

Influence of autogenous shrinkage on mass transport properties of concrete

Alexis Santiago Velez Guayasamin

Faculty of Engineering, Department of Civil and Environmental Engineering, South Kensington Campus, Imperial College London.

Autor para correspondencia: alexis.velez14@imperial.ac.uk

Fecha de recepción: 19 de diciembre 2015 - Fecha de aceptación: 23 de febrero 2016

ABSTRACT

Autogenous shrinkage in concrete is defined as the change of volume after initial setting occurs. It develops at very early ages as a result of chemical shrinkage and self-desiccation effect. These produce significant microcracks in high-strength concrete allowing the entrance of aggressive agents such as carbon dioxide, chlorides, and sulphates which cause concrete deterioration. Although considerable research of autogenous shrinkage has been done, uncertainty remains concerning the influence in concrete durability. Therefore, the purpose of this study was to quantify and analyse the effect of autogenous shrinkage on the mass transport properties of concrete using three transport tests: oxygen diffusion, oxygen permeation, and water absorption. Two methods, for three different binders, were first carried out to determine a control mixture that produces the least autogenous shrinkage: adding SRA and curing in a fog room. Subsequently, transport test results between the selected control mixture and mixtures highly affected by autogenous shrinkage were compared for different binders. Results revealed that specimens with SRA presented the least autogenous shrinkage; therefore, it is suggested to be considered as control samples. It was also found that autogenous shrinkage significantly affects the transport coefficients in concrete made with secondary cementitious materials which from a serviceability point of view could reduce the life span for any structure made with high-strength concrete. This investigation also confirmed that most of the autogenous deformation occurs during the first two weeks after casting therefore enough care should be taken when curing.

Keywords: Concrete, autogenous shrinkage, transport properties.

RESUMEN

La retracción autógena en el hormigón es el cambio volumétrico una vez iniciado su proceso de fraguado. Se desarrolla a edades muy tempranas debido a la retracción química y a la autodesecación. Éstos causan microfisuras en hormigones de alta resistencia y permiten el ingreso de agentes nocivos como dióxido de carbono, cloruros y sulfatos que deterioran al hormigón. A pesar de haber estudios de la retracción autógena, existe incertidumbre sobre su influencia en la durabilidad del hormigón. Por ello, el motivo del presente estudio es cuantificar y analizar el efecto de la retracción autógena en el hormigón usando tres pruebas de transporte: difusión de oxígeno, permeabilidad de oxígeno y absorción de agua. Dos métodos, para tres diferentes aglutinantes, fueron usados para determinar la mezcla control que produce menor retracción: utilizando SRA y realizando el curado en un cuarto de niebla. Posteriormente, los resultados de las pruebas de transporte entre la mezcla de control seleccionada y mezclas altamente afectadas por retracción autógena fueron comparados para diferentes aglutinantes. Resultados revelaron que muestras con SRA presentan menores retracciones autógenas y se sugiere que estas muestras sean consideradas de control. Se demostró que la retracción autógena afecta significativamente los coeficientes de transporte los cuales en un punto de vista de servicio pueden reducir la vida útil de cualquier estructura realizada con hormigón de alta resistencia. Esta investigación además confirmó que la mayor deformación autógena ocurre durante las dos primeras semanas; por lo tanto, se debe tomar cuidado suficiente en el curado.

Palabras clave: Hormigón, retracción autógena, propiedades de transporte.

1. INTRODUCTION

The desire of the world to build sustainable and remarkable mega structures has permitted the change of new technologies and methods to achieve what previously was impossible. These changes are clearly seen in all kind of materials, especially in the most widely used construction material, concrete, which in modern times is not just a mixture of water, cement and aggregates but a composite material that contains minerals, fibres and chemical admixtures. The modifications in the microstructure of concrete yields high strength and/or high performance concrete which are characterised by the particle size and porosity. The applications of high strength concrete have grown over the last years due to the demand of special structures such as high rise buildings, bridge decks, airport pavements, shear walls and foundations (Zhutovsky & Kovler, 2012).

Recent researches have demonstrated that these modern concrete structures are more vulnerable to develop microcracks at an early-age in comparison with ordinary concrete as a result of shrinkage, swelling, creep, thermal and others effects (Bentz & Peltz, 2008). Among them, shrinkage is the most common cause of microcracks since at any circumstance products of hydration occupy less volume than the initial products, due to the loss of water (Holt & Leivo, 2004). Depending on the nature and age, shrinkage can be classified into many types such as drying, thermal, autogenous and carbonation shrinkage. Among this classification, Tazawa (1999) states that autogenous shrinkage is probably the major cause of deterioration in structures when high strength concrete is used.

Autogenous shrinkage was first mentioned by Lyman (1934) to describe the process that concrete shrinks by itself without the influence of any external loads, restrains and change in moisture and temperature. Davis (1940) used a similar expression to describe the change in volume of concrete under sealed condition, i.e., no moisture movement into or out of concrete. Tazawa (1999) stated that this phenomena starts at very early ages as a result of chemical shrinkage (volume reduction because of the hydration process) and self-desiccation (loss of capillary pore water by cement hydration). However, in modern times Concrete Institutes around the world define autogenous shrinkage as a macroscopic volume change caused by the hydration process of cement after initial setting occurs.

According to Davis (1940), autogenous shrinkage in ordinary concrete at 28 days is about $40 \mu\epsilon^1$, much smaller than drying shrinkage that ranges from 400 to 800 $\mu\epsilon$. The same occurred after 5 years of hardening in which autogenous deformation ranges between 50 and 100 $\mu\epsilon$. However, Mak & Torii (1995) reported that autogenous shrinkage can be as high as 200 to 400 $\mu\epsilon$ for an ordinary concrete with a water cement ratio (w/c) lower than 0.30. Zhang *et al.* (2003) studied the effect of autogenous shrinkage in concrete specimens prepared with silica fume. They adopted w/c in the range of 0.26 to 0.35 with silica fume content up to 10% by weight of cement. The results of this last experiment showed that autogenous shrinkage in concrete prepared with w/c of 0.26 was more than 100 $\mu\epsilon$ in 2 days. On the other hand, Chan *et al.* (1998) quantified the effect of GGBS² for high performance concrete. He determined that autogenous shrinkage at day 7 vary between 106 and 170 $\mu\epsilon$ in a mixture with water to cementitious material of 0.32 adopting different content of puzzolan³ to replace cement. Among all of these deformations described above the low water to cement ratio (less than or equal to 0.30) and the addition of secondary cementitious materials were responsible of this change of volume (Tazawa, 1999).

Autogenous shrinkage can be reduced by adopting many methods in concrete. Some of them consist to modify the physical geometry of the cement paste microstructure such as the use of coarser cement, increasing w/c, the use of low or moderate heat cement and the replacement of a fraction of cement by a coarse limestone powder (Bentz & Peltz, 2008). Another method is the use of SRA⁴, which reduces the force that pulls the pores together by decreasing the surface tension of water in the capillary pores of concrete. Alternatively, internal curing is a method that counteracts self-desiccation in concrete

¹ $\mu\epsilon$: linear attenuation coefficient expressed as length to length with unit 10^{-6} also called microstrains.

² GGBS: Ground Granulated Blast-furnace Slag, a by-product of iron production.

³ Puzzolan: a porous variety of volcanic tuff or ash used in making hydraulic cement.

⁴ SRA: Shrinkage Reducing Admixtures.

by using pre-wetted lightweight aggregates or super absorbent polymer (Zhutovsky & Kovler, 2011). The mentioned methods contribute to the strength and durability of concrete.

Durability and mechanism of transport in concrete

A durable material not only helps the environment by conserving resources and reducing wastes but is also associated with economic aspects in terms of reparation and replacement. Different mechanisms of transport affect the durability of concrete, according to Buenfeld (1997) as cited by Wong (2006), the major transport mechanisms of deterioration are water permeability, gas permeability, water vapour diffusion, ionic diffusion, gas diffusion, water absorption and electrical conductivity. Permeation is defined as the ability of liquid or gas to flow through the pores of concrete when pressure is applied. Diffusion is a process in which ions in the pore water of the concrete will dissolve throughout the liquid pursuing a uniform concentration. Absorption in concrete is the process in which a fluid goes into the concrete by capillary action. Although many transport tests in concrete have been carried out to analyse different factors that affect the transport properties, no studies have been found on the influence of autogenous shrinkage. Therefore, the present work aims to analyse and quantify the effect of autogenous shrinkage in concrete specimens that were cast using different binders, admixtures and methods of curing.

2. MATERIALS

2.1. Sample preparation

Two types of samples were prepared for shrinkage measurement and transport tests respectively. The first sample type was a cylindrical concrete specimen of 78 mm in diameter (\varnothing) and 300 mm in length constructed using postal tubes, plastic end caps, and superficial steel studs (\varnothing 5 mm x length 16.5 mm). The second sample type was cylindrical concrete specimen with \varnothing 100 mm and length 50 mm that were elaborated using steel moulds.

2.2. Cementitious materials

An ordinary Portland cement and two secondary cementitious materials were used respectively: CEM I 32.5R⁵, CEM III B 42.5N⁶ and SF⁷. The estimated Bogue⁸ composition of CEM I 32.5R was 52.7% C₃S, 19.3% C₂S, 10.6% C₃A, 7.4% C₄AF by mass. On the other hand, the oxide composition of all cementitious materials is presented in Table 1.

Table 1. Oxide composition of cementitious materials.

Cementitious material	Oxide Compositions (%)											
	CaO	SiO ₂	Al ₂ O ₃	SO ₃	Fe ₂ O ₃	MgO	Na ₂ O	K ₂ O	Cl	TiO ₂	P ₂ O ₅	Mn ₂ O ₃
CEM I	63.4	20.6	5.6	2.9	2.4	1.6	0.2	0.7	<0.1	-	-	-
CEM III	48	29.2	8.9	2.6	1.2	4.8	0.2	0.6	<0.1	-	-	-
SF	0.15	98.7	0.31	-	0.02	0.04	0.09	0.3	-	0.39	0.02	0.01

Note: (-) No data.

⁵ CEM I 32.5R: Portland cement which contains between 95-100% of clinker. It has a standard strength class of 32.5 MPa and it produces rapid early strength.

⁶ CEM III B 42.5N: Blast furnace cement which contains 69.9% of GGBS. It has a standard strength class of 42.5 MPa and it produces normal early strength.

⁷ SF: Silica Fume, a by-product of silicon metal or ferrosilicon alloys.

⁸ Bogue: A simple estimate of the phase composition of a Portland cement assuming that the four main cement minerals occur in their pure form.

2.3. Aggregates

Two types of aggregates were used in the present study: Thames valley sand as a fine aggregate, and uncracked gravel as coarse aggregate. The properties of both aggregates are listed in Table 2 and the particle size distributions are depicted in Fig. 1.

Table 2. Properties of aggregates.

Aggregates	Maximum size (mm)	24/h absorption	Moisture content (%)	Specific gravity
Fine sand	5	0.75 - 0.85	2 - 2.5	2.65
Coarse gravel	10	0.61	2.9	2.6

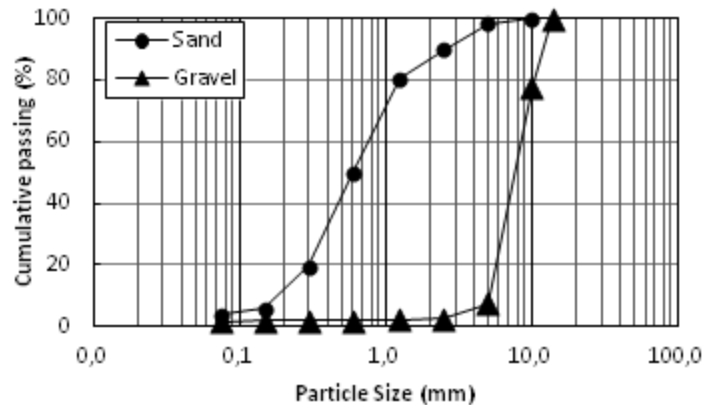


Figure 1: Particle size distribution of fine and coarse aggregates

2.4. Admixtures

Two different admixtures were used in the present work: a superplasticizer and SRA. These admixtures and their main properties are shown in Table 3.

Table 3. Admixtures properties.

Technical data	Sika Viscocrete 20 RM	Sika control 40
Chemical base	Polycarboxylate	Polypropyleneglycol
Density (at +20°C)	1.00 kg/litre	1.01 kg/litre
pH	4±0.5	11.5±1.0
Water soluble chloride content	<0.10% (chloride free)	<0.10% (chloride free)
Alkali content	<0.35%	0.1% max
Solid content *	38%	24%
Water content *	62%	76%

* Information provided by Sika admixture suppliers.

2.5. Design of concrete

The design of concrete was based on a relative method. A w/cm⁹ ratio of 0.30 was considered in all the design of mixtures. An aggregate volume of 68% was used in the mix, setting the content of coarse and fine aggregates to be 60% and 40% of the mass of aggregates. On the other hand, the dosage for both admixtures was taken at 1% the cement content. A summary of materials and proportions are presented in Table 4. The mixing method was followed according to the BS 1881-125:2013.

⁹ w/cm: water to cementitious material ratio, dimensionless.

Table 4. Mix proportions (expressed in kg/m³).

Mix ID	Cementitious material	Water	Super-plasticizer	SRA	Sand	Gravel
C-CEM I + SRA	494.8	148.4	4.9	4.9	712.6	1068.9
C-CEM I f	502.5	150.8	5.0	-	712.6	1068.9
SF-CEM I + SF + SRA	487.5	146.2	4.9	4.9	712.6	1068.9
SF-CEM I + SF f	495.0	148.5	4.9	-	712.6	1068.9
S-CEM III + SRA	481.4	144.6	4.8	4.8	712.6	1068.9
S-CEM III f	488.7	146.8	4.9	-	712.6	1068.9

Note: (-) No added in the mixture.

3. METHODS

3.1. Length test

A linear contact method using a length comparator with a 1/1000 mm dial gauge was used to measure the longitudinal changes of hardened concrete specimens. A total of 18 samples for 6 different mixtures, were daily measured for a period of 14 days. After this, results from the test were compared to a previous work conducted by Mac (2015). Her specimens were prepared with the same dosage and material as those of the present study but sealed at room temperature and without the inclusion of SRA. Mac samples were named “cracked samples” because of the numerous cracks presented in their microstructure. Samples were always positioned up to avoid possible errors in each reading. More details about the equipment used can be found in ASTM C490.

3.2. Transport tests

Three different mechanisms of transport were considered in this study: oxygen diffusion, oxygen permeation and water absorption.

Oxygen diffusivity

Concrete specimens were exposed to oxygen (O₂) and nitrogen (N₂) streams at each of the two opposite flat faces until steady-state flow condition occurred. Once oxygen and nitrogen diffused through the concrete sample, the concentration of oxygen in the nitrogen stream is measured with a Zirconia Oxygen Analyser. This concentration was used to calculate the oxygen diffusivity coefficient.

Oxygen permeation

Constant gas pressures of 0.5, 1.5 and 2.5 bar above atmospheric pressure were applied to concrete specimens. Five readings were taken at each pressure in a steady-state condition to compute the average flow per pressure. Steady-state condition is reached when the pressure gauge shows minimal fluctuation in applied pressure and when consecutive outflow rate indicated minimal differences. Darcy’s principle was applied in order to determine the permeability coefficient (k_g). However, knowing that permeability changes when pressure changes, the coefficient was corrected by using the Klinkenberg method (1941) that calculates the intrinsic permeability (k_{int}).

Water absorption

The water absorption test consisted of weighting the mass gain of concrete samples when they were submerged in water in a level from 2 to 3 mm. The coefficient of sorptivity was derived using the slope of the best-fit line drawn from the mass of absorbed water per unit area of the inflow face against the square root of time. A period of 2.5 hours of control was taken per each specimen after which, there was an insignificant increase in absorption. Additional specimens were immersed in water in order to estimate the porosity of each specimen. A period of 72 hours was estimated to be the time when

specimens reach saturation. More details about the transport measurements methods is described by Wong *et al.* (2007).

4. RESULTS

4.1. Autogenous shrinkage measurement

The shrinkage measurements of the different types of samples and results from the previous study done by Mac (2014) are presented in Fig. 2.

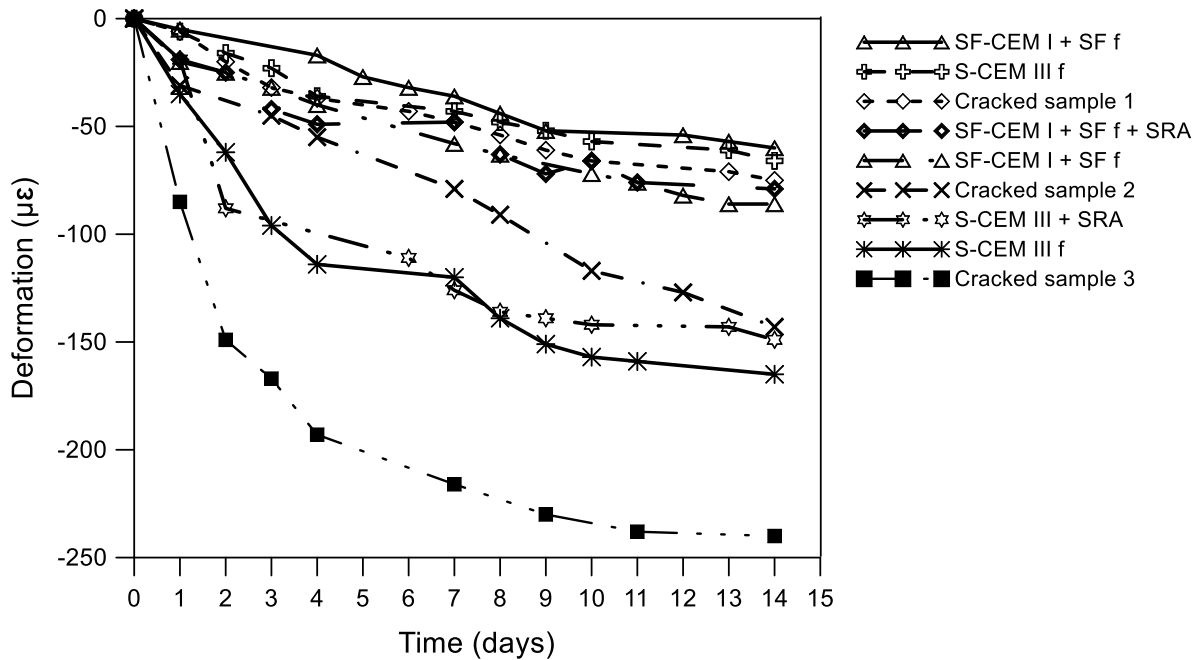


Figure 2. Autogenous shrinkage results ($n=3$)¹⁰. The y-axis represents deformation in microstrains ($\mu\epsilon$) and x-axis denotes the time in days. Samples labelled as ‘cracked sample 1, 2 and 3’ are from Mac (2015) and are represented with dash lines. Samples cured in the fog room are represented with dot lines, and specimens prepared with SRA are represented with continues lines.

In general, autogenous deformation increased with time, being the course of the first 4 days where most autogenous shrinkage occurred, afterwards, slight increments were observed until the 14th day. After day 14, almost all mixtures exhibited little variation of deformation due to autogenous shrinkage.

Samples S-CEM III presented higher autogenous shrinkage in comparison with specimens SF-CEM I + SF and C-CEM I. At 14 days, for instance, samples CEM III had around 2.5 times more shrinkage than concrete specimens CEM I. For the same period, samples CEM III had about 1.85 times more shrinkage than CEM I + SF. At that time, samples prepared with SRA induced less autogenous shrinkage in comparison to specimens cured in the fog room. A brief explanation per each binder is presented below.

It can be noticed that group C-CEM I + SRA had a deformation of 17, 36 and 60 $\mu\epsilon$ at 4, 7 and 14 days, respectively. The rate of deformation was uniform between each day. During the period of measurements specimens prepared with SRA presented less autogenous shrinkage than specimens cured in the fog room. A reduction of 37.5% of shrinkage was obtained on the first two days between control and cracked samples. Alternatively, a deformation of 49, 58 and 79 $\mu\epsilon$ at 4, 7 and 14 days respectively was presented in samples SF-CEM I + SF + SRA. No considerable deformation was seen

¹⁰ $n=3$: Each point of the graph was obtained from the average of three different measures using three different specimens.

in this mixture, except for the first four days. Almost the same pattern in shrinkage was seen in the specimens prepared with the same binder but cured in the fog room. On the other hand, samples S-CEM III + SRA had a deformation of about 94, 126, 149 $\mu\epsilon$ at 4, 7 and 14 days respectively. Shrinkage reduction of 62% at day one and 9% at day 14 was observed in the samples between specimens with and without SRA.

Comparing the results above with the work done by Mac (2015), it was found that group prepared with binder CEM III is more affected by autogenous shrinkage with an increment of 38.07% between control and cracked samples. Then again, an increment of 44.50% for binder CEM I + Silica fume was noticed between control and cracked samples. Finally, a variation of 19.53% between control and cracked samples was obtained in the mixture prepared with CEM I.

4.2. Transport tests

Different transport mechanisms were tested: oxygen diffusion, oxygen permeation and water absorption. After these tests, porosity in concrete specimens was also calculated. Results are presented in Table 5 for cracked (n=3) and control (n=3) samples of C-CEM I, SF-CEM I + SF and S-CEM III.

Table 5. Results of the transport tests conducted on a number of cracked and control samples, and the total porosity.

Parameter	C-CEM I		SF-CEM I + SF		S-CEM III	
	Cracked sample	Control sample	Cracked sample	Control sample	Cracked sample	Control sample
<i>Oxygen diffusion</i>						
Diffusivity coefficient (m ² /s)	3.81*10 ⁻⁹	2.92*10 ⁻⁹	2.90*10 ⁻⁹	2.15*10 ⁻⁹	3.05*10 ⁻⁹	1.98*10 ⁻⁹
Standard error	9.87*10 ⁻¹¹	2.03*10 ⁻¹⁰	4.94*10 ⁻¹¹	3.40*10 ⁻¹²	1.22*10 ⁻¹⁰	5.91*10 ⁻¹¹
Percent change		23.47		25.73		35.10
<i>Oxygen permeation</i>						
Permeability coefficient (m ²)	7.36*10 ⁻¹⁸	5.00*10 ⁻¹⁸	4.12*10 ⁻¹⁸	2.58*10 ⁻¹⁸	4.44*10 ⁻¹⁸	2.08*10 ⁻¹⁸
Standard error	3.10*10 ⁻¹⁹	7.81*10 ⁻¹⁹	6.67*10 ⁻¹⁹	4.20*10 ⁻¹⁹	5.96*10 ⁻¹⁹	2.93*10 ⁻¹⁹
Percent change		32.07		37.55		53.12
<i>Water absorption</i>						
Sorptivity coeff. (g/m ² .min ^{0.5})	37.23	29.20	30.37	22.90	32.10	23.23
Standard error	1.08	0.26	0.97	0.61	0.82	0.47
Percent change		21.58		24.59		27.62
<i>Porosity</i>						
Porosity (%)	2.05	1.83	1.55	1.32	1.84	1.53
Standard error	8.97*10 ⁻²	7.83*10 ⁻²	5.04*10 ⁻²	6.52*10 ⁻²	1.32*10 ⁻¹	1.57*10 ⁻¹
Percent change		10.73		14.84		16.85

Samples C-CEM I showed the largest diffusion coefficients in comparison with the two other binders as is shown in Table 5. The C-CEM I cracked samples had a diffusion coefficient 1.30 times larger than the control samples. Almost the same occurred with the second group, SF-CEM I + SF, where cracked samples had a coefficient about 1.34 more than the control samples. However, the largest change occurred in mixtures S-CEM III where the diffusion coefficient in cracked sample was 1.54 larger in comparison against the control sample.

Oxygen permeability coefficient was larger in group C-CEM I. Similar data were obtained in cracked samples, where the values exceeded those of the control samples. On the other hand, major changes between cracked and control samples were seen in binder prepared with slag, followed by specimens C-CEM I, and SF-CEM I + SF. The experiment showed that autogenous shrinkage at 14 days increased the permeability coefficient in 32.07%, 37.55% and 53.12% for mixtures C-CEM I, SF-CEM I + SF and S-CEM III.

The type of binder used greatly influenced the water sorptivity results as illustrated in Table 5. Mixtures prepared with silica fume showed the lowest transport coefficients. The same tendencies were obtained for control and cracked samples. Sorptivity coefficients in cracked samples were 1.47, 1.40

and 1.15 times higher than in the control samples for binders 1, 2 and 3, correspondingly. It was found that among all the results obtained, the largest effect was seen in the binder prepared with only CEM I.

According to the outcomes shown in Table 5, cracked samples CEM I exhibited the largest porosity between all the mixtures tested, followed by S-CEM III and then SF-CEM I + SF. As expected, control samples showed the same trend, but with a different rate of change compared to the cracked samples. The test showed that autogenous shrinkage may increase the porosity up to 10.73%, 14.84% and 16.85% for mixtures C-CEM I, SF-CEM I + SF and S-CEM III, respectively.

5. DISCUSSION

5.1. Autogenous shrinkage measurement

The results obtained in the experiment were compared with previous studies done by Mac (2015), in order to quantify the effect of autogenous shrinkage for each binder. It was confirmed that concrete mixtures prepared with secondary cementitious materials are more vulnerable to develop autogenous shrinkage because of the rapid absorption of water in the hydration process of secondary cementitious material at early ages, which apart from creating finer pore structures, can produce higher chemical shrinkage and the removal of calcium hydroxide as a shrinkage restraint.

For normal concrete CEM I, Tazawa & Miyazawa (1992) reported that a mixture with w/c ratio of 0.17 can produce a total shrinkage of almost 700 $\mu\epsilon$. Mak & Torii (1995) reported that autogenous shrinkage could be as high as 200 to 400 $\mu\epsilon$ in normal mixtures prepared with a w/c ratio lower than 0.30. Therefore, the results of the present study showed that the data were consistent with both reported studies. On the other hand, Zhang *et al.* (2003), reported that autogenous shrinkage strains in concrete prepared with silica fume were higher than 100 $\mu\epsilon$ after 2 days and that more than 60% of autogenous shrinkage strain occurred in the first two weeks when measured over a period of 98 days. The present data matches with the work of Zhang *et al.* (2013), in which they state that the major changes occurred during the first 14 days. However, results over the first two days were different. The reason for this change is because the study of Zhang *et al.* (2013) was carried out with w/c ratio of 0.26 which significantly increases autogenous shrinkage. The range found in the present study for the first two days was between 25 to 30 $\mu\epsilon$, which is acceptable for a higher ratio of w/c compared with studies. Additionally, Chan *et al.* (1999) reported a deformation range due to autogenous shrinkage between 106 and 170 $\mu\epsilon$ at day 7, coinciding with the currently obtained deformation of 126 $\mu\epsilon$ after the same period.

5.2. Transport tests

Oxygen diffusion

For the oxygen diffusion test, it is known that porosity, interconnectivity of pores in the cement paste and the Interfacial Transition Zone (ITZ) between aggregates and cement are key features that determine concrete performance, based on the work of Leemann *et al.* (2006). These in turn depend upon: the w/c or w/cm ratio, the degree of hydration, the degree of compaction, and the quantity of aggregates. Overall, the coefficient of diffusion for all tested mixtures was relatively small compared to the results presented in other studies. For example, Wong *et al.* (2011) reported a diffusion coefficient of 2.78 E-8 m²/s at day 7 for concrete specimens prepared with a water to cement ratio of 0.35 without either an air entrained agent or air content. Lower values were confirmed in the present study because of the w/cm ratio of 0.30 used in this work. The test results of Wong *et al.* (2007) were also compared to the present work. In their study oxygen diffusion coefficients were between 1 E-7 to 1 E-9 m²/s for different degrees of water saturation.

A more significant change was seen with mixture prepared with GGBS. This is important considering that this mixture had more autogenous shrinkage, therefore, more microcracks, and as a consequence larger transport coefficient. It can also be noticed that the use of SRA helped reduce transport coefficient in concrete, therefore, giving more durability to concrete structures.

Oxygen permeation

Permeability results showed low coefficients as a result of mixtures prepared with lower w/cm ratio that lead to denser microstructure in concrete. Density of microstructure depends on pore sizes, their distribution and most importantly their continuity. For permeability tests, Darcy law was adjusted since the rate of flow changed as the pressure changed. This is due to the gas slippage effect, which is seen when gas molecules travel through fine capillaries. They collide more often with the wall of the pore instead of other gas molecules. Therefore, this effect was neutralised by integrating Darcy's formula to its differential form, assuming that changes in pressure and temperature were negligible when the test was carried out in the concrete sample.

In terms of durability, low permeability in concrete prevents the ingress of external water in the cement paste and even in aggregates, which can cause several types of damage such as those caused during freezing and thawing. It is also important to state that water permeation was not taken into consideration in the present study because practical experience indicates that self-healing in concrete changes the permeability coefficient (Wong, 2015).

Water absorption and porosity

Water absorption is the most famous mechanism that controls the flow of liquid into concrete. It measures the flow of water that penetrates in saturated or unsaturated concrete due to capillary action exerted by the pores. Hence, absorption is governed by porosity and pore distribution of the microstructure of concrete. Wong *et al.* (2011) reported a sorptivity coefficient of $62 \text{ g/m}^2 \cdot \text{min}^{0.5}$ at day 7 for concrete conditioned at 52% RH elaborated with water to cementitious material equal to 0.35. The values obtained in this experiment, $37.2 \text{ g/m}^2 \cdot \text{min}^{0.5}$ for the maximum value of C-CEM I, are lower which confirms the high density and the limited presence of pores in concrete.

It can be shown that the performance of all mixtures was further improved through the use of admixtures. This confirms the fact that SRA changed the microstructure of the concrete by reducing the number and width of cracks as Shah *et al.* (1998) state in their work. The speed and height of water penetration in the samples is influenced by the cracking direction and its connectivity. In this work, the height of water due to capillary absorption was higher in specimens prepared with CEM I in comparison to the other two binders.

6. CONCLUSIONS

The experimental results showed that between the two methods proposed to reduce shrinkage, sealed specimens prepared with SRA had lower autogenous shrinkage compared to those without SRA but cured in the fog room. Therefore, the use of SRA according to this research, is the best method to reduce autogenous shrinkage and to produce control samples. It was also confirmed that among all binders used, mixtures prepared with silica fume were more vulnerable to suffer autogenous shrinkage followed by the mixes prepared with slag and ordinary cement respectively. On the other hand, transport test results revealed that mixtures prepared with secondary cementitious materials, especially GGBS, significantly change their transport coefficients due to autogenous shrinkage. These effect could be critical in terms of durability and economic importance as it would reduce the life span and increase the cost of maintenance of any concrete structure.

REFERENCES

Bentz, D.P., M.A. Peltz, 2008. Reducing thermal and autogenous shrinkage contributions to early-age cracking. *ACI Materials Journal*, 105(48), 414-420.

- Chan, Y.W., C.Y. Liu, Y.S. Lu, 1998. *Effect of slag and fly ash on the autogenous shrinkage of high performance concrete*. In: Tazawa, E. (Ed.), Proc. International Workshop on Autogenous Shrinkage of Concrete, JCI, Hiroshima, Japan, pp. 221-228.
- Davis, H.E., 1940. *Autogenous volume change of concrete*. Proc. 43rd Annual American Society for Testing Materials, 1103-1113. Atlantic City: American Society for Testing and Materials.
- Holt, E., M. Leivo, 2004. Cracking risks associated with early age shrinkage. *Cement and Concrete Composites*, 26(5), 521-530.
- Klinkenberg, L.J., 1941. The permeability of porous media to liquids and gases. *API Drilling and Production Practice*, 200-213.
- Leemann, A., B. Münch, P. Gasser, L. Holzer, 2006. Influence of compaction on the interfacial transition zone and the permeability of concrete. *Cement and Concrete Research*, 36(8), 1425-1433.
- Lynam, C.G., 1934. *Growth and movement in Portland Cement Concrete*. London: Oxford University Press, pp. 25-45.
- Mac, M., 2015. PhD student at Imperial College London (*personal communication*).
- Mak, S.L., K. Torii, 1995. Strength development of high strength concretes with and without silica fume under the influence of high hydration temperatures. *Cement and Concrete Research*, 25(8), 1791-1802.
- Shah, S.P., W.J. Weiss, W. Yang, 1998. Shrinkage cracking: Can it be prevented. *Concrete International*, 20(4), 51-55.
- Tazawa, E. (Ed.), 1999. *Autogenous shrinkage of concrete*. London: E & FN Spon.
- Tazawa, E., S. Miyazawa, 1992. *Autogenous shrinkage caused by self-desiccation in cementitious material*. Proc. 9th International Congress on the Chemistry of Cement, Vol IV, pp. 712-718.
- Wong, H., 2006. *Quantifying the pore structure of cement-based materials using backscattered electron microscopy*. Imperial College London, London.
- Wong, H., 2015. Thesis supervisor (*personal communications*).
- Wong, H., N. Buenfeld, J. Hill, A. Harris, 2007. Mass transport properties of mature wastefrom grouts. *Advances in Cement Research*, 19(1), 35-46.
- Wong, H.S., A.M. Pappas, R.W. Zimmerman, N.R. Buenfeld, 2011. Effect of entrained air voids on the microstructure and mass transport properties of concrete. *Cement and Concrete Research*, 41(10), 1067-1077.
- Wong, H., 2015. *Concrete materials* (lecture) and *personal communications*. Thesis supervisor, Faculty of Engineering, Department of Civil and Environmental Engineering, Imperial College London, London.
- Zhang, M.H., C.T. Tam, M.P. Leow, 2003. Effect of water-to-cementitious materials ratio and silica fume on the autogenous shrinkage of concrete. *Cement and Concrete Research*, 33(10), 1687-1694.
- Zhutovsky, S., K. Kovler, 2012. Effect of internal curing on durability-related properties of high performance concrete. *Cement and Concrete Research*, 42(1), 20-26.