Autogenous Shrinkage of Concrete at Early Ages

N. Gowripalan

Abstract High Performance Concrete (HPC), particularly high strength concrete mixes (60–100 MPa) containing high cementitious content and low w/b ratios (0.40–0.25) is used for some precast elements. Ultra High Performance Concrete (UHPC) up to 200 MPa containing very high cementitious content and very low w/b ratios (0.25–0.17) is also used for precast and prestressed elements in buildings and bridges. Shrinkage characteristics of HPC and UHPC differ considerably from those of conventional concrete. Due to their high cementitious content and low w/b ratios, the drying shrinkage component is significantly smaller when compared with the autogenous shrinkage component. HPC and UHPC elements, when steam-cured, undergo majority of their shrinkage within a few days of casting. In this paper, mechanisms of autogenous shrinkage of HPC and UHPC at early ages are compared under different curing conditions. Contribution of autogenous shrinkage and drying shrinkage components on the total shrinkage is discussed. At very early ages, plastic shrinkage and plastic settlement cracking and factors affecting them for HPC and UHPC are also outlined.

Keywords Autogenous shrinkage · Drying shrinkage · Carbonation shrinkage · Water/cement ratio · Water/binder ratio · High performance concrete · Ultra-high performance concrete · Rheology · Consistency

1 Introduction

Shrinkage of concrete has three main components after hardening: autogenous shrinkage (sometimes called chemical shrinkage but not quite the same), drying shrinkage and carbonation shrinkage. Before hardening, however, concrete undergoes plastic shrinkage and plastic settlement strains. In hardened HPC and UHPC the dominant component is the autogenous shrinkage due to high binder content and

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low water/binder ratio. There is hardly any water present in UHPC to cause drying shrinkage. Also the dense matrix with low permeability may not allow movement of pore water to come to the surface and evaporate. Understanding the shrinkage of HPC and UHPC, particularly at early ages is essential for the successful application of these concrete mixes. Often 100 MPa HPC, which incorporates high range water reducers is used in tall buildings. Self compacting concrete (SCC) which are used for slabs consists of polycarboxylic eather (PCE) based superplasticizers. UHPC often incorporates steel, synthetic and hybrid fibres in the matrix and the mix has high dosage of PCE based superplasticizers. All these factors will influence the early age shrinkage of these types of concrete.

Autogenous shrinkage is defined as the concrete volume change without any moisture transfer to the environment. It is the result of the internal chemical reactions of the concrete components. Autogenous shrinkage is caused by the reduction in volume when cement hydrates and new products are formed. The volume of the hydrated products occupy less volume when compared with the volume of unhydrated cement and water (paste volume at the beginning of hydration 'as cast'—see Fig. 1). Initially, up to the time of final set, the *chemical shrinkage* and the autogenous shrinkage will be equal. After a long period, the *total chemical shrinkage* is considerably more than the *total autogenous shrinkage* (pre-set and post-set) as it also includes partly the cumulated voids generated by hydration. Measuring chemical shrinkage may involve the volume change measurements of various components of cement such as C_3S, C_2S, C_3A and C_4AF. Total autogenous shrinkage should ideally commence at the final set.

Soon after mixing, concrete is in a fluid state and if any stress is applied it will deform initially without cracking. This fluid state is characterised by *plastic viscosity* and *yield* (related to internal resistance of concrete to movement) and at this state concrete is considered as a *Bingham fluid*. However, after a few hours (after about 2 h from the initial setting time), concrete may begin to resist movements and develop stresses due to physical and chemical causes [5]. It is during this period (3–6 h after casting), if concrete does not have sufficient strength, plastic cracking occurs. Up to

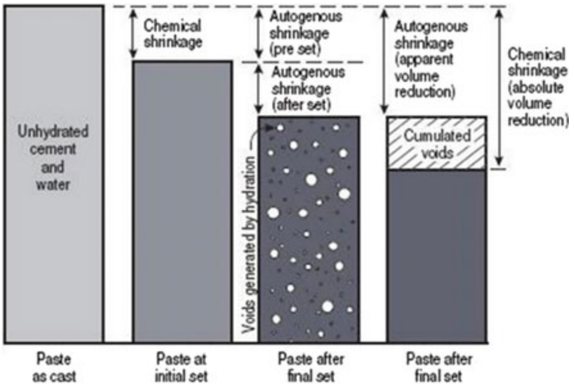

Fig. 1 Autogenous and chemical shrinkage of cement paste

the final set, the shrinkage may be considered as *plastic shrinkage*. Plastic cracking involves both *plastic shrinkage cracking* and *plastic settlement cracking*.

Plastic shrinkage cracking has been investigated by many researchers [7, 3, 9, 1] and there is a general agreement as to the mechanism of it [2]. It is attributed to excessive rate of evaporation of the water from the surface of concrete and the lack of bleed water to replenish it. When the evaporation rate exceeds the bleed rate, near the surface of freshly placed concrete, capillary suction develops within the liquid phase. If the shrinkage is non-uniform or restrains such as aggregate particles are present, then tensile stresses can develop near the top surface. Once these tensile stresses exceed the low tensile strength of the fresh concrete, plastic shrinkage cracking can occur. In the case of plastic settlement cracking, settlement of the freshly placed concrete occurs due to water rising to the top of the member. The steel reinforcement in the member acts as a restraint to settlement and tensile stresses develop in fresh concrete over the positions of reinforcement. This leads to cracking, reflecting the reinforcement arrangement near the top layer of the member. Plastic settlement cracks can also occur at change of depth of sections (for example, where slab thickness changes from a smaller depth to a larger depth) of members.

1.1 Plastic Shrinkage Cracking

Plastic shrinkage on concrete occurs as a result of the surface tension effects present on the finished concrete surface. Usually it is accompanied by considerable amount of bleeding of a concrete element such as a concrete slab and higher rate of evaporation of the bleeding water from the surface. During this process, water lenses may form below large aggregate particles and reinforcing bars, causing poor bond between aggregates and cement paste or concrete and reinforcing bars. Random map pattern cracking of the surface is a result of plastic shrinkage cracking. Although it starts at the surface often it may go through the full depth of a slab and crack widths at the surface can be a few mm in size (Fig. 2). Plastic shrinkage cracking needs to be addressed carefully, particularly for HPC and UHPC due to the use of superplasticizers, higher binder contents with supplementary cementitious materials and low water/binder ratios.

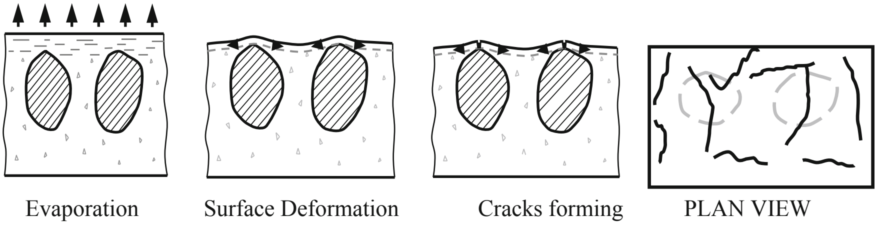

Fig. 2 Plastic shrinkage cracking

1.2 Plastic Settlement Cracking

Plastic settlement cracking also occurs due to excessive bleeding, particularly in deep sections and where change of sections occur. Plastic settlement cracking often reflects the reinforcement pattern underneath as reinforcement provides restraint to settlement of plastic concrete (Fig. 3). In columns plastic settlement cracks may appear at the column head-column connections, In waffle slabs, it may occur where the ribs meet the thin sections of the slab. Often the bond between reinforcement and surrounding concrete is very week. Plastic settlement cracking may different for HPC or UHPC due to the low water/binder ratio as the settlement will be controlled by many factors. For example, a HPC mix containing opc/silica fume binder, may bleed very little and settlement of the concrete will also be considerably small. However, in SCC, the fluidity of the concrete (due to the use of superplasticizers) may influence the settlement and this needs to be addressed. In UHPC, although the binder content is extremely high, the use of steel or synthetic fibres in the mix can control the bleeding and resulting settlement.

The movement taking place near the surface, before concrete sets (before initial set) involves surface tension effects (physical effects) as well as chemical effects (chemical or autogenous shrinkage). These movements are large in magnitude and majority of it is a physical effect drawing the hydrating particles together. Autogenous shrinkage and chemical shrinkage at this stage will be almost equal. Since concrete is in a plastic state, no stresses are developed in the structural element at this stage. Once concrete sets (final set) and the interaction of hydration products are well established, concrete will start to develop tensile strength. The physical movement is now greatly reduced but chemical shrinkage and autogenous shrinkage will continue. At this hardened state, the chemical shrinkage will be considerably larger than the autogenous shrinkage. Autogenous shrinkage has two components: pre-set and post-set (see Fig. 1). The total chemical shrinkage (absolute volume reduction) will be more than autogenous shrinkage (apparent volume reduction) as it also includes the volume of voids generated by hydration. These volume changes take place in the

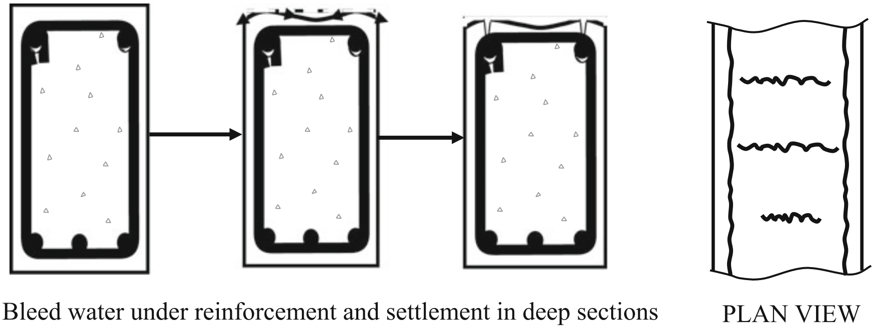

Fig. 3 Plastic settlement cracking

cement paste (cement and water only). After a few days (3–7 days) of casting, the chemical shrinkage can be 8–10 times of the autogenous shrinkage. However, the shrinkage that causes movement in a concrete structure, in a hardened state, is the autogenous shrinkage (and drying shrinkage) and majority of the chemical shrinkage is accommodated within the gel pores and to a lesser degree in the capillary pores. Autogenous shrinkage is usually measured on sealed shrinkage prisms, commencing 1 day after casting (from the time of demoulding) whereas chemical shrinkage cannot be measured from external dimensions of a prism. For HPC or UHPC, however, a component of the autogenous shrinkage (post-set) will not be recorded, even if measurements commence after 1 day of casting. Also the change in temperature due to hydration need to be taken into account and measured autogenous shrinkage should be corrected for thermal effects. In some high performance concrete mixes, due to compatibility of admixtures, the setting times may vary considerably and this can affect the commencement of autogenous shrinkage measurements.

According to RILEM [8] recommendations, the autogenous shrinkage measurements should commence immediately after demoulding and sealing of the specimens, at the age of one day. According to German Standard DIN 1045-1 (2008) also the commencement of autogenous shrinkage is at the age of one day. For HPC or UHPC, however, if the measurements commence at the age of one day, a considerable part of the autogenous shrinkage may lapse before recording commences. This is due to post-set autogenous shrinkage commencing a few hours after casting. Holt [5] and Marusic and Stirmer [6] measured autogenous shrinkage continuously from the onset of setting (or even from the time of casting).

2 Autogenous Shrinkage

2.1 Autogenous Shrinkage of High Performance Concrete (HPC)

There are many types of HPC available, including concrete with very little or no shrinkage. Here, HPC having compressive strengths in the range of 60–100 MPa and having relatively high binder content and low water/binder ratios are discussed. Understanding their shrinkage characteristics are important in order to evaluate their long-term performance in the structure. For example, in prestressed concrete beams, HPC is often used and the long-term loss of prestress due to shrinkage needs to be evaluated accurately. In normal strength structural concrete, the autogenous shrinkage component is very small (typically less than 100 $\mu\varepsilon$). The predominant component is the drying shrinkage. In HPC, however, due to the higher binder content, low water/binder ratio, smaller maximum size aggregates and presence of admixtures, the autogenous shrinkage can vary considerably (up to 500 $\mu\varepsilon$) and is a major component of the total shrinkage. Total shrinkage and autogenous shrinkage values

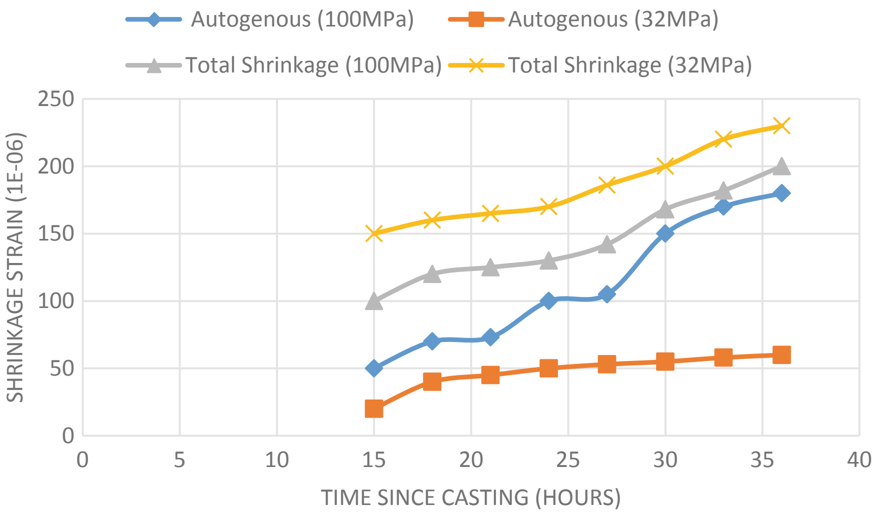

Fig. 4 Total shrinkage and autogenous shrinkage of normal and high strength concrete

(measured from the final setting time) for normal strength and high strength mixes are compared in Fig. 4.

These results were obtained in a study on commercially available concrete mixes as part of a project on high strength concrete. Although many high strength concrete mixes were investigated, autogenous shrinkage measurements were carried out only on a single high strength concrete mix with a silica fume/opc binder and a normal strength concrete mix with opc binder. The maximum size of aggregates in the high strength concrete mix was 14 mm (Basalt) whereas the maximum size of the aggregates in the normal strength mix was 20 mm (River Gravel).

Autogenous shrinkage of a normal strength concrete mix (32 MPa) after 36 h was almost stabilised at 60 $\mu\varepsilon$. On the other hand, the autogenous shrinkage of high strength concrete mix (100 MPa) reached 180 $\mu\varepsilon$ after 36 h and continued to increase with time. After 28 days of age, it reached 360 $\mu\varepsilon$ and after 90 days of age, it was 380 $\mu\varepsilon$. The higher binder content (opc + 10% silica fume) of the HPC mix contributed to the higher autogenous shrinkage. However, the total shrinkage (autogenous + drying) of normal strength mix was higher than that of HPC mix.

2.2 Autogenous Shrinkage of Ultra High Performance Concrete (UHPC)

Ultra High Performance Concrete (UHPC) with a compressive strength of 180 MPa (after 2 days of heat treatment) was produced in Australia for the construction of prestressed girders for bridges. The shrinkage of UHPC is essentially autogenous shrinkage as the mix contained a binder content of 884 kg/m^3 (680 kg of cement and 204 kg of silica fume) and water content of 150 kg/m^3 with a w/b ratio of about 0.17. The drying shrinkage component is very small or neglected due to non-availability of water for evaporation. UHPC has a tendency to shrink even when immersed in water due to the autogenous shrinkage component. Typical shrinkage results of heat cured (at 90 °C hot water for 1 day) and standard water cured (23 °C for 7 days) specimens are shown in Fig. 5. The initial reading for hot water curing was taken immediately after demoulding (at the age of 1 day) and for standard water cured specimens it was at the age of 7 days. Unfortunately, no readings were taken within 24 h of casting as a standard measuring technique with a vertical comparator was used and special testing facilities are required for this measurements.

It can be seen, from Fig. 5, that autogenous shrinkage of 500 $\mu\varepsilon$ in total is recorded for UHPC [4]. For heat-treated UHPC, more than 80% of the long-term shrinkage was recorded immediately after heat treatment at the age of 2 days. It slowly increased to 500 $\mu\varepsilon$ after 420 days. Typically a long-term shrinkage strain of 500 $\mu\varepsilon$ is used for prestress loss calculations. Majority of the shrinkage takes place during the heat treatment and at the end of the heat treatment a stable material (in terms of shrinkage) is obtained. Heat treatment accelerates the chemical reaction and most of the shrinkage is taking place during this curing period. If UHPC is not heat cured and exposed to field conditions, a total shrinkage of about the same magnitude (500 $\mu\varepsilon$) can be expected after a long period. This indicates that the shrinkage mechanism of UHPC with such low w/b ratio is mainly autogenous.

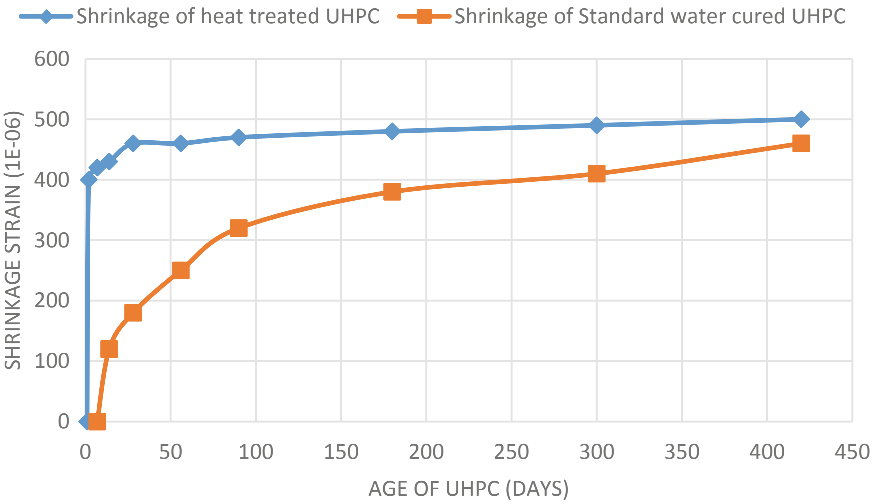

Fig. 5 Total shrinkage of ultra high performance concrete cured under different conditions

3 Conclusions

Autogenous shrinkage commences immediately after casting. Up to the time of final-set, the chemical shrinkage and autogenous shrinkage will be equal. After the final-set, there will be considerable difference between these values. Autogenous shrinkage can be measured whereas the chemical shrinkage requires the measurement of volume change of hydration products.

Autogenous shrinkage has two components: pre-set and post-set. Pre-set component is part of the plastic shrinkage and it is difficult to separate this from total plastic shrinkage. Ideally, measurement of autogenous shrinkage should commence from the onset of final-set.

Measurement of autogenous shrinkage poses significant problems due to the transition nature of concrete from fluid state to a solid state. Special experimental setup is required to commence measurements from final-set. Even measurements of initial and final set need to be re-evaluated.

The autogenous shrinkage component of normal strength concrete (25–50 MPa) is usually very small (less than 100 $\mu\varepsilon$) and most of the long-term shrinkage consists of drying shrinkage. For HPC of high strength grades (60–100 MPa), the autogenous shrinkage component is a substantial proportion of the total long-term shrinkage. For UHPC of up to 200 MPa, the total shrinkage essentially consists of autogenous shrinkage.

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