Early-Age Cracking in Concrete

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Cracking is a common problem in concrete structures in real-life service conditions. In fact, crack-free concrete structures are very rare to find in real world. Concrete can undergo early-age cracking depending on the mix composition, exposure environment, hydration rate, and curing conditions.

Keywords: concrete ; cracking mechanisms ; curing ; early-age cracking ; mix composition ; modeling ; service life

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1. Introduction

Early-age cracks are defined as cracks that generally develop within the first seven days after the placement of concrete; however, 60 days can be considered the maximum limit for early-age cracking, accounting for the initiation of cracks at the bottom of the concrete slab that may take more than one week to be visible [1].

The early-age characteristics of concrete have been a point of research interest for a long time, and researchers have focused on studying different aspects of the early-age characteristics. Bentz [2] reviewed the work on the influence of moisture, temperature, and physical/microstructural characteristics on the early-age cracking of concrete. The other examples of research study include cement hydration and microstructure development by Stark [3], and the characteristics of fresh concrete, such as flocculation, rheology, structural buildup, and formwork pressure, which were reviewed by Kim et al. [4]. Kovler and Roussel [5] focused on the properties of both fresh and hardened concretes, while Nehdi and Soliman [6] studied the mechanisms that affect the properties of concrete and its performance at the early age. On the other hand, Reinhardt [7] investigated the assessment methods to quantify the stiffening and hardening behavior of mortar and concrete. Mihashi and Leite [8] reviewed the mechanisms that cause complex cracking phenomena; they also focused on the methods to control the early-age cracking in concrete.

2. Different Types of Early-Age Crack

Researchers have provided different perspectives on classifying the types of early-age crack in hardened concrete. One approach is grouping according to crack recovering ability. Emborg and Bernander [9] distinguished the cracking in hardened concrete to very early-age temporary or transient cracks and permanent through cracks. The transient cracks tend to close at the end of the cooling period due to compression, while the permanent through cracks do not (generally) tend to close with time. Klemczak and Knoppik-Wróbel [10] grouped the types of crack according to the type of structure, such as massive foundation slabs and medium thick structures, because concrete performs differently accordingly to its element size and structural use.

Many researchers [2][6][8][10][11][12][13] grouped the cracks of concrete according to the causes of cracking, such as drying shrinkage cracks and settlement cracks, while some other researchers [14][15] have grouped the concrete cracks according to the characteristics of cracking, such as random, map, transverse, longitudinal, corner, and re-entrant cracks. Figure 1, Figure 2, Figure 3, Figure 4, Figure 5 and Figure 6 show some of these cracks, which initiated within 3 to 56 days after placing of concrete. However, the grouping of cracks according to the crack characteristics was not only limited to early-age hardened concrete, but also included hardened concrete at later ages, which is beyond the scope of the present study.

Figure 1. Early-age transverse cracks that occurred in a newly cast reinforced concrete column; these cracks occurred within three days after placing of concrete; the column was cured by wet burlap.

Figure 2. Early-age transverse crack in a concrete pavement slab which widened over time; this crack started within 56 days of concrete placement; the slab was cured using curing compound.

Figure 3. Early-age corner crack in a concrete side-walk slab; this crack appeared within 35 days after concrete placement; the concrete slab was cured by curing compound.

Figure 4. Early-age random cracks that occurred in a concrete floor slab; most of these cracks appeared within 42 days after placing of concrete; the slab was cured using thermal curing blanket.

Figure 5. Early-age map cracks that occurred in a newly cast concrete floor slab; these cracks appeared within 14 days of concrete placement; the floor slab was cured by spraying of water.

Figure 6. Restrained shrinkage cracking that occurred in a roadside concrete curb; this crack initiated within 56 days of concrete placement; the curb was cured with curing compound.

3. Causes of Early-Age Cracking

Early-age cracking occurs in concrete structures because of temperature differences and stress development during hardening of concrete. At the early-age of concrete elements or structures, when the tensile strain created from restrained thermal contraction or temperature differential surpasses the tensile strain capacity of concrete, cracking is the outcome (refer to Figure 6); the tensile strain may also be aroused from early contraction caused by autogenous shrinkage [16]. High-strength concrete is more prone to early-age cracking due to autogenous shrinkage [17]. Drying shrinkage hardly plays a role to cause the early-age cracking in concrete. Klemczak and Knoppik-Wróbel [10] divided drying shrinkage into two types: external drying shrinkage and internal drying shrinkage, and this was supported by Mihashi and Leite [8]. Holt and Leivo [12] divided shrinkage into three types, i.e., drying, thermal, and autogenous shrinkages.

Concrete for repair purpose requires high early strength; therefore, accelerators are commonly used in the mixture to increase hydration rate. However, the increased hydration rate also causes high heat of hydration which can potentially increase autogenous deformation and subsequent cracking in concrete [18]. Hence, the proper choice of accelerator is very important regarding the use of high-early-strength concrete in repair or overlay work. Meagher et al. [19] studied the effect of nitrate- and chloride-based accelerators on the cracking risk in concrete at the early-age. They reported similar cracking tendencies for both accelerator types at different concentrations. However, the concrete with the chloride-based accelerator experienced higher shrinkage compared to that with the nitrate-based accelerator.

Thermal strains driven by high temperature gradients occur between the interior and surface of structural elements since concrete has poor thermal conductivity [8][10]. The partial and fully restrained movement from the cooling or other temperature change induces tensile stress in concrete [20][21]; because early-age concrete is generally not strong enough to resist this stress, it cracks. Holt and Leivo [12] named this phenomenon as the thermal dilation effect.

Some researchers [6] have different viewpoints on drying shrinkage cracking and defined drying shrinkage as a reduction in concrete volume due to moisture loss at constant temperature and relative humidity. The loss of water through evaporation results in plastic shrinkage and subsequent internal stresses [13][22], leading to early-age map cracks on the concrete surface, as shown in Figure 5. Branch et al. [23] deduced that the presence of microsilica and the rapid drying of the concrete surface are the main reasons for plastic shrinkage in concrete elements.

Holt [24] pointed out that the chemical shrinkage and autogenous shrinkage of concrete may contribute to its ultimate cracking risk. Chemical shrinkage is induced when the volume of hydration products becomes smaller than the original volume of reacting constituents: cement and water. It is defined as the internal volume reduction in the hydrated cement paste of concrete. In contrast, autogenous shrinkage is considered as the external volume reduction of hydrated cement paste. It happens when the hydration process consumes water and causes internal drying, resulting in a decrease in the material volume [8][10]. At the early stage, when the concrete is still soft, autogenous shrinkage is only attributed to the chemical changes driven by cement hydration, but at a later stage (after approximately 5 h), it is mostly due to self-desiccation, which is intensified by certain mix ingredients (silica fume and superplasticizer) and low water–cement ratio [24]. Therefore, there is a higher risk of autogenous shrinkage in high-strength and high-performance concretes.

Higher coarse aggregate content, the use of very fine and high-angularity sand, poor aggregate gradation, incompatible mineral and chemical admixtures, inadequate curing, delayed finishing, high rate of evaporation from concrete surface, and sudden temperature drop are the major causes of plastic shrinkage cracking. Plastic settlement is one of the common causes of early-age cracks in hardened concrete. The vertical settlement of solid particles and the associated vertical restraint result in differential settlements. Moreover, during the casting of concrete, bleed water moves to the surface, while solid particles settle downwards because of gravity. If the concrete is locally restrained from settling, the settlement of solid particles induces stress. When this stress exceeds the strength of freshly placed concrete, cracking will happen at the source of restraint [25].

Increased coarse aggregate fraction, the presence of very fine sand, poor aggregate gradation, incompatible chemical admixtures, deficient curing, excessively hot conditions, inappropriate control joints, too large joint spacing, and abrupt temperature changes are the main reasons of random cracking in concrete elements [1].

Early loading, the use of dry concrete mixture, poor aggregate gradation, the incorporation of very fine and highly angular sand, inappropriate materials combination, ineffective curing, improper design dimensions, defective joint design, differential support conditions, an excessively hot ambient environment, and rapid temperature decrease are the major reasons of longitudinal cracking in concrete elements. External loading factors such as vibration, traffic, and wind on hardening concrete should not be ignored. The external loading provides extra stress on concrete. However, the tensile strength of early-age concrete is relatively low although it increases with age [26]. In other words, the tensile strength of concrete is very low at the initial stage, especially during the first 3 h, but becomes several times larger in the next few hours [27]. When the tensile stress due to external loading exceeds the ultimate tensile strength of concrete, cracking occurs in concrete.

Higher content of coarse aggregate, unsuitable aggregate gradation, the use of very fine and highly angular sand, the incorporation of incompatible concrete constituents, inadequate curing, inappropriate element dimensions, deficient control joints, misplacement of dowels and/or tie bars, poor stability, extremely hot surrounding environment, and rapid temperature drop are the key causes of transverse cracking in concrete elements [1].

Equipment or traffic loading at the early-age, inadequate curing because of late or poor coverage, excessive curling and warping stresses caused by very long dimensions, poor stability causing excessive deflection under load, and very close dowel and/or tie bars preventing joint corner relaxation are the major reasons for corner cracking in concrete elements [1].

Skewed joints, late sawing, sawing along wind direction, and high wind are some of the reasons for pop-off cracks in concrete elements such as pavement slabs [1]. Mismatched joints in adjacent lanes, joints matching in location but of different types, and cracking from transverse joints in previously paved adjacent lanes can cause sympathy cracks in concrete pavement [1].

High workability, slow setting time, low viscosity, shallow placement of distribution reinforcement as well as dowel or tie bars, and large aggregate size are the major reasons for settlement cracks in concrete pavement [1].

The increased stress due to odd shape and cracking from interior corners can cause re-entrant cracks in concrete elements [1]. They typically originate from beam pockets, window corners, or other openings.

Issa [14] attempted to identify the causes of the early-age cracking in concrete bridge deck through literature review and questionnaire survey throughout the United States. It was deduced that the high evaporation rate and subsequent high magnitude of shrinkage are the most common causes of cracking in concrete bridge deck. The other causes of early-age cracking identified were the use of high-slump concrete, excessive heat of hydration, inefficient curing procedures, improper sequence of concrete pouring, inadequate concrete cover, insufficient compaction, inadequate detailing of joints between new and old decks, etc. [14]. Krauss and Rogalla [28] also identified the deck restraint, improper curing, high early-age modulus of elasticity, creep, shrinkage, and thermal strains as the causes of cracking in concrete bridge decks.

Concrete creep is one of the major causes of the early-age cracking in concrete elements. It is defined as the result of numerous interatomic bond breaks happening at different time periods at different overstressed sites of concrete [29]. Bažant et al. [30] divided the creep into three types: basic creep, drying creep, and transitional thermal creep. Basic creep is strongly dependent on the age at loading and water content [29]. Bažant et al. [30] divided the age at loading into short-term chemical aging and long-term nonchemical aging. The effect of hydration process on the capillary pore structure in the cement paste reduces the creep compliance of concrete [29]. This is referred to as short-term chemical aging. In long-term nonchemical aging, the cement hydration in concrete is practically stopped and the basic creep decreases while the age at loading increases [29].

Drying creep, also referred to as Pickett effect [31][32], occurs when concrete elements undergo deformation during drying as well as after drying. There are two major mechanisms for this form of creep—firstly, a macroscopic mechanism due to microcracking or strain-softening damage and secondly, a nanoscale mechanism due to stress-induced shrinkage [32]. According to the macroscopic mechanism, the nonuniform moisture distribution between the external and internal layers of concrete causes shrinkage to occur in these layers at different time periods due to the loss of water from capillary pores. Consequently, a tensile stress is induced that leads to local microcracking or tensile strain-softening damage in the surface layer, resulting in nonlinear inelastic deformation (unrecoverable creep) of concrete. The second mechanism is stress-induced shrinkage due to moisture loss and temperature rise [32]. Upon drying, a thermodynamic imbalance among the chemical potentials of various phases of pore water develops due to reduced pore vapor pressure and temperature rise [30], resulting in tensile stresses, which are balanced by compressive stresses (micro-prestress) in the surrounding concrete and consequently concrete shrinks. This phenomenon particularly occurs in the nanostructure of concrete comprising calcium silicate hydrates, very small capillary pores, and gel pores. The breakages of bonds in the calcium silicate hydrates may happen by an increase in the magnitude of micro-prestress.

Transitional thermal creep is defined as the transient increase of creep due to changing temperature [30]. The first mechanism is an apparent macroscopic mechanism, which is, like drying creep, owing to thermally induced microcracking. Another mechanism is the nanoscale mechanism, in which the changing temperature alters the level of micro-prestress by changing the chemical potential of nanopore water [30].

4. Factors Affecting Early-Age Cracking

The temperature change, thermal expansion coefficient, tensile strength, and the restraint to movement within the concrete are some of the factors that affect the early-age cracking in concrete [16]. The temperature change depends on the heat evolution in concrete, which is influenced by the amount and type of cement, the thickness of concrete element, and the ambient conditions or the type of formwork where the concrete is placed [10].

Emborg and Bernander [9] discovered that the temperature criteria only influenced hardened concrete in specific situations and the other parameters that should be considered include the type of cracking, transient mechanical properties, and axial and rotational restraints. De Schutter and Taerwe [33] studied the thermal heat and thermal diffusivity of hardening concrete and found that thermal diffusivity decreases linearly with the increase in the degree of hydration.

The factors that affect the early-age cracking in concrete are categorized into five groups, namely design process, materials and mix proportions, construction procedures, environmental conditions, and external loading conditions, as presented in Figure 7. Each group includes 2–7 different factors.

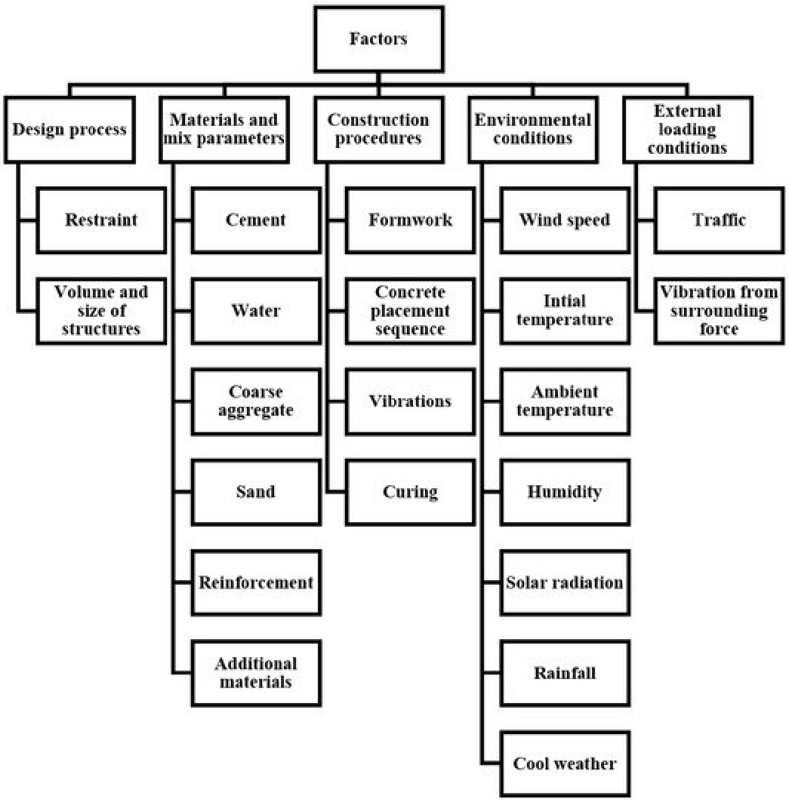

Figure 7. Various factors which influence cracking of hardened concrete.

5. Consequences of Early-Age Cracking

Early-age cracking is a common occurrence in concrete structures. However, early-age cracks do not cause the failure of concrete structures if the structural tolerance level is not exceeded [34]. However, these cracks affect the appearance of structures and raise public concern and attention regarding safety issues. The experts (engineers, architects, and concrete practitioners) understand that early-age cracking does not usually affect the general safety of structures. On the other hand, the public may not understand this. As a result, the image of contractors and consultant may be affected, where the public may blame the construction stakeholders for the lower construction quality. The aesthetic appearance of concrete structures is also greatly affected due to the early-age cracking in concrete surface if not repaired.

Early-age cracking, if left unchecked, may lead to long-term maintenance issues. The early-age cracking may be a temporary shortcoming, but the owners or building management personnel assign contractors to repair early-age cracks rapidly. Improper remedial work leads to further problems, such as water ponding. If these cracks are permanent and are not solved immediately, they could also allow the ingress of aggressive agents, such as chloride, sulfate, and carbonates, which may induce the corrosion of steel reinforcement and the carbonation of concrete to shorten the service life of concrete structures [35][36][37].

The function of some concrete structures may be affected over time, especially in structures like water reservoirs and roofs, due to early-age cracking. The cracking may cause leakage in these structures [38]. If the concrete cracking continues to develop, it may affect the bearing capacity of the structure and speed up fatigue failure [10][39]. Moisture leakages are also harmful to building users and their property, especially to electronic devices. Further research in related topics is encouraged since literature in this area seems to be scarce.

Cracking is not allowed on certain special functional structures, such as nuclear power plants, chemical and radioactive waste storages, nuclear containment vessels, liquefied natural gas tanks, and waste disposal structures. It would be a disaster if the chemicals leak through these structures [40]. These leaking agents are very aggressive and harmful, where they not only pollute the environment, but are also very harmful to humans.

6. Remedial Measures for Early-Age Cracking

Early-age cracking always has some risks for concrete structures. However, these risks can be reduced through many remedial measures. The early-age cracking in concrete can be minimized by limiting temperature differences or using shrinkage reducing admixtures. Low-heat cement has been used to limit the temperature induced cracking in concrete. Also, shrinkage reducing admixtures have been used to decrease the stresses resulting from autogenous shrinkage [17].

Appropriate selection of the constituent materials for concrete, the correct mix design of concrete, the proper planning of concrete casting and construction sequence, the use of insulation for reducing thermal gradients, the installation of control joints, and the cooling of concrete before or after placing are some of the measures to minimize the risk of the early-age cracking in concrete structures [16].

Temperature or distribution reinforcement can be used to control cracks in hardening concrete structures. This type of reinforcement distributes early-age cracks and prevents the formation of through-cracks. Therefore, the strain capacity of reinforced concrete elements is significantly increased in the presence of distribution reinforcement. Also, the main reinforcement configuration is more important than the reinforcement ratio in controlling the cracking in reinforced concrete elements [17]. The probability of cracking is lower in heavily reinforced concrete (generally true for high-strength concrete) structures. Less cooling joints or fewer dilation joints are required to prevent the early-age through-cracking in reinforced concrete structures.

The depth of plastic shrinkage cracks can be determined by coring. The extent of random, longitudinal, and transverse cracking over time can be determined by drawing crack map. The depth of cracking and aggregate breakage in the cases of transverse, longitudinal, and corner cracks as well as the bonding of slab with sub-base in the case of random crack can be determined by coring. The bonding of slab with sub-base can be examined by conducting push-off test in the cases of random, transverse, and longitudinal cracks. The joint function can be examined via the pull-out test while investigating transverse and corner cracks. Employing a good quality curing compound in an adequate amount may reduce the extent of plastic shrinkage, random, longitudinal, transverse, and corner cracking [1]. Well-graded sand and combined aggregates are also conducive to decrease the degree of severity of plastic shrinkage and number of random, longitudinal, and transverse cracks.

From literature survey, the remedial measures can be classified into two groups: materials- and design-based remedial methods and construction-based remedial methods (refer to Table 1). Constituent materials, concrete mix design, and structural design are classed as materials- and design-based remedial measures. In the case of construction-based remedial measures, curing, placing sequence and environmental conditions, vibration, cooling method, and formwork are emphasized.

Table 1. Classification of remedial measures to reduce early-age cracking in concrete.

No	Reference	Designing			Construction				
		A	B	C	D	E	F	G	H
1	Holt [24]	Y	Y	-	-	-	-	-	-
2	Klemczak and Knoppik-Wróbel [10]	Y	Y	-	Y	Y	-	Y	-
3	Krauss and Rogalla [28]	-	Y	-	Y	Y	-	-	-
4	Emborg and Bernander [9]	-	Y	-	-	-	-	Y	-
5	Shing and Abu-Hejleh [41]	Y	Y	-	Y	Y	-	-	-

No	Reference	Designing		Construction					
		A	B	C	D	E	F	G	H
6	Babaei and Purvis [42]	Y	Y	-	-	Y	-	-	-
7	French et al. [43]	Y	Y	Y	-	Y	-	-	-
8	Dippenaar [44]	Y	-	Y	Y	-	Y	-	Y
9	Combrinck and Boshoff [45]	-	Y	-	-	-	-	-	-
10	Kwak and Ha [46]	-	-	-	-	Y	Y	-	-
11	Ah-Sha, Sanders, and Saiidi [47]	-	-	-	-	Y	-	-	-

Legends: A: Concrete constituent materials, B: Concrete mix design, C: Structural design, D: Curing, E: Placing sequence and environment conditions, F: Vibration, G: Cooling method, and H: Formwork.

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