	40	44	39/42	40/37
Bleeding after 6 h [%]	2.00	1.37	1.32	2.28
Plastic shrinkage cracks	Yes, 2/2	Yes, 2/2	Yes, 4/4	Yes, 2/2

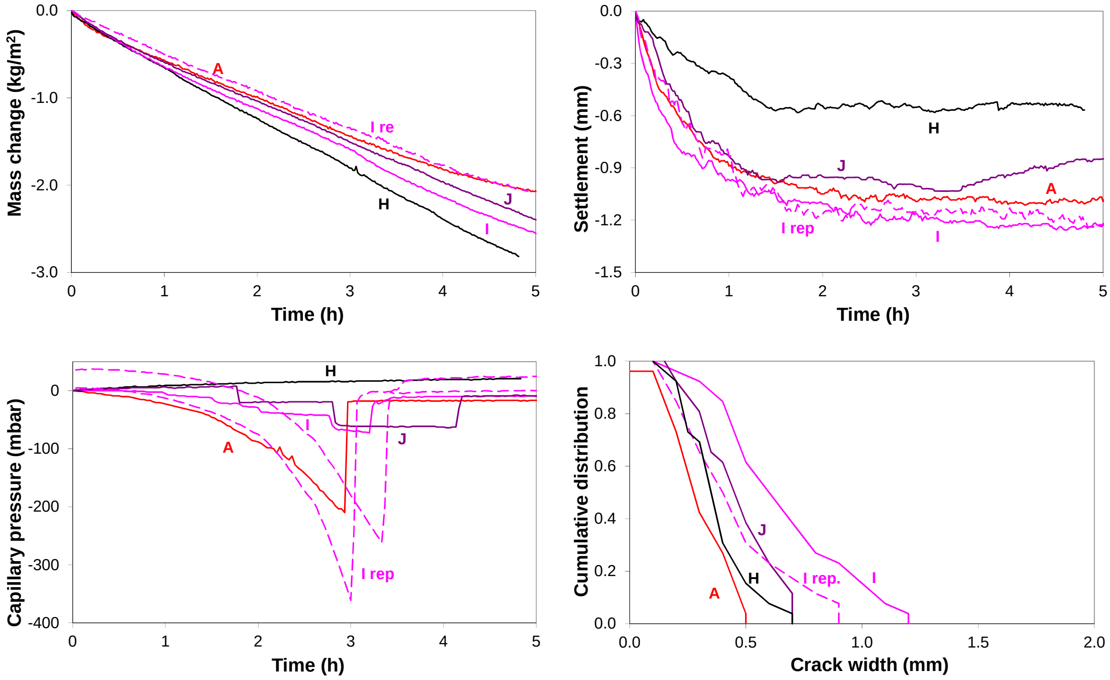

Figure 5. Mass change due to evaporation (upper left), settlement (upper right), capillary pressure (lower left) and cumulative crack width distribution for concrete mixtures (lower right) of concrete mixtures with w/c 0.5 differing in the type of cement.

5 CONCLUSIONS

All concrete components and their proportions have a potential impact on the risk of cracking due to early shrinkage. In order of importance for the risk of cracking:

- **water-to-cement ratio**: The highest risk of cracking is present at a w/c 0.45 to 0.55. If the w/c is higher, the concrete shows high bleeding, so that a film of water on the concrete surface is present for a long time. This prevents or delays the buildup of capillary pressures. In the case of low w/c, the concrete bleeds little. However, because also in the fine particle range particle-to-particle contacts are prevalent, little settlement occurs and the menisci fall quickly beneath the surface. This results also in low capillary pressures and ultimately in little cracking.

- **fineness of the cement**: This parameter affects the process of cracking in two different ways. First, bleeding decreases with increasing fineness of the cement. Correspondingly, the risk of cracking increases. Second, the capillary pressure increases with increasing fineness of the cement, which increases the risk of cracking as well. However, if cement is ground finely it might react faster and the cracking risk might be reduced by an early strength gain.
- **cement paste volume**: In the case of low cement paste volumes, the aggregates form a spatial structure with numerous grain-to-grain contact, which results in small capillary stresses. At high cement paste volumes, the risk of cracking can be estimated based on the w/c ratio.
- **cement type**: When cements of different mineralogical composition but similar fineness are employed, the influence of the cement type on the risk of cracking is small.

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