



PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
SCHOOL OF ENGINEERING

CHARACTERIZING LIGHTWEIGHT AGGREGATES FOR IMPROVING INTERNAL CURING OF CONCRETE

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Thesis submitted to the Office of Research and Graduate Studies
in partial fulfillment of the requirements for the degree of
Master of Science in Engineering

Advisor:

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Santiago de Chile, April, 2010

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*To my family, for their continuous
support and company.*

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ABSTRACT

Manufacturing high performance/strength concrete requires use of low water-cement ratio and addition of supplementary cementitious materials (pozzolans, fly ash, silica fume). The maximum hydration of cement is difficult to obtain due to the higher water requirements and the lower permeability that makes external curing inefficient. Additionally, higher autogenous shrinkage is usually observed. Both, limited hydration and higher shrinkage, can impact the development of mechanical properties and durability of concrete. Thus, a method to provide curing water from the interior of concrete (known as internal curing) has been studied in recent years. Internal curing of concrete can be provided by pre-wetted lightweight aggregates (LWAs) as partial replacement of the normalweight aggregate. The so called internal curing agents retain a high amount of water, which they release once the self-desiccation of concrete starts. Nevertheless, some issues remain unresolved.

This research makes a comparative analysis between natural and artificial LWAs and focuses on their efficiency as internal curing agents. Characterization of the moisture properties and the pore microstructure of LWAs are made in order to explain their performance as internal curing agents. In consideration of the results, two alternatives are analyzed to improve the performance of artificial LWA in internal curing: the use of shrinkage-reducing admixture (SRA) in the internal curing water, and the reduction of the particle size distribution of the aggregate.

The results show higher degree of hydration and reduction of the autogenous shrinkage when internal curing is used. Also, adverse impacts are observed in compressive strength and chloride ion permeability tests when high amount of LWA is used.

Natural LWAs present higher capillary porosity, pore interconnectivity and more accessible porosity than artificial LWAs. In addition, natural LWAs show more efficiency than artificial LWAs, i.e., using a lower replacement of LWAs, similar or better performance as internal curing agent is observed with natural LWAs.

When SRA solution (15% by mass) is used for pre-wetting of LWA, slower rates of water uptake and release, lower diffusion coefficients and higher autogenous shrinkage are observed as compared to pure water. Additionally, when the particle size distribution is reduced, faster rates of water uptake and release, higher diffusion coefficients, and lower autogenous shrinkage are observed.

An extensive analysis is recommended to be performed on water release test. In addition, other properties of concrete, such as the determinations of the Young modulus toughness or total shrinkage, should be tested.

Keywords: lightweight aggregates, pumice, expanded clay, expanded slate, cement hydration, autogenous shrinkage, shrinkage-reducing admixture, water uptake, water release, water diffusion.

RESUMEN

Los hormigones de alto desempeño/resistencia requieren para su fabricación el uso de baja razón agua-cemento y la adición de materiales cementicios suplementarios (puzolanas, ceniza volante, silica fume). La hidratación máxima del cemento es difícil de obtener debido a los mayores requerimientos de agua y a la menor permeabilidad que hace ineficiente el curado externo tradicional. Adicionalmente, es común observar mayor retracción autógena. Estos dos factores pueden impactar el desarrollo de las propiedades mecánicas y la durabilidad del hormigón. Por esta razón, en los últimos años se ha desarrollado un método, conocido como curado interno, para proveer un curado desde el interior del hormigón. El curado interno del hormigón puede ser provisto por agregados livianos, previamente humedecidos, como reemplazo de parte del agregado normal. Los llamados agentes de curado interno retienen una alta cantidad de agua, que luego liberan dentro del hormigón, a medida que ocurre el auto-secado. Sin embargo, algunos aspectos relativos al curado interno aún no han sido resueltos.

Esta investigación realiza un análisis comparativo entre agregados livianos naturales y artificiales, enfocándose en su eficiencia como agentes de curado interno. Se realizó una caracterización de las propiedades de absorción y entrega de agua y de la microestructura de poros de los agregados livianos, con el objetivo de explicar su desempeño posterior en el hormigón. A partir de este análisis, se estudiaron dos alternativas para la mejora del desempeño de los agregados livianos artificiales: el uso de un aditivo reductor de retracción en la solución líquida que provee el curado interno y la reducción de la distribución de tamaños del agregado.

Los resultados muestran un mayor grado de hidratación y una reducción de la retracción autógena cuando se utilizó curado interno. Además, se observó efectos adversos sobre la resistencia a la compresión y en la permeabilidad a iones cloruro, cuando altas cantidades de agregado liviano fueron utilizadas.

Los agregados livianos naturales presentan mayor porosidad capilar, interconectividad de poros y una porosidad más accesible que los agregados livianos artificiales. Además,

los agregados livianos naturales muestran una mayor eficiencia que los agregados livianos artificiales, es decir, utilizando un menor reemplazo de agregado normal por agregado liviano se obtienen desempeños similares o superiores sobre el hormigón al ser utilizados como agentes de curado interno

Cuando se utilizó una solución aditivo reductor de retracción (15% en masa) en la pre-saturación de los agregados, se observó menores tasas de captación y entrega de agua, menores coeficientes de difusión y mayor retracción autógena, al compararlo con el uso de agua pura. Adicionalmente, cuando se redujo la distribución del tamaño de agregado, se obtuvo mayores tasas de captación y entrega de agua, mayores coeficientes de difusión y menores valores de retracción autógena.

Se recomienda realizar un análisis detallado del ensayo de desorción. Junto con lo anterior, otras propiedades del hormigón, como la determinación del módulo de Young, la tenacidad o la retracción total deben ser ensayadas.

Palabras Claves: agregados livianos, piedra pómez, arcilla expandida, pizarra expandida, hidratación del cemento, retracción autógena, aditivo reductor de retracción, absorción de agua, entrega de agua, difusión de agua.

1. STRUCTURE OF THESIS

The thesis is divided as follows:

The second chapter presents an introduction about the cement hydration, the need for curing of concrete and different ways to provide proper curing. Also, it is explained how the internal curing of concrete works, the use of saturated LWAs as internal curing agents and the characteristics of the SRA as surface tension modifiers.

The third chapter includes the questions that the investigation addresses, the hypothesis and objectives from this questions and the adopted structure for the presentation of the document.

The fourth chapter presents the two articles submitted to ISI journals, which contain the main analysis and conclusions obtained from the research. The article “Assessing Lightweight Aggregate Efficiency for Maximizing Internal Curing Performance” was submitted to ACI Materials Journal and was co-authored by the student and the advisor; while the article “Modifying Water Uptake and Release Kinetics: An Attempt to Improve Internal Curing” was submitted to Cement and Concrete Research and was co-authored by the student, the advisor and Magdalena Walczak, professor of the Department of Mechanical and Metallurgical Engineering of the Pontificia Universidad Católica de Chile. The format of the articles was adapted for this thesis, in accordance with the required specifications.

The fifth chapter presents the conclusions and recommendations obtained during the research.

2. INTRODUCTION

Concrete is one of the most widely used construction materials but often one faces with concrete in bad conditions or with excessive deterioration (Neville, 2003). In particular, early-age cracking is observed due to restrained deformations occurred at the first stages of concrete as a result of moisture loss, chemical reaction or temperature loss. These cracks are unsightly, reduce load-carrying capacity, and can lead to durability problems (Hossain *et al.*, 2003). Thus, early-age cracking need to be prevented to minimize the impact in the mechanical properties of concrete and to avoid insufficiency of durability during the life cycle of the concrete structure or element. Several strategies are used to mitigate early-age shrinkage, such as curing of concrete or shrinkage-reducing admixtures, among others.

2.1 Hydration of Cement and Curing of Concrete

After the mixing water of concrete, defined as the water in freshly mixed sand-cement grout, mortar or concrete, excluding water previously absorbed by the aggregate (ACI 116R, 2005), reacts with dry cement, several chemicals reactions take place. A fraction of the water combines chemically to form calcium silicate hydrates (C-S-H), another part forms calcium hydroxide (CH) and another part is adsorbed in the surface of the hydration products. The rest is retained in the capillary pores which are originated during hydration (Mindess *et al.*, 2005). Capillary pores are formed due to the lower volume of the hydrated cement paste relative with the volume of the raw materials after the cement hydration (Neville,

2003). It is necessary that the capillary pores remain fully or partially saturated in order to allow that new hydration products can occupy the available space. Once the water in the capillary pores has been consumed or removed, hydration stops which can produce high porosity and reductions in the mechanical properties and durability of the concrete (Neville, 1996). The objective of the curing water is to keep concrete saturated to allow a continuous hydration of cement. When the relative humidity within the capillary pores drops below 80%, the hydration is greatly reduced (Powers, 1947).

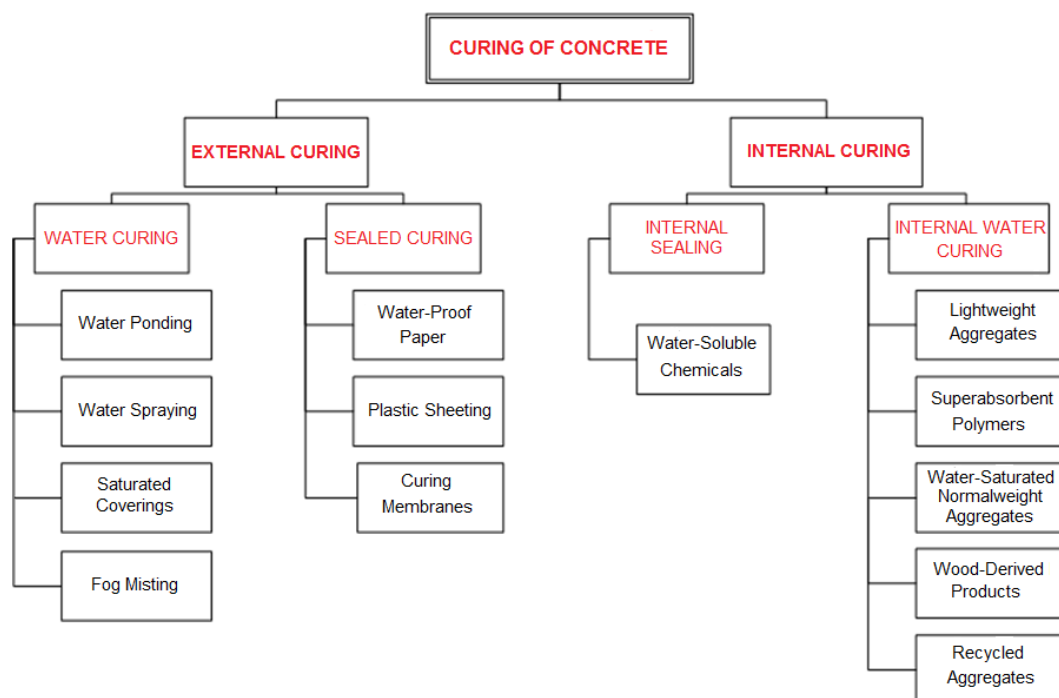


Figure 1: Classification of methods of curing concrete (Kovler and Jensen, 2007)

Curing of concrete is the name given to procedures used for promoting the hydration of cement, and consists of a control of temperature and of the transfer of moisture from and into the concrete (Neville, 1996). Curing of concrete deserves

special attention in the construction practice because inadequate curing frequently leads to the lack of proper strength and durability (Mehta and Monteiro, 2006).

A brief classification of curing methods is shown in Figure 1.

A complete description and recommendations to apply external curing could be seen in ACI308.1 (1998) and ACI 308R (2001).

Since some properties of concrete do not have a standard or unified definition, the following definitions are used along this document (Jensen and Hansen, 2001):

Chemical shrinkage: Reduction of internal volume associated with the hydration reactions in a cementitious material.

Autogenous shrinkage: The bulk deformation of a closed, isothermal, cementitious material system not subjected to external forces.

Autogenous relative humidity change: The change of internal relative humidity (RH) in a closed, isothermal, cementitious material system not subjected to external forces.

Self-desiccation: Change of autogenous relative humidity of a set cementitious material system caused by chemical shrinkage.

Chemical shrinkage is an effect caused by the lower volume occupied by the hydration products as compared to volume of the reacting materials (total volume of raw materials). Before set, this volumetric reduction can be completely converted into a bulk deformation of the system. After set, chemical shrinkage creates inner, empty cavities if the cement paste is kept sealed. Due to the formation of menisci, chemical shrinkage leads to an RH-decrease and a shrinkage

of the cement paste, i.e., self-desiccation and self-desiccation shrinkage, respectively (Jensen and Hansen, 2001).

Kelvin equation (equation 2.1) can be used to explain this phenomenon. It expresses the vapor pressure (relative humidity) above a meniscus in a cylindrical pore of radius r as follows (Alberty and Daniels, 1980):

$$\ln(RH) = \frac{-2\gamma V_m}{rRT} \quad (2.1)$$

where RH is the relative humidity, γ is the surface tension of the pore solution (N/m), V_m is the molar volume of the solution (m³/mol), r is the radius of the largest water-filled cylindrical pore (m), R is the universal gas constant (8.314 J/(mol·K)), and T is the absolute temperature (K). This equation indicates that as vapor-filled pores are created within the concrete, the internal RH decrease (Jensen and Hansen, 1995a).

The capillary tension, σ_{cap} (Pa) in the pore liquid is given by the equation 2.2 (Bentz and Jensen, 2004):

$$\sigma_{cap} = \frac{2\gamma \cos \theta}{r} \quad (2.2)$$

where θ is the contact angle between solid and liquid.

A slight modification of an equation developed by MacKenzie (1950), allows expressing shrinkage of a partially saturated porous medium due to capillary stresses in the water-filled pores can be estimated as follows:

$$\varepsilon = \frac{S\sigma_{cap}}{3} \left(\frac{1}{K} - \frac{1}{K_s} \right) \quad (2.3)$$

where ε is the linear strain of shrinkage, S is the saturation fraction of water-filled pores, K is the bulk modulus of the porous material (Pa), and K_s is the bulk modulus of the solid framework within the porous material (Pa). From equation 2.2 it follows that as water is removed from smaller pores (with a decrease of r) due to self-desiccation, the values of σ_{cap} will increase. However, as water is removed, according to equation 2.3, the saturation value, S , decreases. Since autogenous shrinkage usually occurs at high RH ($> 80\%$), saturation S plays a secondary role in determination of ε (Bentz and Jensen, 2004).

Nearly all the researchers studying chemical shrinkage, the effects of relative humidity (RH) changes and pore water pressure in low water-binder ratio (w/b) systems or low water-cement (w/c) ratio, have come to the conclusion that a major reason of early-age cracking sensitivity of high-strength and high-performance concrete (HSC/HPC) is self-desiccation (Kovler, 2007).

The two critical parameters for self-desiccation shrinkage, as described by equations 2.1-2.3, are surface tension of the pore solution and radius of the meniscus of the largest water-filled pore within the microstructure.

2.2 Internal Curing of Concrete

Internal water curing of concrete is the incorporation of a curing agent that serves as an internal reservoir of water and gradually releases it as the concrete dries out. Internal curing is complementary to the traditional method of curing (external

curing) when complete hydration of cement is difficult to achieve, e.g., low w/c concretes, concrete with supplementary cementitious materials (SCMs) such as fly ash, silica fume, natural pozzolans or slag. These concrete mixtures generally present a denser cement paste and a low superficial permeability, so water access of external curing water is impeded and insufficient mixing water remains to sustain further hydration (ACI 308R, 2001). Internal curing agents do not deliver water during mixing of concrete, so the initial w/c remains unaffected.

During hydration, a system of capillary pores is formed in the cement paste. The radii of these pores are smaller than the pores of an internal curing agent. When the RH decreases due to hydration and drying, a humidity gradient arises. With the internal curing agent acting as a water reservoir, the pores of the cement paste absorb the water from the LWA by capillary suction. Capillary suction, the value of which is the inverse of the pore radius squared, increases as the radius becomes smaller. Therefore, the swelling of cement paste promotes a continuous absorption of water by its pores (Weber and Reinhardt, 1997).

There are several materials that can serve as internal curing agents: bentonite clay, superabsorbent polymers, lightweight aggregates, wood-derived powders and fibers, substances with chemically bound water (e.g., ettringite), recycled aggregates and substances with unbound water (microencapsulation or emulsified water) (Jensen and Lura, 2007). However, the hitherto studies have been focused mainly on the use of lightweight aggregates and superabsorbent polymers.

2.3 Internal Curing of Concrete Using Lightweight Aggregates

Lightweight aggregates (LWAs) can be divided in two main groups depending of its origin or method of production: i) artificial (manufactured) lightweight aggregates and ii) natural lightweight aggregates.

Most of the artificial LWAs are made from clay, shale, slate or pulverized-fuel ash, which are subjected to an expansion or agglomeration process. Expansion of the raw material occurs in effect of heating to fusion temperature at which pyroplasticity of the material is reached simultaneously with the formation of gas. Agglomeration occurs when part of the raw material melts and the various particles are bonded together (Chandra and Berntsson, 2003). Also, some artificial LWAs are waste from industrial processes, typically non-metallic materials (e.g., sugar slag or iron slag). When they are rapidly cooled with water, porous lightweight aggregates are obtained. However, great variability in properties of these materials is often observed in practice. Natural LWAs, in turn, are unprocessed products and organic materials that can be used as lightweight aggregates. The main natural LWAs are pumice, scoria, volcanic cinders, vesiculated lava and diatomite (FIP, 1983).

More detailed information on the main LWAs used in the research is given below.

2.3.1 Expanded Clay

This type of artificial LWA is made from a special grade of clay suitable for bloating. The clay passes through a rotary kiln reaching temperatures of about

1200°C. The expanded clay formed by this process consists of hard rounded particles with a smooth dense skin surrounding a porous core (Chandra and Berntsson, 1983). The porosity of the expanded clay may be as high as 90%; however, a large part of the pores are closed and not available for water absorption (Jensen and Lura, 2007). A typical value of absorbed water after 24 hours of immersion is 0.17 kg/kg (Lura, 2003), (Zhang and Gjrv, 2001a). An image of expanded clay in concrete, obtained from an optical microscope, can be seen in Figure 2.

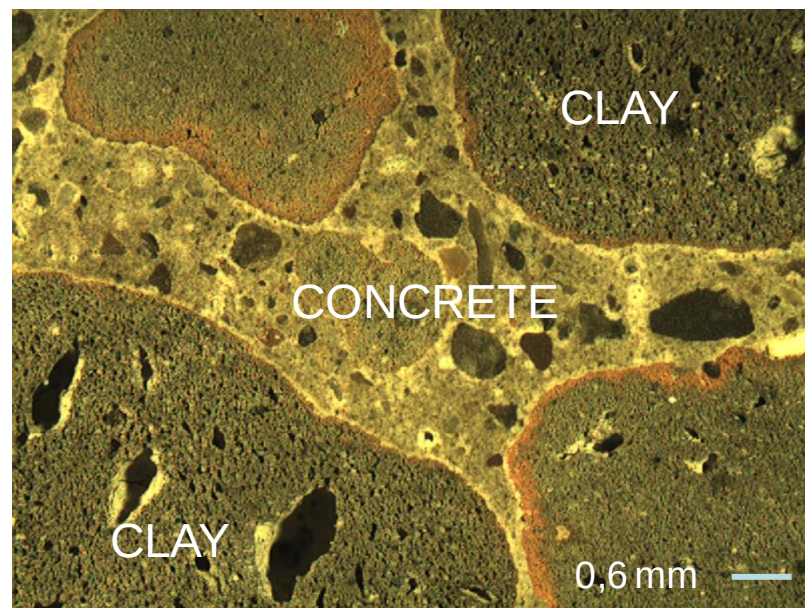


Figure 2: Optical microscopic image of expanded clay in concrete

2.3.2 Expanded Slate

This LWA is formed from selected raw slate. The raw material is crushed to pass a 13 mm screen and fed into a rotary kiln, which expands the slate at a temperature of about 1200°C. After the discharge from the kiln the expanded slate is cooled,

crushed and graded. The final material is chemically inert and has highly vitrified internal pore structure (Short and Kinniburgh, 1963). Compared with other LWAs, expanded slate has a relatively fine and less continuous pore system. The amount of retained water at 24-h saturated surface-dry condition is about 0.06 kg/kg (Jensen and Lura, 2006). However, this value will depend on the particle size distribution of the aggregate. An optical microscopic image of expanded slate is shown in Figure 3.

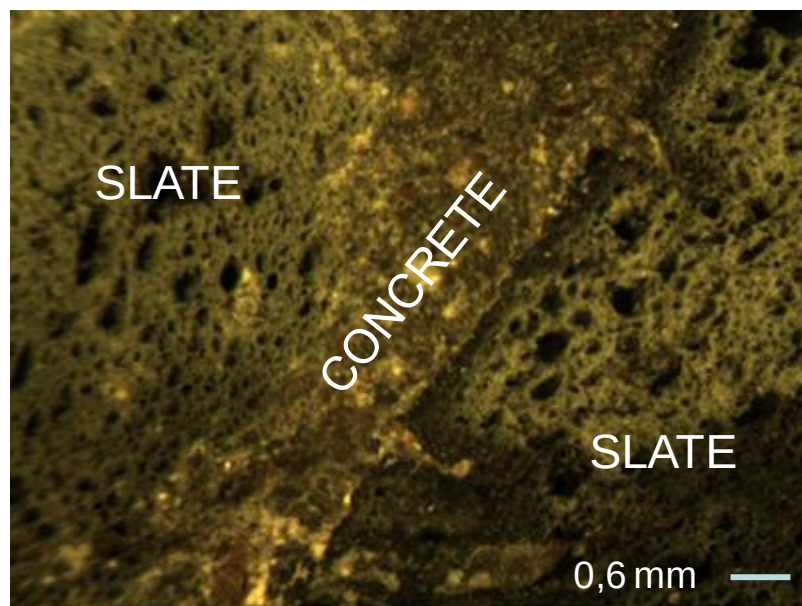


Figure 3: Optical microscopic image of expanded slate in concrete

2.3.3 Pumice

Pumice is a volcanic rock, the porous structure of which is formed by dissolved gasses precipitating during the cooling of lava (Jensen and Lura, 2007). The cells are elongated, parallel to each other and sometimes interconnected. Pumice is chemically inert and has variable qualities depending on its source (FIP, 1983). An

optical microscopic image of concrete, internally cured with pumice, is shown in Figure 4.

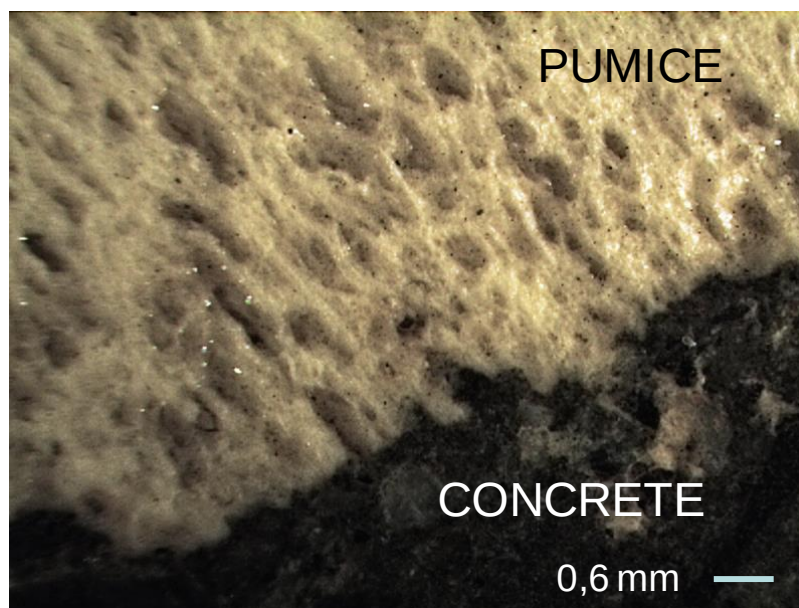


Figure 4: Optical microscopic image of pumice in concrete

2.3.4 LWA Requirements

The attractiveness of LWA is defined by large internal porosity with high degree of interconnectivity. Nevertheless, LWAs present a great variability depending of their sources, way of manufacture, and characteristics of the raw material, among others conditions and properties. It is therefore necessary to establish minimal specifications to be accomplished by an LWA to be used in internal curing. The principal characteristics are:

a) Water uptake (absorption)

It is desired that the LWA can retain high amounts of water and that the rate of water uptake allows for practical use. LWAs have high porosity but it might not

reach complete saturation with water for several weeks or even months (Holm *et al.*, 2003).

b) Water release (desorption)

Since the water stored in internal pores need to be delivered to the drying cement paste, it is required that most of the absorbed water be released from the LWA as quick as possible. The driving force for this process should be the RH gradient.

c) Dispersion of the LWA

Zhutovsky *et al.* (2004) calculated the water flow distance from saturated LWA in cement pastes at various ages (time from mixing). Estimated distances vary from centimeters at early ages to millimeters at middle ages to hundreds of micrometers at later ages (see Table 1). Given the limited radius of action of the internal curing, the chosen LWA has to be well dispersed in concrete, therefore a lower maximum size of aggregate (MSA) is preferred, so the same amount of internal curing water is better distributed throughout the concrete.

Table 1: Estimated travel of internal curing water at different ages (Zhutovsky *et al.*, 2004)

Age	Flow Distance (mm)
Early (< 1 d)	21.4
Middle (1-3 d)	3.90
Late (2-7 d)	0.98
Worst (> 28 d)	0.25

d) Resistance to mixing

Usually, due to its high porosity, LWAs present a lower intrinsic strength than normalweight aggregates (NWAs). Hence, an LWA utilized as internal curing agent should maintain its original particle size distribution.

The availability of the stored water is a central issue for the proper function of internal curing and can be separated into three different topics: (i) total amount of water, (ii) availability determined by the loss of thermodynamics (thermodynamic availability) and (iii) availability determined by kinetics of the involved processes (kinetic availability) (Jensen, 2007). The total amount of needed water depends on the mixture composition, the external curing conditions and the objective of the internal curing. Thermodynamic availability of water in relation to cement hydration requires an equilibrium relative humidity close to 100% (activity close to 1), because lowering the RH significantly affect the cement hydration (Jensen *et al.*, 1999). Kinetic availability refers to the transport of water from the saturated LWA to all parts of the self-desiccating, cementitious material. This requires that the water is not confined but readily available when RH drops and that internal curing water should be homogeneously distributed (Jensen, 2007). This last aspect is hardly impacted in low w/c concrete (HSC and HPC) due to depercolation (disconnection) of the capillary pore structure during concrete hydration.

2.4 Using Shrinkage-Reducing Admixtures (SRA) as Water Modifier.

Shrinkage-reducing admixtures (SRA) were first used in Japan, in 1982. The main component is polyoxyalkylene alkyl ether, a lower alcohol alkyleneoxide adduct.

These admixtures are low viscosity, water-soluble liquids that function by reducing capillary tension developed within the concrete pores during self-desiccation (Nmai *et al.*, 1998).

SRAs belong to a class of organic chemical known as surfactants. Surfactants are amphiphilic molecules, having a hydrophilic (polar) head covalently bonded to a hydrophobic (non-polar) tail (Zana, 2005). The hydrophilic head is attracted by polar and hydrogen bonding solvents, such as water, and oppositely charged surfaces (Adamson and Gast, 1997), while the hydrophobic tail is attracted by non-polar solvents, such as oil, but is repelled from polar molecules such as water (Zana, 2005).

When dissolved in water, amphiphiles are attracted to non-polar interfaces (water-air or water-oil interfaces) (Zana, 2005). Adsorption of surfactants at interfaces causes a reduction in the interfacial energy; thus, addition of SRA leads to reduction in the surface tension of the water-air interface (Rajabipour *et al.*, 2008). At low concentrations, these molecules can be present as monomers dissolved in water. However, at higher concentrations, amphiphiles tend to aggregate and form micelles in order to reduce the unfavorable contact between the hydrophobic tails and water molecules (Zana, 2005). The formation of micelles occurs at concentrations exceeding the so-called critical micelle concentration, which is characteristic for each surfactant. An explanatory diagram of the interactions of amphiphilic molecules in a polar solvent (e.g., water) could be seen in Figure 5 (Zana, 2005).

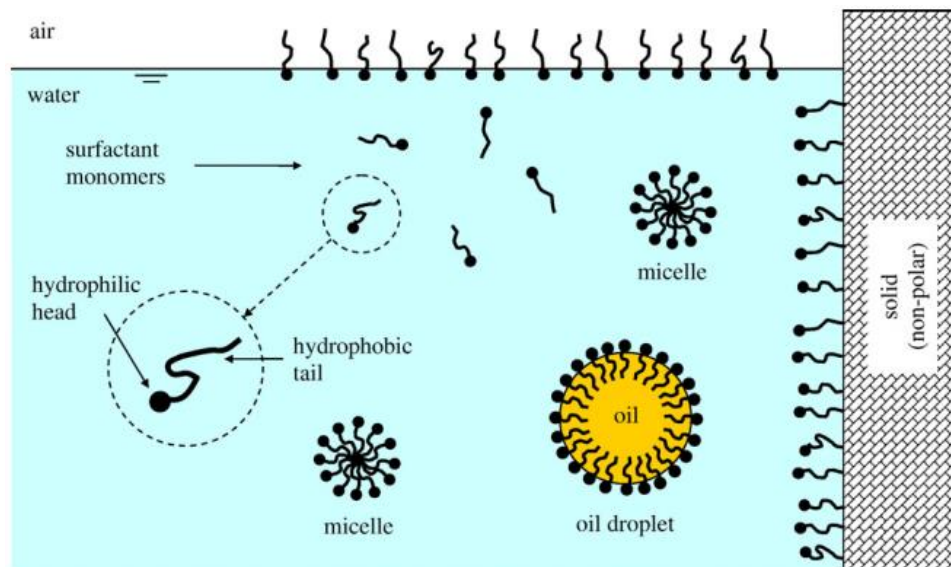


Figure 5: Interactions of surfactant molecules with a polar solvent (Zana, 2005)

Pease (2005) measured a 54 % reduction of surface tension in a 15% by mass concentration of SRA. Exceeding this percentage; the successive addition of SRA did not show changes in the surface tension of the solution. Other research has shown that the same degree of reduction can be obtained with different commercial types of SRAs (Radlinska and Weiss, 2008).

In concrete industry, SRAs had been used to: 1) reduce the magnitude of capillary stresses and shrinkage strains that occur when concrete is drying (Shah *et al.*, 1992), (Tazawa and Miyazawa, 1995), 2) to reduce evaporative water loss during early-age curing (Bentz *et al.*, 2001) and 3) to reduce early-age cracking (Bentz and Weiss, 2008).

3. EXTENDED SUMMARY OF CONDUCTED WORK

3.1 Background

It has been shown that low w/c concrete presents several problems to reach maximum hydration. The lower permeability due to depercolation of the capillary porosity reduce significantly the effect of the traditional curing on cement hydration. The objective of the internal curing is to provide water from the interior of concrete to counteract self-desiccation of cement paste and attain a higher degree of hydration of the cementitious materials. This should result in mitigation of the autogenous shrinkage and reduction of the early-age cracking.

Despite of the research made in the past, the impact of internal curing agents, and specifically lightweight aggregate, on the compressive strength of concrete is still not fully understood. On one hand, LWAs have a lower intrinsic strength so a reduction in the strength of concrete might be expected. On the other hand, some researchers have argued that the improvement of the cement paste due to an enhanced hydration can compensate this effect or even increase the strength of concrete (Bentz, 2007). If the inclusion of LWA reduces the mechanical properties of concrete, then a minimization of the lightweight aggregate replacement will be desirable. More efficient LWAs, which can provide the benefits of internal curing at lower volume fraction than other LWAs, will be preferred.

Additionally, it is interesting to observe how modifications in the properties of internal curing agents such as changes in size distribution and surface-to-volume

ratio and changes in the surface tension of water impact over internal curing performance.

SRA is often used as an additive to reduce drying shrinkage of concrete. If SRA is provided with the internal curing water, a combined effect of shrinkage reduction due to the effect of SRA and the expected enhancement of cement hydration, could be achieved. Nevertheless, the use of SRA might reduce the rate of water diffusion, so a lower uptake and release of water by the LWAs might be expected. Therefore, the effect of a SRA solution in the performance of LWAs as internal curing reservoirs is analyzed.

3.2 Objectives and Methodology

The main objective is to assess the efficiency of LWA as internal curing agent and to identify the relevant contributions. The potential performance of the aggregates as internal curing agents in concrete is assessed by characterization and evaluation of the different properties in artificial and natural LWA (water uptake kinetics, water release kinetics and study of the pore microstructure). The actual performance in concrete mixtures is determined in a permeability test (chloride ion permeability test at 90 days), degree of hydration at 90 days, compressive strength at 28, 56 and 90 days and autogenous shrinkage. Additionally, the modifications in the performance of the internal curing agents is analyzed when different particle size distributions are used, and when the internal curing water contains shrinkage-reducing admixtures (SRA). The detail of the obtained data and images of the tests are collected in appendices of this work.

3.3 Hypothesis

The main hypothesis is that in low w/c concrete, the use of natural LWA as internal curing agents, results in concrete with a higher degree of hydration than that produced using artificial LWA when the same amount of internal curing water is provided. This should be reflected in an improvement in several properties of concrete, such as: lower chloride ion permeability, higher compressive strength and lower autogenous shrinkage.

This hypothesis comprises three specific issues:

- a) The pore structure (pore size distribution, pore connectivity and shape) of an LWA, which allows a more efficient water storage and delivery in case of natural LWA.
- b) The efficiency of a LWA as internal curing agent could be improved by changes on the particle size distribution.
- c) The efficiency of a LWA as internal curing agent could be improved by modifications of the surface tension of the water absorbed by the LWA, before mixing.

3.4 Experimental Procedure

Lightweight aggregates used in this study include:

- a) Pumice from Chile: natural LWA.
- b) Pumice from Ecuador: natural LWA.

c) Expanded clay: artificial LWA, three different particle size distributions:

- Expanded clay 20/10¹.
- Expanded clay 10/5.
- Expanded clay 5/0.08.

d) Expanded slate: artificial LWA, two different particle size distributions:

- Expanded slate 20/5.
- Expanded clay 10/0.08.

e) Industrial slag 1 (iron slag): artificial LWA, waste from steel industrial process.

f) Industrial slag 2 (sugar slag): artificial LWA, waste from fuels used in industrial sugar process.

The experimental work was divided in two parts:

(1) The evaluation of the basic characteristics: (i) the moisture properties (water release/uptake), (ii) the analysis of the microstructure of the LWAs by SEM (scanning electron microscope) micrographs and (iii) porosity test by MIP (mercury intrusion porosimetry).

(2) The performance as internal curing agents in reference to the impact on mechanical properties (compressive strength), chloride ion permeability, mitigation of autogenous shrinkage and degree of hydration.

¹ The numbers correspond to the maximum and the minimum size of particle in the aggregate, respectively.

3.5 Structure of Chapter 4

Two articles were submitted to ISI journals after the research was conducted. These two articles are included in this thesis and present the main results obtained from the investigation. Each article is focused on a particular hypothesis (see 3.3). The first of them is referred to the efficiency of the LWAs used as internal curing agents and a comparative analysis between natural and artificial LWAs. The second one refers to the modification of the moisture properties of the LWA, through the use of SRA solution for the pre-wetting of the aggregate and the use of different particle size distributions to obtain a better dispersion of the internal curing agent.

4. JOURNAL ARTICLES

4.1 Assessing Lightweight Aggregate Efficiency for Maximizing Internal Curing Performance

Abstract

Internal curing, extensively investigated in the last decade, has shown to enhance hydration, diminish autogenous shrinkage, and mitigate early-age cracking due to self-desiccation in high-performance concrete. However, it also increases internal porosity of concrete which might reduce mechanical properties. Thus, a better understanding of what makes a LWA effective and efficient for internal curing is fundamental to maximize the gains and minimize the shortcomings.

The present study analyses the performance of a wide set of LWAs for internal curing including artificial and natural LWAs. Water uptake, water release, and pore structure of LWAs was determined; as well as their performance in concrete assessed using degree of hydration, compressive strength, chloride ion permeability and autogenous shrinkage. Results showed that natural LWA possess higher, coarser, and more interconnected porosity than artificial LWA. This allows natural LWA to store more water and to present higher and faster water release for internal curing. Natural LWAs produced concrete with similar or better performance than that with artificial LWAs in despite of having lower dosages. Selection of a LWA for internal curing needs to consider not only the effectiveness in reducing autogenous shrinkage but also efficiency and other performance criteria such as permeability and compressive strength.

Keywords: pumice; chloride ion permeability; autogenous shrinkage; pore microstructure; degree of hydration; water release; water uptake.

Introduction

After concrete is batched, the mixing water - defined as the water in freshly mixed concrete exclusive of any previously absorbed water by the aggregate (ACI 116R, 2005) - reacts with the cementitious materials carrying out diverse chemical reactions. Some portion of the water combines to form calcium silicate hydrates (C-S-H), primary strength-giving phase in portland cement concrete; some water forms other hydration products such as calcium hydroxide, ettringite or monosulphate; some water is adsorbed by the surface of the hydration products; and the rest remains within the capillary pores originated during hydration (Neville, 2003).

As cement hydration develops necessary water to continue hydration is partially obtained from the capillary pores. The emptying of the capillary pores produces an increase in surface tensions over the aggregates and hydration products developed. The macroscopic effect of the drying, under sealed isothermal unrestrained conditions, produces dimensional deformations of the cementitious system known as autogenous deformations (Kovler and Jensen, 2007) (Jensen and Hansen, 2001). Two factors determine the cement maximum attainable degree of hydration: the availability of space for hydration products and the availability of water for the cement hydration (Mindess *et al.*, 2003). Powers (1947) established a theoretical lower limit of 0.36 for water-to-cement ratio (w/c) to have enough space for the

formation of the hydration products while for w/c between 0.36 and 0.42 an additional supply of water is needed to reach complete hydration of cement (Mindess *et al.*, 2003). When the additional supply of water is external to concrete, its water permeability becomes a key factor allowing that water reaches unreacted cement.

High-performance / high-strength concretes present a challenging scenario with respect to hydration, autogenous deformation, and curing because they usually have low w/c and low permeability (Durán-Herrera *et al.*, 2007), (Aïtcin, 1998); thus, traditional curing might not be sufficiently effective in such concretes.

Philleo (1991) suggested a partial replacement of fine normalweight aggregate by pre-wetted lightweight aggregate (LWA) in order to reduce self-desiccation and to provide curing from the interior of the concrete. This is now known as “internal curing” – IC. The principle behind IC lays on the water migration from the pre-wetted LWA to cement paste, by capillary suction according to the Kelvin-Laplace equation as relative humidity on cement paste decreases (Kovler and Zhutovsky, 2006). IC takes advantage of the LWA high porosity and absorption. That is, water uptake through 24 hours immersion ranges between 5 and 30% for artificial LWA and could reach even 50 to 60% in the case of some natural LWA such as pumice.

During the last years, many authors had continued investigating IC (Weber and Reinhardt, 1997), (Bentz and Snyder, 1999), (Bentz *et al.*, 2005), (Bentur *et al.*, 2001), (Lura, 2003), (Lam and Hooton, 2005), (Henkensiefken *et al.*, 2009), (Lopez *et al.*, 2005), (Lopez *et al.*, 2008a) and new data on the benefits of IC on

hydration, mechanical properties, control and mitigation of the autogenous and drying shrinkage, cracking susceptibility, and creep has been obtained. Bentz and Snyder (1999) developed the first theoretical estimation to determine the required amount of pre-wetted LWA to ensure enough water for complete cement hydration, based on a 3-D concrete microstructural model. Later on, Bentz *et al.* (2005) developed a procedure that has become one of the preferred methods to estimate the amount of pre-wetted LWA needed for IC. This method considered the aggregate desorption (water release) rather than absorption (water uptake) in proportioning LWA for IC.

Even though IC has proven to enhance hydration and to bring important benefits, the use of IC agents, such as LWA, might limit the compressive strength of concrete due to their high porosity and lower intrinsic strength (Videla and Lopez, 2000a), (Videla and Lopez, 2000b). This is well known in lightweight aggregate concrete as ceiling strength (ACI 213R, 2003). Therefore, the use of IC, and particularly the selection of a LWA for IC, needs to be evaluated not only considering hydration but also the possible effects in mechanical properties (Videla and Lopez, 2002).

Most of the research in IC has been carried out using artificial LWA (i.e., expanded clay, expanded shale, expanded slate, etc.) as IC agents; although natural LWA (i.e., pumice) might be a more efficient IC agent as suggested by its high absorption and open porosity.

Improving the efficiency of the IC agent might reduce collateral effects on

mechanical properties of concrete.

The few studies using natural LWA for IC (Lura *et al.*, 2004), (Lura *et al.*, 2006), (Zhutovsky *et al.*, 2002) have not addressed the efficiency of LWA from the mechanical properties of concrete perspective; furthermore, some of them observed problems to reach enough saturation for practical applications in natural LWA.

Experimental Procedure

The experimental program evaluated seven LWA for IC purposes. The evaluation considered the aggregates' intrinsic properties and their performance as IC agents.

Two types of characterization were considered for the aggregates' intrinsic properties,: (i) aggregates' moisture-related properties such as water adsorption and absorption in time (referred as water uptake) and water desorption and evaporation in time (referred as water release); and (ii) aggregates' microstructure such as pore size distribution through mercury intrusion porosimetry (MIP), and qualitative analysis through scanning electron microscope (SEM) images. The assessment of the different IC agents performance was based on the concrete compressive strength [ASTM C39 (2001)], chloride ion permeability [ASTM C1202 (2005)], degree of hydration [ASTM C150 (2005)], and autogenous shrinkage [method developed by Jensen and Hansen (1995b)].

Aggregate Characterization

To provide enough water for IC in a timely manner, a LWA must possess a good water uptake capacity, high rates of water release, and an appropriate dispersion since the limited travel distance of the IC water within the concrete (Lura *et al.*, 2006), (Bentz *et al.*, 2006).

Seven kinds of aggregates were considered in the study: two natural LWA (pumice from Chile and Ecuador), and two artificial LWA (expanded slate and expanded clay) each of one with different particle size distribution. The main properties of the aggregates are shown in Table 2 where open porosity was obtained by filling the pores with toluene before the MIP test.

Table 2: Main characteristics of the LWA analyzed in the research

LIGHTWEIGHT AGGREGATE	3-day Absorption	Dry Specific Gravity	24-h SSD Specific Gravity	Fineness Modulus	Open Porosity
	%	kg/m ³ (lb/yd ³)	kg/m ³ (lb/yd ³)	mm/mm (in/in)	%
Pumice from Ecuador 10/0.08 ¹	62.4%	711 (1,198)	1,195 (2,014)	3.69	68.8%
Pumice from Chile 20/0.63	56.8%	710 (1,197)	1,063 (1,792)	5.96	67.9%
Expanded Slate 20/5	5.5%	1,364 (2,299)	1,439 (2,426)	6.58	----- ²
Expanded Slate 10/0.08	13.8%	1,543 (2,601)	1,656 (2,791)	3.92	27.7%
Expanded Clay 20/10	22.3%	1,115 (1,879)	1,364 (2,299)	6.96	----- ²
Expanded Clay 10/5	23.3%	1,231 (2,075)	1,517 (2,557)	5.77	----- ²
Expanded Clay 5/0.08	32.5%	1,653 (2,786)	1,920 (3,236)	4.16	41.0%

1: numbers in the name indicate the maximum and minimum particle sizes in mm

2: not measured

Aggregate water uptake was assessed by submerging 500 g [1.1 lb] of each aggregate, in an oven-dry condition, in 2-liter [67.6 fl oz.] flasks. As the level of

water decreased due to the aggregate's uptake of water, the flasks were refilled and the change in mass was registered to obtain the amount of water retained by the aggregate in time. Water evaporation and aggregate floating were avoided. Since initial semi-instantaneous water uptake occurred when the oven-dry LWA first take contact with water, the measured values needed to be corrected to include that initial amount of water not registered the first time. Thus, the mass of water retained by the aggregate after 24 hours was obtained in parallel samples to make the adjustment.

Aggregate water release was assessed by drying 400 g [0.88 lb] of 3-day saturated surface dry (SSD) aggregate at controlled relative humidity (RH) conditions. The mass change was registered to obtain the amount of water released by the aggregate in time. Three samples were tested for each aggregate. In order to control water release, aggregates were kept in hermetic containers with saturated salts to set the RH. This procedure aimed to represent the autogenous change of RH within concrete. The RH imposed by the salts ranged between 97 and 75% (see Table 3). This range was chosen based in Powers' work, which proved that the hydration of cement stops when the RH in the capillary pores drops below 80% (Powers, 1947).

Two criteria were established to determine the time for reaching hygral equilibrium between the LWA and the environment: 1) the water loss in the last 24 hours being less than 0.5% of the total amount of water contained by the LWA, and 2) the drying rate in the last week being lower than the 25% of that in the first

week (initial drying rate). The test methodology was based on ASTM C1498 (2004), but considered significantly larger samples to obtain more representative results, and stricter criteria to determine hygral equilibrium.

Table 3: Salts used for control of RH in the measurement of water release

Salt Name	Chemical Formula	Equilibrium RH at 23°C (73°F)
Potassium sulphate	K_2SO_4	97%
Potassium nitrate	KNO_3	94%
Barium chloride dehydrate	$BaCl_2 \cdot 2H_2O$	90%
Potassium chloride	KCl	85%
Potassium bromide	KBr	81%
Sodium chloride	NaCl	75%

Additionally, two tests were performed to assess the LWA microstructure characteristics. Pore size distribution using MIP test (Swanson, 1981) was measured in the natural and artificial LWA. The MIP test allowed measuring accesible pores with diameters ranging from 1 mm to 1 nm. Also, SEM micrographs were taken in the aggregates to observe qualitative differences in pore size and inner conectivity. The aggregates were embedded in an ultra-low viscosity resin and then saw cut. The cut surfaces were polished using 120, 240, 360, and 600 silicon carbide (SiC) grit to obtain a suitable surface for imaging. Then the samples were gold coated to improve the electrical conductivity of the surface. The micrographs were obtained using a backscatter electron detector.

Performance of aggregates in concrete

Aggregate performance, as IC agents, was assessed when used in concrete and measuring concrete autogenous shrinkage. Concrete mixture design considered 65% of aggregate by volume. Portland cement type I at a water-to-cement ratio of 0.3 was chosen for all the mixtures. The cement had a blaine fineness of $360 \text{ m}^2/\text{kg}$ [$3,600 \text{ cm}^2/\text{g}$] and the estimated composition was as follows: 20.8% of SiO_2 , 2.9% of Fe_2O_3 , 6% of Al_2O_3 , 63.2% of CaO , and 1.8% of SO_3 . Samples were demolded 24 hours after casting and kept in at RH higher than 90% and 23°C [73.4°F] until the time of testing.

The method developed by Bentz and Snyder (1999) was used to estimate the amount of IC water needed to maintain complete saturation of the cement paste during hydration. The amount of LWA was calculated from this value and from each particular aggregate desorption. This amount of LWA was then replaced by an equal volume of normal weight aggregate already present in the concrete mixture. In order to minimize changes in grading, the replacement of NWA by LWA considered fine aggregate, coarse aggregate or both, depending on the particle size distribution of the specific LWA. It should be noted that the quantity of IC water, rather than the quantity of IC agent, was kept constant in all mixtures. Thus, little differences in autogenous shrinkage and degree of hydration and large differences in mechanical properties are expected among the mixtures with different LWA.

The details of the concretes mixture designs are shown in Table 4. The LWAs were prewetted for three days since water storage is considerably higher than that obtained with one day only; and at the same time, it is still a feasible period for field applications.

Table 4: Mixture designs in kg/m³

Constituent	Control	Pumice from Chile	Pumice from Ecuador	Exp Clay 10/5	Exp Clay 5/0.08	Exp Slate 20/5	Exp Slate 10/0.08
Portland Cement	518	518	518	518	518	518	518
Water	155	155	155	155	155	155	155
Coarse Aggregate	790	709	790	589	790	0	790
Fine Aggregate	965	866	814	965	799	814	496
LWA (3-day SSD)	-----	71	67	142	119	498	261
Superplasticizer	13	13	13	13	13	13	13

Autogenous shrinkage of mixtures using each LWA was measured by the method developed by Jensen and Hansen (1995). It uses flexible corrugated tubes as molds, with a negligible axial stiffness, to obtain linear deformations after setting. Three specimens were used for each mixture. Specimens were sealed and stored in an environmental chamber at constant temperature (23 °C [73.4 °F]) to avoid drying and thermal deformations. The initial measurement (zero time) was taken after setting time according to the Vicat test (ASTM C191, 1999). Specimens were periodically weighted to verify that specimens remained sealed.

Compressive strength was measured in 100 x 200 mm [4 x 8 in] cylinder specimens at 28, 56 and 90 days of age. Detwiler *et al.* (2009) concluded that the average of two 100 x 200 mm [4 x 8 in.] cylinders did not have a greater

variability than the average of three 150 x 300 mm [6 x 12 in.] cylinders, so at least two specimens were considered on each test.

Chloride ion permeability was measured according to ASTM C1202 (2005). This method has shown a direct relationship with water permeability (Zhang and Gjrv, 1991b), being a good indicator of the concrete expected durability and a suitable method for evaluating materials. The samples were obtained sawing 100 x 200 mm, [4 x 8 in.] cylinders to obtain 100 x 50 mm [4 x 2 in] cylinders. Two samples were tested per each mixture.

Finally, samples of concrete at 90 days of age were grinded down using a mortar to obtain each concrete mixture degree of hydration. At least three samples of approximately 30 g [1.058 oz.] of crushed concrete passing 5-mm [0.2-in] sieve were placed in ceramic crucibles. First, samples were kept at 105 °C [221 °F] during 24 hours, in order to remove the evaporable water (water in the capillary pores of concrete). Then, samples were weighted and ignited in a muffle furnace at a controlled temperature of 1,100 °C [2,012 °F] during 3 hours and weighed again. At high temperatures, over 1,000 °C [1,832 °F], chemical bonds in the cement paste are broken and the water that has reacted with cement to form the hydration products (known as chemically bonded water), is removed. The cement degree of hydration was calculated based on the mass loss between 105 and 1,100 °C [221 and 2,012 °F], and correcting by the loss on ignition of the unhydrated cement, and aggregates (NWA and LWA). To calculate the cement degree of hydration, the

non-evaporable water content for fully hydrated cement is considered to be 0.23 g [0.008 oz.] of water per 1 g [0.035 oz.] of cement (Bentz and Hansen, 2000).

Experimental Results and Discussion

From the results shown in Table 2, it can be concluded that the aggregates present a wide range in their properties to provide IC water, even among those of the same kind (i.e., expanded slate or expanded clay). However, in a preliminary analysis, the two pumices (natural LWAs) appear as the more promising ones due to its high initial absorption and open porosity.

Aggregates Properties

Water uptake of LWAs, expressed as the percentage of water with respect to the aggregate oven-dry mass, presents great differences within the aggregates studied herein (see Figure 6). LWAs showed a high initial water uptake with a subsequent decrease in water uptake with time. This would happen because water starts by filling large pores first and then continues filling increasingly smaller pores by diffusion. This continues to occur until all the open pores are full or until there is not enough energy (pressure) to keep filling the smaller pores. This is manifested by an equilibrium value when no more water is absorbed or adsorbed by the aggregate.

Large differences can be noted when comparing the different LWAs shown in Figure 6. First of all, Natural LWAs had a considerably higher initial and final water uptake when compared to any of the artificial LWAs. Moreover, natural

LWAs presented the highest water uptake, even exceeding the open porosity value shown in Table 2.

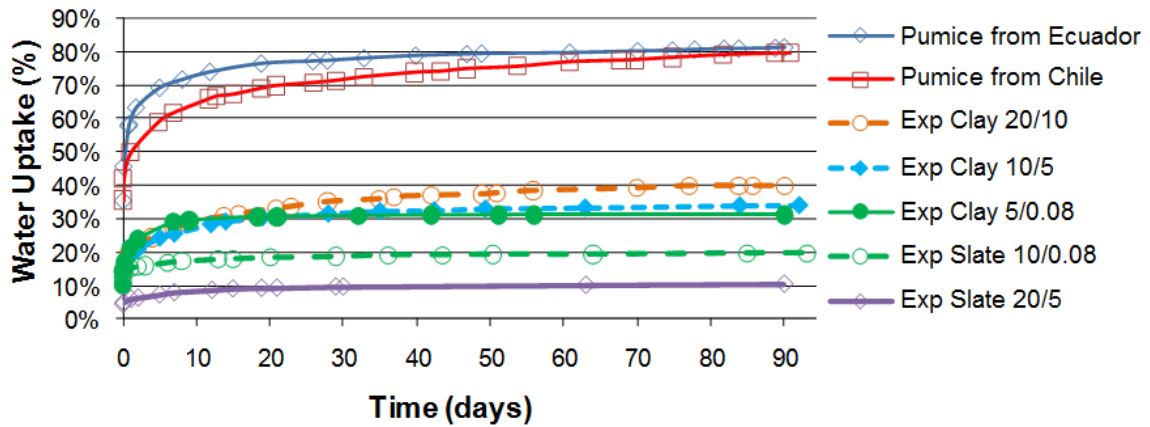


Figure 6: Water uptake in time

When comparing natural LWAs, it can be concluded that even though pumice from Ecuador presented a higher initial water uptake, both pumices had relatively similar final water uptake of approximately 80% of its initial oven-dry mass.

When comparing artificial LWAs, considerable differences between expanded slate and expanded clay can be observed. Expanded slate exhibited final water uptake between 10 and 20% depending on the maximum size aggregate (MSA) while expanded clay ranged between 30 and 40%. In addition, expanded slate exhibited higher initial and final water uptake as its MSA decreased; i.e., water uptake of expanded slate 10/0.08 that nearly doubled the one of expanded slate 20/5. On the other hand, expanded clay did not show higher water uptakes as the MSA decreased; in fact, expanded clay 20/10 (the largest MSA fraction) showed the highest water uptake, and no significant differences between expanded clay

10/5 and expanded clay 5/0.08 were recorded. This difference between expanded slate and expanded clay is believed to be caused by differences in their pore interconnectivity. That is, in poorly interconnected porosity, water uptake is greatly influenced by the exposed surface; i.e., accessible pores. As MSA decreases, the exposed surface and accessible pores increases and the same happens with water uptake. This would be the case of expanded slate where the smaller MSA fraction was obtained by crushing down the larger MSA fraction, so new internal pores become accessible.

In contrast, expanded clay, which various MSA are obtained by sieving particle sizes after the rotary kiln expansion process, presents similar access to internal porosity regardless of the MSA. Moreover, the larger water uptake of the expanded clay 20/10 can be attributed to the bigger internal pores that such particles can contain as compared to the smaller fractions.

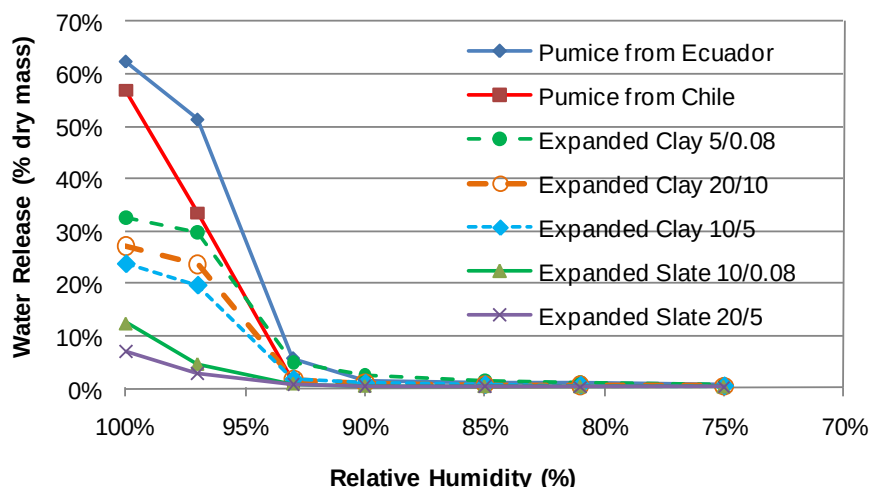


Figure 7: Water release of LWA under decreasing RH conditions

Figure 7 shows the water release (evaporation and desorption of water) of the LWAs. Water release due to relative humidity (RH) gradients in a closed system characterizes differences in the water delivery capabilities of each LWA.

Figure 7 shows that regardless of the LWA, most of the stored water is release for HR of 93%. Nevertheless, large differences between the LWAs are observed in the amount and rate of water release. Natural LWAs released more water and at a higher rate than any of the artificial LWAs. Pumice from Ecuador exhibited the highest amount of water released while expanded slate 20/5 exhibit the lowest. Additionally, natural LWAs presented the highest rates of water delivery (Table 5) at 97% and 93% RH. Thus, natural LWA are expected to release more water more rapidly allowing better cement hydration if used as IC reservoir.

Table 5: Rate of released water at 97% and 93% RH

LIGHTWEIGHT AGGREGATE	97% RH¹ ($\times 10^{-4}$)	93% RH¹ ($\times 10^{-4}$)
Pumice from Ecuador	10.1	17.2
Pumice from Chile	7.7	15.6
Expanded Slate 20/5	4.5	5.6
Expanded Slate 10/0.08	5.9	10.7
Expanded Clay 20/10	7.1	13.9
Expanded Clay 10/5	6.0	11.2
Expanded Clay 5/0.08	6.5	13.0

1: Grams of water released by grams of dry LWA per day

When comparing results from Figure 6 and Figure 7, it can be concluded that even water uptake and water release are governed by different physical processes (Ruthven, 1984), the aggregate with the highest water uptake also exhibited the

highest water release (natural LWAs). Likewise, the aggregates with the lowest water uptake also exhibited the lowest water release (expanded slate). A more detailed analysis of the moisture-related properties of LWAs could be seen elsewhere (Paul *et al.*, 2010).

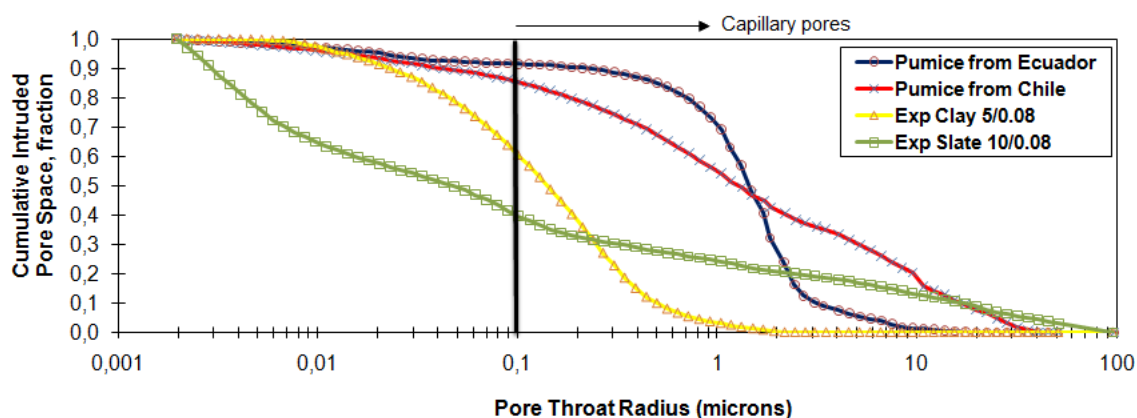


Figure 8: Pore size distribution of natural and artificial LWAs (MIP test). Vertical line indicates the theoretical limit for capillary pores

Figure 8 presents the results of the MIP test. It can be seen that natural LWAs present pores with larger diameters than artificial LWA. Pores with diameter larger than 100 nm approximately can be considered capillary pores, which are useful for IC water storage (Jensen and Lura, 2003). While the pumice from Ecuador and Chile presented 91.6% and 85.4%, respectively of capillary pores relative to the total porosity registered, expanded clay 5/0.08 and expanded slate 10/0.08 presented only 60.5% and 39.7%, respectively of capillary pores. Pores that are smaller than 100 nm cannot be drained by capillary suction, so they are not available for IC. Therefore, besides of the higher porosity of natural LWAs with

respect to artificial LWAs, a better performance as IC agents is expected in natural LWAs due to their coarser pore size distribution.

SEM images taken in the aggregates showed a greater open and more interconnected porosity in natural LWAs with respect to artificial LWAs (Figure 9 and Figure 10). These differences are believed to be caused by the formation processes involved on each kind of aggregate. While the artificial LWAs form its pores from the gases evolved within the pyroplastic mass through heating in rotary kilns or in the sintering process (ACI 213R, 2003), the natural LWAs studied herein are volcanic rocks originated by dissolved gases precipitated during cooling as the lava hurtles through the air (Lura *et al.*, 2004).

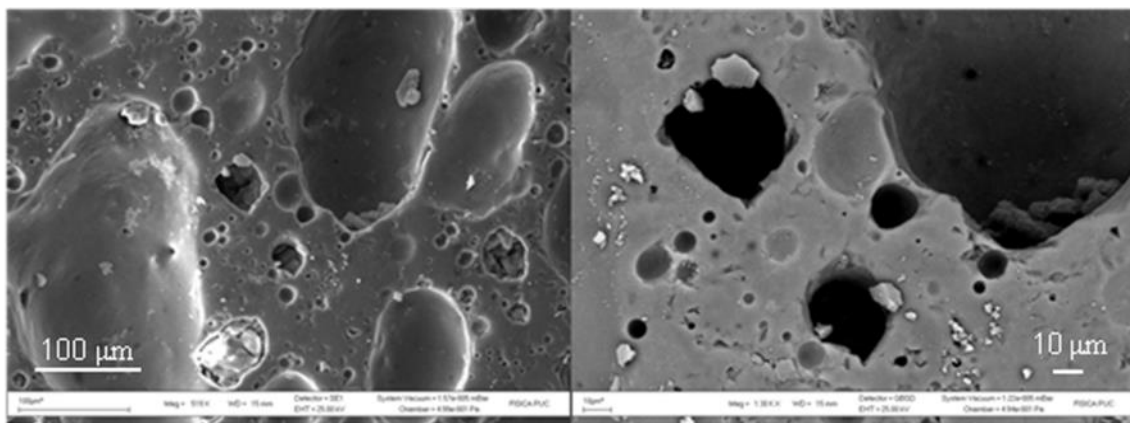


Figure 9: SEM image of expanded slate, 520X (left) and 1,300X (right)

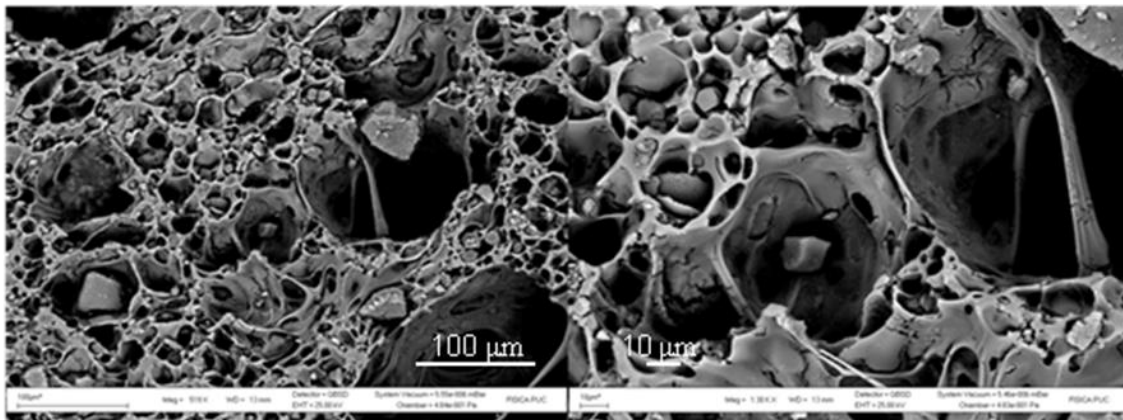


Figure 10: SEM image of pumice from Ecuador, 520X (left) and 1,300X (right)

Concrete Performance

The degree of hydration of cement pastes was calculated at 90 days of age. Table 6 presents the results of degree of hydration and the coefficient of variation. From the results, it can be observed that all the mixtures with IC presented higher degree of hydration than the control sample (with no IC). These results suggest an effective transport of water from LWA to the cement paste.

Table 6: Degree of hydration of concrete mixtures

MIXTURE	Degree of Hydration	Coefficient of variation
Control	52.1%	0.09
Pumice from Ecuador	66.0%	0.15
Pumice from Chile	54.2%	0.17
Expanded Clay 5/0.08	61.1%	0.15
Expanded Slate 20/5	61.3%	0.20
Expanded Slate 10/0.08	60.7%	0.16

Even though all mixtures were proportioned considering the same amount of IC water, the obtained degree of hydration varied widely among them. While

mixtures with artificial LWAs had similar degrees of hydration ranging from 60.7 to 61.3%, mixtures with natural LWAs showed a great difference between them. The mixture with pumice from Ecuador as IC agent presented the highest degree of hydration (66%) with the lowest coefficient of variation while that with pumice from Chile presented a degree of hydration of 54.2%. This important difference in hydration is believed to be caused by the finer size distribution of the pumice from Ecuador (fineness modulus of 3.69) with respect to the pumice from Chile (fineness modulus of 5.96) that allowed a better dispersion within the concrete. This effect became important for the natural LWAs, rather than the artificial LWAs, because of the low volumes of natural LWAs used in such mixtures (see Table 4).

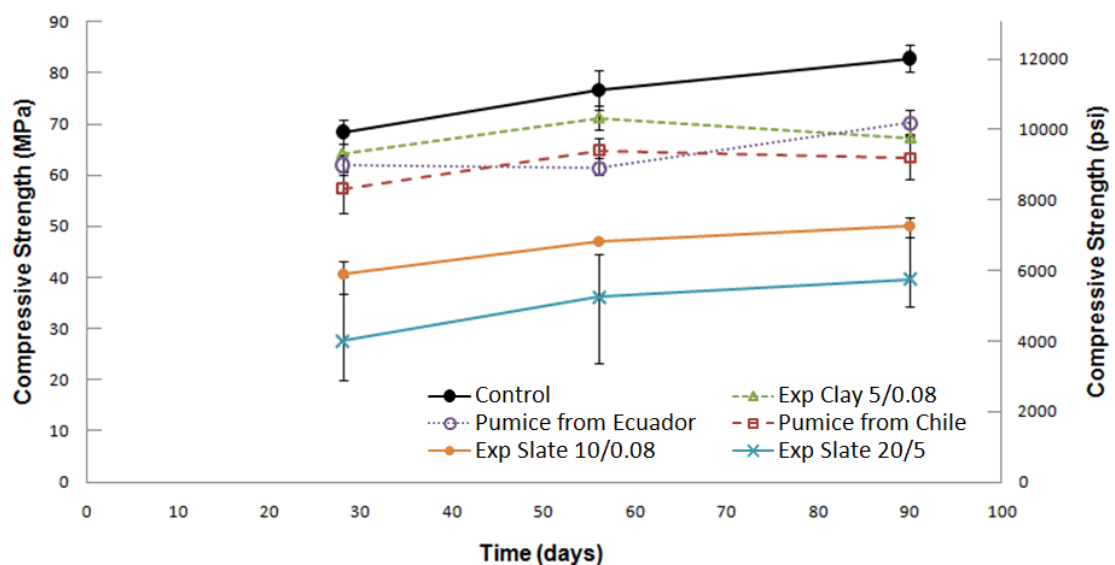


Figure 11: Compressive strength of concrete mixtures

As mentioned above, the use of an aggregate with lower intrinsic strength than NWA could limit the strength attained by the concrete. This effect can be seen in

Figure 11, where the concrete compressive strengths at 28, 56 and 90 days of age are displayed. Although 28-day compressive strength of mixtures with natural LWAs and expanded clay 5/0.08 are similar to that of the control mixture, the 90-day compressive strength showed reductions between 14 and 23% when using these aggregates as IC agents. For mixtures containing expanded slate (20/5 and 10/0.08), the reduction in compressive strength is apparent since the 28 days of age.

Furthermore, there is a good correlation between the 90-day compressive strength and the level of replacement of the NWA by LWA. When expanded slate 20/5 was used as IC agent, more than 50% of the NWA aggregate was replaced by LWA which brought reductions in strength of about 50%. On the other hand, when pumice from Ecuador was used as IC agent, only 8.6% the NWA aggregate was replaced by LWA which brought reductions in strength of about 14%.

Reduction of the compressive strength has been reported by several authors when replacement of NWA by LWA is made (Durán-Herrera *et al.*, 2007), (Bentur *et al.*, 2001), (Lopez *et al.*, 2008a), (Videla and Lopez, 2000a), (Videla and Lopez, 2000b), (Ackay and Tasdemir, 2009), (Lopez *et al.*, 2008b). Nevertheless, other investigation measured higher compressive strength when IC is used in blended cements concretes (Bentz, 2007), attributable to a denser interfacial transition zone between the LWA and the hydrated cement paste due to a better hydration of the cementitious system. Not always an increase in the degree of hydration leads to an increase in compressive strength of concrete when IC is provided. Usually, the

increase in strength of the cement paste binder cannot be balanced by the increased porosity of the whole system due to the high internal porosity of the LWAs (Geiker *et al.*, 2004) and an overall decrease in compressive strength is observed. It should be noticed that the benefits of IC in other properties such as autogenous shrinkage and cracking might be enough to accept a decrease in compressive strength.

It is concluded that the more efficient the IC agent, the lower the volume needed to provide effective IC and the lower the strength losses due to the ceiling strength. Therefore, a desirable IC agent not only maximizes beneficial effects but also minimizes possible detrimental effects.

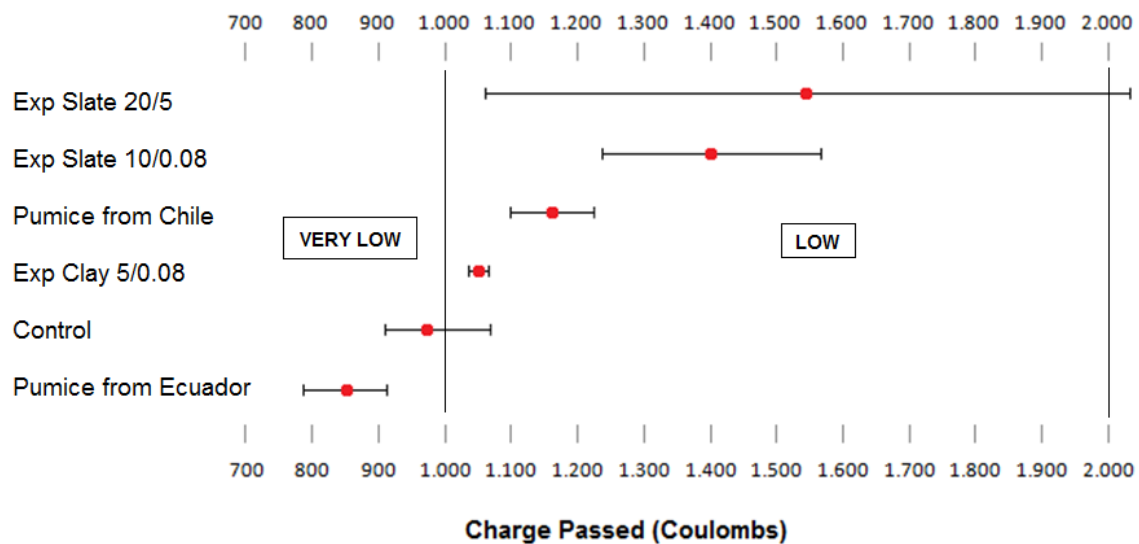


Figure 12: Rapid chloride permeability test. Text in boxes corresponds to the category of penetrability according to the standard

Chloride ion permeability test was performed at 90 days of age as shown in Figure 12. From the results, it can be observed a moderate correlation between the

chloride ion permeability and the volume of LWA replacement. Although most of internally cured mixtures showed higher permeability than the control mixture, all the obtained results were considered as “Low” according to the ASTM standard.

The increase in chloride ion permeability was not expected since improvement in degree of hydration suggests lower permeability. However, it seems that the addition of LWA showed an adverse impact in permeability with the exceptions of the mixture with pumice from Ecuador and with expanded clay 5/0.08 which presented lower or similar chloride ion permeability, respectively than that of the control mixture.

Zhang and Gjrv (1991b) measured higher 28-day chloride ion permeability in their high-strength lightweight concrete mixtures when using LWA of higher absorption. This would indicate that porosity of the LWA might facilitate chloride ion diffusion through concrete. A more recent study (Thomas, 2006) concluded that the 3-year chloride ion permeability of internally cured mixtures having silica fume was lower than that of the control mixture. One possible difference is that the present study did not use supplementary cementing materials such as fly-ash or silica fume in the mixture design, so the beneficial effect of IC in chloride ion permeability observed in the long-term by Thomas might not be as clear in the mixtures used herein. In order to assess this, 120-day chloride ion permeability was measured only in the control mixture and in the internally cured mixture containing expanded slate 20/5. Results showed no significant differences in chloride ion permeability between the two mixtures indicating that as hydration

continues beneficial effects in permeability could counteract the possible initial detrimental effect for using porous aggregates.

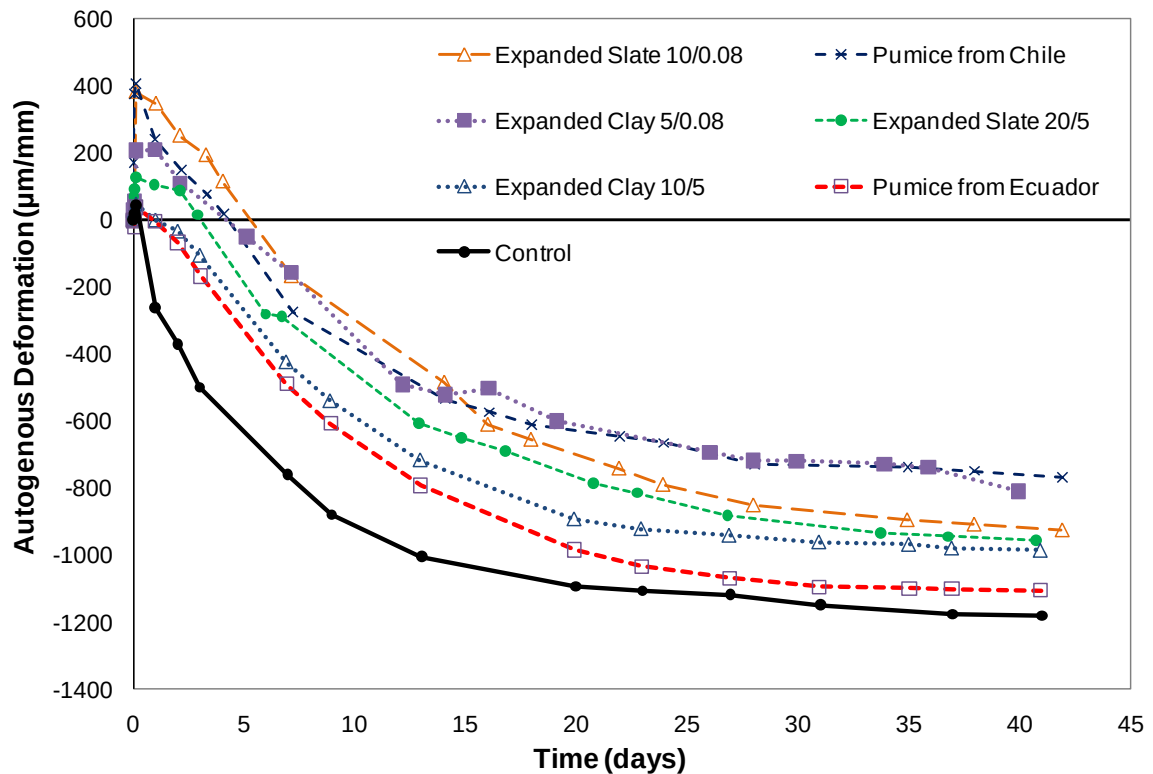


Figure 13: Autogenous shrinkage. Zero time corresponds to the setting time

Figure 13 shows the results of autogenous shrinkage measured on each of the mixtures under study. The mitigation of the autogenous shrinkage is one of the main objectives to use IC of concrete, and as can be seen in Figure 13, the inclusion of pre-wetted LWA in concrete reduced the autogenous shrinkage in all cases with respect to the control mixture. Internally cured mixtures exhibited an initial expansion after setting, followed by shrinkage that developed at a lower rate than that in the control mixture. This effect in autogenous deformation can be very advantageous for controlling early-age cracking since autogenous shrinkage is

reduced and shifted to later ages when concrete has developed most of its strength. For example, an autogenous shrinkage of 600 microstrains was reached after four days for the control mixture while it was reached after 10 to 30 days for the internally cured mixtures.

Nevertheless, significant differences between LWAs could be observed even though all mixtures were proportioned considering the same amount of IC water. Mixtures with pumice from Chile showed the highest expansion and one of the two lowest autogenous shrinkage results.

The reduction in the MSA of the artificial LWAs allowed for further decrease in autogenous shrinkage, but none of these seemed to be a better alternative than pumice from Chile.

Surprisingly, the use of pumice from Ecuador as IC agent did not provide the greatest improvements as the previous tests suggested. One possible explanation of this unexpected behavior of the mixture with pumice from Ecuador could be that an accelerated hydration produced an early depercolation of pores which makes difficult the water transport and facilitates self desiccation within concrete. Even so, this possible explanation could not be verified in this paper and needs to be further investigated. Effects in autogenous shrinkage as those seen herein using pumice from Ecuador has been reported elsewhere (Ackay and Tasdemir, 2009) using similar amounts of pumice, although other test was used to measure autogenous shrinkage (ASTM C157, 1999). When the same autogenous deformation test was performed, higher autogenous shrinkage were obtained in

concrete with w/c of 0.3 and 20% of silica fume addition (Lura and Jensen, 2007), but lower 40-day autogenous shrinkages were measured in blended cement (silica fume, fly ash or ground granulated blast furnace slag), w/cm = 0.3 mortar mixtures (Bentz, 2007).

Summary and Conclusions

IC is a technique which objective is to mitigate or avoid the problems derived of the concrete self-desiccation after setting, i.e., early-age cracking, autogenous shrinkage and poor hydration of the cementitious materials. The success of this technique depends of the characteristics of the water reservoirs chosen (i.e., IC agent). A good IC agent should provide enough water at the right time. Thus, water uptake, water release and characteristics of the microstructure of various LWA were analyzed. Two types of natural LWAs (specifically pumices) and two types of artificial LWAs (specifically expanded clay and expanded slate) were investigated. Based on these LWAs, the following conclusions were obtained:

- (1) Natural LWAs presented higher water storage capacity and higher rates of water uptake than the artificial LWAs.
- (2) Natural LWAs presented higher and faster water release due to RH gradients than the artificial LWAs.
- (3) Natural LWAs presented higher capillary porosity than the artificial LWAs according to the MIP test.
- (4) Natural LWAs showed a higher open porosity and better pore interconnectivity than the artificial LWAs according to the SEM micrographs.

As a consequence of the previous results, lower volumes of pre-wetted natural LWA were needed to provide internal water curing as compared to artificial LWA. Thus, the natural LWAs allowed minimizing the replacement of NWA by LWA which lowers the impacts in compressive strength.

The performance of the LWAs as IC agent was assessed by comparing degree of hydration, compressive strength, chloride ion permeability, and autogenous shrinkage in concrete mixtures with portland cement type I at w/c of 0.3, and 65% of aggregate by volume, so conclusions obtained herein are limited to mixtures with such characteristics.

(5) Concrete mixtures with LWA as IC agent performed generally better than the control mixture without IC.

(6) Concrete mixtures with natural LWA as IC agent performed similar or better than concrete mixtures with artificial LWA even though lower volumes of natural LWA as compared to artificial LWAS were used.

(7) LWA proportioning method for IC needs to be improved if autogenous shrinkage wants to be prevented as anticipated previously (Cusson, 2008). From the results obtained herein, variables such as the rate of water release and the particle size distribution need to be taken into account to determine the quantity of pre-wetted LWA for replacement.

(8) Although autogenous shrinkage mitigation is the primary goal of IC, this cannot be the only test used to evaluate the effectiveness of an aggregate as IC agent. As seen in this study, LWA that produce a high mitigation of autogenous

shrinkage can also have considerable detrimental effects on other properties such as chloride ion permeability and compressive strength. Thus, a balance between beneficial and detrimental impacts should be considered for concrete design in high-performance concrete.

4.2 Modifying Water Uptake and Release: An Attempt to Improve Internal Curing

Abstract

The curing of high performance concrete with traditional methods is challenging due to the relatively low permeability of the concrete. One approach to prevent the consequent self- desiccation and autogenous shrinkage derived from improper curing is to provide the curing water from within the concrete. This technique is usually performed by introducing pre-wetted lightweight aggregates (LWA) into the concrete mix which supply water during the process of cement hydration. In this work, a further improvement to this technique is considered by supplying an admixture with the stored water and by reducing the LWA particle size. The admixture aims at a twofold improvement: decrease of shrinkage and a simultaneous maximization of the amount of stored water (increased amount of filled porosity of the LWA). The reduction of the particle size aims at increase on the amount of stored water. In particular, a shrinkage reducing admixture (SRA) in the concentration of 15% by mass is studied. The kinetics of absorption (uptake) and desorption (release) is measured for two types of aggregates, each in two different particle sizes. The obtained results are discussed in the context of diffusion, taking into account the particle size, the presence of surface diffusion barrier as well as the SRA-induced change of the surface tension of the liquid. Improvements in the performance of the internal curing agents, i.e., the increase in

the loading capacity and faster release of the stored water, were obtained with smaller particle sizes. The presence of SRA did not improved internal curing because it resulted in slower diffusion coefficients and slightly lower water loading capacity of the LWA.

Keywords: Aggregate, Particle Size Distribution, Admixture, Shrinkage, Diffusion.

Introduction

High performance concrete (HPC) usually has a low water-to-binder ratio (w/b) and contains supplementary cementitious materials (SCM's) such as fly ash, silica fume, and granulated blast furnace slag. Both of these characteristics are likely to prevent a complete hydration of the cement because there would be insufficient water to chemically bond with the unreacted cement and/or insufficient space for new hydration products to form. This is why the risk of early cracking in HPC, being a result of self-desiccation, is greater than that of regular concrete (Mehta and Monteiro, 2006)

Internal curing of concrete is a promising technique for reducing shrinkage and cracking of HPC and it has been intensively investigated in recent years (Bentz *et al.*, 2006), (Henkensiefken *et al.*, 2009), (Lopez *et al.*, 2005), (Lopez *et al.*, 2008a). The method relies on the inclusion of internal water reservoirs into the concrete during mixing. The reservoirs are often referred to as internal curing agents. After setting of concrete, the water contained within these internal curing agents is released due to the gradient of relative humidity (RH) that builds up

between the cement paste and the water reservoirs during hydration of the cement. The hitherto research has focused on the application of lightweight aggregates (LWA) as internal curing agent due to their high porosity and the related absorption capacity as well as wide availability. In fact, LWA can provide enough water to counteract the chemical shrinkage during hydration, and thus avoid self-desiccation of concrete (Weber and Reinhardt, 1997), (Kohno *et al.*, 1999), (Bentur *et al.*, 2001), (Bentz, 2007). Moreover, the internal supply of water can be used to deliver additives and other chemical compounds that could further improve the performance of concrete (Bentz, 2005).

However, the sheer enclosure of LWA in HCP may result in “strength ceiling” (ACI 213R, 2003), i.e. reduction in mechanical resistance caused by the presence of a weaker phase. Maximization of the amount of internal curing water to be stored and released per gram of LWA would be of straightforward advantage. Of additional relevance is the time needed to deliver the water from LWA to the surrounding cement paste (release time) because the faster the release, the faster the overall curing. Therefore, the ideal aggregate for internal curing should combine a high capacity for water storage with reasonably fast release kinetics.

In this paper, the approach of improving the performance of LWA used as internal curing agent is focused on the understanding of its water uptake (absorption) and release (desorption) behavior. Two modifications affecting this behavior are investigated: (i) reduction of the characteristic length for the transportation of water through LWA (LWA with lower volume to surface ratio); and (ii)

modification of water transportation properties by modification of water surface tension. The first modification is carried out by crushing down the aggregate and thus reducing its volume-to-surface ratio. The second modification is achieved by the addition of surface tension modifiers such as those commonly used in shrinkage reducing admixtures (SRA). SRAs are surface active agents (surfactants) that diminish autogenous shrinkage by reducing the magnitude of capillary stresses and shrinkage strains that occur during drying of concrete (Shah *et al.*, 1992). A related reduction of plastic shrinkage has also been reported (Lura *et al.*, 2007). All the described effects of SRA in concrete performance can be ascribed to a reduced surface tension (Rajabipour, 2008). Water solution of SRA at the concentration 15% by mass has a surface tension reduced by 50% (Radlinska and Weiss, 2006), so the effect on capillary stresses and shrinkage can be expected to be reduced proportionally as suggested by Kelvin-Laplace equation (Bentz *et al.*, 1998). Moreover, since surface tension determines the wetting character of solid surfaces (Bonn *et al.*, 2009); lower values can be expected to result in faster filling of porous materials (Starov, 2004). In order to evaluate the capability of SRA for improving the curing function of LWA (uptake/release), relevant solutions are studied in the present work. Also, the effect of the maximum size of aggregate (MSA) as well as particle size distribution in the performance of selected aggregates are studied. The relevance of the results for specific mixtures of concrete is demonstrated by assessing autogenous shrinkage of the mixtures.

Experimental Procedure

The LWAs used in the study included expanded clay and expanded slate denominated after their particle size distributions as follows: expanded clay 10/5, expanded clay 5/0.08, expanded slate 20/5 and expanded slate 10/0.08, where the numbers correspond to the maximum and minimum particle size expressed in millimetres, respectively. The MSA as well as particle size distribution were determined by a sieve analysis. The main properties of the aggregates are shown in Table 7. The water uptake measurement (absorption test) was carried out using 500 g of the aggregate (oven-dry condition). The aggregate was placed in a 2-litre flask and the flask was then filled with the desired solution, up to the 2-litre mark. The reduction in volume, corresponding to the mass of water absorbed by the aggregate, was measured periodically by refilling the flask with the relevant solution up to the 2-litre mark and registering the new mass. Mass losses due to evaporation were avoided by a rubber cap. Uptake curves were produced by calculating the total water absorbed at given time intervals, normalized to the dry mass of LWA.

Table 7: The main characteristics of the LWA used in the study

LIGHTWEIGHT AGGREGATE	3-day Absorption (%)	Dry Specific Gravity (kg/m^3)	24-h SSD Specific Gravity (kg/m^3)	Open Porosity (%)	Mean Particle Size (mm)
Expanded Clay 10/5	23.3%	1,231	1,517	-----	2.35
Expanded Clay 5/0.08	32.5%	1,653	1,920	41.0%	0.77
Expanded Slate 20/5	5.5%	1,364	1,439	-----	3.99
Expanded Slate 10/0.08	13.8%	1,543	1,656	27.7%	1.28

The water release experiment (desorption test) was performed using 400 g of LWA. Each sample was previously pre-wetted in surface-dry condition for exactly 3 days. The LWA was kept in a hermetic repository containing saturated salt solutions for controlling the relative humidity (RH) in the inner ambient. In order to simulate the dessication process in concrete, six salts with equilibrium RHs ranging from 75% to 97% were used (see Table 8). Two criteria were used to determine whether hygral equilibrium between the LWA and the ambient was established: 1) loss of water in the last 24 hours being less than 0.5% of the total amount of water contained by the LWA, and 2) drying rate of the current week being lower than 25% of that in the first week. These criteria agree with those of ASTM C1498, however, with more demanding conditions. Once both criteria were met the LWA was moved to the next lower RH condition. In order to obtain statistically reliable results, three samples of each LWA were tested.

Table 8: Salts used for control of RH in the measurement of water release

SALT NAME	Chemical Formula	Equilibrium RH at 23°C (73°F)
Potassium sulphate	K_2SO_4	97%
Potassium nitrate	KNO_3	94%
Barium chloride dehydrate	$BaCl_2 \cdot 2H_2O$	90%
Potassium chloride	KCl	85%
Potassium bromide	KBr	81%
Sodium chloride	NaCl	75%

Autogenous shrinkage was measured applying the method developed by Jensen and Hansen (1995b). Flexible corrugated tubes of negligible axial stiffness were

used as molds for concrete in order to measure linear deformations immediately after setting (Jensen and Hansen, 2001). Autogenous shrinkage of concrete mixtures with each LWA was measured on three specimens prepared with a water-to-cement ratio (w/c) of 0.3. The mix designs of each concrete mixture are shown in Table 9. The amount of LWA required to provide sufficient water for internal curing was estimated using the equation developed by Bentz and Snyder (1999). The method considers the water necessary to maintain complete saturation within the hydrating cement paste in the quantity that compensates the chemical shrinkage at the expected maximum degree of hydration (Bentz *et al.*, 2005).

Table 9: Concrete mixture designs used for evaluation of autogenous shrinkage (kg/m³)

Mixture Compositions	Control	Exp Clay 10/5	Exp Clay 5/0.08	Exp Slate 10/0.08	Exp Slate 10/0.08 + SRA	Exp Slate 20/5
Portland Cement Type I	518	518	518	518	518	518
Water	155	155	155	155	155	155
Coarse aggregate	790	589	790	790	790	0
Fine aggregate (sand)	965	965	798	496	539	814
LWA (ssd condition)	-----	142	119	261	237	498
Superplasticizer	13	13	13	13	13	13

Results and Discussion

Water Uptake

The measured uptake curves for water and the SRA solution are shown in Figure 14. The amount of water absorbed by the LWA can be as high as 35% of its oven-dry mass and the process of water loading can take up to several weeks. However, the amount of water and loading time are strongly affected by the particle size

distribution and the presence or absence of SRA. The smaller particle size distributions are associated with higher loading capacity and faster absorption rates.

The presence of SRA generally slows down the progress of absorption. Some of the particles could not be fully filled for 90 days resulting in a non-asymptotic uptake curve. Since loading times of more than few weeks are impractical for field applications, this observation can be interpreted as an apparent lowering of loading capacity.

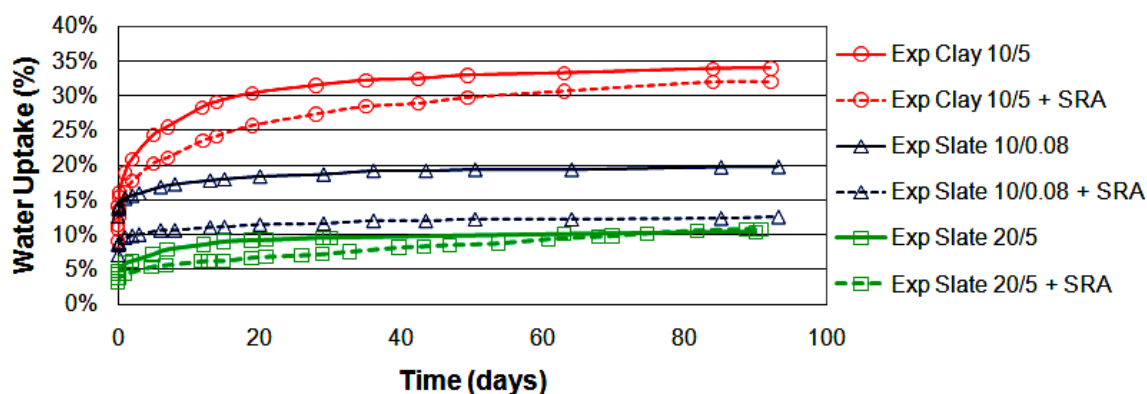


Figure 14: Absorption kinetics of water and water-SRA solution in the three indicated LWAs. The presence of SRA slows down the process of filling the aggregate.

Another feature of the water uptake process is the early absorption considered for the first 3 days and further referred to as the 3-day absorption. This indicator serves for distinguishing different behaviours with respect to size distribution. For instance, the 3-day absorption of expanded slate 10/0.08 is 150% higher than that of its 20/10 counterpart. This difference indicates that the inner porosity is not entirely exposed on the surface of the larger particles (20/10). Upon crushing, the

particle size is reduced resulting in faster filling of the aggregate. In particular, the smaller size distributions results in faster 3-day absorption, which can be explained based by easier access to the inner porosity. The 3-day absorption is also sensitive to the presence of SRA. That is, expanded clay 10/5 shows a 20% reduction and the expanded slate 10/0.08 an 18% reduction in 3-day absorption upon addition of SRA. This effect can be explained by the increase of viscosity caused by the surfactant. In fact, addition of 10% by mass of SRA can increase viscosity of distilled water by 45% or even 55% (Bentz, 2006). The increased viscosity inevitably results in slower filling because the available energy is consumed to overcome the internal friction of the liquid phase (Starov, 2004) rather than for the mass transport.

The rate of uptake is quantified in terms of uptake half times ($t_{1/2}$), i.e. the times to absorb 50% of the maximum water load. In cases where the maximum load was not achieved, the last value of the 90-day measurement is taken. The obtained values of half times (Table 10) support the qualitative description of absorption kinetics discussed above.

Table 10: Half times and diffusion coefficients obtained from the uptake measurements

LIGHTWEIGHT AGGREGATE	$t_{1/2}$ (days)	Coefficient of Diffusion (m^2/s)
Expanded Clay 20/10	4.5	1.51×10^{-12}
Expanded Clay 10/5	4	6.15×10^{-13}
Expanded Clay 10/5 + SRA	5	3.15×10^{-13}
Expanded Clay 5/0.08	0.8	1.47×10^{-13}
Expanded Slate 20/5	6	1.10×10^{-12}
Expanded Slate 20/5 + SRA	25	3.39×10^{-13}
Expanded Slate 10/0.08	4	1.38×10^{-13}
Expanded Slate 10/0.08 + SRA	2	1.50×10^{-13}

The different absorption behavior between expanded clay and expanded slate is ascribed to the inherent differences in aggregate microstructure (porosity, pore size distribution, tortuosity, pore interconnectivity, etc.).

Interpretation of the uptake curves in terms of diffusion is conducted in section “*Diffusion in LWA*”.

Water Release

The equilibrium desorption curves are shown in Figure 15. The amount of water released at a given RH depends on the particle size distribution, and it is affected by the presence of SRA only for the smaller particles and only at the higher RHs. This can be explained by the number of pores at which evaporation takes place. The more pores are exposed, the more intense is the process, so that the effect of SRA is more pronounced.

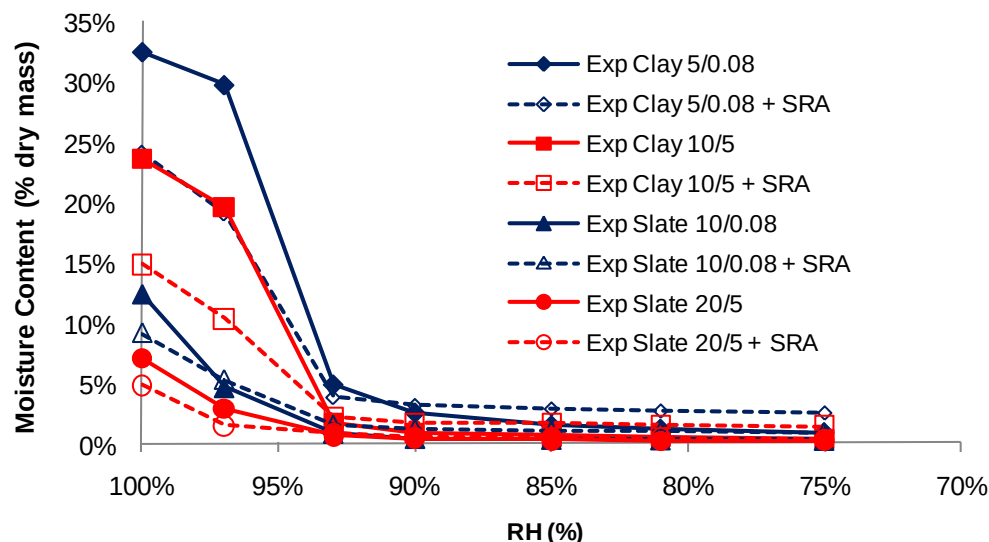


Figure 15: Equilibrium desorption curves of water and water-SRA solutions for the indicated LWAs internal curing reservoirs comparison. For clarity of the figure only selected results are included.

Initially, evaporation from the sample with the SRA solution is enhanced due to the lower activation energy required for evaporation (Rusdi *et al.*, 2005). As evaporation progresses, the concentration of surfactant in the pores increases (Rajabipour *et al.*, 2008), which increases the activation energy for evaporation and thus decreases its rate (Hui *et al.*, 2003). This interpretation is additionally supported by the observed decrease of desorption rates (grams of water delivered per day at a given RH relative to the grams of dry LWA) in the presence of SRA. The specific values are collected in Table 11. The desorption rate of expanded slate 10/0.08 is 46% slower at 97% RH, and 38% slower at 93% RH, in the presence of SRA. At the same conditions, expanded slate 20/5 shows analogous decreases by 28% and 37%.

Table 11: Desorption rates of each LWA for constant 97% and 93% RH

LIGHTWEIGHT AGGREGATE	97 % RH * ($\times 10^{-4}$)	93 % RH * ($\times 10^{-4}$)
Expanded Clay 10/5	6,0	11,2
Expanded Clay 10/5 + SRA	3,3	7,5
Expanded Clay 5/0.08	6,7	13,0
Expanded Clay 5/0.08 + SRA	4,4	10,0
Expanded Slate 20/5	4,5	5,6
Expanded Slate 20/5 + SRA	3,3	3,6
Expanded Slate 10/0.08	5,9	10,7
Expanded Slate 10/0.08 + SRA	3,2	6,6

* Grams of water released by grams of dry LWA per day

Similarly to the uptake measurements, here, the desorption kinetics could be quantified in terms of half times, i.e, times at which 50% of the initial amount of water is released at a given RH. The desorption half times for 97% and 93% RH (Table 12) are generally at least one order of magnitude lower than the corresponding absorption half times. This discrepancy is due to the so-called evaporation barrier (Crank, 1957) that limits the mass transfer at the surface of the aggregate.

Table 12: Half times of desorption (water release) obtained for constant 97% and 93%

RH.

Desorption / Water Release	97% RH $t_{1/2}$ (days)	93% RH $t_{1/2}$ (days)
Expanded Clay 20/10	33	56
Expanded Clay 10/5	34	51
Expanded Clay 10/5 + SRA	58	55
Expanded Clay 5/0.08	32	83
Expanded Slate 20/5	48	11
Expanded Slate 20/5 + SRA	39	13
Expanded Slate 10/0.08	65	15
Expanded Slate 10/0.08 + SRA	45	17

Diffusion in LWA

Since both uptake and release of water are strongly related to the process of diffusion in the porous medium of LWA, it is reasonable to discuss this aspect separately. Diffusion is generally understood as transport of mass driven by the difference in concentration. It is typically characterized by the coefficient of diffusion, which puts a figure on the time associated with the transport. Since the desorption curves are additionally affected by the evaporation barrier, determination of diffusion coefficients is conducted using exclusively the absorption data. The initial rapid uptake associated with the filling of large cracks, readily available pores, and interparticular spaces is neglected in the analysis. This correction is justified by the fact that the initial filling is not a limiting factor for

the absorption kinetics and thus does not contribute to the diffusion coefficient of the porous microstructure.

Considering a single aggregate as a homogeneous diffusion domain the filling with water can be described by second Fick's law of diffusion. Taking into account the regular shape of the particles the diffusion problem can be described in spherical geometry giving equation 4.1:

$$\frac{\partial C}{\partial t} = D_{eff} \left(\frac{\partial^2 C}{\partial r^2} + \frac{2}{r} \frac{\partial C}{\partial r} \right) \quad (4.1)$$

where t , r , C and D_{eff} are time, radius coordinate, actual water content at $r(t)$, and the effective diffusion coefficient, respectively. Since the equation is solved for a homogenous domain the effective diffusion coefficient already contains the information on porosity and tortuosity of the medium. The possible effect of surface diffusion (Hui *et al.*, 2003) is likewise included. The abundance of water outside the particle in comparison to the immersed mass allows for solving equation 4.1 under the assumption of constant water concentration at the aggregate surface. The amount of water absorbed at a given time is then obtained by integration of the solution from $r = 0$ to the actual particle radius resulting in equation 4.2 (Ruthven, 1984):

$$\frac{m_t}{m_\infty} = 1 - \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp \left(- \frac{n^2 \pi^2 D t}{r_c^2} \right) \quad (4.2)$$

where m_t , m_∞ and r_c is the mass absorbed at time t , the total absorbed mass when $t = \infty$ and the particle radius, respectively. However, some of the measured uptake curves were not fully saturated, so for the purpose of this analysis the last measured value (90 days) was assumed as the maximum absorbed amount, i.e., $m_\infty = m_{90}$. This assumption may result in a slight overestimation of the determined diffusion coefficients, but is justified by the difficulty in determination of the precise value. The representative value of aggregate particle radius, r_c , was taken as the mean particle size $\bar{r}_c$ (Table 7). A least square fitting procedure was used for fitting equation 4.2 (with $n = 11$) to the experimental curves. The obtained diffusion coefficients are shown in Table 10.

The obtained diffusion coefficients range from $1.50 \cdot 10^{-13} \text{ m}^2 \text{ s}^{-1}$ to $1.51 \cdot 10^{-12} \text{ m}^2 \text{ s}^{-1}$, which is at least two orders of magnitude lower than the value obtained by Takahara *et al.* (2005) for pure water in a mesoporous medium (pore size of approx. 2 nm). Although the values of Takahara *et al.* correspond with the self-diffusion coefficient obtained from a quasielastic neutron scattering (QENS) spectra, the values obtained in this study by a transient method can be interpreted as an indication of microporosity (pore size $< 2 \text{ nm}$) or high tortuosity. Whereas the existence of micropores is known for some LWAs, e.g. (Zhang and Gjørsv, 1991a), there is not much information concerning tortuosity. Since tortuosity can alter the effective coefficient of diffusion by an order of magnitude (Stempniewicz *et al.*, 2007) none of the interpretations is preferred.

The presence of SRA in the absorbed water is negatively correlated with the obtained diffusion coefficient. As discussed in 4.1, this effect can be explained by the increased viscosity of the solution. The only exception from this rule is expanded slate 10/0.08 where no appreciable decrease of D_{eff} is observed.

A positive correlation between the mean particle radius and the corresponding diffusion coefficient has been found (Figure 16). This observation suggests that the diffusion process is at least partially controlled by mass transfer through the external surface (surface diffusion barrier). This surface mass transfer is crucial for the interaction with the cement paste. In particular, it determines the extent of the interfacial transition zone (Zhang and Gjrv, 1990), (Bentz, 2009).

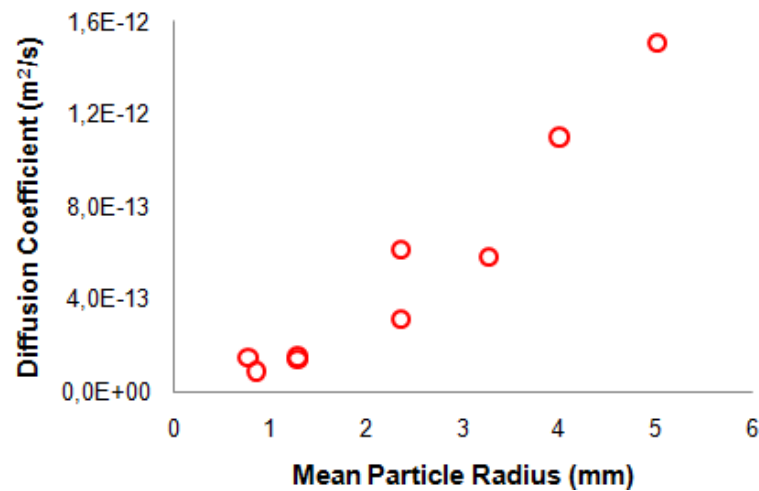


Figure 16: Relationship between the obtained diffusion coefficients and the corresponding mean particle radius. The positive correlation indicates the presence of surface resistance to diffusion.

Autogenous Deformation

The results of the autogenous shrinkage test for mixtures containing expanded clay and expanded slate are shown in Figure 17 and Figure 18, respectively.

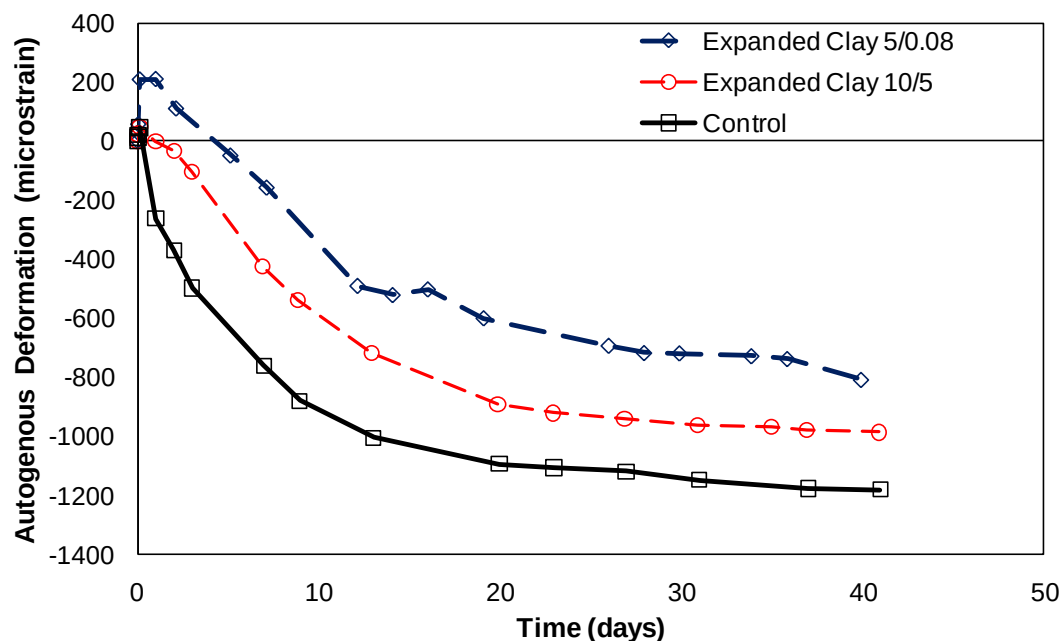


Figure 17: Autogenous deformation of concrete containing expanded clay aggregate.

The presence of LWA diminishes the shrinkage depending on its particle size distribution.

In general, the use of LWA appreciably reduces the extent of autogenous shrinkage. Unlike the control mixture, the internally cured samples show an initial expansion between 200 and 400 microstrains followed by a consistent reduction of the autogenous deformation. Mixtures prepared using LWA with reduced maximums size aggregate (MSA) are characterized by a greater reduction of autogenous shrinkage as compared with their larger size counterparts. It should be noted that mixtures with smaller MSA contained lower fraction of the respective

LWA (details in Table 9), so the lower autogenous shrinkage cannot be explained solely by the quantity of provided water. This effect is likely caused by a more homogeneous distribution of the internal curing water and an enhanced availability of water due to the greater surface-to-volume ratio. These features promote water supply at a timely manner.

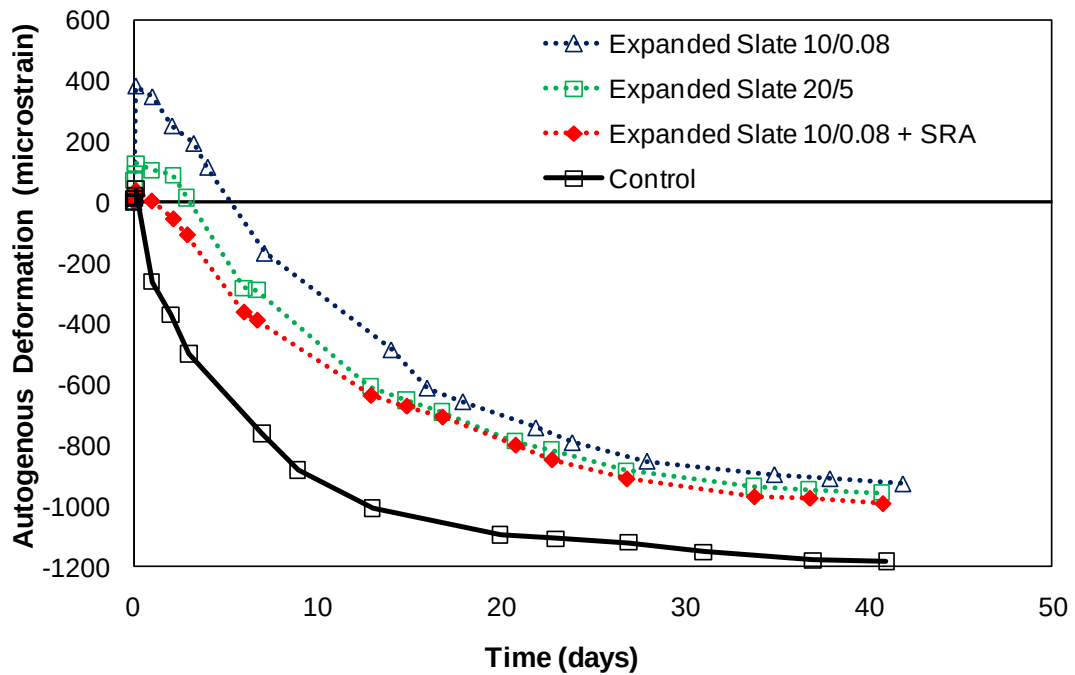


Figure 18: Autogenous deformation of concrete containing expanded slate aggregate. The presence of LWA diminishes the shrinkage and is further affected by the particle size of the LWA as well as the presence of the 15% by mass SRA solution

Mixtures prepared with the same MSA show higher autogenous shrinkage when soaked with the solution of SRA (Figure 17). That is, the use of SRA solution instead of pure water brings no advantage with respect to autogenous shrinkage. A possible reason for the limited improvement is the limited transfer of the organic molecules of SRA from the aggregate to the surrounding paste. Since most of the

water is transferred in the form of humidity the possibility for SRA to be carried by diffusion is restricted. On the other hand, as evaporation proceeds, the concentration of SRA increases inside the LWA and the rate of evaporation is decreased; thus, less water is effectively delivered in a given time interval. These two causes add together to the worse performance of the mixtures with SRA solution.

Summary and Conclusions

The use of SRA solution to enhance internal curing of concrete is a new approach of providing a secondary function to the current internal curing technology. Apart from reducing autogenous shrinkage by lowering self-desiccation, it could also reduce autogenous shrinkage by lowering capillary stresses. This should be possible because SRA, being inherently a surfactant, reduces surface tension upon solution in water. In addition, the effect of MSA and size distribution of LWA on internal curing of concrete has been studied with the rationale of improving the overall distribution and availability of water.

The present study, with 15% by mass polyoxyalkylene alkyl ether as SRA performed on expanded clay and expanded slate on different size distributions, contributes to the understanding of mechanisms involved in water uptake and release present in internal curing of concrete. In particular, the following conclusions are reported:

- (1) The uptake and release kinetics of LWAs loaded with the SRA solution is from 28% to 46% slower as compared with pure water. The specific value depends

on the actual type of the aggregate and its size distribution. This result is explained by a higher viscosity of the SRA solution, which delays the transport of the solution through the porous medium.

(2) The water loading capacity of LWAs (maximum absorbed volume) is apparently reduced in the presence of SRA. This reduction is attributed to the slow uptake kinetics that prevents the complete loading within the provided time (90 days). The amount of water absorbed and delivered by LWA cannot be anticipated based solely on the general characteristics of the aggregate (specific gravity, 24-h absorption, porosity).

(3) The particle size distribution of the aggregate has a strong influence on the water loading characteristics. Smaller particle sizes present higher loading capacity and faster absorption rates, which is ascribed to enhanced accessibility to the inner porosity after crushing the aggregate.

(4) Quantification of the kinetics of water transport through LWAs can be realized in terms of either half times, delivering mean times of absorption, or diffusion coefficients. The later requires modeling of the diffusion process but delivers additional information on processes.

(5) In spite of lowering surface tension the presence of SRA did not prove advantageous for neither water transport in LWA nor reduction of autogenous shrinkage.

(6) Lower values of autogenous shrinkage are obtained by using LWA of lower MSA and smaller size distribution. The improved absorption and release kinetics together with the better spatial distribution explain these results.

Corroborating, it is the geometry, structure and distribution of the aggregate rather than presence of SRA that improves performance of internal curing. A simple improvement of wetting properties is evidently insufficient for improving the internal curing of concrete. Thus, interplay of multiple parameters and phenomena has to be taken into account when designing strategies to improve LWA performance as internal curing agent. Due to the potential impact of improved technology of internal curing, the incorporation of alternative SRAs or the use of lower dosages is expected to provide a balance between lower surface tension and reasonable viscosity.

5. CONCLUSIONS AND RECOMMENDATIONS

Internal curing of concrete has been intensively studied during recent years, but there are several questions that need to be answered if it is expected a wide use within concrete industry. For instance, it is common that only the beneficial effects of internal curing are visible in researches or that the publications focused the investigations on artificial lightweight aggregates (LWAs).

Internal curing has proved to mitigate autogenous shrinkage in high performance concrete (HPC) effectively, but it is also attractive to provide, additionally, benefits on other pathologies of concrete to reaching an “internal healing”. Thus, corrosion inhibitors, shrinkage-reducing admixtures (SRAs) or admixtures for mitigating alkali-silica reaction (ASR) could be included in the water solution used for the saturation of the LWA. A well-distributed delivery of specific chemicals from inside concrete could have a great impact improving durability of concrete.

5.1 Conclusions

In this research, a series of natural and artificial LWAs were studied in order to analyze their performance as internal curing agents in concrete as well as to know the main differences in the properties of the aggregates. From this part of the study, the following results and conclusions were obtained:

- Natural LWAs present a higher, well-interconnected porosity that allow a higher and faster water uptake during immersion.

- Natural LWAs can release a higher amount of water, at higher rates, when they are subjected to a RH gradient, as it is expected within concrete during self-desiccation.
- The replacement of normalweight aggregate by LWA for providing internal curing showed a significant reduction of compressive strength and increase in chloride ion penetrability of concrete. The same amount of internal curing water was considered to be delivered by the LWAs. It could be seen that the smaller the amount of the replacement; the smaller the impact over the properties of concrete.
- The high water uptake and release capacity of natural LWAs allows for reduction in the replacement of the normalweight aggregate by LWA which brings lower impacts in compressive strength of concrete.
- Concrete using LWA as internal curing agent showed a higher degree of hydration than that obtained in the control mixture without internal curing.
- Concrete using LWA as internal curing agent showed reductions of the 7-day autogenous shrinkage between 36 and 78% with respect of the control mixture and reductions of the 40-day autogenous shrinkage between 6 and 37% with respect of the control mixture.

Additionally, two alternatives for improving internal curing benefits in artificial LWAs were evaluated: the use of SRA solution (15% by mass) and changes in LWA particle size distributions. SRA solution (15% by mass) is expected to decrease the surface tension of water by 50%, but also increase viscosity between

45 and 55% Reduction of particle size distribution is expected to increase the surface-to-volume ratio. Thus, a higher porous surface is expected to be exposed for water transport. From this part of the study, the following conclusions were obtained:

- The water uptake and release kinetics of LWA loaded with SRA are slower compared with pure water. A higher viscosity of SRA solution delays the transport of the solution through the porous medium.
- The mitigation of autogenous shrinkage using SRA solution as internal curing provision does not show an improvement compared to the use of pure water, when the same aggregate was used.
- Particle size distribution of the aggregate showed a strong influence in water loading. Higher water uptake capacity and higher rates of water release were observed.
- The use of aggregates with lower particle size distribution showed a better performance than using a SRA solution (15% by mass) in the mitigation of the autogenous shrinkage.

5.2 Recommendations and Further Research

The use of SRA in concrete has showed significant reductions in shrinkage. Nevertheless, the use of a SRA solution for the loading of internal curing agents presents some difficulties that make this method inadvisable at the moment. The increase in the viscosity derived from SRA reduces the diffusion coefficient of the

internal curing solution, decreasing the efficiency of the internal curing agents. Therefore, a topical application or the inclusion as a current additive during mixing seems to be a better way to provide SRA. If other chemical additives are intended to be applied through internal curing agents, a balance between the adverse and the expected beneficial effects need to be done.

Different concentrations of SRA could be tested to determine a balance between the reduction of the surface tension (which reduces shrinkage) and the increment of viscosity (which difficult the transport of water through a porous medium). Thus, an optimal value for internal curing could be obtained.

The reduction of the particle size distribution and the maximum size of the aggregate appear as a sound modification to improve the efficiency of internal curing agents. Nevertheless, the reduction of the LWA dosage due to the increase in efficiency can increase the distance that water needs to travel in such way that water will not be able to reach unhydrated cement particles and a reduction in the efficiency of the internal curing might occur. Thus, different particles size distribution could be tested in natural LWAs, as it was performed in artificial LWAs.

Natural LWAs are a good alternative for internal curing, when they are compared to the extensively studied artificial LWAs. Some developing countries have extensive sources of natural LWAs such as pumice, so the analysis of their properties is recommended and the use of this type of aggregate seem to be an economic way to enhance properties of concrete.

This research made an extensive analysis of the water uptake results, but to make a similar review with the water release test, further literature review is necessary and more complex equations are needed to be solved. Besides, an experimental observation of the water transport during internal curing could be performed by X-ray microtomography, making an empirical testing of the theoretical calculations. Also, a higher analysis of the smaller pores (nanopores) of the aggregates could be achieved using nitrogen BET analysis instead of the MIP test.

The method used to estimate the amount of LWA for replacement did not totally eliminate autogenous shrinkage. Besides, relevant variables such as rate of water release or particle size distribution of the LWA are not taken in account. Thus, a modification of the formula is desired to determine the volume of pre-wetted LWA needed to control autogenous shrinkage.

The effect of internal curing could be tested in other properties of concrete such as modulus of Young, toughness, resistance to cracking under restrained shrinkage or strength in tension. Also, analysis of actual concrete elements or in-site application of internal curing could be performed.

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APPENDIX A: IMAGES OF THE EXPERIMENTAL WORK

a) Autogenous Shrinkage



Appendix A Figure 1: Constant climate chamber for autogenous shrinkage specimens

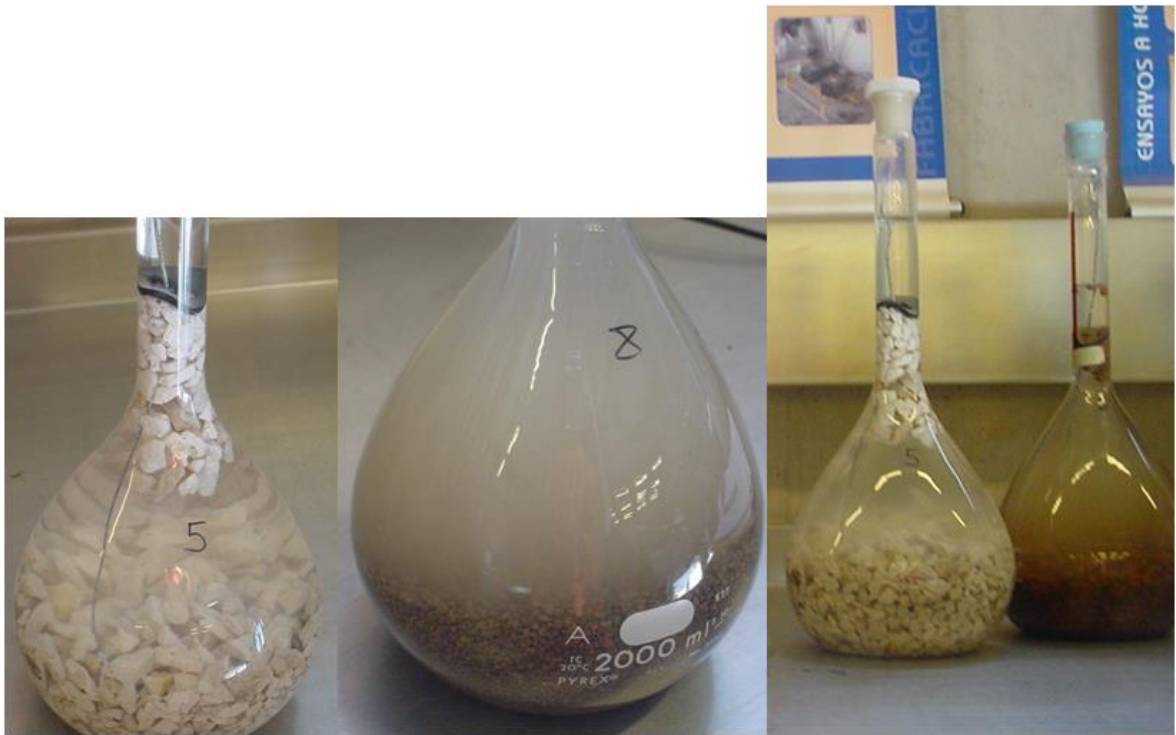


Appendix A Figure 2: Apparatus for determination of length change of specimens

b) Compressive Strength

Appendix A Figure 3: Compressive strength test for 200 x 100 mm cylindrical specimens

c) Water Uptake (absorption)



Appendix A Figure 4: Flasks used in the test of water uptake

d) Water Release (desorption)



Appendix A Figure 5: Inside the climate chamber: recipients with saturated salt and relative humidity sensor



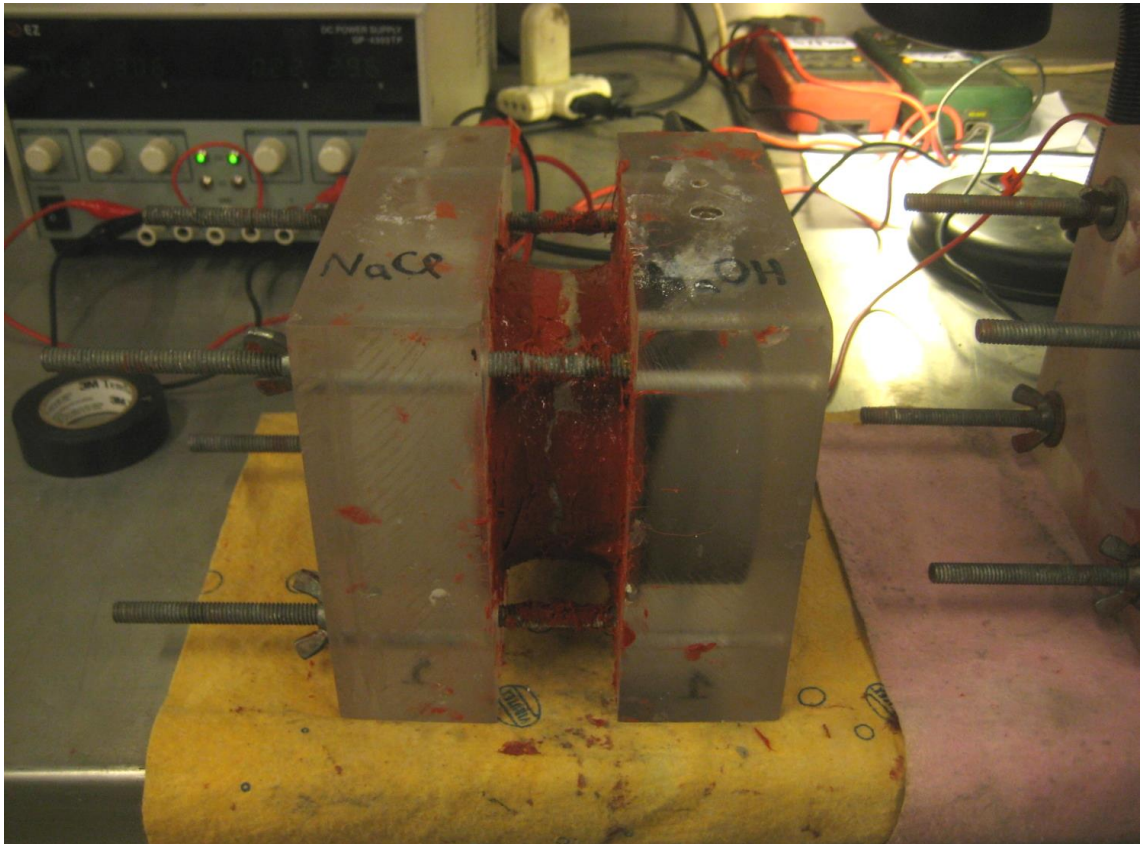
Appendix A Figure 6: Measurement of the mass loss due to water release of the LWA (weighing)

e) Mercury Intrusion Porosimetry (MIP)



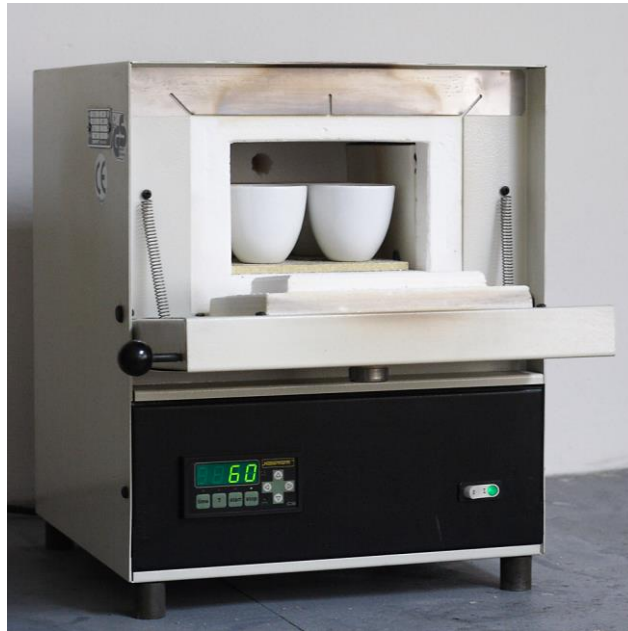
Appendix A Figure 7: Micromeritics autopore mercury injection instrument

f) Chloride Ion Permeability



Appendix A Figure 8: Chloride ion permeability test

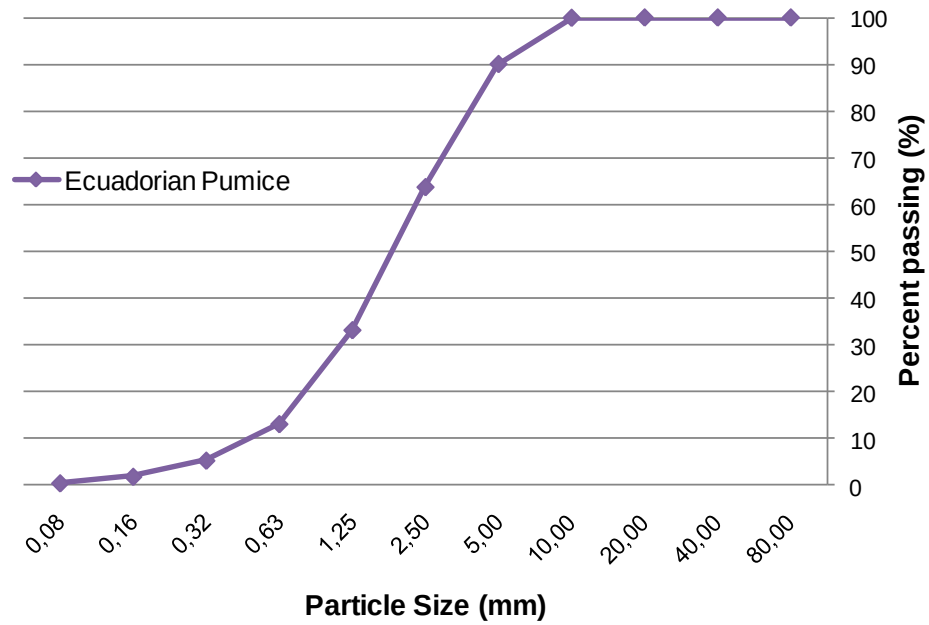
g) Degree of Hydration (loss on ignition)



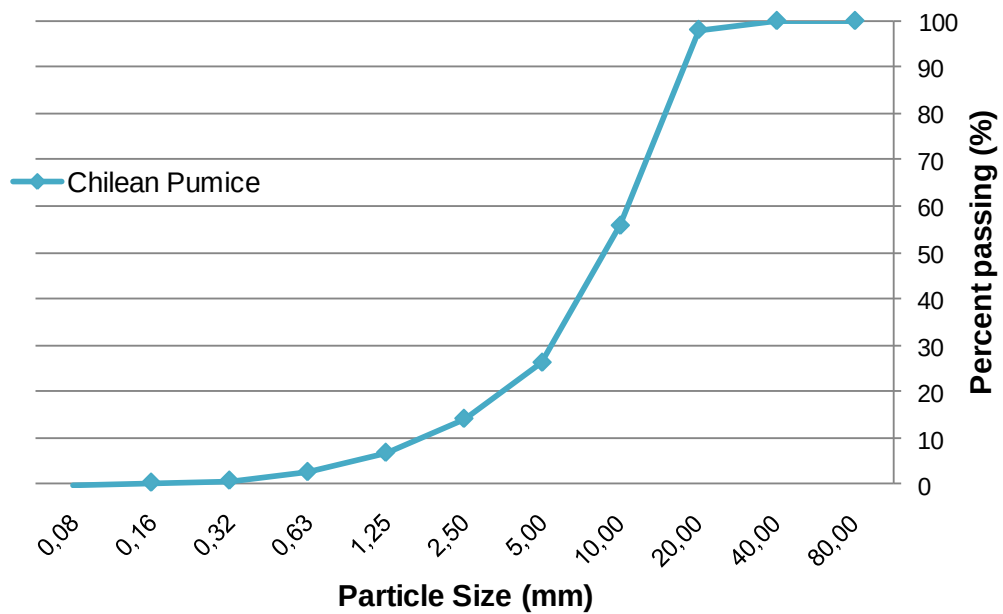
Appendix A Figure 9: Ignition of samples in the muffle furnace



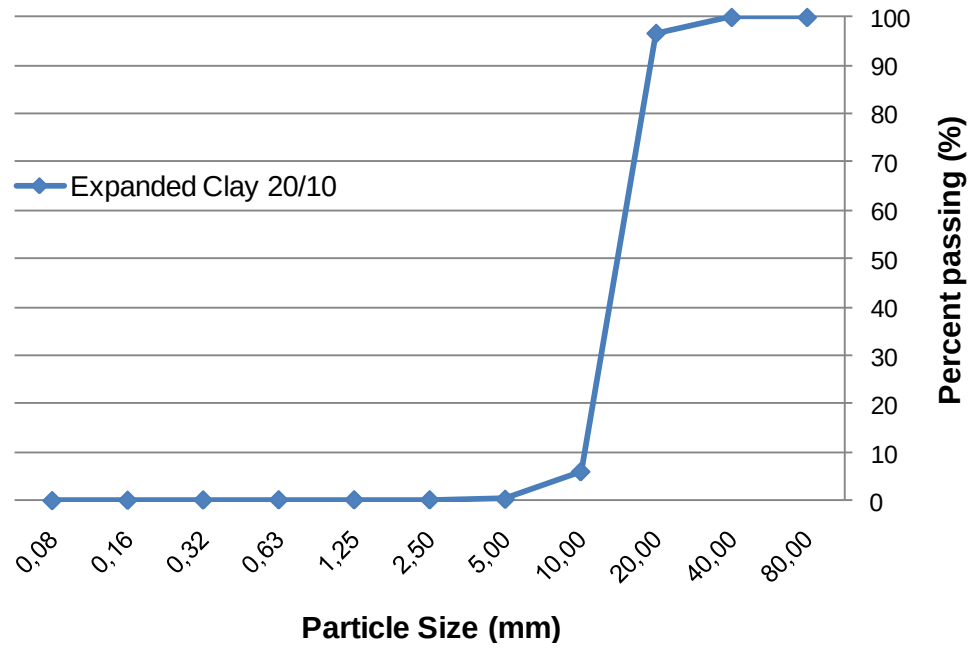
Appendix A Figure 10: Ceramic crucibles to determine the degree of hydration

APPENDIX B: PROPERTIES OF THE AGREGATES**a) Sieve Analysis for Particle Size Distribution (granulometry)**

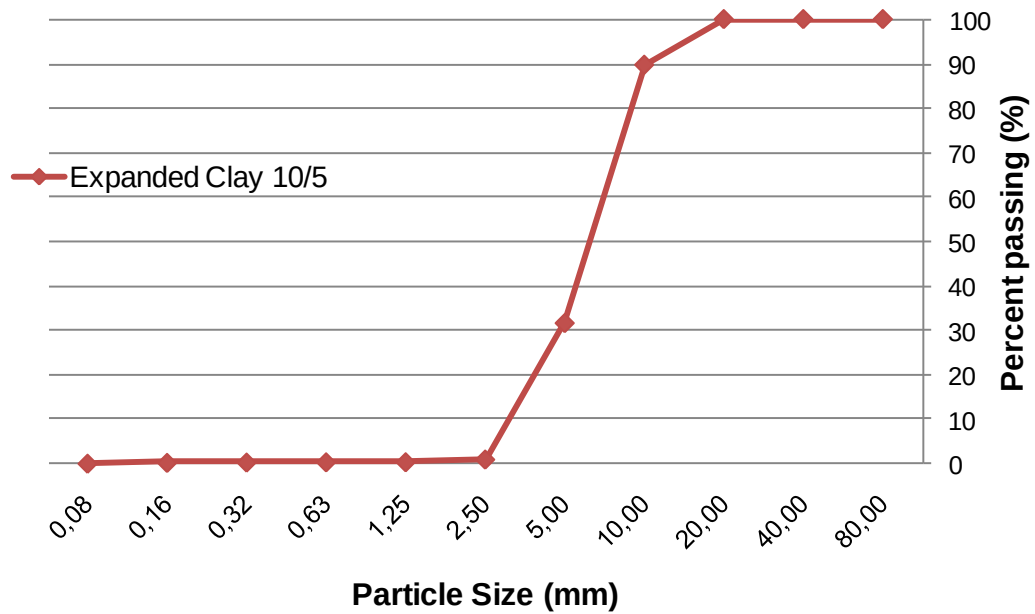
Appendix B Figure 1: Sieve analysis for pumice from Ecuador



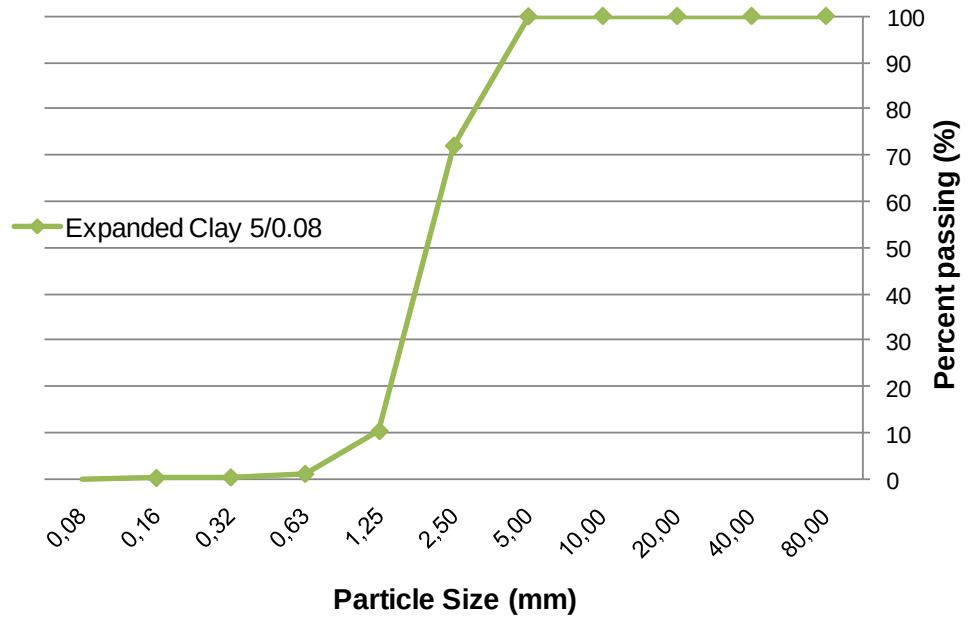
Appendix B Figure 2: Sieve analysis for pumice from Chile



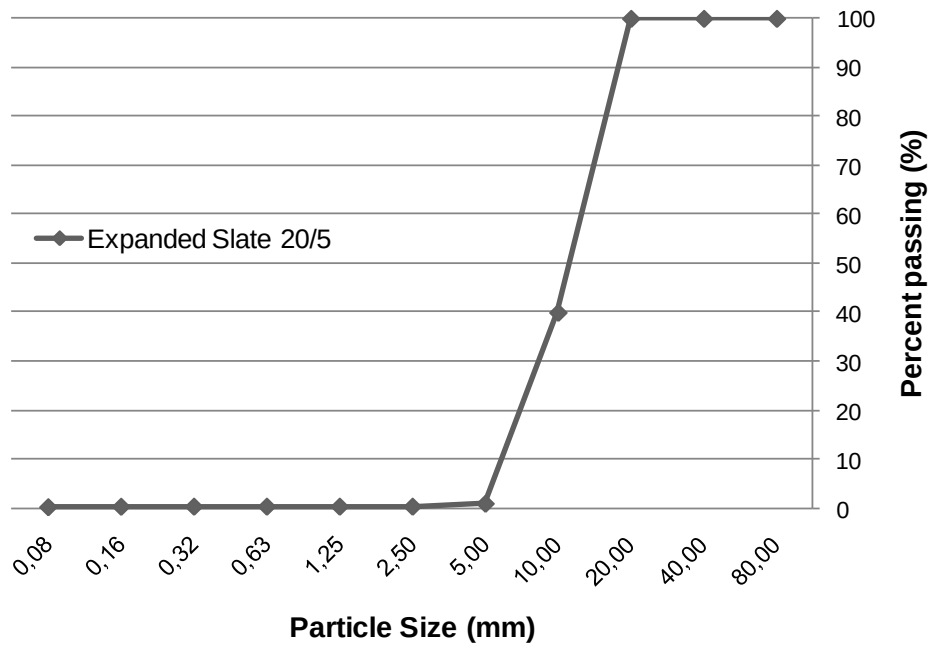
Appendix B Figure 3: Sieve analysis for expanded clay 20/10



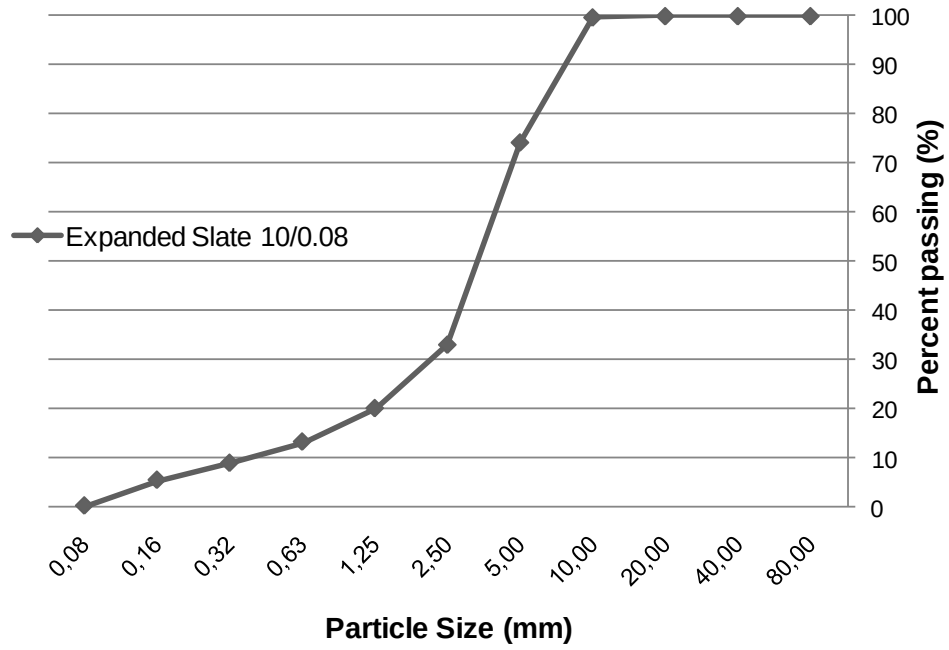
Appendix B Figure 4: Sieve analysis for expanded clay 10/5



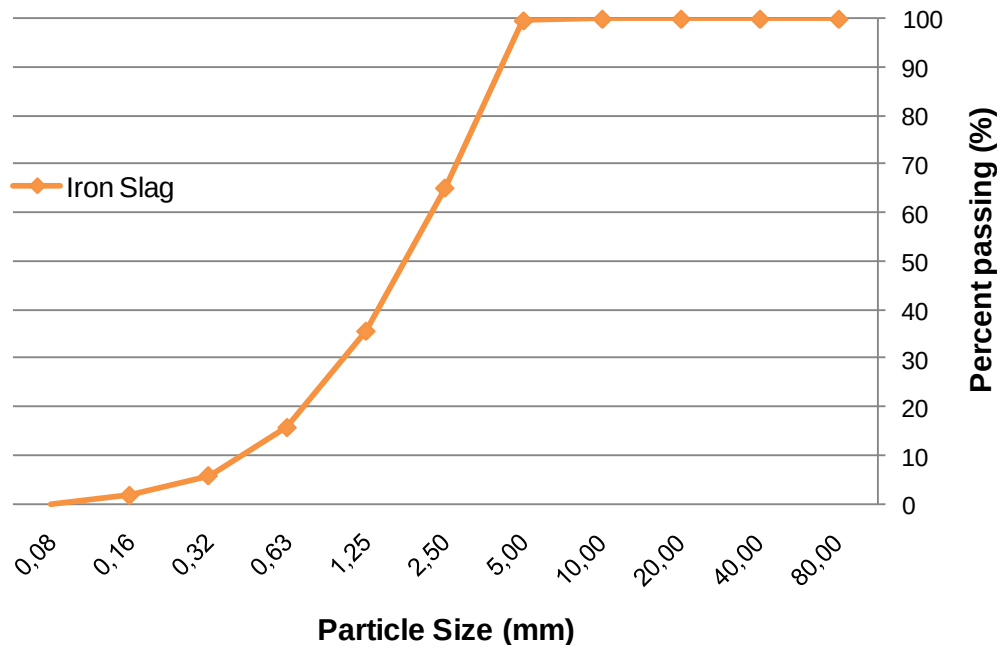
Appendix B Figure 5: Sieve analysis for expanded clay 5/0.08



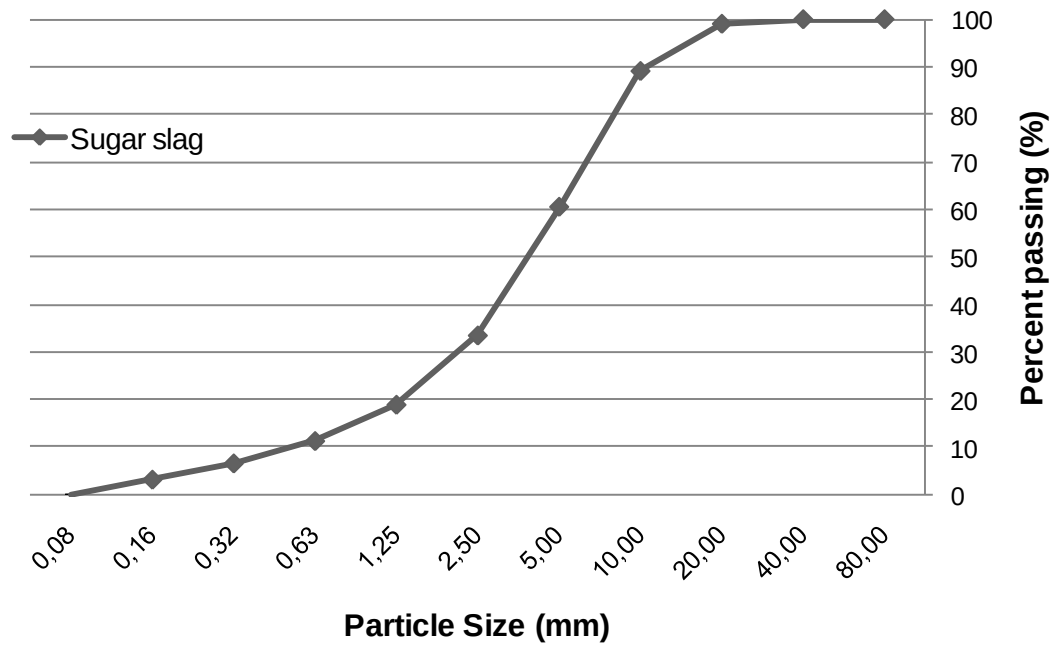
Appendix B Figure 6: Sieve analysis for expanded slate 20/5



Appendix B Figure 7: Sieve analysis for expanded slate 10/0.08

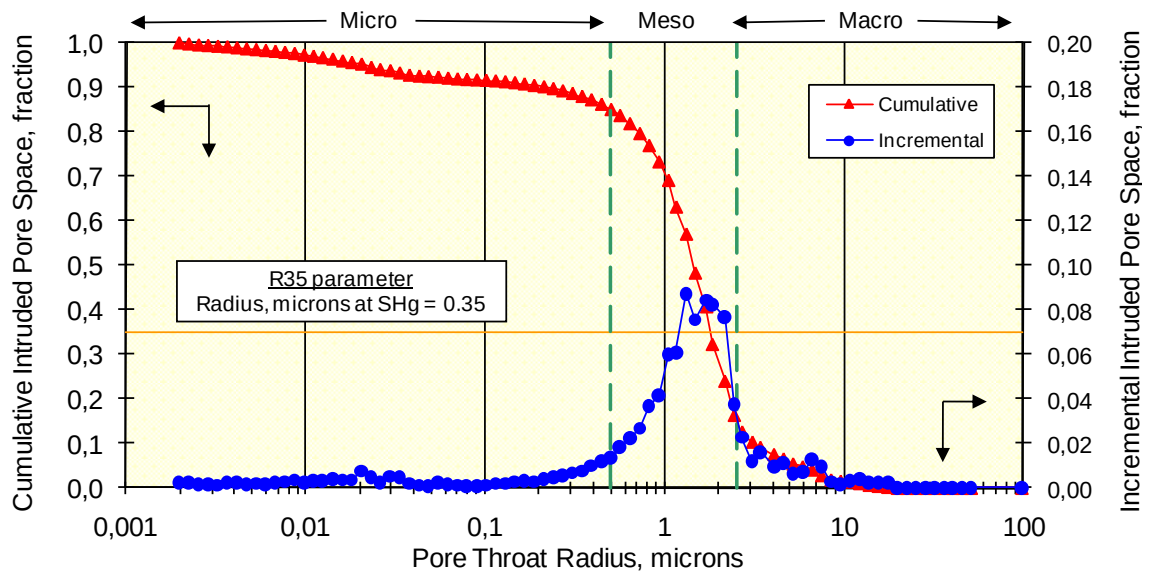


Appendix B Figure 8: Sieve analysis for iron slag

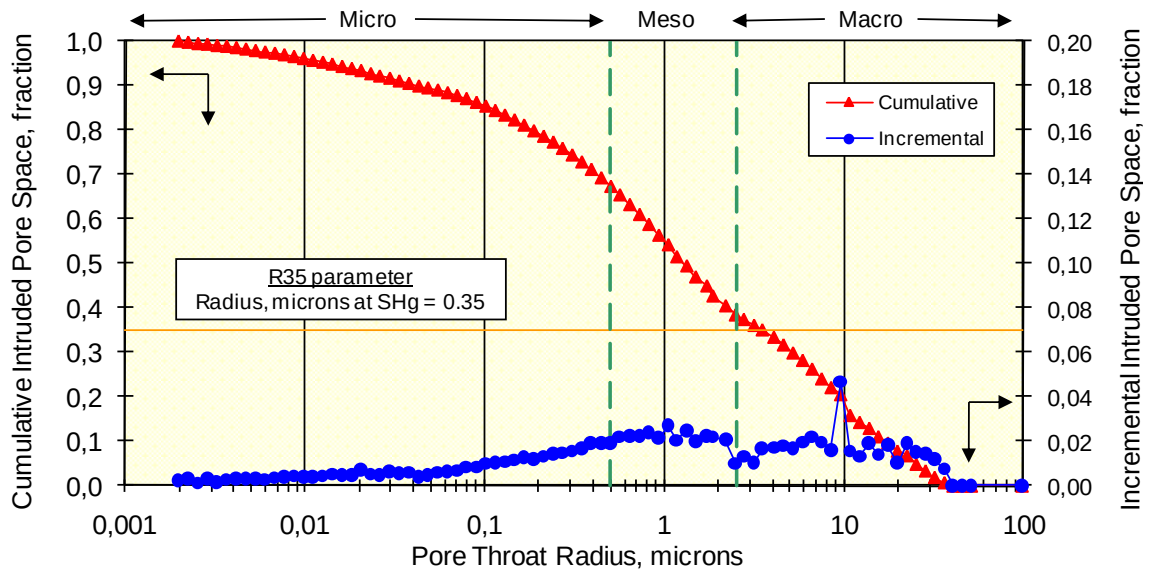


Appendix B Figure 9: Sieve analysis for sugar slag

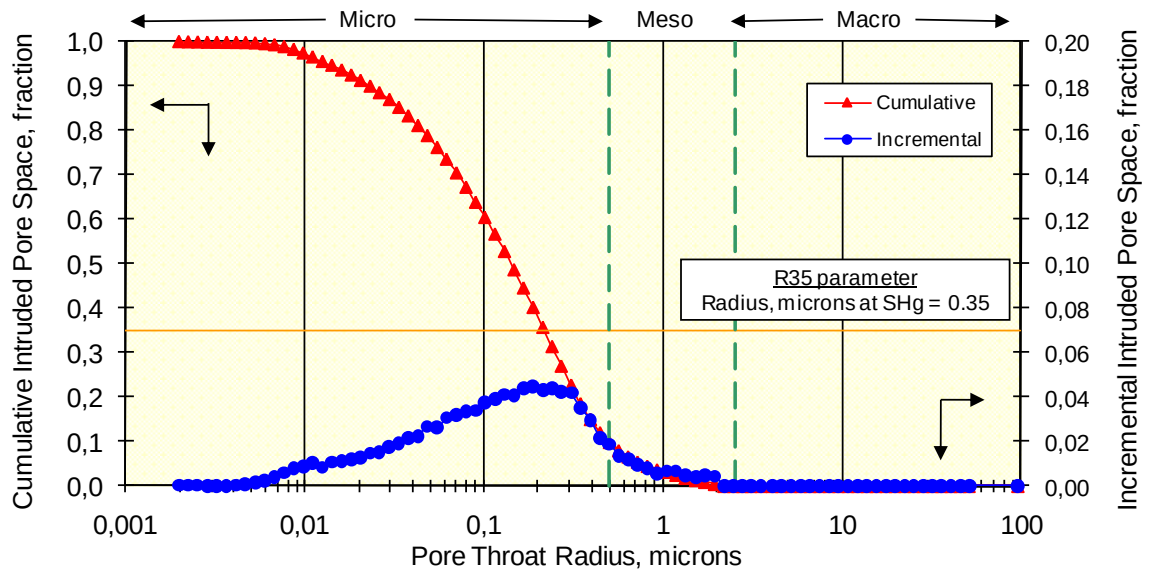
b) MIP Test for Pore Size Distribution



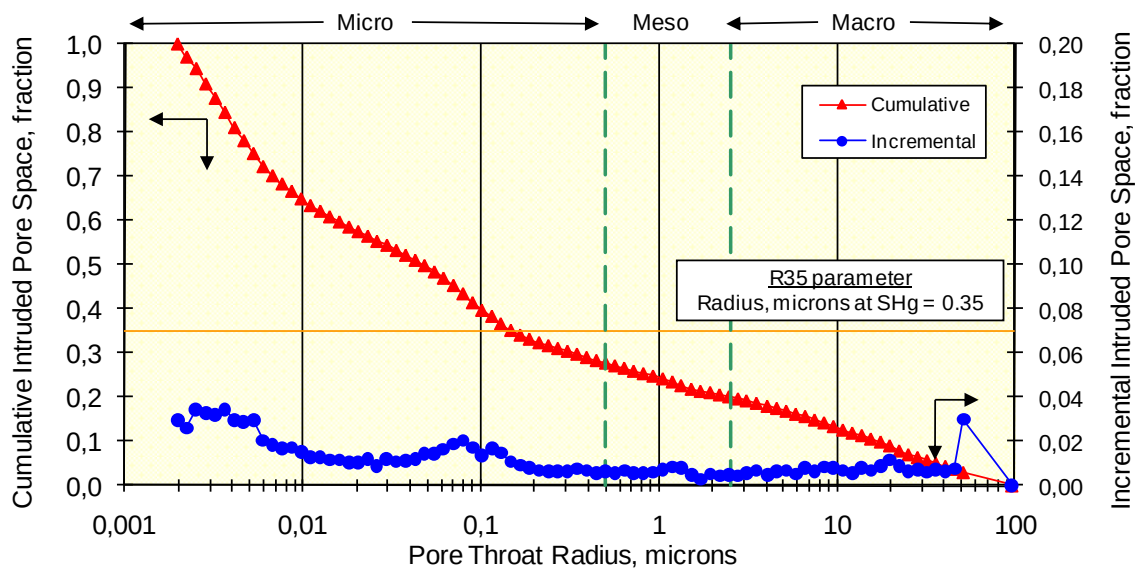
Appendix B Figure 10: MIP analysis of pumice from Ecuador



Appendix B Figure 11: MIP analysis of pumice from Chile



Appendix B Figure 12: MIP analysis of expanded clay 5/0.08



Appendix B Figure 13: MIP analysis of expanded slate 10/0.08

b) Images of the Lightweight Aggregates Analyzed in the Research.



Appendix B Figure 14: Pumice from Ecuador



Appendix B Figure 15: Pumice from Chile



Appendix B Figure 16: Expanded clay 20/10



Appendix B Figure 17: Expanded clay 10/5



Appendix B Figure 18: Expanded clay 5/0.08



Appendix B Figure 19: Expanded slate 20/5



Appendix B Figure 20: Expanded slate 10/0.08



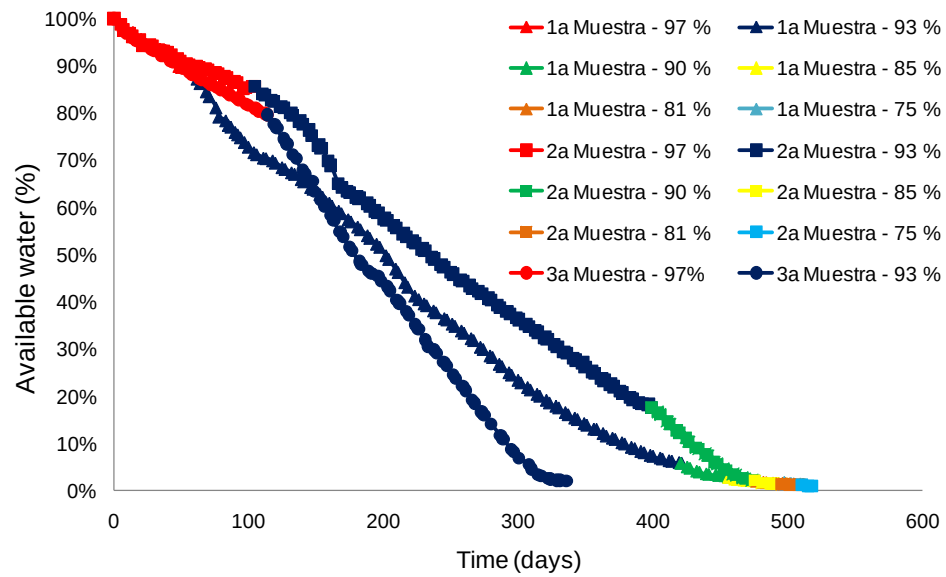
Appendix B Figure 21: Sugar slag



Appendix B Figure 22: Iron slag

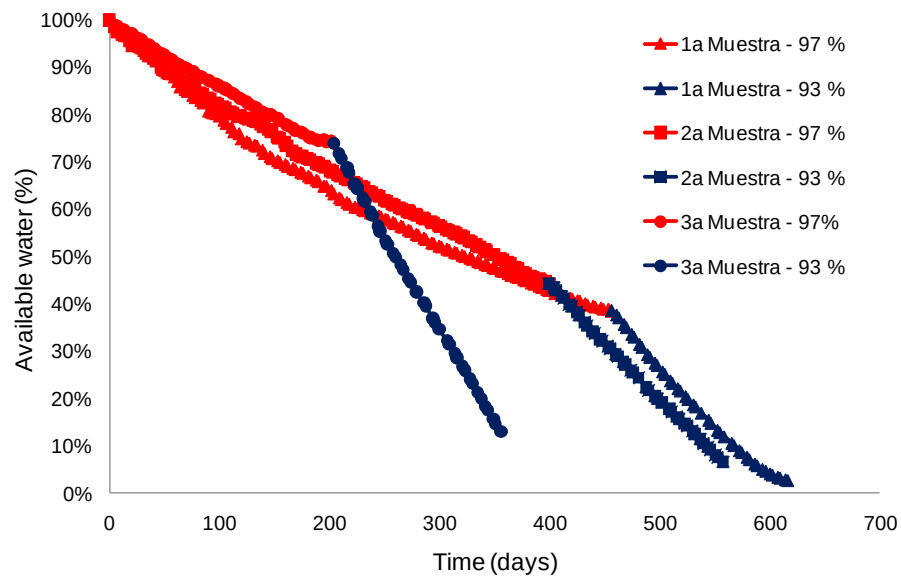
c) Water Release Graphs.

- Pumice from Ecuador:



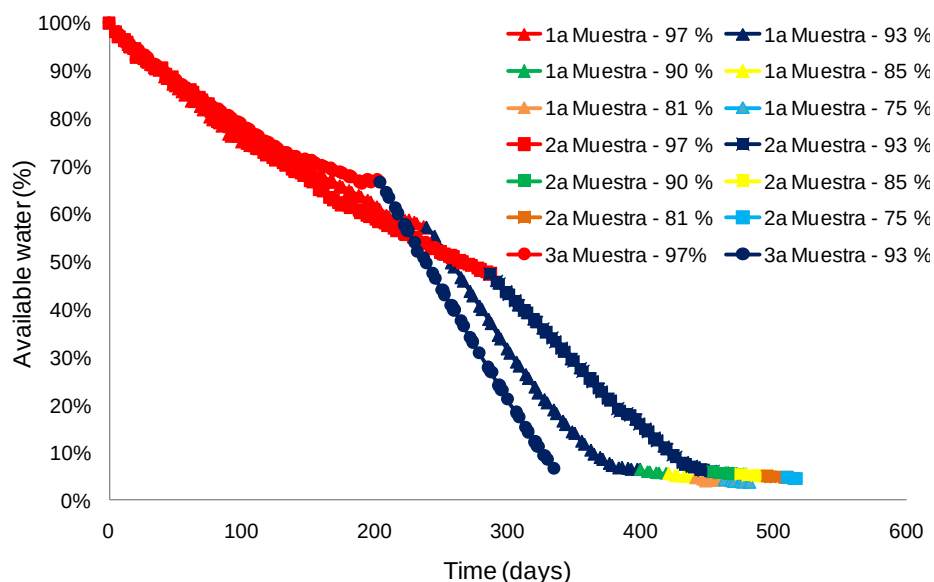
Appendix B Figure 23: Release of water for pumice from Ecuador (instant availability)

- Pumice from Chile:



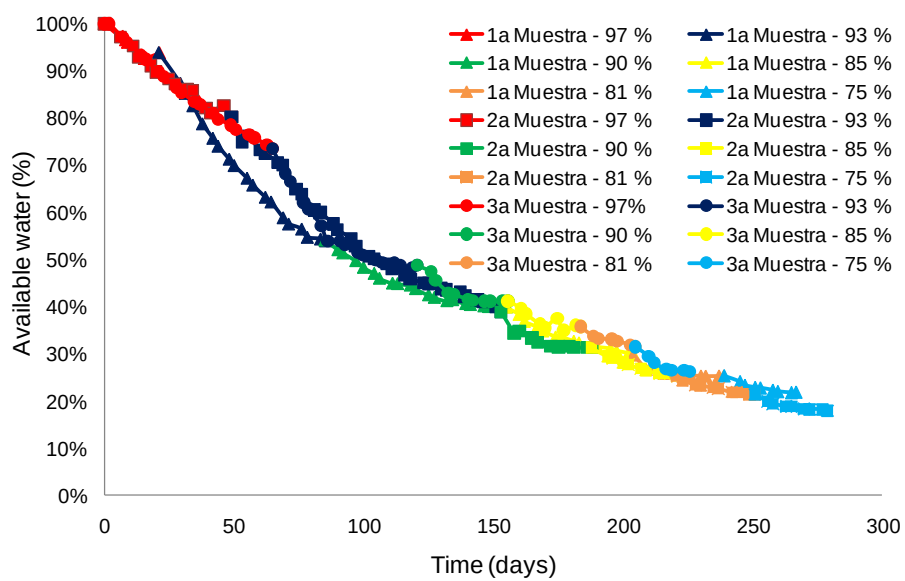
Appendix B Figure 24: Release of water for pumice from Chile (instant availability)

- Sugar slag:



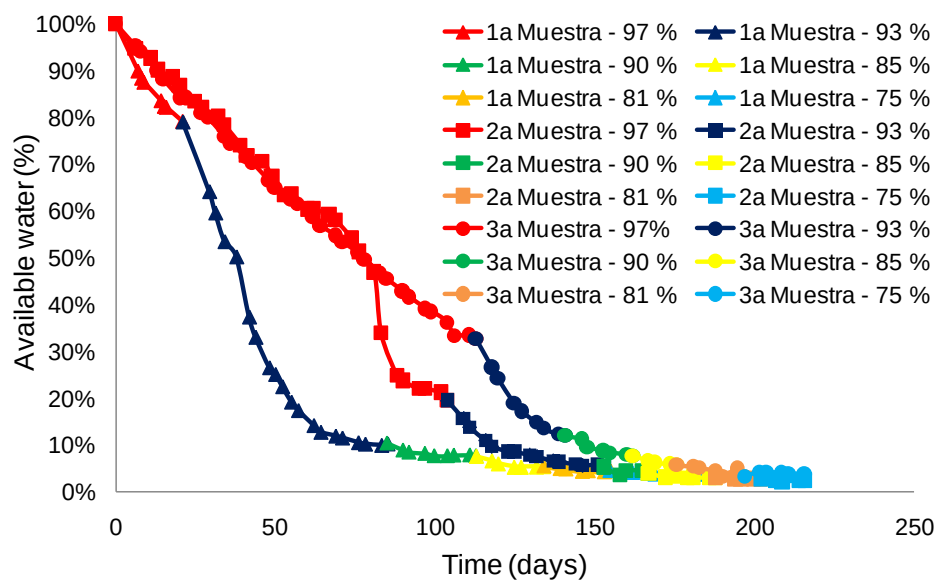
Appendix B Figure 25: Release of water for sugar slag (instant availability)

- Iron slag:



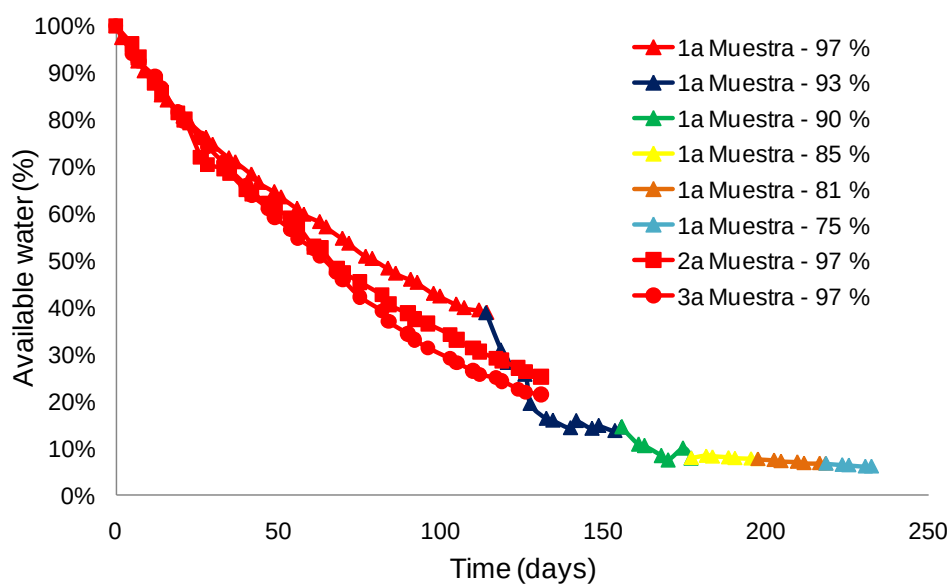
Appendix B Figure 26: Release of water for iron slag (instant availability)

- Expanded slate 20/5:



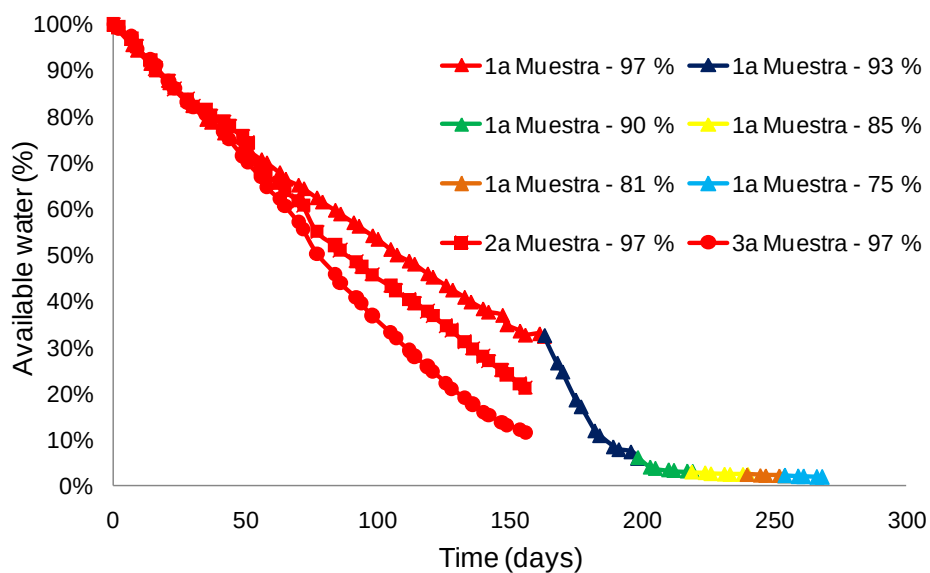
Appendix B Figure 27: Release of water for expanded slate 20/5 (instant availability)

- Expanded slate 20/5 + SRA:



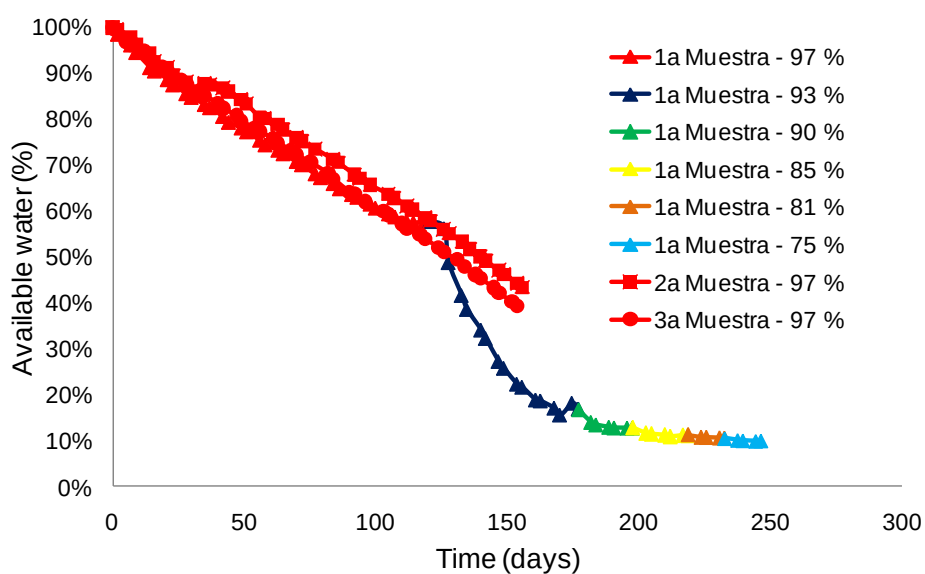
Appendix B Figure 28: Release of water for expanded slate 20/5 + SRA (instant availability)

- Expanded slate 10/0.08:



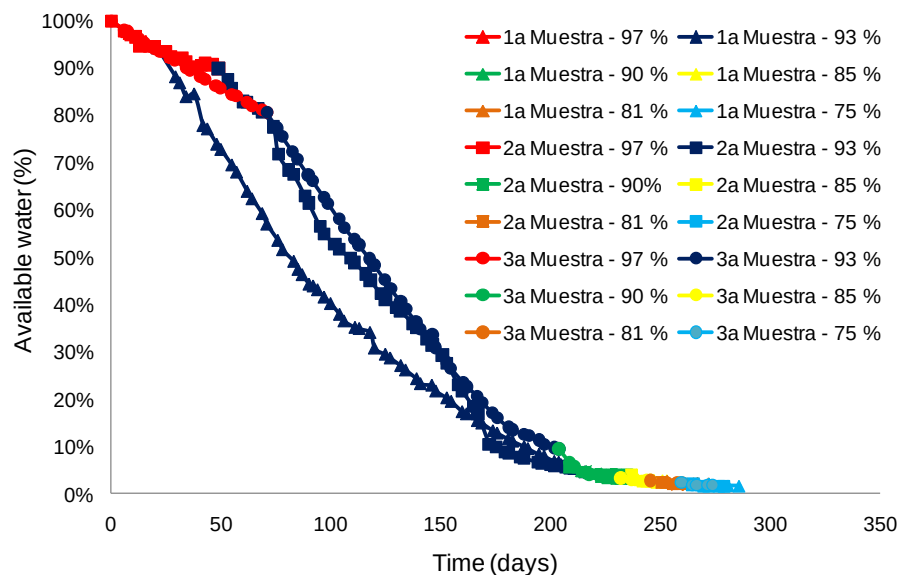
Appendix B Figure 29: Release of water for expanded slate 10/0.08 (instant availability)

- Expanded slate 10/0.08 + SRA:



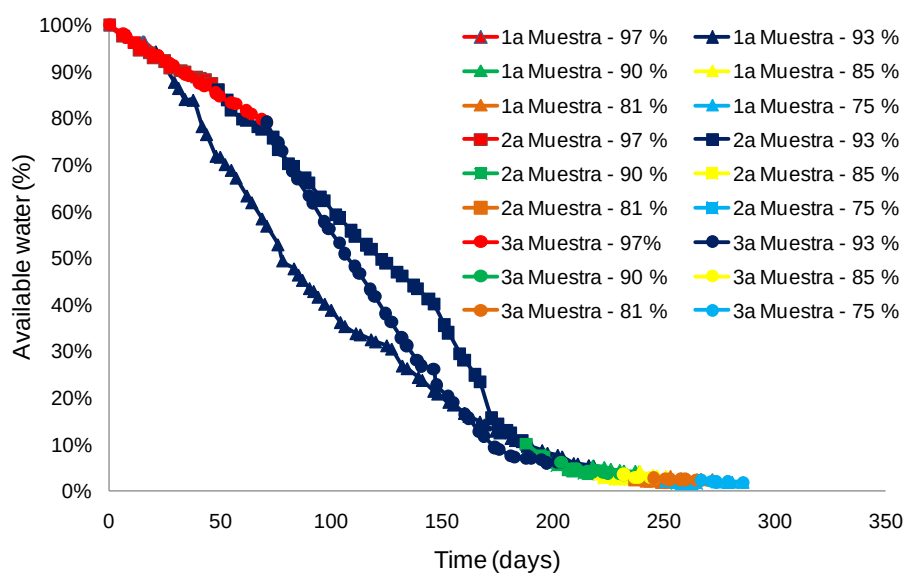
Appendix B Figure 30: Release of water for expanded slate 10/0.08 + SRA (instant availability)

- Expanded clay 20/10:



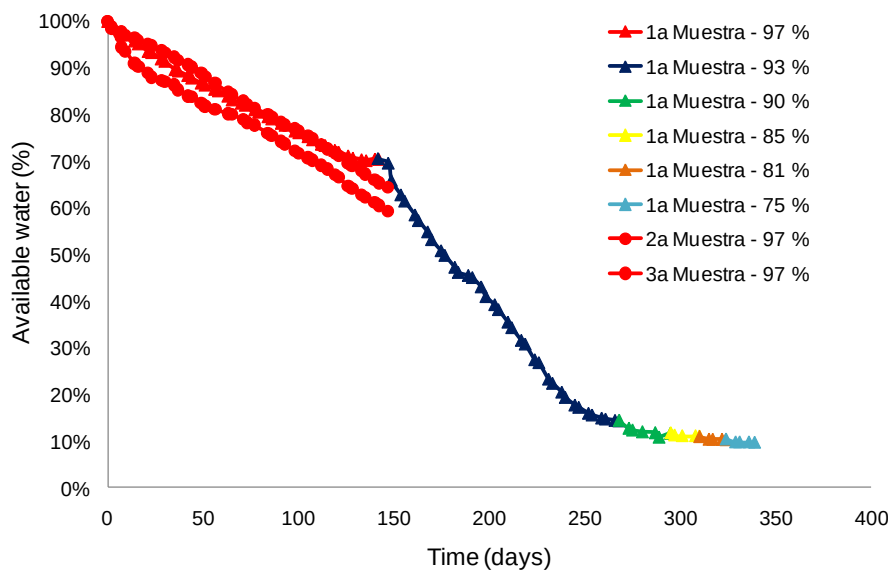
Appendix B Figure 31: Releases of water for expanded clay 20/10 (instant availability)

- Expanded clay 10/5:



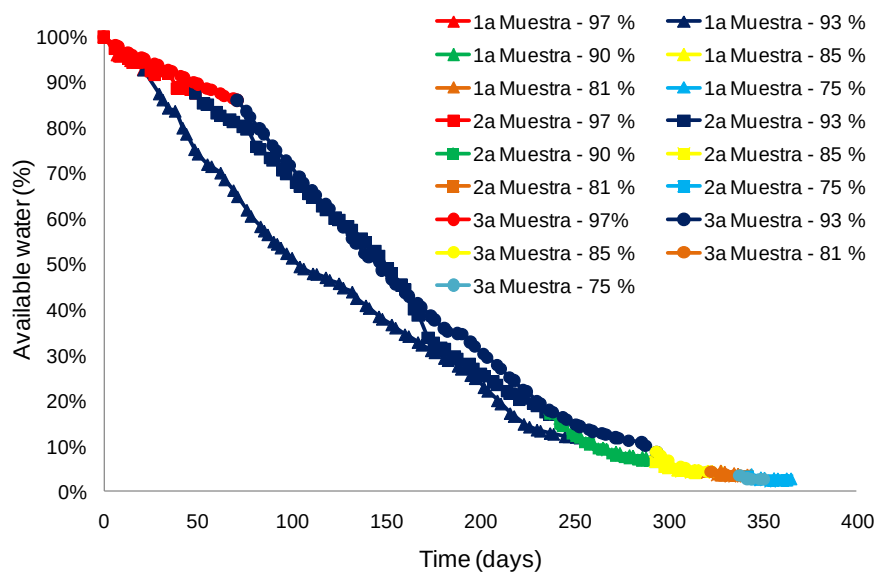
Appendix B Figure 32: Release of water for expanded clay 10/5 (instant availability)

- Expanded clay 10/5 + SRA:



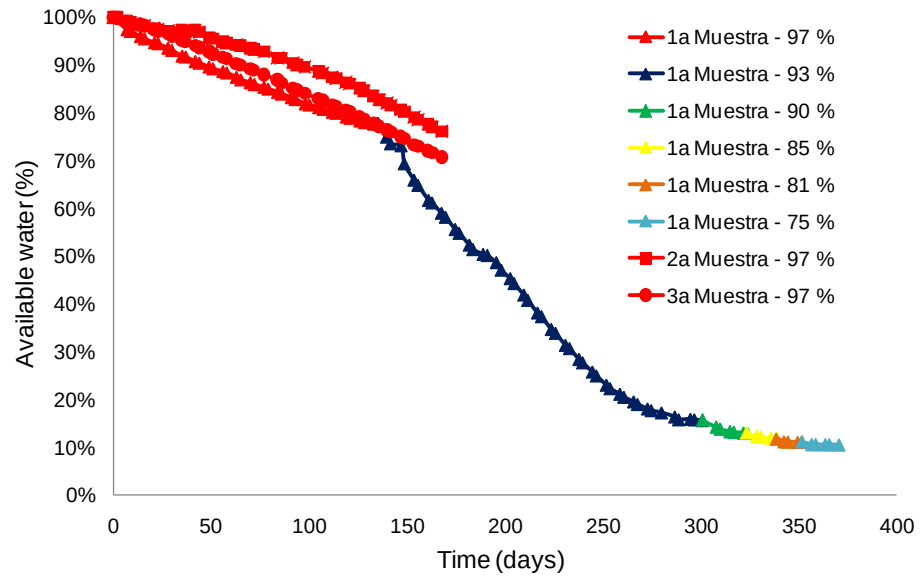
Appendix B Figure 33: Release of water for expanded clay 10/5 + SRA (instant availability)

- Expanded clay 5/0.08:



Appendix B Figure 34: Release of water for expanded clay 5/0.08 (instant availability)

- Expanded clay 5/0.08 + SRA:



Appendix B Figure 34: Release of water for expanded clay 5/0.08 + SRA (instant availability)

APPENDIX C: PROPERTIES OF CONCRETE

a) Compressive Strength (at 28, 56 and 90 days)

- Reference mixture (control):

STRENGTH AT 28 DAYS

Specimens: 18-02-2009 14:45

1	Diameter	99,10 mm	Area	77,132 cm ²
	Force	52 ton		
	Strength	66,113 MPa		
2**	Diameter	98,45 mm	Area	76,124 cm ²
	Force	50,7 ton		
	Strength	65,314 MPa		
3	Diameter	98,68 mm	Area	76,480 cm ²
	Force	55,2 ton		
	Strength	70,78 MPa		
Average:			68,45 MPa	

STRENGTH AT 56 DAYS

Specimens: 18-03-2009 10:30

specimens: 10-05-2009 10:59				
1**	Diameter	98,60 mm	Area	76,356 cm ²
	Force	50,55 ton	Density:	2468,7 kg/m ³
	Strength	64,923 MPa		
2	Diameter	98,75 mm	Area	76,589 cm ²
	Force	56,77 ton	Density:	2474,3 kg/m ³
	Strength	72,69 MPa		
3	Diameter	98,94 mm	Area	76,884 cm ²
	Force	63,22 ton	Density:	2508,0 kg/m ³
	Strength	80,638 MPa	Average:	76,66 MPa

STRENGTH AT 90 DAYS

Specimens: 21-04-2009 9:30

1	Diameter	98,36 mm	Area	75,985 cm ²
	Force	66,28 ton	Density:	2488,8 kg/m ³
	Strength	85,541 MPa		
2	Diameter	98,36 mm	Area	75,985 cm ²
	Force	62,11 ton	Density:	2418,2 kg/m ³
	Strength	80,16 MPa		
3**	Diameter	98,32 mm	Area	75,923 cm ²
	Force	58,88 ton	Density:	2406,0 kg/m ³
	Strength	76,053 MPa	Average:	82,85 MPa

** : discarded specimen due to wrong mode of failure

- Pumice from Ecuador mixture:

STRENGTH AT 28 DAYS

Specimens: 3-03-2009 11:00

1	Diameter	98,80 mm	Area	76,666 cm ²
	Force	50,00 ton		
	Strength	63,957 MPa		
2**	Diameter	98,93 mm	Area	76,868 cm ²
	Force	47,01 ton		
	Strength	59,974 MPa		
3	Diameter	98,88 mm	Area	76,790 cm ²
	Force	45,62 ton		
	Strength	58,26 MPa		
Average:			61,97 MPa	

STRENGTH AT 56 DAYS

Specimens: 31-03-2009 10:30

1**	Diameter	99,05 mm	Area	77,055 cm ²
	Force	47,7 ton	Density:	2374,9 kg/m ³
	Strength	60,707 MPa		
2	Diameter	99 mm	Area	76,977 cm ²
	Force	49,7 ton	Density:	2403,3 kg/m ³
	Strength	63,316 MPa		
3	Diameter	99,6 mm	Area	77,913 cm ²
	Force	47,75 ton	Density:	2406,5 kg/m ³
	Strength	60,102 MPa	Average:	62,01 MPa

STRENGTH AT 90 DAYS

Specimens: 4-05-2009 14:00

1	Diameter	98,11 mm	Area	75,599 cm ²	Density:	2314,1 kg/m ³
	Force	539,54 ton				
	Strength	69,941 MPa				
2	Diameter	98,33 mm	Area	75,938 cm ²	Density:	2435,7 kg/m ³
	Force	563,67 ton				
	Strength	72,743 MPa				
3**	Diameter	99,14 mm	Area	77,195 cm ²	Density:	2315,2 kg/m ³
	Force	534,05 ton				
	Strength	67,799 MPa				
Average:			71,34 MPa			

** : discarded specimen due to wrong mode of failure

- Pumice from Chile mixture:

STRENGTH AT 28 DAYS

Specimens: 18-02-2009 14:45

1	Diameter	99,45 mm	Area	77,678 cm ²
	Force	41,60 ton		
	Strength	52,519 MPa		
2**	Diameter	97,91 mm	Area	75,291 cm ²
	Force	46,80 ton		
	Strength	60,957 MPa		
3	Diameter	98,59 mm	Area	76,341 cm ²
	Force	45,60 ton		
	Strength	58,577 MPa		
Average:				57,35 MPa

STRENGTH AT 56 DAYS

Specimens: 18-03-2009 10:30

1**	Diameter	99,12 mm	Area	77,164 cm ²	Density:	2459,0 kg/m ³
	Force	49,29 ton				
	Strength	62,642 MPa				
2	Diameter	99,10 mm	Area	77,132 cm ²	Density:	2379,0 kg/m ³
	Force	43,79 ton				
	Strength	55,675 MPa				
3	Diameter	98,79 mm	Area	76,651 cm ²	Density:	2495,5 kg/m ³
	Force	52,46 ton				
	Strength	67,117 MPa				
Average:			64,88 MPa			

STRENGTH AT 90 DAYS

Specimens: 21-04-2009 9:30

1	Diameter	99,08 mm	Area	77,101 cm ²	Density:	2394,9 kg/m ³
	Force	46,58 ton				
	Strength	59,246 MPa				
2	Diameter	99,01 mm	Area	76,992 cm ²	Density:	2386,5 kg/m ³
	Force	53,06 ton				
	Strength	67,583 MPa				
3**	Diameter	98,25 mm	Area	75,815 cm ²	Density:	2409,5 kg/m ³
	Force	45,52 ton				
	Strength	58,88 MPa				
Average:			63,41 MPa			

** : discarded specimen due to wrong mode of failure

- Expanded clay 5/0.08 mixture:

STRENGTH AT 28 DAYS

Specimens: 24-02-2009 10:20

1	Diameter	98,78 mm	Area	76,635 cm ²
	Force	53,02 ton		
	Strength	67,847 MPa		
2**	Diameter	98,92 mm	Area	76,853 cm ²
	Force	49,35 ton		
	Strength	62,972 MPa		
3	Diameter	98,93 mm	Area	76,868 cm ²
	Force	47,59 ton		
	Strength	60,714 MPa		
Average:			64,28 MPa	

STRENGTH AT 56 DAYS

Specimens: 24-03-2009 11:30

1**	Diameter	99,05 mm	Area	77,055 cm ²	Density:	2400,9 kg/m ³
	Force	57,76 ton				
	Strength	73,51 MPa				
2	Diameter	99,05 mm	Area	77,055 cm ²	Density:	2433,3 kg/m ³
	Force	54,07 ton				
	Strength	68,814 MPa				
3	Diameter	99 mm	Area	76,977 cm ²	Density:	2409,8 kg/m ³
	Force	56,02 ton				
	Strength	71,368 MPa				
Average:			71,23 MPa			

STRENGTH AT 90 DAYS

Specimens: 27-04-2009 11:00

1	Diameter	98,62 mm	Area	76,387 cm ²	Density:	2422,1 kg/m ³
	Force	52,29 ton				
	Strength	67,13 MPa				
2	Diameter	98,91 mm	Area	76,837 cm ²	Density:	2393,9 kg/m ³
	Force	52,35 ton				
	Strength	66,814 MPa				
3**	Diameter	99,04 mm	Area	77,039 cm ²	Density:	2421,0 kg/m ³
	Force	53,43 ton				
	Strength	68,013 MPa				
Average:			67,32 MPa			

** : discarded specimen due to wrong mode of failure

- Expanded slate 20/5 mixture:

STRENGTH AT 28 DAYS

Specimens: 5-03-2009 16:00

1	Diameter	98,00 mm	Area	75,430 cm ²
	Force	15,25 ton		
	Strength	19,827 MPa		
2**	Diameter	98 mm	Area	75,43 cm ²
	Force	17,66 ton		
	Strength	22,96 MPa		
3	Diameter	97 mm	Area	73,898 cm ²
	Force	30,21 ton		
	Strength	40,09 MPa		
Average:			27,63 MPa	

STRENGTH AT 56 DAYS

Specimens: 2-04-2009

1**	Diameter	99,50 mm	Area	77,756 cm ²
	Force	35,27 ton	Density:	1999,8 kg/m ³
	Strength	44,483 MPa		
2	Diameter	99,4 mm	Area	77,6 cm ²
	Force	18,39 ton	Density:	1939,4 kg/m ³
	Strength	23,24 MPa		
3	Diameter	99,2 mm	Area	77,288 cm ²
	Force	32,12 ton	Density:	2005,5 kg/m ³
	Strength	40,755 MPa	Average:	36,16 MPa

STRENGTH AT 90 DAYS

Specimens: 6-05-2009

1	Diameter	97,89 mm	Area	75,260 cm ²	
	Force	383,84 ton		Density:	2150,7 kg/m ³
	Strength	49,982 MPa			
2	Diameter	98,42 mm	Area	76,078 cm ²	
	Force	265,95 ton		Density:	2120,1 kg/m ³
	Strength	34,259 MPa			
3**	Diameter	98,82 mm	Area	76,697 cm ²	
	Force	271,8 ton		Density:	1929,0 kg/m ³
	Strength	34,729 MPa		Average:	39,66 MPa

** : discarded specimen due to wrong mode of failure

- Expanded slate 10/0.08 mixture:

STRENGTH AT 28 DAYS

Specimens: 10-03-2009 10:45

1	Diameter	98,58 mm	Area	76,325 cm ²
	Force	28,68 ton		
	Strength	36,85 MPa		
2**	Diameter	98,2 mm	Area	75,738 cm ²
	Force	32,30 ton		
	Strength	41,823 MPa		
3	Diameter	98,19 mm	Area	75,722 cm ²
	Force	33,38 ton		
	Strength	43,23 MPa		
Average:				40,63 MPa

STRENGTH AT 56 DAYS

Specimens: 7-04-2009

1**	Diameter	98,65 mm	Area	76,434 cm ²
	Force	30,06 ton	Density:	2243,8 kg/m ³
	Strength	38,568 MPa		
2	Diameter	99 mm	Area	76,977 cm ²
	Force	36,99 ton	Density:	2253,9 kg/m ³
	Strength	47,124 MPa		
3	Diameter	98,55 mm	Area	76,279 cm ²
	Force	31,47 ton	Density:	2300,8 kg/m ³
	Strength	40,459 MPa	Average:	47,12 MPa

STRENGTH AT 90 DAYS

Specimens: 11-05-2009 13:30

1	Diameter	98,67 mm	Area	76,465 cm ²	
	Force	394,93 ton		Density:	2141,7 kg/m ³
	Strength	50,616 MPa			
2	Diameter	98,46 mm	Area	76,139 cm ²	
	Force	372,43 ton		Density:	2226,1 kg/m ³
	Strength	47,936 MPa			
3**	Diameter	98,48 mm	Area	76,170 cm ²	
	Force	402,32 ton		Density:	2332,5 kg/m ³
	Strength	51,762 MPa		Average:	50,10 MPa

** : discarded specimen due to wrong mode of failure

b) Chloride Ion Permeability

Control Mixture

Specimen 1 (D = 99,05 mm; h = 5,23 cm) 23/4/09													
Current (mA)	48,02	50,91	51,65	52,45	53,31	53,9	54,45	54,84	55,01	55,1	55,63	55,7	55,46
Time (min)	0	30	60	90	120	150	180	210	240	270	300	330	360
Specimen 2 (D = 98,15 mm; h = 5,10 cm) 23/4/09													
Current (mA)	42,5	43,9	44,2	44,7	44,9	45,0	45,2	46,2	45,5	45,2	45,1	45,3	45,0
Time (min)	0	30	60	90	120	150	180	210	240	270	300	330	360
Specimen 3 (D = 98,50 mm; h = 5,35 cm) 24/4/09													
Current (mA)	43,7	45,3	45,6	45,9	46,3	46,7	47,1	47,4	47,8	48,0	48,0	48,1	47,9
Time (min)	0	30	60	90	120	150	180	210	240	270	300	330	360
Charge Passed (C)	Corrected Charge	Penetrability											
1.160	1.067	Low		Average	972								
970	909	Very Low		Minimum	909								
				Maximum	1.067								
1.012	941	Very Low											

Pumice from Chile

Specimen 1 (D = 99,05 mm; h = 5,075 cm; m = 943,66 g) 23/4/09													
Current (mA)	54,4	53,11	49,04	53,86	60,8	63,5	65,9	64,9	65,3	66,3	67,5	67,6	67,6
Time (min)	0	30	60	90	120	150	180	210	240	270	300	330	360
Specimen 2 (D = 99,10 mm; h = 5,05 cm; m = 919,87 g) 23/4/09													
Current (mA)	55,4	58,3	58,7	59,0	59,3	59,7	59,7	59,6	59,5	59,4	59,3	57,2	56,5
Time (min)	0	30	60	90	120	150	180	210	240	270	300	330	360
Specimen 3 (D = 99,25 mm; h = 5,245 cm)													
Current (mA)	41,56	47,73	51,52	53,81	55,61	56,29	57,24	58,01	58,45	58,78	58,88	58,92	58,85
Time (min)	0	30	60	90	120	150	180	210	240	270	300	330	360
Charge Passed (C)	Corrected Charge	Penetrability											
1.330	1.223	Low		Average	1.163								
1.270	1.167	Low		Minimum	1.097								
				Maximum	1.223								
1.198	1.097	Low											

Expanded Slate 20/5

Specimen 1 (D = 98,82 mm; h =5,20 cm) 11/5/09													
Current (mA)	48,11	51,20	51,77	53,16	54,10	54,14	53,94	54,25	53,69	53,96	53,71	52,71	52,81
Time (min)	0	30	60	90	120	150	180	210	240	270	300	330	360
Specimen 2 (D = 98,11 mm; h = 4,99 cm) 11/5/09													
Current (mA)	70,6	83,6	89,0	93,3	98,3	102,1	98,1	108,1	109,1	110,9	109,9	110,2	110,4
Time (min)	0	30	60	90	120	150	180	210	240	270	300	330	360
Charge Passed (C)	Corrected Charge	Penetrability											
1.147	1.060	Low			Average		1.545						
					Minimum		1.060						
2.166	2.030	Moderate			Maximum		2.030						

Expanded Slate 10/0.08

Specimen 1 (D = 98,10 mm; h =5,13 cm) 13/5/09													
Current (mA)	18,30	56,71	60,20	60,70	65,30	64,00	63,90	64,60	64,20	64,40	65,00	62,40	64,10
Time (min)	0	30	60	90	120	150	180	210	240	270	300	330	360
Specimen 2 (D = 98,85 mm; h = 5,025 cm) 13/5/09													
Current (mA)	59,0	70,3	77,3	78,9	79,8	80,4	80,7	80,7	81,1	81,1	81,1	80,8	80,4
Time (min)	0	30	60	90	120	150	180	210	240	270	300	330	360
Charge Passed (C)	Corrected Charge	Penetrability											
1.319	1.237	Low		Average		1.401							
				Minimum		1.237							
1.695	1.566	Low		Maximum		1.566							

c) Degree of Hydration

	Crucible	Initial	105 °C	1.050 °C	Loss on Ignition (g/g)	
Portland cement (pure)						Average
Specimen 1	235,52	265,55	265,2	264,27	0,031	0,029
Specimen 2	201,48	231,27	230,95	230,17	0,026	

	Crucible	Initial	105 °C	1.050 °C	Loss on Ignition (g/g)	
Coarse aggregate						Average
Specimen 1	162,88	196,98	196,78	195,65	0,033	0,034
Specimen 2	156,31	185,50	185,35	184,37	0,034	
Fine aggregate						
Specimen 1	201,25	231,94	231,70	230,45	0,041	0,041
Specimen 2	163,19	196,95	196,67	195,33	0,040	

- LIGHTWEIGHT AGGREGATES

Pumice from Chile						
	Crucible	Initial	105 °C	1.050 °C	Loss on Ignition (g/g)	
Specimen 1	237,83	264,30	264,30	263,62	0,0257	
Specimen 2	190,05	210,62	210,62	210,10	0,0253	
Specimen 3	202,27	224,85	224,85	224,27	0,0257	
					Average	0,0256
					Av-Min	0,0003
					Max-Av	0,0001
					CV	0,0092

Expanded clay						
	Crucible	Initial	105 °C	1.050 °C	Loss on Ignition (g/g)	
Specimen 1	201,17	230,82	230,82	230,73	0,0030	
Specimen 2	201,32	231,91	231,91	231,80	0,0036	
Specimen 3	189,71	219,68	219,68	219,54	0,0047	
					Average	0,0038
					Av-Min	0,0007
					Max-Av	0,0009
					CV	0,2207

Pumice from Ecuador					
	Crucible	Initial	105 °C	1.050 °C	Loss on Ignition (g/g)
Specimen 1	197,19	216,60	216,60	215,93	0,0345
Specimen 2	235,43	257,81	257,81	257,03	0,0349
Specimen 3	227,17	251,90	251,90	251,04	0,0348
Average					0,0347
Av-Min					0,0002
Max-Av					0,0001
CV					0,0050

Expanded slate					
	Crucible	Initial	105 °C	1.050 °C	Loss on Ignition (g/g)
Specimen 1	221,71	257,77	257,77	257,77	0,0000
Specimen 2	203,72	233,04	233,04	233,04	0,0000
Specimen 3	162,70	185,20	185,20	185,20	0,0000
Average					0,0000
Av-Min					0,0000
Max-Av					0,0000
CV					0,0000

- CONCRETE MIXTURES

Control mixture									
	Crucible	Initial	105 °C	1.050 °C	Capillary water (%)	Non-evaporable water (g)	Hydrated cement (g)	Total cement (g)	Degree of Hydration
Specimen 1	201,75	232,34	231,16	229,46	3,86%	0,785	3,414	6,485	52,64%
Specimen 2	201,09	231,78	230,53	228,85	4,07%	0,764	3,320	6,506	51,02%
Specimen 3	202,60	233,83	232,65	230,84	3,78%	0,878	3,816	6,621	57,64%
Mixed	197,72	228,93	227,72	226,07	3,88%	0,714	3,105	6,617	46,92%
Average					3,90%	0,79	3,41	6,56	52,06%
Av-Min					0,12%	0,07	0,31	0,07	5,13%
Max-Av					0,18%	0,09	0,40	0,06	5,58%
CV					3,21%	8,73%	8,73%	1,09%	8,51%

Pumice from Chile									
	Crucible	Initial	105 °C	1.050 °C	Capillary water (%)	Non-evaporable water (g)	Hydrated cement (g)	Total cement (g)	Degree of Hydration
Specimen 1	193,79	228,61	226,82	224,74	5,14%	1,076	4,678	7,727	60,54%
Specimen 2	203,94	234,91	233,67	232,12	4,00%	0,636	2,764	6,872	40,22%
Specimen 3	201,73	232,73	231,30	229,48	4,61%	0,920	3,998	6,879	58,13%
Mixed	201,50	232,27	231,00	229,19	4,13%	0,912	3,963	6,828	58,05%
Average					4,47%	0,89	3,85	7,08	54,23%
Av-Min					0,47%	0,25	1,09	0,25	14,01%
Max-Av					0,67%	0,19	0,83	0,65	6,31%
CV					11,58%	20,66%	20,66%	6,13%	17,36%

Exp clay 5/0.08									
	Crucible	Initial	105 °C	1.050 °C	Capillary water (%)	Non-evaporable water (g)	Hydrated cement (g)	Total cement (g)	Degree of Hydration
Specimen 1	201,60	237,44	235,82	233,78	4,52%	1,041	4,527	7,752	58,39%
Specimen 2	201,54	232,52	231,24	229,55	4,13%	0,821	3,568	6,701	53,24%
Specimen 3	197,57	231,83	230,52	228,57	3,82%	0,988	4,295	7,410	57,95%
Mixed	193,60	227,14	225,46	223,29	5,01%	1,248	5,428	7,255	74,82%
Average					4,37%	1,02	4,45	7,28	61,10%
Av-Min					0,55%	0,20	0,89	0,58	7,86%
Max-Av					0,64%	0,22	0,97	0,47	13,72%
CV					11,71%	17,22%	17,22%	6,02%	15,45%

Pumice from Ecuador

	Crucible	Initial	105 °C	1.050 °C	Capillary water (%)	Non- evaporable water (g)	Hydrated cement (g)	Total cement (g)	Degree of Hydration	
Specimen 1	190,11	217,89	216,85	215,03	3,74%	1,008	4,383	6,100	71,85%	
Specimen 2	201,24	231,69	230,47	228,40	4,01%	1,185	5,153	6,687	77,06%	
Specimen 3	227,26	267,20	265,64	263,31	3,91%	1,156	5,024	8,771	57,29%	
Mixed	235,48	265,81	264,69	262,91	3,69%	0,886	3,854	6,660	57,86%	
					Average	3,84%	1,06	4,60	7,05	66,02%
					Av-Min	0,14%	0,17	0,75	0,95	8,73%
					Max-Av	0,17%	0,13	0,55	1,72	11,05%
					CV	3,78%	13,09%	13,09%	16,66%	15,12%

Exp slate 20/5

	Crucible	Initial	105 °C	1.050 °C	Capillary water (%)	Non-evaporable water (g)	Hydrated cement (g)	Total cement (g)	Degree of Hydration	
Specimen 1	221,90	250,97	249,67	248,20	4,47%	0,839	3,647	7,532	48,41%	
Specimen 2	237,97	275,21	273,37	271,35	4,94%	1,219	5,299	9,649	54,92%	
Specimen 3	202,44	229,43	227,41	225,64	7,48%	1,213	5,274	6,993	75,42%	
Mixed	203,84	234,19	232,70	230,85	4,91%	1,202	5,225	7,864	66,44%	
					Average	5,45%	1,12	4,86	8,01	61,30%
					Av-Min	0,98%	0,28	1,21	1,02	12,88%
					Max-Av	2,03%	0,10	0,44	1,64	14,12%
					CV	25.16%	16.67%	16.67%	14.36%	19.59%

Exp slate 10/0.08

	Crucible	Initial	105 °C	1.050 °C	Capillary water (%)	Non-evaporable water (g)	Hydrated cement (g)	Total cement (g)	Degree of Hydration
Specimen 1	237,85	268,13	267,04	265,28	3,60%	1,004	4,364	7,022	62,15%
Specimen 2	221,80	253,17	252,10	250,46	3,41%	0,850	3,695	7,275	50,79%
Specimen 3	202,37	232,21	230,99	229,35	4,09%	0,896	3,896	6,920	56,30%
Mixed	203,76	233,23	231,86	229,98	4,65%	1,157	5,031	6,834	73,61%
				Average	3,94%	0,98	4,25	7,01	60,71%
				Av-Min	0,53%	0,13	0,55	0,18	9,92%
				Max-Av	0,71%	0,18	0,78	0,26	12,90%
				CV	14,07%	13,97%	13,97%	2,72%	16,09%

d) Autogenous Shrinkage

CONTROL MIXTURE

Cast			10-6-09									
2:15	Zero	0,41										
Date	Hour	DAYS	TIME	1A	1B	1C	2A	2B	2C	3A	3B	3C
10-06-09	12:00	0,00	0	-1,133	-1,229	-1,257	3,355	3,292	3,425	3,185	3,135	3,175
10-06-09	12:30	0,02	0,5	-1,145	-1,246	-1,264	3,375	3,270	3,389	3,222	3,173	3,210
10-06-09	13:00	0,04	1	-1,144	-1,240	-1,261	3,367	3,268	3,381	3,230	3,185	3,220
10-06-09	15:00	0,13	3	-1,131	-1,232	-1,256	3,371	3,262	3,375	3,242	3,203	3,238
10-07-09	12:00	1,00	1	-1,221	-1,314	-1,344	3,274	3,164	3,282	3,139	3,099	3,137
10-08-09	12:00	2,00	2	-1,254	-1,325	-1,383	3,235	3,149	3,238	3,104	3,056	3,098
10-09-09	12:00	3,00	3	-1,293	-1,391	-1,419	3,197	3,119	3,197	3,065	3,022	3,060
10-13-09	11:15	6,97	7	-1,366	-1,474	-1,482	3,102	3,008	3,113	2,993	2,947	2,986
10-15-09	10:40	8,94	9	-1,405	-1,508	-1,522	3,065	2,973	3,071	2,958	2,911	2,953
10-19-09	12:20	13,01	13	-1,450	-1,541	-1,569	3,022	2,931	3,028	2,926	2,879	2,919
10-26-09	10:55	19,95	20	-1,478	-1,560	-1,597	2,992	2,903	2,997	2,899	2,852	2,890
10-29-09	11:25	22,98	23	-1,474	-1,567	-1,601	2,989	2,898	2,995	2,892	2,846	2,885
11-02-09	10:45	26,95	27	-1,474	-1,574	-1,603	2,986	2,883	2,988	2,891	2,848	2,885
11-06-09	12:00	31,00	31	-1,473	-1,586	-1,613	2,979	2,862	2,971	2,889	2,838	2,878
11-10-09	13:20	35,06	35	-1,483	-1,580	-1,602	2,961	2,878	2,971	2,890	2,846	2,884
11-12-09	11:35	36,98	37	-1,484	-1,587	-1,603	2,955	2,856	2,964	2,885	2,835	2,875
11-16-09	11:35	40,98	41	-1,489	-1,587	-1,607	2,951	2,856	2,957	2,885	2,838	2,875

CONTROL MIXTURE

Actual Length (mm)								
1A	1B	1C	2A	2B	2C	3A	3B	3C
306,707	306,611	306,583	310,885	310,822	310,955	310,605	310,555	310,595
306,695	306,594	306,576	310,905	310,800	310,919	310,642	310,593	310,630
306,696	306,600	306,579	310,897	310,798	310,911	310,650	310,605	310,640
306,709	306,608	306,584	310,901	310,792	310,905	310,662	310,623	310,658
306,619	306,526	306,496	310,804	310,694	310,812	310,559	310,519	310,557
306,586	306,515	306,457	310,765	310,679	310,768	310,524	310,476	310,518
306,547	306,449	306,421	310,727	310,649	310,727	310,485	310,442	310,480
306,474	306,366	306,358	310,632	310,538	310,643	310,413	310,367	310,406
306,435	306,332	306,318	310,595	310,503	310,601	310,378	310,331	310,373
306,390	306,299	306,271	310,552	310,461	310,558	310,346	310,299	310,339
306,362	306,280	306,243	310,522	310,433	310,527	310,319	310,272	310,310
306,366	306,273	306,239	310,519	310,428	310,525	310,312	310,266	310,305
306,366	306,266	306,237	310,516	310,413	310,518	310,311	310,268	310,305
306,367	306,254	306,227	310,509	310,392	310,501	310,309	310,258	310,298
306,357	306,260	306,238	310,491	310,408	310,501	310,310	310,266	310,304
306,356	306,253	306,237	310,485	310,386	310,494	310,305	310,255	310,295
306,351	306,253	306,233	310,481	310,386	310,487	310,305	310,258	310,295

CONTROL MIXTURE

Actual shrinkage ($\mu\epsilon$)												
1A	1B	1C	2A	2B	2C	3A	3B	3C	1	2	3	Average
0	0	0	0	0	0	0	0	0	0	0	0	0
39	55	23	-64	71	116	-119	-122	-113	39	41	-118	13
36	36	13	-39	77	141	-145	-161	-145	28	60	-150	21
-7	10	-3	-51	97	161	-184	-219	-203	0	69	-202	44
287	277	284	261	412	460	148	116	122	283	377	129	-263
395	313	411	386	460	601	261	254	248	373	482	254	-370
522	528	528	508	557	733	386	364	370	526	599	373	-500
760	799	734	814	914	1003	618	605	609	764	910	611	-762
887	910	864	933	1026	1138	731	721	715	887	1033	722	-881
1034	1018	1018	1071	1161	1277	834	824	824	1023	1170	827	-1007
1125	1080	1109	1168	1252	1376	921	911	918	1104	1265	917	-1095
1112	1102	1122	1177	1268	1383	943	931	934	1112	1276	936	-1108
1112	1125	1129	1187	1316	1405	947	924	934	1122	1303	935	-1120
1109	1164	1161	1209	1383	1460	953	956	956	1145	1351	955	-1150
1141	1145	1125	1267	1332	1460	950	931	937	1137	1353	939	-1146
1144	1168	1129	1287	1403	1483	966	966	966	1147	1391	966	-1178
1161	1168	1142	1300	1403	1505	966	956	966	1157	1402	963	-1183

PUMICE FROM ECUADOR

Cast			10-6-09									
2:50	Zero	0,42										
Date	Hour	DAYS	TIME	1A	1B	1C	2A	2B	2C	3A	3B	3C
10-06-09	13:00	0,00	0	4,525	4,381	4,572	-1,414	-1,316	-1,349	3,792	3,802	3,764
10-06-09	13:30	0,02	0,5	4,518	4,369	4,596	-1,413	-1,323	-1,353	3,788	3,800	3,762
10-06-09	14:00	0,04	1	4,507	4,366	4,587	-1,419	-1,323	-1,361	3,786	3,798	3,758
10-06-09	16:00	0,13	3	4,524	4,387	4,602	-1,401	-1,305	-1,333	3,798	3,812	3,776
10-07-09	13:00	1,00	1	4,510	4,377	4,582	-1,410	-1,319	-1,348	3,792	3,797	3,761
10-08-09	13:00	2,00	2	4,495	4,353	4,568	-1,430	-1,333	-1,357	3,762	3,774	3,737
10-09-09	14:00	3,04	3	4,467	4,331	4,534	-1,459	-1,364	-1,397	3,730	3,744	3,704
10-13-09	11:20	6,93	7	4,370	4,225	4,429	-1,556	-1,458	-1,494	3,627	3,643	3,605
10-15-09	10:45	8,91	9	4,328	4,194	4,399	-1,595	-1,498	-1,535	3,591	3,606	3,570
10-19-09	12:25	12,98	13	4,280	4,141	4,338	-1,649	-1,561	-1,591	3,530	3,550	3,509
10-26-09	11:00	19,92	20	4,211	4,095	4,284	-1,712	-1,615	-1,658	3,474	3,484	3,448
10-29-09	11:30	22,94	23	4,199	4,074	4,266	-1,729	-1,634	-1,680	3,460	3,477	3,437
11-02-09	10:50	26,91	27	4,185	4,066	4,256	-1,742	-1,652	-1,691	3,458	3,467	3,427
11-06-09	12:00	30,96	31	4,187	4,038	4,231	-1,754	-1,660	-1,705	3,461	3,471	3,432
11-10-09	13:20	35,01	35	4,186	4,045	4,245	-1,763	-1,670	-1,711	3,455	3,469	3,433
11-12-09	11:40	36,94	37	4,189	4,044	4,244	-1,762	-1,668	-1,716	3,455	3,467	3,431
11-16-09	11:40	40,94	41	4,177	4,044	4,242	-1,766	-1,665	-1,712	3,455	3,467	3,431

PUMICE FROM ECUADOR

Actual Length (mm)								
1A	1B	1C	2A	2B	2C	3A	3B	3C
311,885	311,741	311,932	305,826	305,924	305,891	311,282	311,292	311,254
311,878	311,729	311,956	305,827	305,917	305,887	311,278	311,290	311,252
311,867	311,726	311,947	305,821	305,917	305,879	311,276	311,288	311,248
311,884	311,747	311,962	305,839	305,935	305,907	311,288	311,302	311,266
311,870	311,737	311,942	305,830	305,921	305,892	311,282	311,287	311,251
311,855	311,713	311,928	305,810	305,907	305,883	311,252	311,264	311,227
311,827	311,691	311,894	305,781	305,876	305,843	311,220	311,234	311,194
311,730	311,585	311,789	305,684	305,782	305,746	311,117	311,133	311,095
311,688	311,554	311,759	305,645	305,742	305,705	311,081	311,096	311,060
311,640	311,501	311,698	305,591	305,679	305,649	311,020	311,040	310,999
311,571	311,455	311,644	305,528	305,625	305,582	310,964	310,974	310,938
311,559	311,434	311,626	305,511	305,606	305,560	310,950	310,967	310,927
311,545	311,426	311,616	305,498	305,588	305,549	310,948	310,957	310,917
311,547	311,398	311,591	305,486	305,580	305,535	310,951	310,961	310,922
311,546	311,405	311,605	305,477	305,570	305,529	310,945	310,959	310,923
311,549	311,404	311,604	305,478	305,572	305,524	310,945	310,957	310,921
311,537	311,404	311,602	305,474	305,575	305,528	310,945	310,957	310,921

PUMICE FROM ECUADOR

Actual shrinkage ($\mu\epsilon$)												
1A	1B	1C	2A	2B	2C	3A	3B	3C	1	2	3	Average
0	0	0	0	0	0	0	0	0	0	0	0	0
22	38	-77	-3	23	13	13	6	6	-5	11	9	-5
58	48	-48	16	23	39	19	13	19	19	26	17	-21
3	-19	-96	-43	-36	-52	-19	-32	-39	-37	-44	-30	37
48	13	-32	-13	10	-3	0	16	10	10	-2	9	-5
96	90	13	52	56	26	96	90	87	66	45	91	-67
186	160	122	147	157	157	199	186	193	156	154	193	-167
497	500	458	464	464	474	530	511	511	485	468	517	-490
632	600	555	592	595	608	646	630	623	595	598	633	-609
786	770	750	768	801	791	842	810	819	769	787	823	-793
1007	917	923	974	977	1010	1022	1022	1015	949	987	1019	-985
1045	985	981	1030	1039	1082	1067	1044	1051	1004	1051	1054	-1036
1090	1010	1013	1073	1098	1118	1073	1076	1083	1038	1096	1077	-1070
1084	1100	1093	1112	1124	1164	1063	1063	1067	1092	1133	1064	-1097
1087	1078	1048	1141	1157	1183	1083	1070	1063	1071	1161	1072	-1101
1077	1081	1052	1138	1151	1200	1083	1076	1070	1070	1163	1076	-1103
1116	1081	1058	1151	1141	1187	1083	1076	1070	1085	1159	1076	-1107

EXPANDED CLAY 5/0.08

Cast			9-9-09									
2:45	Zero	0,43										
Date	Hour	DAYS	TIME	1A	1B	1C	2A	2B	2C	3A	3B	3C
09-09-09	13:00	0,00	0	6,426	6,482	6,492	3,116	3,094	3,227	2,380	2,344	2,507
09-09-09	13:30	0,02	0,5	6,585	6,567	6,581	3,202	3,103	3,132	2,453	2,487	2,344
09-09-09	14:00	0,04	1	6,610	6,640	6,681	3,129	3,092	3,221	2,401	2,417	2,514
09-09-09	16:00	0,13	3	6,747	6,771	6,793	3,256	3,263	3,141	2,410	2,441	2,546
09-10-09	13:00	1,00	1	6,913	6,744	6,696	3,205	3,259	3,178	2,553	2,435	2,430
09-11-09	16:00	2,13	2	6,825	6,881	6,673	3,252	3,109	3,143	2,528	2,480	2,361
09-14-09	16:00	5,13	5	6,783	6,853	6,624	3,205	3,054	3,078	2,480	2,441	2,317
09-16-09	16:00	7,13	7	6,745	6,826	6,594	3,169	3,018	3,046	2,444	2,413	2,282
09-21-09	16:30	12,15	12	6,649	6,716	6,496	3,065	2,911	2,926	2,347	2,319	2,182
09-23-09	15:00	14,08	14	6,618	6,697	6,479	3,054	2,907	2,925	2,323	2,303	2,180
09-25-09	13:40	16,03	16	6,638	6,713	6,496	3,064	2,913	2,941	2,329	2,301	2,180
09-28-09	15:40	19,11	19	6,612	6,710	6,469	3,034	2,885	2,914	2,300	2,267	2,145
10-05-09	13:20	26,01	26	6,586	6,659	6,443	3,008	2,861	2,881	2,268	2,244	2,109
10-07-09	12:15	27,97	28	6,581	6,645	6,435	2,996	2,855	2,873	2,258	2,232	2,111
10-09-09	11:05	29,92	30	6,572	6,652	6,435	2,996	2,854	2,875	2,258	2,232	2,108
10-13-09	10:25	33,89	34	6,568	6,649	6,429	2,992	2,849	2,873	2,258	2,228	2,105
10-15-09	9:55	35,87	36	6,564	6,642	6,424	2,990	2,843	2,873	2,256	2,224	2,101
10-19-09	11:45	39,95	40	6,544	6,625	6,407	2,966	2,821	2,842	2,235	2,205	2,086
10-26-09	10:20	46,89	47	6,540	6,623	6,406	2,962	2,818	2,842	2,230	2,202	2,077
10-29-09	10:40	49,90	50	6,535	6,620	6,400	2,955	2,814	2,839	2,226	2,195	2,069
11-02-09	10:05	53,88	54	6,531	6,619	6,394	2,952	2,814	2,838	2,226	2,194	2,070
11-06-09	11:10	57,92	58	6,513	6,598	6,538	2,936	2,792	2,816	2,209	2,177	2,050
11-10-09	14:20	62,06	62	6,513	6,605	6,382	2,955	2,799	2,816	2,215	2,185	2,060
11-12-09	10:40	63,90	64	6,518	6,608	6,378	2,935	2,798	2,817	2,213	2,184	2,063

EXPANDED CLAY 5/0.08

Actual length (mm)			Actual shrinkage (µε)						
1	2	3	1	2	3	1	2	3	Average
314,637	311,686	310,720	0	0	0	0	0	0	0
314,748	311,686	310,738	-353	0	-57	-353	0	-57	28
314,814	311,687	310,754	-563	-5	-108	-563	-5	-108	57
314,940	311,760	310,776	-965	-238	-178	-965	-238	-178	208
314,954	311,754	310,783	-1010	-219	-201	-1010	-219	-201	210
314,963	311,708	310,766	-1037	-72	-148	-1037	-72	-148	110
314,923	311,652	310,723	-911	107	-8	-911	107	-8	-50
314,892	311,618	310,690	-810	218	99	-810	218	99	-158
314,790	311,507	310,593	-488	572	411	-488	572	411	-492
314,768	311,502	310,579	-417	589	456	-417	589	456	-523
314,786	311,513	310,580	-474	555	452	-474	555	452	-503
314,767	311,484	310,547	-414	646	557	-414	646	557	-601
314,733	311,457	310,517	-305	735	654	-305	735	654	-695
314,724	311,448	310,510	-277	763	676	-277	763	676	-719
314,723	311,448	310,509	-274	761	679	-274	761	679	-720
314,719	311,445	310,507	-261	773	687	-261	773	687	-730
314,713	311,442	310,504	-244	782	697	-244	782	697	-740
314,695	311,416	310,485	-186	864	756	-186	864	756	-810
314,693	311,414	310,480	-179	872	775	-179	872	775	-823
314,688	311,409	310,473	-164	887	795	-164	887	795	-841
314,685	311,408	310,473	-153	891	795	-153	891	795	-843
314,720	311,388	310,455	-264	955	853	-264	955	853	-904
314,670	311,397	310,463	-106	927	827	-106	927	827	-877
314,671	311,390	310,463	-110	949	827	-110	949	827	-888

PUMICE FROM CHILE

Cast			9-21-09									
1:45	Zero	0,41										
Date	Hour	DAYS	TIME	1A	1B	1C	2A	2B	2C	3A	3B	3C
09-21-09	11:30	0,00	0	4,016	3,893	3,991	-0,404	-0,378	-0,422	-1,565	-1,394	-1,423
09-21-09	12:00	0,02	0,5	4,014	3,923	3,971	-0,363	-0,315	-0,344	-1,484	-1,298	-1,315
09-21-09	12:30	0,04	1	4,022	3,933	4,003	-0,250	-0,209	-0,250	-1,431	-1,177	-1,282
09-21-09	14:30	0,13	3	4,055	3,931	4,045	-0,257	-0,213	-0,253	-1,432	-1,167	-1,270
09-22-09	11:30	1,00	1	4,013	3,912	3,969	-0,265	-0,250	-0,286	-1,425	-1,333	-1,359
09-23-09	15:20	2,16	2	3,968	3,861	3,981	-0,303	-0,290	-0,323	-1,466	-1,337	-1,369
09-24-09	19:30	3,33	3	3,952	3,846	3,953	-0,335	-0,319	-0,346	-1,482	-1,355	-1,391
09-25-09	13:55	4,10	4	3,925	3,816	3,972	-0,364	-0,345	-0,379	-1,486	-1,362	-1,416
09-28-09	15:55	7,18	7	3,843	3,748	3,810	-0,450	-0,432	-0,459	-1,578	-1,428	-1,504
10-05-09	13:30	14,08	14	3,772	3,687	3,776	-0,542	-0,533	-0,562	-1,678	-1,518	-1,579
10-07-09	12:30	16,04	16	3,760	3,656	3,776	-0,559	-0,550	-0,577	-1,675	-1,522	-1,592
10-09-09	11:15	17,99	18	3,752	3,636	3,758	-0,575	-0,562	-0,589	-1,680	-1,530	-1,599
10-13-09	10:35	21,96	22	3,738	3,636	3,754	-0,579	-0,570	-0,595	-1,691	-1,556	-1,619
10-15-09	10:10	23,94	24	3,727	3,631	3,747	-0,582	-0,573	-0,599	-1,696	-1,566	-1,628
10-19-09	11:55	28,02	28	3,710	3,603	3,704	-0,594	-0,587	-0,615	-1,722	-1,575	-1,637
10-26-09	10:30	34,96	35	3,704	3,600	3,702	-0,593	-0,579	-0,611	-1,730	-1,587	-1,645
10-29-09	10:55	37,98	38	3,700	3,584	3,704	-0,593	-0,586	-0,613	-1,733	-1,590	-1,646
11-02-09	10:15	41,95	42	3,683	3,580	3,707	-0,605	-0,593	-0,625	-1,726	-1,597	-1,653
11-06-09	11:25	46,00	46	3,667	3,565	3,693	-0,612	-0,617	-0,642	-1,747	-1,594	-1,664
11-10-09	14:05	50,11	50	3,675	3,574	3,687	-0,614	-0,604	-0,640	-1,735	-1,595	-1,652
11-12-09	10:55	51,98	52	3,671	3,572	3,693	-0,611	-0,606	-0,641	-1,734	-1,593	-1,652

PUMICE FROM CHILE

Actual Length (mm)								
1A	1B	1C	2A	2B	2C	3A	3B	3C
311,776	311,653	311,751	307,776	307,802	307,758	306,255	306,426	306,397
311,774	311,683	311,731	307,817	307,865	307,836	306,336	306,522	306,505
311,782	311,693	311,763	307,930	307,971	307,930	306,389	306,643	306,538
311,815	311,691	311,805	307,923	307,967	307,927	306,388	306,653	306,550
311,773	311,672	311,729	307,915	307,930	307,894	306,395	306,487	306,461
311,728	311,621	311,741	307,877	307,890	307,857	306,354	306,483	306,451
311,712	311,606	311,713	307,845	307,861	307,834	306,338	306,465	306,429
311,685	311,576	311,732	307,816	307,835	307,801	306,334	306,458	306,404
311,603	311,508	311,570	307,730	307,748	307,721	306,242	306,392	306,316
311,532	311,447	311,536	307,638	307,647	307,618	306,142	306,302	306,241
311,520	311,416	311,536	307,621	307,630	307,603	306,145	306,298	306,228
311,512	311,396	311,518	307,605	307,618	307,591	306,140	306,290	306,221
311,498	311,396	311,514	307,601	307,610	307,585	306,129	306,264	306,201
311,487	311,391	311,507	307,598	307,607	307,581	306,124	306,254	306,192
311,470	311,363	311,464	307,586	307,593	307,565	306,098	306,245	306,183
311,464	311,360	311,462	307,587	307,601	307,569	306,090	306,233	306,175
311,460	311,344	311,464	307,587	307,594	307,567	306,087	306,230	306,174
311,443	311,340	311,467	307,575	307,587	307,555	306,094	306,223	306,167
311,427	311,325	311,453	307,568	307,563	307,538	306,073	306,226	306,156
311,435	311,334	311,447	307,566	307,576	307,540	306,085	306,225	306,168
311,431	311,332	311,453	307,569	307,574	307,539	306,086	306,227	306,168

PUMICE FROM CHILE

Actual shrinkage ($\mu\epsilon$)												
1A	1B	1C	2A	2B	2C	3A	3B	3C	1	2	3	Average
0	0	0	0	0	0	0	0	0	0	0	0	0
6	-96	64	-133	-205	-253	-264	-313	-352	-9	-197	-310	172
-19	-128	-38	-500	-549	-559	-438	-708	-460	-62	-536	-535	378
-125	-122	-173	-478	-536	-549	-434	-741	-499	-140	-521	-558	406
10	-61	71	-452	-416	-442	-457	-199	-209	6	-436	-288	239
154	103	32	-328	-286	-322	-323	-186	-176	96	-312	-229	148
205	151	122	-224	-192	-247	-271	-127	-104	159	-221	-168	76
292	247	61	-130	-107	-140	-258	-104	-23	200	-126	-128	18
555	465	581	149	175	120	42	111	264	534	148	139	-274
783	661	690	448	504	455	369	405	509	711	469	428	-536
821	760	690	504	559	504	359	418	552	757	522	443	-574
847	825	747	556	598	543	376	444	574	806	565	465	-612
892	825	760	569	624	562	411	529	640	826	585	527	-646
927	841	783	578	634	575	428	561	669	850	596	553	-666
981	931	921	617	679	627	513	591	698	944	641	601	-729
1001	940	927	614	653	614	539	630	725	956	627	631	-738
1014	991	921	614	676	621	549	640	728	975	637	639	-750
1068	1004	911	653	699	660	526	662	751	994	670	646	-770
1119	1052	956	676	776	715	594	653	787	1043	722	678	-814
1094	1024	975	682	734	708	555	656	747	1031	708	653	-797
1107	1030	956	673	741	712	552	649	747	1031	708	650	-796

EXPANDED SLATE 10/0.08

Cast			9-21-09									
2:20	Zero	0,44										
Date	Hour	DAYS	TIME	1A	1B	1C	2A	2B	2C	3A	3B	3C
09-21-09	13:00	0,00	0	-2,272	-2,191	-2,300	-1,217	-1,091	-1,166	1,719	1,805	1,676
09-21-09	13:30	0,02	0,5	-2,272	-2,191	-2,300	-1,217	-1,091	-1,166	1,719	1,805	1,676
09-21-09	14:00	0,04	1	-2,255	-2,204	-2,240	-1,258	-1,137	-1,135	1,726	1,871	1,693
09-21-09	16:00	0,13	3	-2,220	-2,189	-2,213	-1,057	-0,781	-0,877	1,774	1,820	1,763
09-22-09	13:30	1,02	1	-2,087	-2,099	-2,196	-1,079	-0,999	-1,068	1,770	1,870	1,810
09-23-09	15:25	2,10	2	-2,155	-2,111	-2,203	-1,111	-1,023	-1,091	1,730	1,847	1,774
09-24-09	19:40	3,28	3	-2,180	-2,137	-2,228	-1,123	-1,052	-1,111	1,740	1,824	1,764
09-25-09	14:00	4,04	4	-2,206	-2,166	-2,262	-1,141	-1,073	-1,130	1,722	1,800	1,736
09-28-09	16:00	7,13	7	-2,290	-2,228	-2,343	-1,228	-1,143	-1,212	1,602	1,705	1,634
10-05-09	13:35	14,02	14	-2,395	-2,276	-2,448	-1,321	-1,273	-1,325	1,502	1,607	1,548
10-07-09	12:35	15,98	16	-2,419	-2,373	-2,476	-1,369	-1,327	-1,350	1,486	1,579	1,520
10-09-09	11:20	17,93	18	-2,435	-2,394	-2,490	-1,377	-1,339	-1,365	1,468	1,570	1,509
10-13-09	10:40	21,90	22	-2,464	-2,445	-2,516	-1,397	-1,360	-1,395	1,454	1,545	1,488
10-15-09	10:15	23,89	24	-2,476	-2,468	-2,530	-1,408	-1,378	-1,409	1,441	1,528	1,475
10-19-09	12:00	27,96	28	-2,498	-2,486	-2,550	-1,436	-1,391	-1,434	1,428	1,514	1,459
10-26-09	10:30	34,90	35	-2,498	-2,496	-2,569	-1,448	-1,416	-1,448	1,411	1,506	1,442
10-29-09	11:00	37,92	38	-2,506	-2,491	-2,565	-1,457	-1,421	-1,457	1,404	1,503	1,437
11-02-09	10:20	41,89	42	-2,513	-2,506	-2,574	-1,458	-1,423	-1,456	1,399	1,498	1,433
11-06-09	11:30	45,94	46	-2,521	-2,512	-2,582	-1,468	-1,433	-1,466	1,385	1,482	1,425
11-10-09	14:00	50,04	50	-2,519	-2,496	-2,584	-1,478	-1,428	-1,465	1,385	1,481	1,422
11-12-09	10:55	51,91	52	-2,512	-2,496	-2,572	-1,482	-1,434	-1,468	1,385	1,481	1,423

EXPANDED SLATE 10/0.08

Actual Length (mm)								
1A	1B	1C	2A	2B	2C	3A	3B	3C
305,868	305,949	305,840	306,923	307,049	306,974	309,639	309,725	309,596
305,868	305,949	305,840	306,923	307,049	306,974	309,639	309,725	309,596
305,885	305,936	305,900	306,882	307,003	307,005	309,646	309,791	309,613
305,920	305,951	305,927	307,083	307,359	307,263	309,694	309,740	309,683
306,053	306,041	305,944	307,061	307,141	307,072	309,690	309,790	309,730
305,985	306,029	305,937	307,029	307,117	307,049	309,650	309,767	309,694
305,960	306,003	305,912	307,017	307,088	307,029	309,660	309,744	309,684
305,934	305,974	305,878	306,999	307,067	307,010	309,642	309,720	309,656
305,850	305,912	305,797	306,912	306,997	306,928	309,522	309,625	309,554
305,745	305,864	305,692	306,819	306,867	306,815	309,422	309,527	309,468
305,721	305,767	305,664	306,771	306,813	306,790	309,406	309,499	309,440
305,705	305,746	305,650	306,763	306,801	306,775	309,388	309,490	309,429
305,676	305,695	305,624	306,743	306,780	306,745	309,374	309,465	309,408
305,664	305,672	305,610	306,732	306,762	306,731	309,361	309,448	309,395
305,642	305,654	305,590	306,704	306,749	306,706	309,348	309,434	309,379
305,642	305,644	305,571	306,692	306,724	306,692	309,331	309,426	309,362
305,634	305,649	305,575	306,683	306,719	306,683	309,324	309,423	309,357
305,627	305,634	305,566	306,682	306,717	306,684	309,319	309,418	309,353
305,619	305,628	305,558	306,672	306,707	306,674	309,305	309,402	309,345
305,621	305,644	305,556	306,662	306,712	306,675	309,305	309,401	309,342
305,628	305,644	305,568	306,658	306,706	306,672	309,305	309,401	309,343

EXPANDED SLATE 10/0.08

Actual shrinkage ($\mu\epsilon$)												
1A	1B	1C	2A	2B	2C	3A	3B	3C	1	2	3	Average
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
-56	42	-196	134	150	-101	-23	-213	-55	-70	61	-97	35
-170	-7	-284	-521	-1010	-941	-178	-48	-281	-154	-824	-169	382
-605	-301	-340	-450	-300	-319	-165	-210	-433	-415	-356	-269	347
-383	-261	-317	-345	-221	-244	-36	-136	-317	-320	-270	-163	251
-301	-177	-235	-306	-127	-179	-68	-61	-284	-238	-204	-138	193
-216	-82	-124	-248	-59	-117	-10	16	-194	-141	-141	-62	115
59	121	141	36	169	150	378	323	136	107	118	279	-168
402	278	484	339	593	518	701	639	413	388	483	585	-485
481	595	575	495	769	599	752	730	504	550	621	662	-611
533	664	621	521	808	648	811	759	539	606	659	703	-656
628	830	706	586	876	746	856	839	607	721	736	768	-742
667	905	752	622	935	792	898	894	649	775	783	814	-790
739	964	817	714	977	873	940	940	701	840	855	860	-852
739	997	880	753	1058	919	995	965	756	872	910	905	-896
765	981	866	782	1075	948	1017	975	772	871	935	921	-909
788	1030	896	785	1081	945	1033	991	785	904	937	937	-926
814	1049	922	818	1114	977	1079	1043	811	928	970	977	-958
808	997	929	850	1098	974	1079	1046	820	911	974	982	-956
785	997	889	863	1117	984	1079	1046	817	890	988	981	-953

EXPANDED CLAY 10/5

Cast			10-6-09									
3:30	Zero	0,44										
Date	Hour	DAYS	TIME	1A	1B	1C	2A	2B	2C	3A	3B	3C
10-06-09	14:00	0,00	0	6,935	6,925	6,832	1,927	1,923	2,010	-2,355	-2,403	-2,423
10-06-09	14:30	0,02	0,5	6,923	6,925	6,882	1,934	1,931	2,017	-2,353	-2,401	-2,423
10-06-09	15:00	0,04	1	6,923	6,927	6,826	1,939	1,932	2,045	-2,349	-2,397	-2,419
10-06-09	17:00	0,13	3	6,943	6,942	6,845	1,955	1,942	2,015	-2,341	-2,387	-2,413
10-07-09	14:00	1,00	1	6,939	6,940	6,846	1,934	1,925	1,976	-2,356	-2,407	-2,429
10-08-09	14:00	2,00	2	6,931	6,931	6,832	1,920	1,905	1,966	-2,365	-2,410	-2,435
10-09-09	14:00	3,00	3	6,910	6,912	6,822	1,894	1,877	1,950	-2,391	-2,437	-2,463
10-13-09	11:20	6,89	7	6,822	6,817	6,723	1,799	1,777	1,835	-2,486	-2,538	-2,562
10-15-09	10:50	8,87	9	6,792	6,783	6,689	1,760	1,732	1,811	-2,525	-2,578	-2,601
10-19-09	12:30	12,94	13	6,743	6,737	6,649	1,691	1,683	1,748	-2,582	-2,639	-2,659
10-26-09	11:05	19,88	20	6,692	6,679	6,587	1,635	1,633	1,682	-2,634	-2,685	-2,710
10-29-09	11:35	22,90	23	6,679	6,662	6,576	1,637	1,630	1,667	-2,642	-2,698	-2,714
11-02-09	10:50	26,87	27	6,667	6,654	6,562	1,625	1,621	1,667	-2,642	-2,698	-2,715
11-06-09	12:05	30,92	31	6,660	6,644	6,555	1,617	1,612	1,671	-2,649	-2,700	-2,724
11-10-09	13:15	34,97	35	6,662	6,644	6,559	1,610	1,606	1,672	-2,654	-2,707	-2,727
11-12-09	11:45	36,91	37	6,657	6,641	6,560	1,612	1,598	1,673	-2,664	-2,711	-2,731
11-16-09	11:45	40,91	41	6,654	6,641	6,556	1,615	1,599	1,673	-2,668	-2,720	-2,734

EXPANDED CLAY 10/5

Actual Length (mm)								
1A	1B	1C	2A	2B	2C	3A	3B	3C
314,695	314,685	314,592	310,107	310,103	310,190	305,465	305,417	305,397
314,683	314,685	314,642	310,114	310,111	310,197	305,467	305,419	305,397
314,683	314,687	314,586	310,119	310,112	310,225	305,471	305,423	305,401
314,703	314,702	314,605	310,135	310,122	310,195	305,479	305,433	305,407
314,699	314,700	314,606	310,114	310,105	310,156	305,464	305,413	305,391
314,691	314,691	314,592	310,100	310,085	310,146	305,455	305,410	305,385
314,670	314,672	314,582	310,074	310,057	310,130	305,429	305,383	305,357
314,582	314,577	314,483	309,979	309,957	310,015	305,334	305,282	305,258
314,552	314,543	314,449	309,940	309,912	309,991	305,295	305,242	305,219
314,503	314,497	314,409	309,871	309,863	309,928	305,238	305,181	305,161
314,452	314,439	314,347	309,815	309,813	309,862	305,186	305,135	305,110
314,439	314,422	314,336	309,817	309,810	309,847	305,178	305,122	305,106
314,427	314,414	314,322	309,805	309,801	309,847	305,178	305,122	305,105
314,420	314,404	314,315	309,797	309,792	309,851	305,171	305,120	305,096
314,422	314,404	314,319	309,790	309,786	309,852	305,166	305,113	305,093
314,417	314,401	314,320	309,792	309,778	309,853	305,156	305,109	305,089
314,414	314,401	314,316	309,795	309,779	309,853	305,152	305,100	305,086

EXPANDED CLAY 10/5

Actual shrinkage ($\mu\epsilon$)												
1A	1B	1C	2A	2B	2C	3A	3B	3C	1	2	3	Average
0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	-159	-23	-26	-23	-7	-7	0	-40	-24	-4	23
38	-6	19	-39	-29	-113	-20	-20	-13	17	-60	-17	20
-25	-54	-41	-90	-61	-16	-46	-52	-33	-40	-56	-44	47
-13	-48	-45	-23	-6	110	3	13	20	-35	27	12	-1
13	-19	0	23	58	142	33	23	39	-2	74	32	-35
79	41	32	106	148	193	118	111	131	51	149	120	-107
359	343	346	413	471	564	429	442	455	350	483	442	-425
454	451	455	539	616	642	557	573	583	453	599	571	-541
610	597	582	761	774	845	743	773	773	596	793	763	-717
772	782	779	942	935	1057	913	923	940	778	978	925	-894
813	836	814	935	945	1106	940	966	953	821	995	953	-923
852	861	858	974	974	1106	940	966	956	857	1018	954	-943
874	893	881	1000	1003	1093	962	972	986	882	1032	974	-963
868	893	868	1022	1022	1090	979	995	995	876	1045	990	-970
883	902	865	1016	1048	1086	1012	1008	1009	883	1050	1010	-981
893	902	877	1006	1045	1086	1025	1038	1018	891	1046	1027	-988

EXPANDED SLATE 20/5

Cast			9-22-09									
3:40	Zero	0,56										
Date	Hour	DAYS	TIME	1A	1B	1C	2A	2B	2C	3A	3B	3C
09-22-09	17:00	0,00	0	-3,103	-2,930	-3,047	-2,795	-2,652	-2,549	-1,363	-1,304	-1,505
09-22-09	17:30	0,02	0,5	-3,051	-2,936	-3,010	-2,748	-2,648	-2,534	-1,367	-1,291	-1,466
09-22-09	18:00	0,04	1	-3,077	-2,873	-3,004	-2,768	-2,645	-2,544	-1,343	-1,296	-1,444
09-22-09	20:00	0,13	3	-3,028	-2,905	-2,968	-2,750	-2,635	-2,530	-1,355	-1,285	-1,439
09-23-09	15:45	0,95	1	-3,031	-2,907	-2,966	-2,746	-2,657	-2,534	-1,369	-1,303	-1,443
09-24-09	20:00	2,13	2	-3,047	-2,926	-2,963	-2,756	-2,663	-2,540	-1,371	-1,303	-1,434
09-25-09	14:20	2,89	3	-3,070	-2,955	-2,994	-2,776	-2,688	-2,563	-1,387	-1,320	-1,454
09-28-09	16:20	5,97	6	-3,163	-3,053	-3,105	-2,878	-2,777	-2,652	-1,470	-1,400	-1,524
09-29-09	9:45	6,70	7	-3,167	-3,051	-3,113	-2,886	-2,774	-2,651	-1,468	-1,400	-1,532
10-05-09	14:00	12,88	13	-3,270	-3,155	-3,198	-2,966	-2,879	-2,740	-1,564	-1,507	-1,637
10-07-09	12:50	14,83	15	-3,284	-3,179	-3,212	-2,977	-2,885	-2,753	-1,592	-1,526	-1,632
10-09-09	11:35	16,77	17	-3,298	-3,188	-3,236	-2,984	-2,893	-2,766	-1,603	-1,536	-1,641
10-13-09	11:05	20,75	21	-3,332	-3,220	-3,260	-3,018	-2,919	-2,800	-1,628	-1,567	-1,666
10-15-09	10:30	22,73	23	-3,338	-3,230	-3,270	-3,024	-2,930	-2,808	-1,639	-1,573	-1,679
10-19-09	12:15	26,80	27	-3,353	-3,246	-3,285	-3,046	-2,955	-2,828	-1,662	-1,598	-1,702
10-26-09	10:50	33,74	34	-3,369	-3,266	-3,309	-3,051	-2,960	-2,847	-1,683	-1,618	-1,720
10-29-09	11:15	36,76	37	-3,374	-3,266	-3,309	-3,057	-2,960	-2,849	-1,691	-1,620	-1,724
11-02-09	10:40	40,74	41	-3,381	-3,270	-3,307	-3,056	-2,962	-2,853	-1,690	-1,631	-1,728
11-06-09	11:45	44,78	45	-3,392	-3,282	-3,318	-3,059	-2,965	-2,860	-1,694	-1,644	-1,743
11-10-09	13:35	48,86	49	-3,391	-3,283	-3,319	-3,063	-2,962	-2,864	-1,698	-1,649	-1,745
11-12-09	11:20	50,76	51	-3,395	-3,284	-3,319	-3,063	-2,962	-2,865	-1,695	-1,650	-1,753

EXPANDED SLATE 20/5

Actual Length (mm)								
1A	1B	1C	2A	2B	2C	3A	3B	3C
304,787	304,960	304,843	305,205	305,348	305,451	306,587	306,646	306,445
304,839	304,954	304,880	305,252	305,352	305,466	306,583	306,659	306,484
304,813	305,017	304,886	305,232	305,355	305,456	306,607	306,654	306,506
304,862	304,985	304,922	305,250	305,365	305,470	306,595	306,665	306,511
304,859	304,983	304,924	305,254	305,343	305,466	306,581	306,647	306,507
304,843	304,964	304,927	305,244	305,337	305,460	306,579	306,647	306,516
304,820	304,935	304,896	305,224	305,312	305,437	306,563	306,630	306,496
304,727	304,837	304,785	305,122	305,223	305,348	306,480	306,550	306,426
304,723	304,839	304,777	305,114	305,226	305,349	306,482	306,550	306,418
304,620	304,735	304,692	305,034	305,121	305,260	306,386	306,443	306,313
304,606	304,711	304,678	305,023	305,115	305,247	306,358	306,424	306,318
304,592	304,702	304,654	305,016	305,107	305,234	306,347	306,414	306,309
304,558	304,670	304,630	304,982	305,081	305,200	306,322	306,383	306,284
304,552	304,660	304,620	304,976	305,070	305,192	306,311	306,377	306,271
304,537	304,644	304,605	304,954	305,045	305,172	306,288	306,352	306,248
304,521	304,624	304,581	304,949	305,040	305,153	306,267	306,332	306,230
304,516	304,624	304,581	304,943	305,040	305,151	306,259	306,330	306,226
304,509	304,620	304,583	304,944	305,038	305,147	306,260	306,319	306,222
304,498	304,608	304,572	304,941	305,035	305,140	306,256	306,306	306,207
304,499	304,607	304,571	304,937	305,038	305,136	306,252	306,301	306,205
304,495	304,606	304,571	304,937	305,038	305,135	306,255	306,300	306,197

EXPANDED SLATE 20/5

Actual shrinkage ($\mu\epsilon$)												
1A	1B	1C	2A	2B	2C	3A	3B	3C	1	2	3	Average
0	0	0	0	0	0	0	0	0	0	0	0	0
-171	20	-121	-154	-13	-49	13	-42	-127	-91	-72	-52	72
-85	-187	-141	-88	-23	-16	-65	-26	-199	-138	-43	-97	92
-246	-82	-259	-147	-56	-62	-26	-62	-215	-196	-88	-101	128
-236	-75	-266	-161	16	-49	20	-3	-202	-192	-64	-62	106
-184	-13	-276	-128	36	-29	26	-3	-232	-157	-40	-70	89
-108	82	-174	-62	118	46	78	52	-166	-67	34	-12	15
197	403	190	272	409	337	349	313	62	263	340	241	-281
210	397	217	298	400	334	342	313	88	274	344	248	-289
548	738	495	560	743	625	656	662	431	594	643	583	-606
594	817	541	596	763	668	747	724	414	651	676	628	-652
640	846	620	619	789	710	783	757	444	702	706	661	-690
751	951	699	731	874	822	864	858	525	800	809	749	-786
771	984	732	750	910	848	900	877	568	829	836	782	-816
820	1036	781	822	992	913	975	959	643	879	909	859	-882
873	1102	859	839	1009	976	1044	1024	702	945	941	923	-936
889	1102	859	858	1009	982	1070	1031	715	950	950	938	-946
912	1115	853	855	1015	995	1067	1066	728	960	955	954	-956
948	1154	889	865	1025	1018	1080	1109	777	997	969	988	-985
945	1158	892	878	1015	1031	1093	1125	783	998	975	1000	-991
958	1161	892	878	1015	1035	1083	1128	809	1004	976	1007	-995

EXPANDED SLATE 10/0.08 + SRA

Cast			9-22-09									
4:10	Zero	0,49										
Date	Hour	DAYS	TIME	1A	1B	1C	2A	2B	2C	3A	3B	3C
09-22-09	16:00	0,00	0	4,132	3,956	4,339	1,031	2,007	1,501	-0,304	-0,625	-0,268
09-22-09	16:30	0,02	0,5	4,132	3,956	4,339	1,031	2,007	1,501	-0,304	-0,625	-0,268
09-22-09	17:00	0,04	1	4,135	3,972	4,198	1,056	2,045	1,532	-0,311	-0,603	-0,244
09-22-09	19:00	0,13	3	4,118	3,987	4,185	1,097	2,054	1,556	-0,297	-0,596	-0,237
09-23-09	15:50	0,99	1	4,114	3,988	4,187	1,026	2,065	1,579	-0,337	-0,591	-0,260
09-24-09	20:05	2,17	2	4,096	3,965	4,169	1,040	2,047	1,548	-0,365	-0,619	-0,273
09-25-09	14:25	2,93	3	4,074	3,941	4,150	1,026	2,020	1,568	-0,385	-0,639	-0,293
09-28-09	16:25	6,02	6	3,994	3,859	4,066	0,922	1,943	1,516	-0,468	-0,715	-0,361
09-29-09	9:45	6,74	7	3,993	3,855	4,055	0,913	1,923	1,509	-0,474	-0,722	-0,370
10-05-09	14:05	12,92	13	3,901	3,786	3,970	0,846	1,835	1,462	-0,555	-0,789	-0,462
10-07-09	12:55	14,87	15	3,885	3,771	3,966	0,829	1,821	1,456	-0,571	-0,798	-0,463
10-09-09	11:40	16,82	17	3,873	3,760	3,956	0,816	1,812	1,431	-0,577	-0,811	-0,464
10-13-09	11:10	20,80	21	3,851	3,734	3,929	0,811	1,770	1,387	-0,604	-0,849	-0,489
10-15-09	10:35	22,77	23	3,839	3,721	3,909	0,811	1,754	1,361	-0,625	-0,855	-0,509
10-19-09	12:20	26,85	27	3,816	3,695	3,890	0,796	1,736	1,349	-0,649	-0,877	-0,525
10-26-09	10:50	33,78	34	3,801	3,675	3,873	0,786	1,718	1,322	-0,664	-0,900	-0,543
10-29-09	11:20	36,81	37	3,799	3,673	3,872	0,783	1,717	1,318	-0,664	-0,896	-0,548
11-02-09	10:40	40,78	41	3,798	3,675	3,873	0,770	1,699	1,307	-0,673	-0,901	-0,543
11-06-09	11:50	44,83	45	3,793	3,663	3,852	0,765	1,683	1,304	-0,675	-0,904	-0,544
11-10-09	13:25	48,89	49	3,799	3,660	3,856	0,759	1,676	1,306	-0,675	-0,902	-0,550
11-12-09	11:30	50,81	51	3,798	3,649	3,864	0,768	1,678	1,303	-0,678	-0,902	-0,552

EXPANDED SLATE 10/0.08 + SRA

Actual Length (mm)								
1A	1B	1C	2A	2B	2C	3A	3B	3C
312,032	311,856	312,239	308,981	309,957	309,451	307,586	307,265	307,622
312,032	311,856	312,239	308,981	309,957	309,451	307,586	307,265	307,622
312,035	311,872	312,098	309,006	309,995	309,482	307,579	307,287	307,646
312,018	311,887	312,085	309,047	310,004	309,506	307,593	307,294	307,653
312,014	311,888	312,087	308,976	310,015	309,529	307,553	307,299	307,630
311,996	311,865	312,069	308,990	309,997	309,498	307,525	307,271	307,617
311,974	311,841	312,050	308,976	309,970	309,518	307,505	307,251	307,597
311,894	311,759	311,966	308,872	309,893	309,466	307,422	307,175	307,529
311,893	311,755	311,955	308,863	309,873	309,459	307,416	307,168	307,520
311,801	311,686	311,870	308,796	309,785	309,412	307,335	307,101	307,428
311,785	311,671	311,866	308,779	309,771	309,406	307,319	307,092	307,427
311,773	311,660	311,856	308,766	309,762	309,381	307,313	307,079	307,426
311,751	311,634	311,829	308,761	309,720	309,337	307,286	307,041	307,401
311,739	311,621	311,809	308,761	309,704	309,311	307,265	307,035	307,381
311,716	311,595	311,790	308,746	309,686	309,299	307,241	307,013	307,365
311,701	311,575	311,773	308,736	309,668	309,272	307,226	306,990	307,347
311,699	311,573	311,772	308,733	309,667	309,268	307,226	306,994	307,342
311,698	311,575	311,773	308,720	309,649	309,257	307,217	306,989	307,347
311,693	311,563	311,752	308,715	309,633	309,254	307,215	306,986	307,346
311,699	311,560	311,756	308,709	309,626	309,256	307,215	306,988	307,340
311,698	311,549	311,764	308,718	309,628	309,253	307,212	306,988	307,338

EXPANDED SLATE 10/0.08 + SRA

Actual shrinkage ($\mu\epsilon$)												
1A	1B	1C	2A	2B	2C	3A	3B	3C	1	2	3	Average
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
-10	-51	452	-81	-123	-100	23	-72	-78	130	-101	-42	4
45	-99	493	-214	-152	-178	-23	-94	-101	146	-181	-73	36
58	-103	487	16	-187	-252	107	-111	-26	147	-141	-10	1
115	-29	544	-29	-129	-152	198	-20	16	210	-103	65	-57
186	48	605	16	-42	-217	263	46	81	280	-81	130	-110
442	311	874	353	206	-48	533	293	302	543	170	376	-363
445	324	910	382	271	-26	553	316	332	560	209	400	-390
740	545	1182	599	555	126	816	534	631	822	427	660	-636
792	593	1195	654	600	145	868	563	634	860	466	688	-672
830	628	1227	696	629	226	888	605	637	895	517	710	-707
901	712	1313	712	765	368	975	729	718	975	615	808	-799
939	754	1377	712	816	452	1044	749	783	1023	660	859	-847
1013	837	1438	761	874	491	1122	820	835	1096	709	926	-910
1061	901	1492	793	932	578	1170	895	894	1151	768	986	-969
1067	907	1496	803	936	591	1170	882	910	1157	777	988	-974
1070	901	1492	845	994	627	1200	898	894	1155	822	997	-991
1086	940	1560	861	1045	637	1206	908	897	1195	848	1004	-1016
1067	949	1547	880	1068	630	1206	902	917	1188	859	1008	-1018
1070	984	1521	851	1061	640	1216	902	923	1192	851	1014	-1019