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Interaction between settlement and shrinkage cracking in plastic concrete

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HIGHLIGHTS

- Five different cracking behaviours of plastic concrete have been identified.
- No cracking in conditions with low evaporation and differential settlement.
- Pure plastic settlement cracking show internal cracks and multiple surface cracks.
- Pure plastic shrinkage cracking shows sudden single cracking through the slap depth.
- Combining both cracks results in interaction and cracking long before expected.

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ABSTRACT

The plastic period in conventional concrete is dominated by two volume changes namely, plastic settlement and plastic shrinkage, which if restrained can result in cracking. Although both volume changes and the resulting cracking have been well documented cracking during the plastic period remains a problem. One reason is the complex interaction between these cracks. This paper shows the necessity of considering the combined effect of plastic settlement and plastic shrinkage cracking when investigating the cracking of plastic concrete. This is achieved by isolating both cracking types individually, followed by the interaction between these cracks. Plastic settlement cracking shows multiple tensile surface cracks and shear induced cracks below the surface. Plastic shrinkage cracking shows a single well defined crack pattern which forms suddenly throughout the entire depth of the concrete. When combined significant crack widening can occur long before normally expected due to the negative synergy between these two crack types.

1. Introduction

Concrete is only plastic for the brief period from being cast to around the final setting time [1,2]. During this plastic period the concrete is a fluid or semi-fluid mixture of solid cementitious and aggregate particles with water and often admixtures, and does not possess any significant strength or stiffness, especially when compared to hardened concrete [3–5]. This plastic period only lasts for a few hours, depending on the binder type, mix proportions and environment, and is insignificantly short when compared to the intended life of any concrete structure.

It is further necessary to distinguish between plastic concrete and early age concrete. Although plastic concrete can be thought of as early age concrete, the term early age concrete normally refers to the period from after final setting to a concrete age of around 7 days [1]. During both the plastic and early age periods, concrete is subjected to volume changes. If the concrete is restrained against these volume changes, stresses will develop within the concrete which may lead to cracking. The plastic period of conventional concrete is dominated by two volume changes namely, plastic settlement and plastic shrinkage [3,6]. Concrete mixes with water-to-binder ratios lower than 0.4 can also undergo significant autogenous shrinkage, which is equivalent to the absolute volume reduction caused by chemical shrinkage during this plastic period [2,6].

Plastic settlement is a vertical volume reduction caused by the gravitational settlement of solid particles in the fresh concrete mixture [3,5,7]. Freshly mixed concrete is a mixture of solid particles and water as well as possibly admixtures. For conventional concrete, the solid particles range in sizes of micrometers in the form of cementitious and filler particles to sizes in millimeters in

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the form of sand and stone particles. These solid particles are denser than water and tend to settle vertically displacing water to the surface, called bleeding water. The bleeding water is removed, normally through evaporation, leaving a concrete body with reduced vertical dimension, called settlement. If settlement is restrained, cracks are likely to develop near the cause of the restraint [8,9]. The potential for plastic settlement cracking is only present if settlement occurs. Particle settlement can be ceased mechanically and/or by hydration and can also be increased by negative capillary pressure build-up due to evaporation [7,10]. Admixtures such as viscosity modifiers and air entrainers can also influence the settlement as discussed elsewhere [11].

Plastic shrinkage is a three dimensional volume reduction, caused by a suction in the capillary pores of the fresh concrete [10,12]. Once all the bleed water on the surface has evaporated, the free water within the concrete pore system is drawn out by the continuing evaporation. This causes a negative capillary pressure build-up within the concrete pore system which results in a volume reduction, called plastic shrinkage. Once the concrete is no longer plastic and solidifies it forms a solid skeleton able of resisting the shrinkage stresses caused by the evaporation of pore water [10,12]. If plastic shrinkage is restrained by for example reinforcing steel, cracks are likely to form. These cracks often occur in conditions with high evaporation rates especially in slab-like concrete elements with large exposed surfaces such as bridge decks, pavements, slabs on ground and suspended slabs [6,13]. For slabs with a uniform thickness, cracking is mostly random and referred to as a "crazed" crack pattern as shown in Fig. 1a [10]. For slabs with a non-uniform thickness, cracks are normally linked to the positions of these non-uniformities, such as reinforcing steel, as shown in Fig. 1b. However, the latter may include crack growth due to both plastic shrinkage and plastic settlement cracking as discussed further in this paper.

After the plastic period, there are also several other volume changes that occur within the early age period. This includes volume changes due to temperature variations, self-desiccation and drying. All these volume changes can result in cracking, which not only degrade the aesthetical appearance of any concrete structure but also accelerates the degradation of the concrete as well as any reinforcing steel embedded within the concrete [14,15].

This paper only considers the cracking that can occur in the plastic period for conventional concrete, due to the importance of this period with regard to the durability and service life of a structure. Any plastic crack that occurs within the first few hours after the concrete has been cast can potentially shorten the intended service life of a concrete structure with decades [3,16,17]. This highlights the importance of preventing these cracks which forms during one of the shortest periods or phases in a concretes life.

Both plastic settlement and shrinkage as well as the resulting cracking have been well documented in literature over the past 60 years [12,18–22]. Although the causing mechanisms of both cracking types are known, cracking during the plastic period remains a problem in the construction industry. One of the main reasons is the complex interaction between plastic settlement cracking and plastic shrinkage cracking which can result in unexpected cracking behaviour. Although both cracking types can occur separately, it is postulated in this paper that this is seldom the case for the majority of exposed slab-like elements, especially elements containing reinforcing steel.

Despite this, most research conducted on this topic either focuses on plastic settlement cracking or plastic shrinkage cracking and never the interaction between the two. In fact, no literature could be found that deliberately investigated this interaction, with only a few making reference to it. Lura et al. [11] investigated the influence of shrinkage-reducing admixtures on plastic shrinkage cracks and identified differential settlement as one of four driving forces for cracking. Ghoddousi et al. [9] investigated the effect of reinforcement on plastic shrinkage and settlement of self-consolidating concrete as repair material and mentioned that plastic settlement cracking dominates plastic shrinkage cracking when the steel bars are placed near the surface of the concrete. Finally, Kwak et al. [3] conducted experimental and numerical investigations on plastic settlement and briefly mentioned that plastic shrinkage cracks can be caused by plastic settlement and further stated that a study based on Korean conditions estimated that 40% of plastic shrinkage cracking are caused by plastic settlement.

The apparent interaction between plastic settlement and plastic shrinkage cracking under certain conditions is evident and even obvious, since both cracks occur in quick succession of each other in a short time period and since both cracks share several important influencing factors such as bleeding, capillary pressure and sources of restraint. This, together with the short time period within which these cracks occur, increases the difficulty of clearly distinguishing between the cracks. In general, plastic settlement cracking occurs first followed by plastic shrinkage cracking [23]. However, the exact interaction between these two cracking types remains complex and to a large extent unknown.

With this in mind, the objective of this paper is to show the necessity of considering the combined effect of plastic settlement cracking and plastic shrinkage cracking when investigating the cracking of plastic concrete in the plastic period. The methodology followed to achieve this is to firstly isolate and characterise the behaviour of plastic settlement cracking and plastic shrinkage cracking individually, followed by the combined effect of or interaction between these cracks. The experiments conducted and the results achieved on plastic settlement cracking without the influence of plastic shrinkage cracking as well as on plastic shrinkage cracking without any plastic settlement cracks are discussed in Sections 2 and 3 respectively. The experiments and results on the

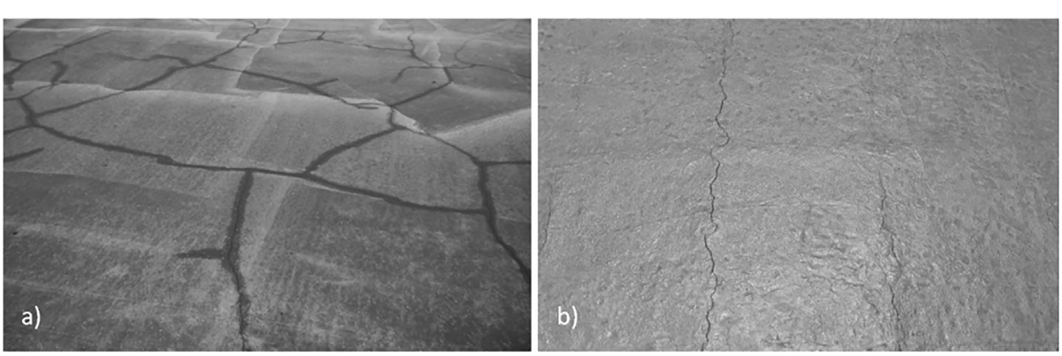

Fig. 1. Plastic shrinkage cracking patterns. a) Crazed crack pattern [10]. b) Crack pattern linked to steel reinforcement layout.