PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
ESCUELA DE INGENIERIA

EFFECT OF INTERNAL STRUCTURE ON THE INTERACTION OF MECHANICAL AND THERMAL PROPERTIES OF CONCRETE

JOSÉ CARLOS REMESAR LERA

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

Advisors:

MAURICIO LÓPEZ CASANOVA

SERGIO VERA ARAYA

Santiago de Chile, (September, 2015)

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To my family and friends

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ABSTRACT

Energy efficient concrete houses demand cement based materials with reduced thermal conductivity. This study focus on the effect of the internal structure on the interaction of mechanical and thermal properties of concrete. The internal structure was evaluated individually and combined with the variation of three constituents: supplementary cementing materials (SCM) (fly ash), fine lightweight aggregates (LWA) (fine expanded clay) and coarse LWA (expanded shale, expanded clay, expanded polystyrene). The effect of LWA in pervious concrete was also evaluated.

The three constituents individually presented a higher decrement on compressive strength than on the thermal conductivity. Fly ash was the least effective for thermal conductivity reduction (14%), while coarse expanded clay (54%) was the most effective. The replacement of expanded clay for expanded polystyrene, which represent a reduction of LWA thermal conductivity of 90%, reduced the thermal conductivity of LWA concrete in less than 15%, for a 30% LWA volume. The thermal conductivity behaved closer to a parallel composite model, with the minimum tortuosity effect on the heat flux.

The combined effect reduced the thermal conductivity in 75%. Fine expanded clay (FEC) produced a greater reduction on thermal conductivity and a lower reduction on compressive strength than coarse expanded clay (CEC) for the pore size distribution refinement, decrease in maximum pore size and increase in spatial distribution of FEC within the concrete. The combination of constituents generates a higher tortuosity effect in the heat flux with the reduction of thermal bridges within the concrete. In despite of the higher rate in compressive strength reduction, the use of FA allows to achieve lower values of thermal conductivity, reducing the heat flux through the binder. LWA pervious concrete was less efficient on the mechanical and thermal properties due the increase of pore size distribution and maximum pore size.

Keywords: Lightweight aggregates, expanded clay, expanded shale, expanded polystyrene, fly ash, thermal conductivity, compressive strength, two-phase models, porosity properties, pore size distribution, CT scan, pervious concrete, porous concrete

RESUMEN

En vías de aumentar la eficiencia energética de las casas, la conductividad térmica del hormigón debe reducirse. Este estudio se enfoca en el efecto de la estructura interna en la interacción de las propiedades mecánicas y térmicas del hormigón. La estructura interna se evaluó de forma individual y combinada con la variación de tres constituyentes: materiales cementantes suplementarios (cenizas volantes), agregado liviano (LWA) fino (arcilla expandida fina) y LWA grueso (lutita expandida, arcilla expandida, poliestireno expandido). También se evaluó el efecto de LWA en hormigón permeable.

Los tres constituyentes presentados individualmente una mayor disminución en la resistencia a la compresión que en la conductividad térmica del hormigón. Las cenizas volantes fue el menos efectivo en la reducción de la conductividad térmica (14%), mientras que la arcilla expandida gruesa (54%) fue el más efectivo. La sustitución de arcilla expandida por poliestireno expandido, que representa una reducción de la conductividad térmica del 90%, redujo la conductividad térmica del hormigón en menos de 15%, para un volumen de 30% del constituyente. Esto último es debido a que la conductividad térmica se comporta más cerca de un modelo compuesto en paralelo, con un efecto mínimo de tortuosidad en el flujo de calor.

El efecto combinado redujo la conductividad térmica en un 75%. La Arcilla expandida fina (FEC) provocó una mayor reducción en la conductividad térmica y una menor reducción en la resistencia a la compresión que la arcilla expandida gruesa (CEC) debido a: refinamiento de la distribución del tamaño de poros, disminución de máximo tamaño de poros y aumento en la distribución espacial de FEC dentro del hormigón. La combinación de los constituyentes genera un mayor efecto de tortuosidad en el flujo de calor con la reducción de puentes térmicos dentro del hormigón. A pesar de la tasa más alta en la reducción de resistencia a la compresión, el uso de FA permite conseguir valores más bajos de conductividad térmica, lo que reduce el flujo de calor a través de la pasta. El hormigón permeable con LWA fue menos eficiente en las propiedades

mecánicas y térmicas, debido al aumento de la distribución de tamaño de poro y tamaño de poro máximo.

Palabras clave: agregados livianos, arcilla expandida, lutita expandida, poliestireno expandido, cenizas volantes, conductividad térmica, resistencia a la compresión, modelos de dos fases, propiedades de porosidad, distribución de tamaño de poros, tomografía computarizada, hormigón permeable, hormigón poroso

1. STRUCTURE OF THESIS

Chapter Two presents an introduction of the state of the art of mechanical and thermal properties of concretes. The chapter analyzes the changes in the internal structure that reduce the thermal conductivity of concrete with their collateral effect in the compressive strength. Chapter Three presents the knowledge gap identified from the state of the art. It also includes the hypothesis, objectives and methodology.

Chapters Four, Five and Six presents three articles that are going to be submitted to ISI journals. Chapter Four analyses the independent effect of constituents (fly ash, lightweight aggregates) in the interaction of mechanical and thermal properties of concrete. Chapter Five aims to understand and assess the effect and interaction of the combination of constituents (fly ash, lightweight aggregates) in the thermal and mechanical properties of concrete in order to reduce the thermal conductivity with the lowest impact in compressive strength. Chapter Six explores the effect of the combination of lightweight aggregates with no-fines concrete in the mechanical and thermal properties. Chapter Seven presents the conclusions and recommendations generated from the research.

2. INTRODUCTION

Space heating and cooling of residential sector account over 10% of total primary energy consumption in United States, Europe and Chile (Corporacion de Desarrollo Tecnológico, 2010; DOE, 2012; Pérez-Lombard, Ortiz, & Pout, 2008). This is the main reason behind design energy codes demand thermal resistance for building's envelope to improve the energy efficiency (IEA, 2013). Therefore, the thermal performance must be considered as important as the mechanical performance in a building's design. Concrete, the most used construction material, excels in mechanical properties and constructability, but lacks in thermal resistance.

Building codes demand thermal insulation for concrete wall houses in most populated areas of Chile (MINVU, 2011) and worldwide (EURIMA, 2007; IECC, 2009) to improve the energy efficiency (IEA, 2013). Concrete houses with walls of 15 cm width in Santiago, Chile demand a thermal conductivity of 0.42 W/mK, whereas the thermal conductivity of conventional concrete ranges 1.4-2.3 W/mK (Khan, 2002; K.-H. Kim, Jeon, Kim, & Yang, 2003; Lamond & Pielert, 2006). This has limited the market share of concrete home building systems. Cast in place concrete wall home share is 20% in Chile (INE, 2013) and less than 2% in USA (Portland Cement Association, 2012). The required thermal insulation increases the direct costs (labor, material) and limits its use compared to other construction systems.

The inclusion of pores in concrete increments the thermal resistance but reduces the mechanical resistance (ACI Committee 213, 2013; Chandra & Berntsson, 2002; Holm & Bremner, 2000; Popovics, 1998; Short & Kinniburgh, 1963). Therefore, a careful design of the internal structure of concrete is required to enhance the balance between thermal conductivity and compressive strength. Previous studies showed that the increase of porosity in concrete with the inclusion of lightweight aggregates and the replacement of Portland cement for supplementary cementing materials (SCM) decrease the thermal conductivity, which is inversely proportional to the thermal resistance, but in expense of a lower compressive strength (ACI Committee 213, 2013; Chandra & Berntsson, 2002; Demirboga, 2003b). The changes presented in the literature of the internal structure of concrete considered the binder, the aggregates and the internal porosity. The latter corresponds to a special type of concrete: pervious or no-fines concrete.

2.1. Binder effect on mechanical and thermal properties

The binder, a mix of cementitious materials and water, is the binding agent that agglomerates the aggregates of concretes. Ordinary Portland cement (OPC) is the most used cementitious material, while supplementary cementing materials (SCM) are used as partial replacement of OPC. SCM present the benefits of cost reduction, recycle of waste products, and the reduction of carbon footprint of concrete due the CO_2 emissions associated with OPC (Bilodeau & Malhotra, 2000; Metha & Monteiro, 2014; Metha, 2004). Between the SCM that correspond to industrial by-products are fly ash (FA), silica fume (SF) and blast-furnace slag (BFS). FA is a by-product of coal power plants, SF of the production of silicon or ferrosilicon alloys and BFS of the iron production (Metha & Monteiro, 2014).

The influence of FA, SF and BFS in the mechanical properties of concrete have been widely studied (Berry & Malhotra, 1981; Bilodeau & Malhotra, 2000; Bouzoubaâ, Zhang, & Malhotra, 2001; Li & Zhao, 2003; Megat Johari, Brooks, Kabir, & Rivard, 2011; Metha & Monteiro, 2014; Metha, 2004; Papadakis, Antiohos, & Tsimas, 2002; Ramezanianpour & Malhotra, 1995; Türkmen, Gül, Çelik, & Demirboğa, 2003). On the other hand, only few studies have characterized the influence of these SCM in the thermal properties of concrete. The increase of SCM replacement level for OPC decreased the thermal conductivity of mortar and binder (K.-H. Kim et al., 2003). The interaction between thermal and mechanical properties has been more limited studied.

The Water to Binder ratio (W/B) is one of the most important parameters to design the mechanical strength of normal weight aggregate concretes. It is widely known that the increment of W/B reduces the compressive strength (Metha & Monteiro, 2014). Figure 2-1 shows that the increment of W/B also reduces the thermal conductivity of binders at oven-dry density. The increment of W/B from 0.25 to 0.40

reduced the thermal conductivity of binder in 27% at oven-dry density, while at fully saturated conditions remained constant (K.-H. Kim et al., 2003). Nevertheless, the replacement of OPC for FA, SF or BFS presents a higher impact in the reduction of thermal conductivity than the increment of W/B. Figure 2-1 also shows differences on the thermal conductivity for similar W/B and 100% OPC between previous studies. The chemical composition of cement, hydration rate, measurement conditions and techniques might influence the variation in the results.

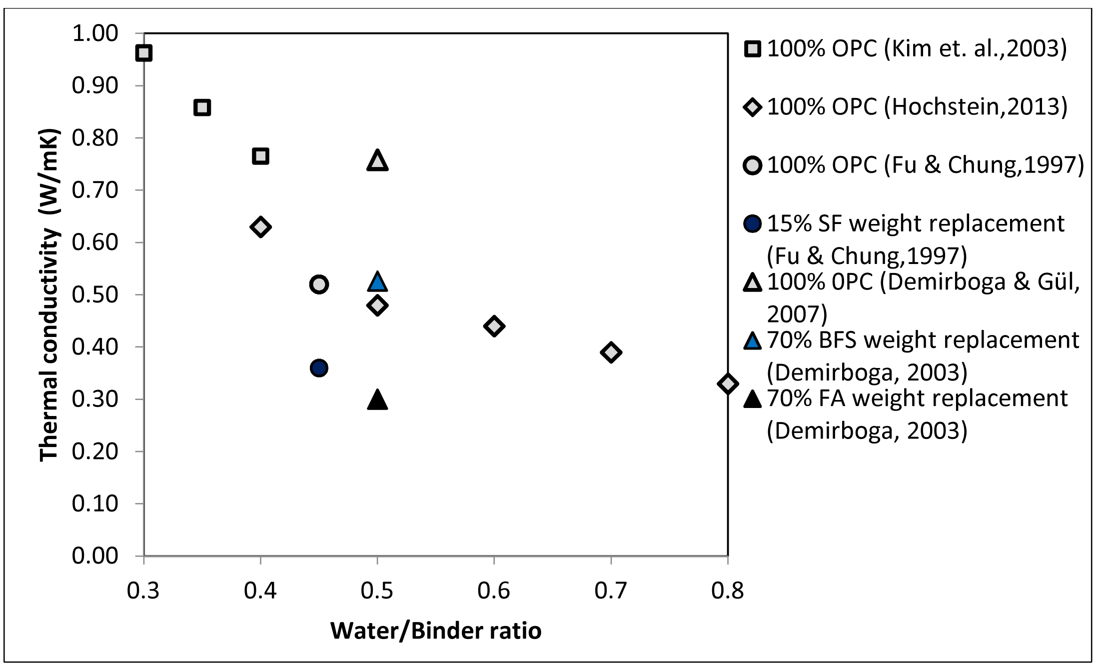

Figure 2-1: Relationship between thermal conductivity and W/B of binders. (Demirboga, 2003b; Fu & Chung, 1997; Hochstein, 2013; K.-H. Kim et al., 2003)

Figure 2-2 shows the effect of FA, SF and BFS replacement level in the compressive strength and thermal conductivity of mortars (Demirboga, 2003a, 2003b). The increment of replacement level reduced both the compressive strength and thermal conductivity. A 10% replacement level of SF for OPC was the only mixture where the compressive strength was higher than the control mortar. BFS presented the smaller effect in both properties with the increase of the replacement and is not recommended compared to FA and SF. The two latter presented a similar thermal conductivity for the same replacement level, with the SF being slightly more efficient. SF was also more efficient than FA in reducing the decrement of compressive strength. Nevertheless, SF does not allow high volume replacement levels due its higher fineness (Metha & Monteiro, 2014), as opposed to FA and BFS.

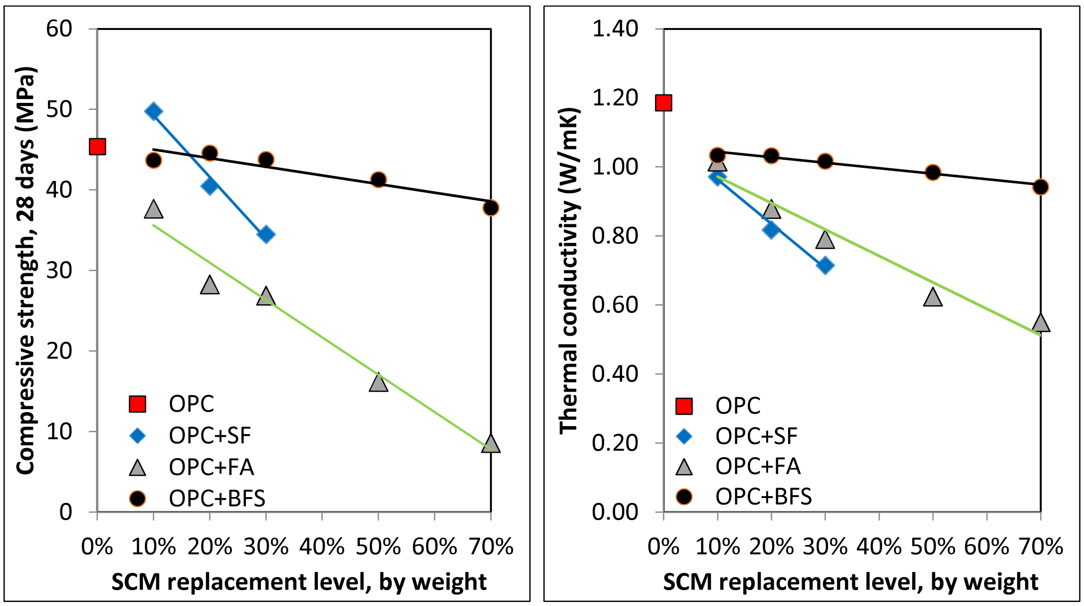

Figure 2-2: Effect of the SCM replacement level in the compressive strength and thermal conductivity for mortars (Demirboga, 2003a, 2003b)

Figure 2-3 shows that the thermal conductivity tends to decrease linearly with the increment of OPC replacement ratio. The slopes of Figure 2-3 represent the cost in compressive strength of lowering the thermal conductivity. Beside FA, SF and BFS presented similar slopes, the effect in compressive strength varied for the same thermal conductivity. SF allowed a higher compressive strength for the same thermal conductivity than FA. BFS presented the higher thermal conductivity of the three SCM.

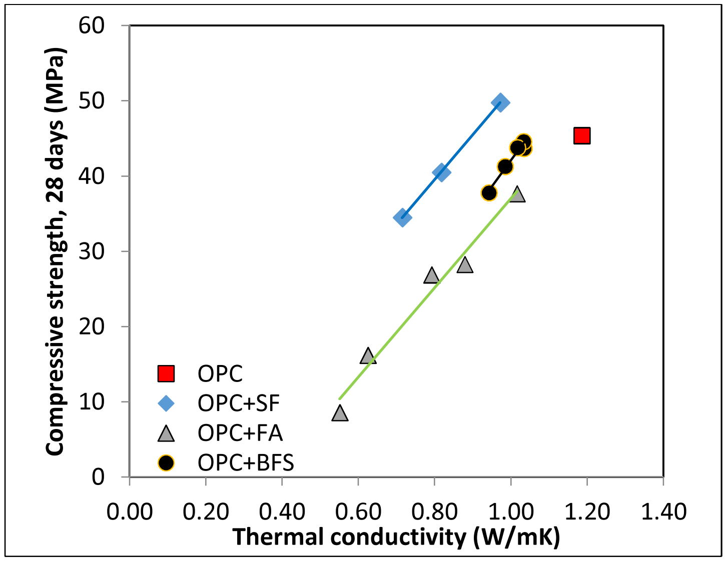

Figure 2-3: Relationship between thermal conductivity and OPC replacement ratio of different SCM in mortars. (Demirboga, 2003a, 2003b)

Other studies reported a decrease in thermal conductivity and compressive strength with the increment of FA replacement level in mortar and concrete (Bentz, Peltz, Duran-Herrera, Valdez, & Juarez, 2010). Moreover, the thermal conductivity of mortars presented a higher reduction for Class C FA than Class F FA (Bentz et al., 2010). A ternary mixture of SF and FA was also studied for low replacement levels. A 7.5% of SF and 7.5% of FA replacement level by weight for OPC reduced the thermal conductivity in 19% and increased the 28d compressive strength in 21% (Demirboğa, 2007).

There is a lack in the analysis of the interaction between thermal conductivity and compressive strength for SCM concretes. The effect of SCM in the thermal conductivity have been associated with the increment of porosity with the increase of SCM replacement level and the lower thermal conductivity of anhydrate SCM compared to anhydrate OPC (Demirboga, 2003b). The changes in the microstructure caused by SCM might be the cause of the reduction of thermal conductivity. There is also a lack of understanding in the relationship between the changes in microstructure with FA and thermal conductivity.

2.2. Aggregates effect on mechanical and thermal properties

The main factors that affect the thermal conductivity of concrete with normal weight aggregates (NWA) are the aggregate volume fraction, mineralogical composition and degree of crystallization (Demirboğa, 2007; K.-H. Kim et al., 2003; Lamond & Pielert, 2006). Khan reported that the thermal conductivity of limestone NWA is 3.15 and quartzite NWA is 8.58 W/mK for oven-dry density (Khan, 2002). Figure 2-4 shows the effect of aggregates with different mineralogical compositions. The thermal conductivity of concretes ranged from 1.60 W/mK for limestone to 2.29 W/mK for quartzite. It is well known that crystalline structure present higher thermal conductivity than amorphous and vitreous (Ghoshdastidar, 2012). In other study, mortars with siliceous fine NWA presented a higher thermal conductivity than concrete with limestone fine NWA (Bentz et al., 2010).

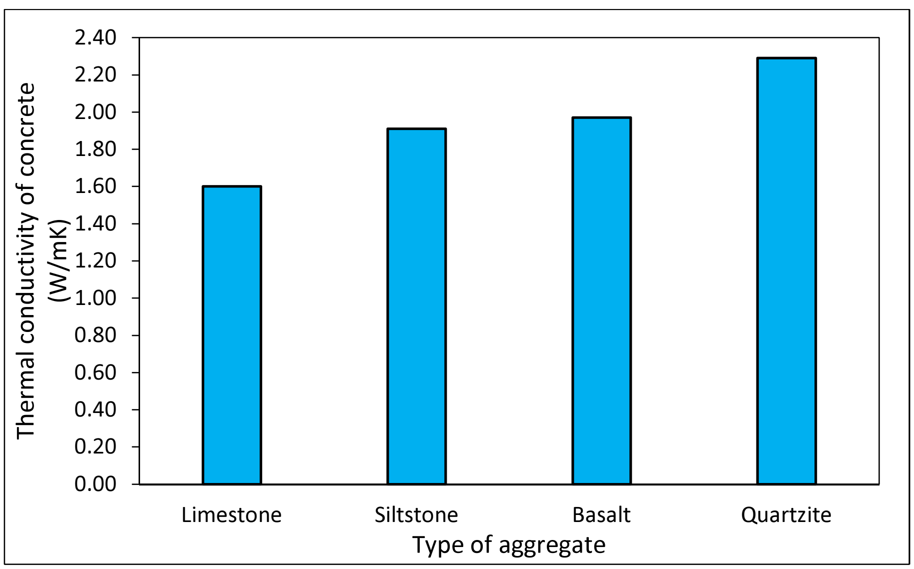

Figure 2-4: Effect of type of aggregate in the thermal conductivity of concrete (Khan, 2002)

Lightweight concretes present a lower density due a higher porosity and can be classified in (Short & Kinniburgh, 1963): (1) lightweight aggregates concrete, where the normal weight aggregates are replaced by lightweight aggregates, (2) no-fines concretes, where the fine aggregates are removed and (3) foamed concrete, where gas bubbles are created in a cement slurry before hardening. The present research focuses in the first two types of lightweight concrete.

Lightweight aggregates (LWA) present a cellular pore structure and a higher porosity than NWA. Figure 2-5 shows the effect on density and compressive strength of the most common LWA. LWA can be classified as natural, where present a volcanic origin (scoria, expanded perlite, pumice) and synthetic, where are produced by a thermal treatment of materials with expansive properties (expanded clay, shale, slate) (Chandra & Berntsson, 2002). Other synthetic LWA are industrial by-products, which may require the addition of materials and thermal treatment for expansion (expanded glass, fly ash LWA) or may not (cenospheres, poliutherane, PET).

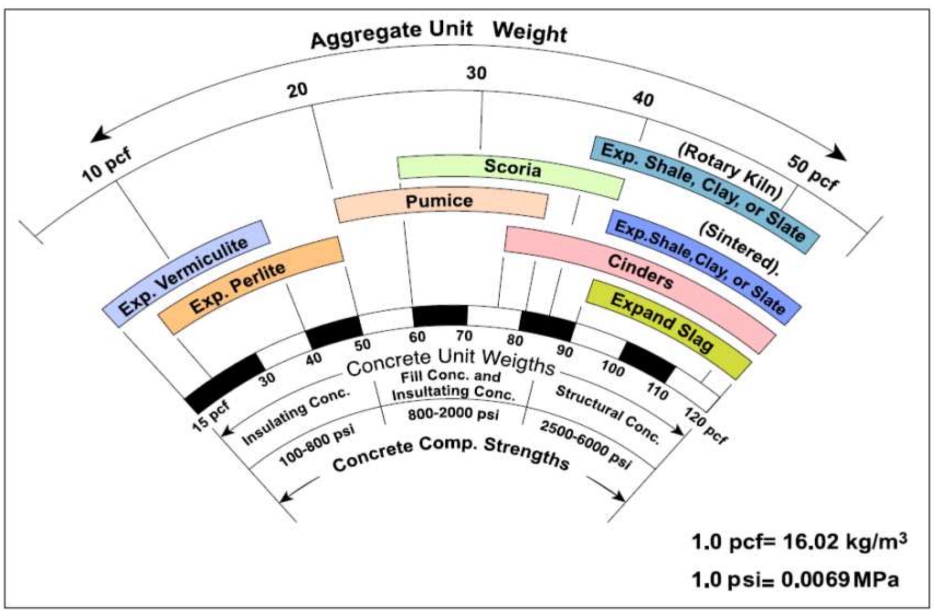

Figure 2-5: Ranges of densities of LWA concretes (Metha & Monteiro, 2014)

There are many studies focused on mechanical properties of LWA concretes with compressive strength ranging 20-100 MPa for instance (Caldarone & Burg, 2004; Chandra & Berntsson, 2002; Holm & Bremner, 2000; Moreno, Martinez, & Lopez, 2014; Short & Kinniburgh, 1963; Videla & Lopez, 2001; Zhang & Gjjrv, 1992). Literature shows that LWA reduces the thermal conductivity of concrete (Chen &

Liu, 2013; Gündüz, 2008; H. K. Kim, Jeon, & Lee, 2012; Mateos, Ayala, Blanco, & Garcõ, 2000; L H Nguyen, Beaucour, Ortola, & Noumowé, 2014; Q L Yu, Spiesz, & Brouwers, 2013; Yun, Jeong, Han, & Youm, 2013).

It is widely known that the reduction of concrete density reduces the thermal conductivity (ACI Committee 213, 2013; Valore Jr., 1980). Figure 2-6 show that the reduction of concrete density with the replacement of NWA for LWA reduces the thermal conductivity in more than 90%. Figure 2-6 shows a wide variation on the thermal conductivity for the same density. The reduction in thermal conductivity of LWA concretes is associated with the porosity of LWA. The differences in mixture design, moisture content and thermal measurement techniques affected the variation obtained. Figure 2-7 shows the thermal conductivity for reported LWA concretes with oven-dry density. The model proposed by Valore (1980) underestimates the thermal conductivity of recent results of LWA concretes for oven-dry density higher than 1200 kg/m^3.

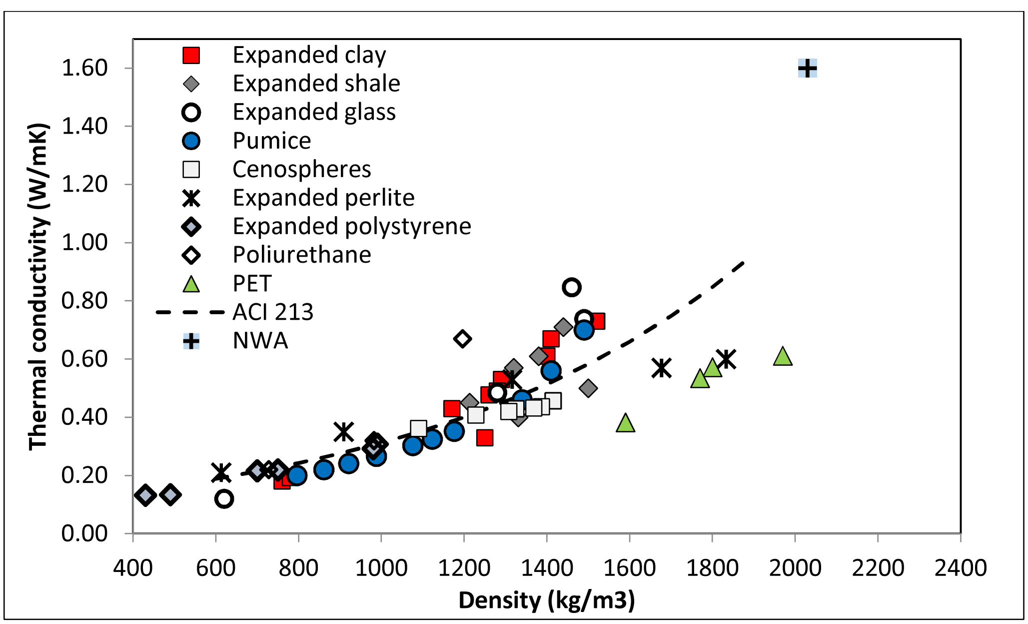

Figure 2-6: Relationship between thermal conductivity and density of LWA concretes.

Note: Expanded clay (Meille, Chanvillard, Schwartzentruber, & Emmanuel Bonnet, 2013; L H Nguyen et al., 2014; M Schlaich & Zareef, 2008; Yun et al., 2013), *expanded shale* (Meille et al., 2013; L H Nguyen et al., 2014; Yun et al., 2013), *expanded glass (Q L Yu et al., 2013; Q.L. Yu, Spiesz, & Brouwers, 2013), pumice* (Gündüz, 2008; L H Nguyen et al., 2014), *cenospheres (Mateos et al., 2000), expanded perlite (Sengul, Azizi, Karaosmanoglu, & Ali, 2011), expanded polystyrene (Park & Chilsholm, 1999), poliutherane, PET (Fraternali et al., 2011), NWA*(L H Nguyen et al., 2014)

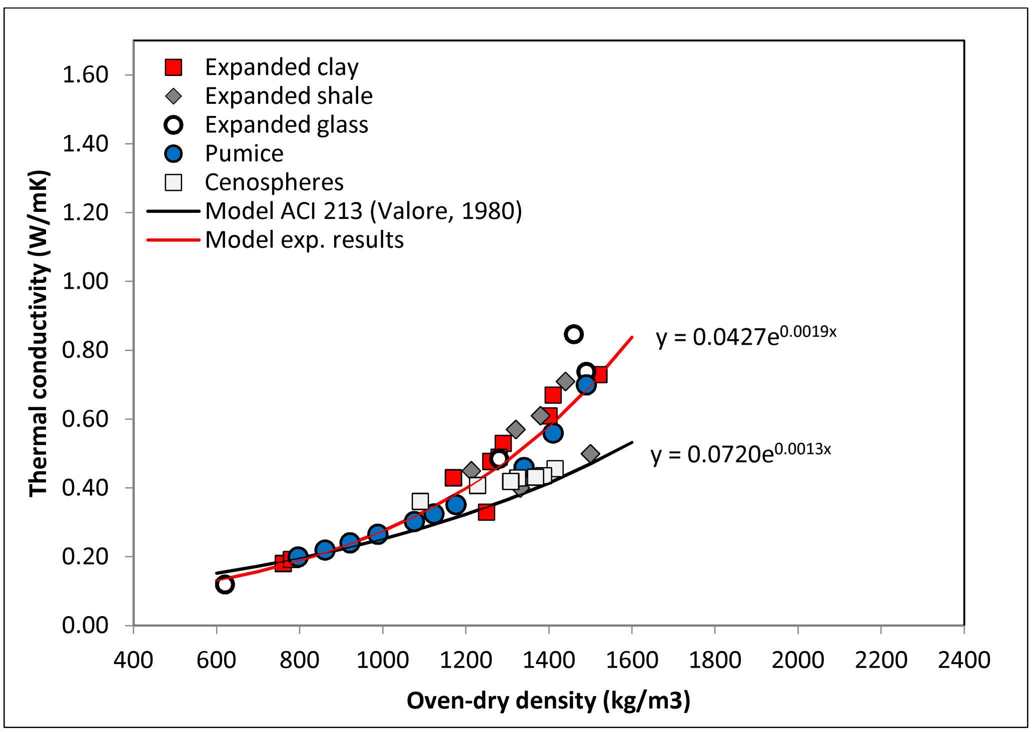

Figure 2-7: Relationship between thermal conductivity and oven-dry density for LWA concretes

Note: Expanded clay (Meille et al., 2013; L H Nguyen et al., 2014; M Schlaich & Zareef, 2008; Yun et al., 2013), *expanded shale* (Meille et al., 2013; L H Nguyen et al., 2014; Yun et al., 2013), *expanded glass* (Q L Yu et al., 2013; Q.L. Yu et al., 2013), *pumice* (Gündüz, 2008; L H Nguyen et al., 2014), *cenospheres (Mateos et al., 2000).*

Few studies in the recent years have characterized the thermal and mechanical properties of LWA concretes simultaneously for expanded clay (L H Nguyen et al., 2014; Mike Schlaich & Zareef, 2008; Yun et al., 2013), expanded shale (L H Nguyen et al., 2014; Yun et al., 2013), expanded polystyrene (Park & Chilsholm, 1999) and other LWA (Gündüz, 2008; Mateos et al., 2000; Uysal, Demirboğa, Şahin, & Gül, 2004; Q.L. Yu et al., 2013).

Recent studies developed structural LWA concretes with low thermal conductivity. Kim et. al. elaborated LWC with expanded shale as coarse aggregate and bottom ash as fine aggregate. It reported dry thermal conductivity, compressive strength and porosity of 0.5 W/mK, 22 MPa and 29%. (H. K. Kim et al., 2012). Mateo et. al. reported LWC with cenospheres as aggregates with density and dry thermal conductivity of 1100-1500 kg/m3 and 0.46-0.63 W/mK. Cubic compressive strength ranged 5-35 MPa (Mateos et al., 2000). Another study with cenospheres obtained thermal conductivity at oven-dry density of 0.28 W/mK, with compressive strength over 30 MPa (Wu, Wang, Monteiro, & Zhang, 2015).

Q. L. Yu et. al. developed self-compacting lightweight concrete with expanded glass as aggregates. Compressive strength and dry thermal conductivity were 23 MPa and 0.49 W/mK respectively (Q.L. Yu et al., 2013). Lafarge developed 100% lightweight structural concretes with low thermal conductivity. It reported compressive strength at 28 days of 29 MPa and thermal conductivity of 0.52 W/mK with expanded clay concrete. (Meille et al., 2013). The influence of fine LWA in structural LWA concrete was studied with pumice, expanded shale and expanded clay as lightweight aggregates. Dry density and dry thermal conductivity of LWC with fine NWA ranged 1410-1520 kg/m3 0.67-0.71 W/mK, while compressive strength ranged 31-40 MPa. A 100% fine NWA for LWA replacement decreased the thermal conductivity thermal conductivity at oven-dry density to 0.43-0.57 W/mK with compressive strength ranging 22-34 W/mK. Nevertheless, there is a lack on the effect of LWA volume in those properties, as fine or coarse aggregate.

There is also recent evidence of LWA concretes with lower thermal conductivity used in concrete wall houses. In Switzerland, architect Patrick Gartmann elaborated an insulating concrete with expanded clay and expanded glass, with cubic compressive strength of 8 MPa and thermal conductivity of 0.32 W/mK. (Zareef, 2010). Schlaich and Zareef reported a lightweight concrete elaborated with expanded clay and air entraining agent for external wall houses. They reported a cubic compressive strength of 7 MPa, thermal conductivity at oven-dry density of 0.18 W/mK and oven-dry density of 760 kg/m^3 (Mike Schlaich & Zareef, 2008).

Gündüz reported a pumice LWA concrete with compressive strength of 14 MPa and thermal conductivity of 0.35 W/mK (Gündüz, 2008). Foam concrete dry density ranged 650-1850 kg/m3, while the thermal conductivity ranged 0.23-0.48 W/mK (Othuman & Wang, 2011). Concrete with 60% of silica aerogel volume exhibited thermal conductivity of 0.26 W/mK, cubic compressive strength of 8.3 MPa and density of 1000 kg/m3 (Gao, Jelle, Gustavsen, & Jacobsen, 2014).

Figure 2-8 shows a wide variation of results on the compressive strength and thermal conductivity between different LWA and for the same type of LWA. The mixture design (binder content, W/B, fine NWA volume), moisture content, measurement techniques for thermal properties make difficult to compare the effect of the type of coarse LWA in the thermal and mechanical properties. Only one study reported the influence of fine LWA in the interaction of thermal and mechanical properties for structural LWA concretes (Q.L. Yu et al., 2013). Therefore, there is still a lack of knowledge on the effect of the type and volume of coarse LWA in thermal and mechanical properties of lightweight concretes. Moreover, previous studies have not assessed the effect of the lightweight aggregates in the thermo-mechanical performance of concrete.

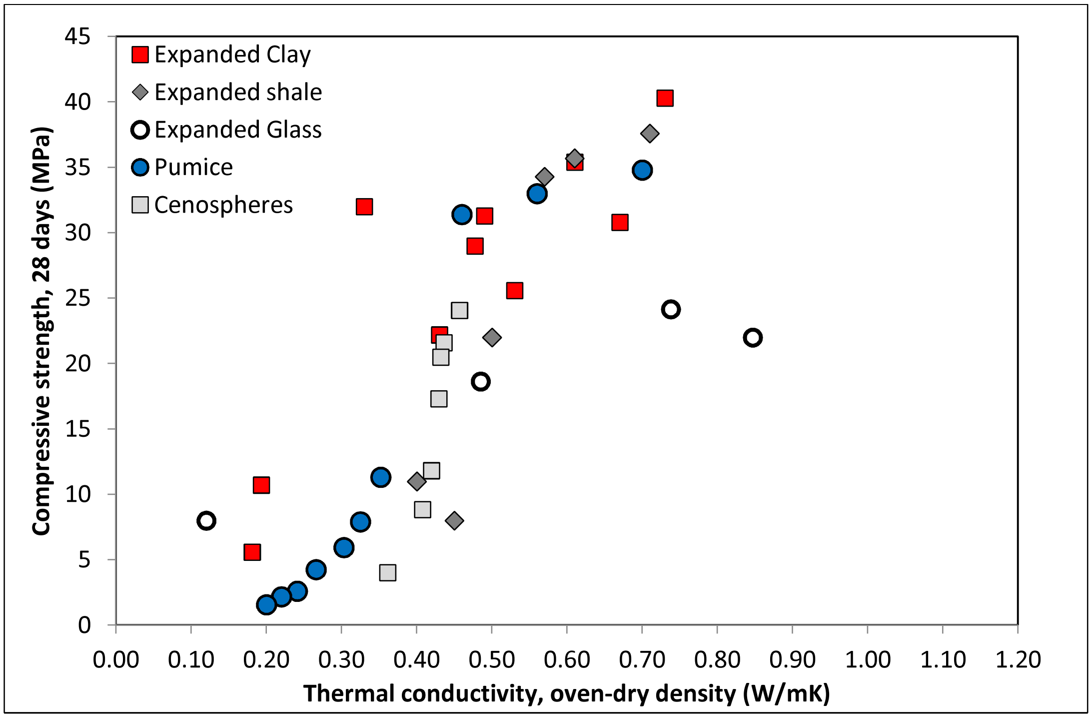

Figure 2-8: Interaction between compressive strength and thermal conductivity of LWA concretes

Note: Expanded clay (Meille et al., 2013; L H Nguyen et al., 2014; M Schlaich & Zareef, 2008; Yun et al., 2013), *expanded shale* (Meille et al., 2013; L H Nguyen et al., 2014; Yun et al., 2013), *expanded glass* (Q L Yu et al., 2013; Q.L. Yu et al., 2013), *pumice* (Gündüz, 2008; L H Nguyen et al., 2014), *cenospheres (Mateos et al., 2000).*

The moisture content also affects the thermal conductivity. Limestone NWA concrete exhibited 57.1% and 21.4% higher thermal conductivity for moist and 50% RH ambient conditions compared to oven dry (Lamond & Pielert, 2006). A fully saturated concrete increased the thermal conductivity in 70% compared to oven-dry density (Khan, 2002). Thermal conductivity of fully saturated concrete, mortar and paste were independent of curing age between 3 and 28 days of hydration; it decreased less than 3% between 3 and 28 days (K.-H. Kim et al., 2003).

One limitation of the previous studies is that they generally measure the thermal conductivity of oven-dry density (L H Nguyen et al., 2014; Q.L. Yu & Brouwers, 2012), but this is not the actual moisture condition in the field. In fact, the equilibrium density (ASTM, 2014c; Holm & Bremner, 2000) is used to represent the in-service ambient density of LWA concretes, which contains a moisture content of approximately 4% by volume (Valore Jr., 1980). In fact, the term equilibrium density is used for LWA concretes (ASTM, 2014c) which contains more water, compared to the oven-dry density. This additional water increases the thermal conductivity up to 20% (Holm & Bremner, 2000; Khan, 2002; Lamond & Pielert, 2006). Therefore, it is required to use the equilibrium density for better represent the actual performance of the mixtures.

In despite of the effects of LWA and FA in thermal properties of concrete, there is a lack of studies analyzing their effects simultaneously. Demirboğa & Gül (Demirboğa & Gül, 2003) showed that the combination of fine LWA (expanded perlite, pumice) with FA replacement level of 10%-30% decreased the dry thermal conductivity of concrete to 0.15 W/mK, but also decreased the 28-day compressive strength to 3 MPa (Demirboğa & Gül, 2003). Therefore, the resulting mixture was not suitable for structural concrete walls. To the authors knowledge there are not previous studies focused in the understanding of the factors that influence the interaction of mechanical and thermal properties.

2.3. Pervious concrete effect on mechanical and thermal properties

Pervious concrete, also known as no-fines or porous concrete is composed of paste and gap-graded coarse aggregates, where the components form an internal pore structure, with the porosity ranging 15-30% (Deo & Neithalath, 2011; J. Kevern, Schaefer, & Wang, 2009; J. T. Kevern, Schaefer, & Wang, 2008; Sumanasooriya, Deo, & Neithalath, 2013; K. Wang, Schaefer, Kevern, & Suleiman, 2006). Pervious concrete have been used in pavement for water runoff management (Manahiloh, Muhunthan, Kayhanian, & Gebremariam, 2012; Sansalone, Kuang, & Ranieri, 2008), air purifying (Asadi, Hassan, Kevern, & Rupnow, 2012) and noise reduction (H. K. Kim & Lee, 2010). It was also used for external walls in buildings (Short &

Kinniburgh, 1963) and its durability has been assessed (Carsana, Tittarelli, & Bertolini, 2013).

It has been reported that the increase of porosity in pervious concrete decrease the thermal conductivity of concrete (Short & Kinniburgh, 1963; Valore Jr. & Green, 1951; Wong, Glasser, & Imbabi, 2007) Nevertheless, it is still higher than the demanded for external walls and the mechanical properties were not measured in the same study. The thermal and mechanical properties of pervious concretes have not been assessed yet, with most of studies focusing on the mechanical properties.

There are limited results in the literature of pervious concretes with LWA. One study evaluated the mechanical and thermal properties of LWA pervious concretes, with compressive strength ranging 2.5-6.0 MPa and thermal conductivity ranging 0.16-0.25 W/mK (Zaetang, Wongsa, Sata, & Chindaprasirt, 2013). The LWA used were not suitable for structural concrete and limited the compressive strength for no structural application. It is desired to explore the mechanical and thermal properties of pervious concretes with LWA suitable for structural concretes. Expanded shale have been highly used for LWA structural concrete (H.Z. Cui, Lo, Memon, Xing, & Shi, 2012; Y. Kea, A.L. Beaucour , S. Ortola , H. Dumontetb, 2009; Yun et al., 2013). It seems suitable to increase the compressive strength of LWA pervious concretes.

The total porosity of pervious concretes affects the mechanical and thermal properties. Current methods for determine pervious concrete porosity are based in a volumetric approach and allow measuring the total effective porosity for a specific drying method (ASTM, 2014a; Montes, Valavala, & Haselbach, 2005). Nevertheless, this method cannot quantify the porosity formed in the internal structure in a LWA pervious concrete. The LWA porosity increases the total effective porosity of a LWA pervious concrete. There was not found a method that allows bring a pervious concrete to SSD. It is desired to determine the surface-dry porosity of pervious concrete in order to quantify the effective porosity at SSD and the internal porosity

3. SUMMARY OF CONDUCTED WORK

3.1. Research gap

Mechanical properties (Caldarone & Burg, 2004; Holm & Bremner, 2000; Metha & Monteiro, 2014) and thermal properties (Hochstein, 2013; Hong, Kim, & Kim, 2004; Khan, 2002) of concrete have been generally studied by separate. There has been an increased interest in the last years in studying the compressive strength and the thermal conductivity of concretes (Demirboğa, 2007; L H Nguyen et al., 2014; Ünal, Uygunoğlu, & Yildiz, 2007; Q.L. Yu et al., 2013).

The mechanical and thermal properties are inversely proportional and depend of the internal structure of concrete. The wide variation of compressive strength for the same thermal conductivity presented in literature might be influence by the lack of assessment of the effect of the internal structure. The internal structure is reflected in the constituents that compose the concrete. There is a lack of knowledge on the effect of the type and volume of coarse LWA in mechanical and thermal properties of lightweight concretes. The effect of SCM in mechanical and thermal properties has not been completely assessed neither. There is also a gap in the thermal and mechanical properties of pervious concrete for normal weight aggregates and LWA. It is desired a proper selection of the internal structure of concrete to enhance the balance between thermal conductivity and compressive strength.

The increment of porosity is the most used strategy to reduce the thermal conductivity of concrete, but its effect in the interaction of mechanical and thermal properties has not been assessed. Studies generally analyze the effect of the total porosity. A recent theoretical study showed that the porosity properties, such as pore size distribution, affect the thermal conductivity for the same total porosity (Pia & Sanna, 2013). A proper characterization of the porosity properties is desired to evaluate the effect in compressive strength and thermal conductivity.

3.2. Hypotheses

The formulated hypotheses are going to be addressed in the articles presented in Chapter Four, Chapter Five and Chapter Six. Hypothesis 1 corresponds to Chapter Four. Hypothesis 2 and 3 corresponds to Chapter Five. Finally, hypothesis 4 corresponds to Chapter Six.

3.2.1. Hypothesis 1

The increment of porosity of lightweight aggregates does not increment the efficiency of the compressive strength, elastic modulus and thermal conductivity of lightweight aggregates concretes.

3.2.2. Hypothesis 2

The combination of constituents enhances the thermal conductivity reduction with a smaller negative detriment on the compressive strength than each constituent by separate.

3.2.3. Hypothesis 3

The porosity properties of lightweight aggregates influence the compressive strength and thermal conductivity of lightweight aggregates concretes.

3.2.4. Hypothesis 4

The thermal conductivity of the aggregates present a higher effect in the thermal conductivity of no-fines concretes than the effective porosity of no-fines concretes.

3.3. Objectives

The main objective is the assessment of the effect of the internal structure of concrete in the mechanical and thermal properties of concrete and the the interaction of between both properties.

The specific objectives are:

i) Evaluate the independent effect of constituents modifications (coarse lightweight aggregates, fine lightweight aggregates, binder) in the mechanical and thermal properties of concrete.
ii) Evaluate the combined effect of constituents modifications (coarse lightweight aggregates, fine lightweight aggregates, binder) in thermal and mechanical properties of concrete.
iii) Characterize the porosity properties (pore size distribution, maximum pore size and pore spatial distribution) of lightweight aggregates.
iv) Evaluate the effect of the porosity properties on the mechanical and thermal properties of lightweight aggregates concretes.
v) Evaluate the combined effect of constituents modifications (coarse lightweight aggregates) in no-fines concretes.
vi) Propose strategies that minimize the thermal conductivity with the minimum decrement in the compressive strength of concrete.

3.4. Methodology

A literature review was conducted to analyze the state of the art of concrete technologies and constituents than reduce the thermal conductivity and their effect in the compressive strength. The methods and equipments for thermal properties and current experimental procedures for physical, mechanical and thermal properties were also studied. The materials were selected based on the literature results and their availability in Chile. The experimental program was designed in order to assess with the objectives proposed. The experimental program consisted in 47 concrete mixtures divided in three phases (Chapter Four, Chapter Five, and Chapter Six) where their physical, mechanical and thermal properties were measured. Two-phase models for compressive strength, elastic modulus and thermal conductivity were also investigated to evaluate the effect of the type of lightweight aggregates. Multiple linear regression models for compressive strength and thermal conductivity were assessed to evaluate the impact of each component for the combined constituents. The conclusions were obtained from the analysis of the results.

4. TOWARDS AN INSULATING-STRUCTURAL CONCRETE BY ASSESSING AND UNDERSTANDING THE INTERACTION OF MECHANICAL AND THERMAL PROPERTIES

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Highlights:

- The three constituents modifications presented a higher impact in the reduction of compressive strength than the thermal conductivity of concrete and LWA was more efficient in the reduction of thermal conductivity.
- While a series composite model represents better the elastic modulus of LWA concrete, a parallel composite model represents better its thermal conductivity.
- The effect of the replacement of expanded clay for expanded polystyrene, which represent a reduction of LWA thermal conductivity of 90%, reduced the thermal conductivity of LWA concrete in less than 15%, for a 30% LWA volume.

Abstract

It is important to reduce the thermal conductivity of concrete; however, impacts negatively the mechanical properties, which undermine its use. This study focus on the understanding of the interaction of mechanical and thermal properties of concrete for three constituents modifications: supplementary cementing materials, fine lightweight aggregates (LWA) and coarse LWA. The thermal conductivity behaves closer to a parallel composite model while

the elastic modulus behave closer to a series composite model; this determines the efficiency of each constituent. Fine LWA had one of the highest efficiencies 0.017 [W/mK]/MPa, while FA had the lowest 0.008 [W/mK]/MPa.

Keywords:

Lightweight aggregates, fly ash, thermal conductivity, compressive strength, structural concrete, two-phase models

4.1. Introduction

Buildings account 20-40% of total final energy consumed worldwide (Pérez-Lombard et al., 2008). This is the main reason behind design energy codes demand thermal resistance for building's envelope to improve the energy efficiency (IEA, 2013). Therefore, the thermal performance must be considered as important as the mechanical performance in a building's design. Concrete, the most used construction material, excels in mechanical properties and constructability, but lacks in thermal resistance, which depends of its constituents: binder, fine and coarse aggregates.

It has been showed that the inclusion of pores/voids in concrete increments the thermal resistance (Chandra & Berntsson, 2002) but reduces the mechanical resistance (Popovics, 1998). Therefore, a very careful selection of concrete constituents is required to enhance the balance between thermal and mechanical properties. Previous studies demonstrated that the replacement of Portland cement for fly ash (FA) and normal weight aggregates for lightweight aggregates (LWA) decrease the thermal conductivity (i.e., increase thermal resistance), in expense of a lower compressive strength (ACI Committee 213, 2013; Chandra & Berntsson, 2002; Demirboga, 2003b).

FA, a by-product of coal power plants, is used as a partial replacement of Portland cement in the binder. The influence of FA in the mechanical properties of concrete have been widely studied (Berry & Malhotra, 1981; Bilodeau & Malhotra, 2000; Langley, Carette, & Malhotra, 1990; Metha, 2004; Oner, Akyuz, & Yildiz, 2005; A.

Wang, Zhang, & Sun, 2003). On the other hand, only few studies have characterized the influence of FA in the thermal properties of concrete. The increase of FA replacement level decreased the thermal conductivity of cement paste and mortar (Demirboga, 2003a, 2003b). Other studies reported a decrease in thermal conductivity and compressive strength with the increment of FA replacement level for mortar (Demirboğa, 2007) and concrete (Bentz et al., 2010). Moreover, thermal conductivity was more intensively reduced by Class C than Class F FA (Bentz et al., 2010). Nevertheless, there is a lack in the analysis of the interaction between thermal conductivity and compressive strength. There is also a lack of understanding in the relationship between the changes in microstructure with FA and thermal conductivity.

LWA present a higher porosity than normal weight aggregates (NWA), which produce a decrement in the compressive strength and the thermal conductivity. There are many studies focused on mechanical properties of LWA concretes with compressive strength ranging 20-100 MPa for instance (Caldarone & Burg, 2004; Chandra & Berntsson, 2002; Holm & Bremner, 2000; Moreno et al., 2014; Videla & Lopez, 2001; Zhang & Gjjrv, 1992). On the other hand, some studies have been focused on thermal properties of LWA concrete in recent years. However, only few studies characterized the thermal and mechanical properties of LWA concretes simultaneously for expanded clay (L H Nguyen et al., 2014; Mike Schlaich & Zareef, 2008; Yun et al., 2013), expanded shale (L H Nguyen et al., 2014; Yun et al., 2013), expanded polystyrene (Park & Chilsholm, 1999) and other LWA’s(Gündüz, 2008; Mateos et al., 2000; Uysal et al., 2004; Q.L. Yu et al., 2013). There is a wide variation of results on the mechanical and thermal properties for the same type of LWA. The mixture design, moisture content and the measurement techniques for thermal properties make difficult to compare the effect of the type of coarse LWA in the thermal and mechanical properties simultaneously. Only one study reported the influence of fine LWA in the interaction of thermal and mechanical properties for structural LWA concretes (Q.L. Yu et al., 2013). Therefore, there is still a lack of understanding on the effect of the type and volume of coarse LWA in thermal and mechanical properties of lightweight concretes. Moreover, previous studies have not assessed the effect of the lightweight aggregates in the thermo-mechanical performance of concrete.

This article aims to provide an exploratory study of the interaction between mechanical and thermal properties with the use of different constituents. The trade-off between thermal conductivity and compressive strength was investigated by systematically modifying the mixture designs in three aspects independently: (i) replacement of Portland cement by FA, (ii) replacement of mortar by coarse LWA (expanded clay, expanded shale, expanded polystyrene), and (iii) replacement of normal weight fine aggregate by fine LWA (expanded clay). Two-phase models (mortar, coarse aggregate) for compressive strength, elastic modulus and thermal conductivity were used to assess the thermo-mechanical performance and compare the efficiency of the three coarse LWA examined. Finally, the interaction between thermal conductivity and compressive strength were analyzed to select the strategies that most enhance the thermal performance (i.e., reduction in thermal conductivity) with the lowest impact in the compressive strength.

4.2. Experimental program

4.2.1. Materials and mix proportion

Ordinary Portland cement (OPC) with a specific gravity of 3.14 and Blaine fineness of 410 m^2/kg and a class C Fly ash(FA), with specific gravity of 2.37 (Rivera, Martinez, Castro, & Lopez, n.d.), were used as cementitious materials. The OPC and FA were produced in Chile. The coarse and fine normal weight aggregate (siliceous) were also produced in Chile while the LWA were coarse expanded clay from Spain, coarse expanded shale from USA and expanded polystyrene beads from Chile. Fine expanded clay was produced in the laboratory by crushing the coarse expanded clay in a stone crusher machine. The crushed material was sieved between No.4 and No. 50 mesh to obtain the fine expanded clay. The physical properties of normal weight and LWA used in the study are given in Table 4-1: Physical properties of aggregates. The LWA were submerged for 72 hours and the absorption was obtained according to ASTM C1761 (ASTM, 2013). Also, high range water reducer admixture (HRWA) was used in a dose of 0.5% by binder weight for all concretes mixture with the exception of fine expanded clay mixtures which used a dose of 0.2% to avoid segregation.

The total porosity, P, of LWA was estimated from Equation 1. The density of the solid portion ρ_{solid}, was assumed from previous studies as 2650 kg/m^3 for expanded clay and expanded shale (Bogas, Mauricio, & Pereira, 2012; Holm & Bremner, 2000) and 1020 kg/m^3 for polystyrene (D. S. Babu, Ganesh Babu, & Tiong-Huan, 2006). The oven-dry density, ρ_{O-D}, was measured according to ASTM C1761 (ASTM, 2013).

$$P = 1 - \frac{\rho_{O-D}}{\rho_{solid}} \quad (1)$$

Table 4-1: Physical properties of aggregates

Aggregate	Size (mm)	Oven-dry density (kg/m^3)	Saturated surface dry density (kg/m^3)	Total porosity (%)	Absorption, 72 hr (%)
Coarse expanded clay	20 /10	784	941	70%	20.1%
Coarse expanded shale	20 /10	1254	1423	53%	13.5%
Expanded polystyrene	10 /2	-----	15	99%	-----
Fine expanded clay	4 /0	885	1260	67%	42.3%
Normal weight coarse aggregate	20 /10	2679	2700	-----	0.8%
Normal weight fine aggregate	4 /0	2617	2662	-----	1.7%

FA concrete consisted on normal weight coarse and fine aggregates, water, OPC and FA. OPC was partially replaced by FA for volumetric replacement levels of 20 to 60%, as shown in Table 4-2. The water-to-cementitious material ratio (W/CM) by weight was kept at 0.5, and the volumetric proportion of aggregates remained constant for all the mixtures.

Table 4-2: Mixture proportions of fly ash concretes

Mix	OPC (kg/m^3)	FA by volume (%)	FA (kg/m^3)	Total cementitious (kg/m^3)	Water (kg/m^3)	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	HRWA (Kg/m^3)
PC	400	0	0	400	200	870	890	2.0
FA20	320	20	60	380	190	870	890	1.9
FA30	280	30	91	371	185	870	890	1.9
FA40	240	40	121	361	180	870	890	1.8
FA50	200	50	151	351	175	870	890	1.8
FA60	160	60	181	341	171	870	890	1.7

Lightweight concrete was conceived as a two-phase material: coarse LWA and a mortar matrix (OPC, water and normal weight fine aggregate). The mixture designs were based in the methodology developed by Videla and Lopez (Videla & Lopez, 2001). A proportion of the mortar matrix was replaced by coarse LWA. The volume fraction of LWA varied from 20 to 50% for ES and EC and from 10 to 30% for EPS, as shown in Table 4-3. The paste-to-fine aggregate ratio by volume and Water-to-Cement ratio by mass (W/C) remained as 0.8 and 0.4, respectively for the mortar matrix in all the mixtures.

Table 4-3: Mix proportions of coarse lightweight aggregates concretes

Mix	OPC (kg/m^3)	Water (kg/m^3)	Coarse LWA (kg/m^3)	Mortar matrix volume (%)	Coarse LWA by volume (%)	Fine aggregate (kg/m^3)	HRWA (Kg/m3)
EC20	480	192	188	34%	20.0	1176	2.4
EC27.5	435	174	259	31%	27.5	1066	2.2
EC35	390	156	329	31%	35.0	956	2.0
EC42.5	345	138	400	31%	42.5	845	1.7
EC50	300	120	471	31%	50.0	735	1.5
ES20	480	192	285	34%	20.0	1176	2.4
ES27.5	435	174	391	31%	27.5	1066	2.2
ES35	390	156	498	28%	35.0	956	2.0
ES42.5	345	138	605	25%	42.5	845	1.7
ES50	300	120	712	22%	50.0	735	1.5
EPS10	540	216	1.50	39%	10.0	1323	2.7
EPS15	510	204	2.25	37%	15.0	1250	2.6
EPS20	480	192	3.00	34%	20.0	1176	2.4
EPS25	450	180	3.75	32%	25.0	1103	2.3
EPS30	420	168	4.50	30%	30.0	1029	2.1

Fine lightweight aggregate mixtures consisted on normal weight fine aggregate, fine expanded clay, OPC and water. Normal weight fine aggregate was partially replaced for fine expanded clay in the mortar matrix keeping the paste-to-fine aggregate ratio by volume at 0.8 and W/C at 0.4. Normal weight fine aggregate replacement varied from 16% to 75% by mass and from 9 to 41% by volume, as shown in Table 4-4.

Table 4-4: Mix proportions of fine lightweight aggregates concretes

Mix	OPC (kg/m^3)	Water (kg/m^3)	Fine aggregate (kg/m^3)	Fine LWA (kg/m^3)	Fine LWA by volume (%)	HRWA (Kg/m^3)
Mortar	600	240	1470	0	0	1.2
FEC16	600	240	1235	109	16	1.2
FEC45	600	240	809	308	45	1.2
FEC75	600	240	368	513	75	1.2

Concrete mixtures were produces in an 80-liter vertical axis mixer. Expanded shale and expanded clay (both coarse and fine) were submerged in water for 72 hours and drained in a No. 50 sieve for 10 minutes before the mixing. Moisture content was considered in adjusting the mixing water and aggregate doses. Four 100x200 mm cylindrical specimens were cast for each batch for mechanical testing and two 150 mm cubic specimens were cast for thermal testing. Concrete was compacted by rodding, according to ASTM C192 (ASTM, 2006).

Specimens were left in their molds for 24 hours and submerged in water at 20(±1) °C for 7 days after demolding. Two 150x150x75 mm prismatic specimens were saw-cut from each cubic specimen. The cut was perpendicular to the filling face of the specimen. Then, the specimens (prisms and cylinders) were stored in a chamber at 22°C (±2) and 50% (±3) R.H., until the age of the mechanical and thermal tests.

4.2.2. Test procedures

The compressive strength and elastic modulus of concrete were measured at the age of 28 days. Compressive strength was measured on four specimens and the elastic modulus was measured on three specimens. The elastic modulus was measured following the ASTM C469 guidelines (ASTM, 2014b), by applying up to 33% of the maximum compressive strength and measuring the strain using 3 gauges and a data acquisition system.

The thermal properties were measured with a Hot Disk TPS1500 in the single side mode; which is a state of the art transient technique that measures thermal conductivity (k) and thermal diffusivity (α) of materials (Gustafsson, 1991). The volumetric specific heat was calculated from these two properties. The hot disk consists on a thin sensor, which acts both as a heat source and a temperature sensor. In the single side mode, the sensor was located atop the specimen and the other sides were covered with polyurethane (k=0.025W/mK, α=0.25 mm^2/s) to avoid heat losses. The maximum increase of temperature during the test was 5 °C for all the measurements. The sensor model was 4922, with diameter of 29.2 mm. The penetration depth in horizontal and perpendicular direction from the sensor was at least 23 mm. The measurement time was 320 seconds. The tests were developed under laboratory conditions at 20° C (±1). One measurement was taken for each of the four prismatic specimens. The thermal properties were registered in equilibrium density, according to (ASTM, 2014c).

4.3. Results and discussion

4.3.1. Effect of fly ash ratio on the mechanical and thermal properties

The 28-day compressive strength of concrete decreased as the FA replacement level of the mixture increased. Figure 4-1 a) shows a linear trend between the FA replacement level and the compressive strength. The 28-day compressive strength was reduced in up to 56% with at 60% of FA replacement level by volume. The 28-day elastic modulus also decreased as the FA replacement level of the mixture increased. The elastic modulus was reduced in up to 37% with at 60% of FA replacement level by volume (see Table 4-5). In the present study, concretes with up to 60% FA replacement level are classified as structural concretes, with 28-day compressive strength over 30 MPa.

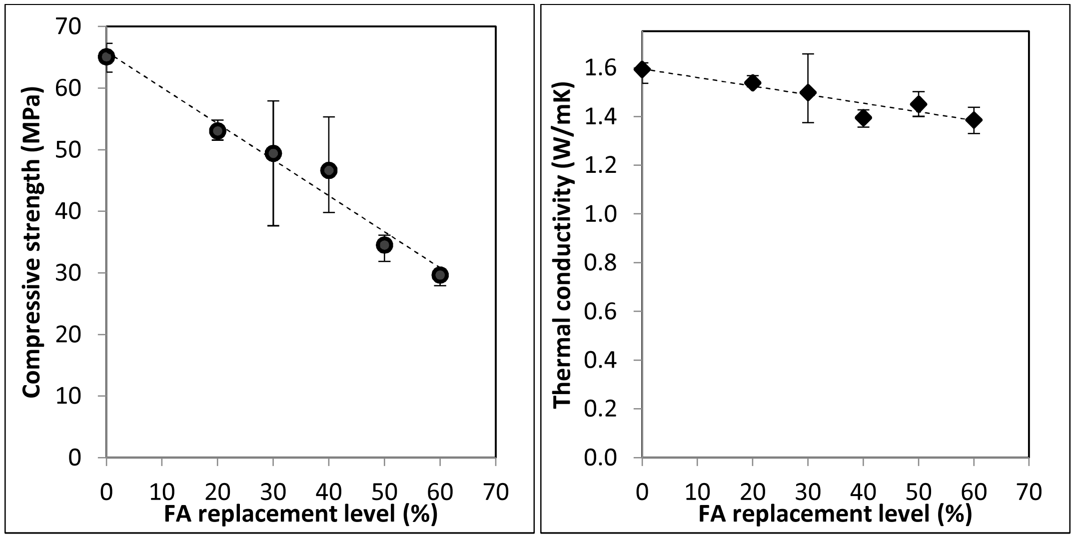

Figure 4-1:a) Effect of fly ash on 28 days compressive strength b) Effect of fly ash on thermal conductivity at equilibrium density

The decrease in the mechanical properties at 28 days is caused by the relatively slower pozzolanic reaction of FA compared to OPC hydration (Berry & Malhotra, 1981; Metha & Monteiro, 2014; Oner et al., 2005; A. Wang, Zhang, & Sun, 2004; Z. Yu & Ye, 2013). That is, the increase of FA replacement level reduces the cement available for hydration and causes the decrement of mechanical properties at early ages. Previous studies also reported an increase in the porosity with the increment of FA replacement level (A. Wang et al., 2004; Z. Yu & Ye, 2013). Curing conditions also affected the strength gain rate. The samples were stored in a chamber at 22°C (±2) and 50% (±3) relative humidity after 7 days of water curing. Then, there was less water available for cement and fly ash hydration after 7 days. Previous studies reported that the hydration of the cement paste stops for an interior relative humidity below 80% (Flatt, Scherer, & Bullard, 2011; Patel, Killoh, Parrott, & Gutteridge, 1988).

Table 4-5: Mechanical properties of fly ash concretes

Mix	Equilibrium density (kg/m^3)	Oven-dry density (kg/m^3)	28 days Compressive strength (MPa)	28 days Elastic Modulus (GPa)
PC0	2391	2350	65.1	48.3
FA20	2383	2357	53.1	45.1
FA30	2366	2311	49.5	42.8
FA40	2358	2305	46.7	33.3
FA50	2334	2291	34.6	31.5
FA60	2311	2285	29.7	28.3

The thermal conductivity decreased with the increase of replacement level, as Figure 4-1 b) shows. The reduction ranged 10-14% while the FA replacement level ranged 40-60%. These values are consistent with previous studies. For instance, one study reported that the thermal conductivity at oven-dry density decreased 24% and 33% for 20% and 30% of replacement level respectively (Demirboga, 2003a) and other study that the thermal conductivity at equilibrium density decreased 19% for 75% replacement level (Bentz et al., 2010).

Figure 4-1 shows that a modification at the paste level (i.e., increase in the FA replacement level), impacts compressive strength at a higher level than the thermal conductivity. In fact, a 60% FA replacement level showed a 56% reduction in compressive strength but only a 14% reduction in thermal conductivity. The increase of FA reduces the cement content, which causes a decrease 28-day compressive strength. On the other hand, the effect in thermal conductivity is important at the paste level, but limited at the concrete level by the relatively low volume of paste (34%) in the concrete. The thermal conductivity of normal weight aggregates is reported to be at least to be three times larger than paste binders with fly ash (Demirboga, 2003b; Khan, 2002). When the heat flows through the composite, the aggregate particles behave as thermal bridges due to the higher thermal conductivity of the aggregates. The latter limits the effect of decreasing the thermal conductivity of the paste in NWA concrete. The thermal bridges effect and the stop of hydration due the curing conditions might influence that the thermal conductivity did not decrease for FA replacement level higher than 40%.

The effect of FA replacement level in the mechanical properties of concrete has been widely studied, as previously referenced. Nevertheless, its effect in the thermal conductivity might be caused by other factors not considered in previous studies. Researchers reported that porosity increments with the increase of FA replacement level (A. Wang et al., 2004; Z. Yu & Ye, 2013), while the thermal conductivity decreases (Demirboğa, 2007). The lower thermal conductivity of anhydrate FA compared to anhydrate OPC also contributes to the decrease in thermal conductivity (Demirboga, 2003a).

The change on hydration products due to the replacement of OPC for FA impacts the thermal conductivity of concrete. The main solids hydration products of a completely hydrated OPC are calcium silicate hydrate, CSH (50-60%), and calcium hydroxide, CH (20-25%) (Metha & Monteiro, 2014). CH is a highly crystalline compound, as opposed to CSH, which varies from poorly crystalline to reticular network. The CSH interlayer space is supposed to vary from 0.5 to 2.5 nm (Metha & Monteiro, 2014). CH is 1000 times larger than CSH. The pozzolanic effect of FA-which transforms CH into CSH if water is available-decreases the CH volume for FA replacement level higher than 30% (A. Wang et al., 2004). Also, FA enhances the hydration of OPC (A. Wang et al., 2004). Wang measured that CH volume decreased from 20% to 4% with the increase of FA from 0% to 40% and less than 0.1% for 60% of FA at 365 days (A. Wang et al., 2004). Materials with higher degree of crystallinity present higher thermal conductivity than those more poorly crystalline (Ghoshdastidar, 2012; Raman, 2007). Then, the reduction on thermal conductivity can be further explained by the transformation of CH into CSH as the pozzolanic reaction occurs.

The pore refinement also affects the thermal conductivity. Despite the increase in porosity, previous studies show that FA hydration products refines the pore size distribution (Zeng, Li, Fen-chong, & Dangla, 2012). FA enhances a higher hydration level for cement grains since provides more nucleation sites for the cement hydration products (A. Wang et al., 2004). The hydration products of FA fill the existing pore structure, enhancing a global refinement of pore distribution (Zeng et al., 2012). The total amount of mesopores (4.5-50 nanometers) increased with the increase of FA (Zeng et al., 2012). The thermal conductivity of the air decreases with the decrease of pore diameter less than 10 micrometers (10^4 nanometers), due to the Knudsen effect (Berge & Johansson, 2012; B. P. Jelle, Gustavsen, & Baetens, 2010). This occurs when the mean free path between gas molecules is larger than the pore diameter. A gas molecule collision is more likely to impact with the pore solid wall than with another gas molecule. Collisions between gas molecules transfer larger amounts of energy than collisions between a gas molecule and the solid wall of the pore (Berge & Johansson, 2012). Therefore, smaller pores in FA concrete enhance the reduction of thermal conductivity.

The hydration degree also affects the thermal conductivity. Concrete with anhydrate FA presents a lower thermal conductivity than anhydrate OPC. FA present a larger proportion of amorphous material than OPC and the thermal conductivity of crystalline silica is reported to be up to 15 larger than amorphous silica (Demirboga, 2003a).

In the present study neither the porosity, pore size distribution nor the hydration products were measured. The effects of FA on these parameters were based on previous studies that confirm these effects. The obtained results are also limited by the constant water to binder ratio; its variation affects the porosity and pore size of the paste.

There must be an optimum FA replacement level that enhances the compressive strength and reduces the thermal conductivity. As previously explained, the increment of CSH must reduce the thermal conductivity, while also increases the compressive strength (Metha & Monteiro, 2014). With the increase of FA replacement level, the total CH produced initially increases for the cement hydration enhancement produced by the FA, but at some point begins to decrease because there is less OPC to hydrate. The decrease of CH volume also limits the FA hydration to form CSH. Then, the anhydrate FA portion that behaves as inert aggregate increases with the increase of the FA replacement level. An optimum FA replacement level of 40% in weight for concrete was reported to increase long term mechanical properties (Oner et al., 2005). The optimum also depends of the FA and OPC chemical composition, the curing conditions, the measurement age and other factors. The balance between the hydration products, pore size distribution and portion of anhydrate FA leads to the optimum on compressive strength and thermal conductivity.

4.3.2. Effect of lightweight aggregates on the mechanical and thermal properties

Figure 4-2 shows that the increment of LWA volume reduces the compressive strength of concrete. Table 4-6 shows that the increment of LWA volume also reduces the elastic modulus. These effects on mechanical properties were also previously reported (H Z Cui, Yiu, Ali, & Xu, 2012; Moreno et al., 2014; Videla & Lopez, 2001; Y. Kea, A.L. Beaucour , S. Ortola , H. Dumontetb, 2009; Yang, 1997; Zhang & Gjjrv, 1992). The properties of lightweight aggregate also affected the mechanical properties of concrete by other means. Previous studies propose that a lower water absorption (Y. Kea, A.L. Beaucour , S. Ortola , H. Dumontetb, 2009) and a more angular shape (H Z Cui et al., 2012) increases the compressive strength and elastic modulus. Intrinsic strength measurement of aggregates (ACV, TPFV) is also highly related with the compressive strength, but present a considerable variability (Moreno et al., 2014; Videla & Lopez, 2001; Videla & López, 2000). Nevertheless, the increase in porosity of LWA weakens the compressive strength of concrete (Moreno, 2011). Table 4-1 shows that expanded shale presents the lowest porosity (53%), compared to expanded clay (70%) and expanded polystyrene (99%).

Table 4-6: Density, compressive strength and elastic modulus of lightweight concretes

Mix	Equilibrium density (kg/m^3)	Oven-dry density (kg/m^3)	28 days Compressive strength (MPa)	28 days Elastic Modulus (GPa)
M	2304	2222	84.6	38.9
ES20	2021	1928	68.1	32.2
ES27.5	1932	1855	66.9	30.6
ES35	1850	1779	58.8	27.0
ES42.5	1789	1716	50.8	24.0
ES50	1761	1715	43.1	22.7
EC20	1954	1881	43.1	0.0
EC27.5	1861	1792	26.4	23.6
EC35	1723	1684	24.1	22.1
EC42.5	1599	1516	18.4	16.0
EC50	1535	1486	17.6	13.0
EPS10	2038	-	43.9	25.6
EPS15	1948	-	42.4	21.2
EPS20	1794	-	31.6	19.6
EPS25	1701	-	23.2	17.4
EPS30	1601	-	22.8	19.4
FEC16	2131	1989	70.6	33.6
FEC45	1850	1702	46.7	22.3
FEC75	1558	1387	23.2	17.7

Figure 4-2 a) shows that the expanded shale presents the lowest detriment on the compressive strength compared to expanded clay and expanded polystyrene, for the same volume of LWA. Expanded shale presents a lower porosity, lower absorption and more angular shape than expanded clay. From the mechanical standpoint, the pores in the LWA act as weak locations; thus, when concrete is under compressive stress, there is stress concentration in the vicinity of LWA pores triggering crack formation and propagation and ultimately failure. Expanded polystyrene presents the highest porosity (Table 4-1), which causes a negligible strength for the aggregate and the highest weakening effect on the compressive strength.

Fine expanded clay presents a higher compressive strength that coarse expanded clay. Previous studies reported the increase of compressive strength in lightweight concretes when then maximum aggregate size was reduced (D. S. Babu et al., 2006; Holm & Bremner, 2000; Le Roy, Parant, & Boulay, 2005; Miled, Sab, & Le Roy, 2007). This effect also benefited the compressive strength of expanded polystyrene because presented a smaller maximum aggregate size of all the coarse LWA.

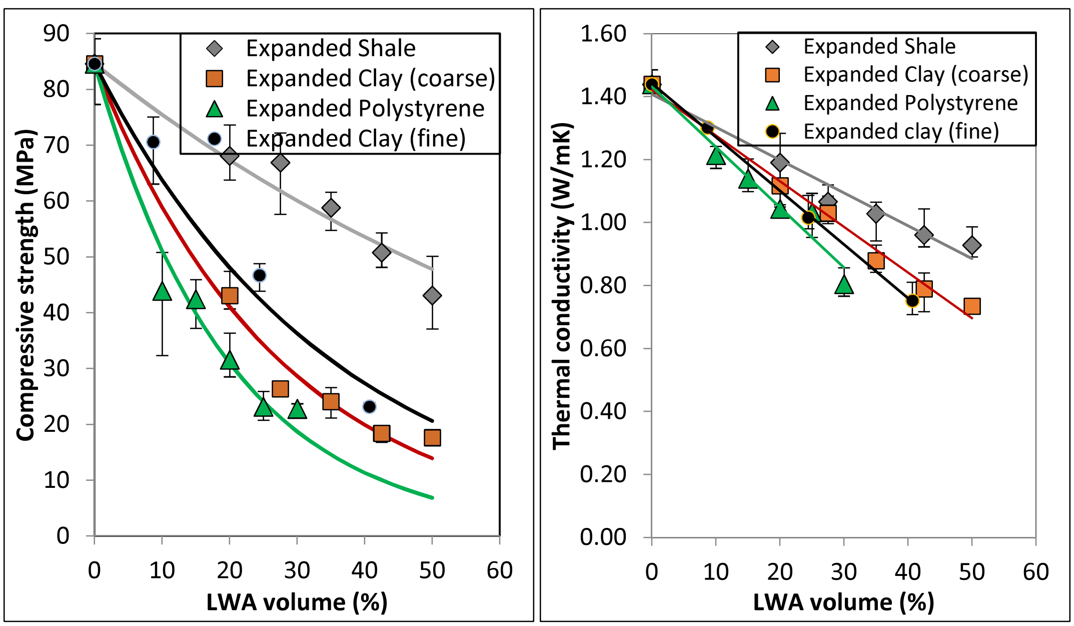

Figure 4-2: a) Effect of LWA in compressive strength; b) Effect of LWA in thermal conductivity

Figure 4-2 b) shows that the thermal conductivity at equilibrium density linearly decreases with the increase of the lightweight aggregate volume. The slope reflects the impact in the thermal conductivity due to a change in the volume. An increase of 10% of the lightweight aggregate volume decreases the thermal conductivity of expanded shale concrete in 0.106 W/mK. For the same increase of lightweight aggregate volume, the reduction in thermal conductivity is 0.147 W/mK for coarse expanded clay, 0.173 W/mK for fine expanded clay and 0.195 W/mK for expanded polystyrene.

The thermal conductivity of LWA concretes is mainly affected for the porosity and the mineralogical composition of LWA. The higher total porosity of expanded clay (70%) compared to expanded shale (53%) explains its lower estimated thermal conductivity. The mineralogical composition of expanded clay and expanded shale are similar and mainly crystalline structure, according to a previous study (L H Nguyen et al., 2014). On the other hand, expanded polystyrene is mainly amorphous (Sperling, 2006) and the thermal conductivity of crystalline materials is reported to be higher than amorphous (Demirboga, 2003a; Ghoshdastidar, 2012). Therefore, the lowest measured values on EPS concrete are caused by a combination of its amorphous microstructure and its high porosity.

The aggregate size also affected the compressive strength and thermal conductivity of concrete. Figure 4-2 shows that the fine expanded clay presented a higher compressive strength and lower thermal conductivity than the coarse expanded clay. These results might be influenced by the experimental design because the fine expanded clay replaced normal weight fine aggregate, whereas the coarse expanded clay replaced mortar matrix. As the normal weight fine aggregate present a higher thermal conductivity than the cement paste (Khan, 2002), its replacement might cause a larger decrease in thermal conductivity.

The thermal diffusivity decrease is highly influenced for the decrease in thermal conductivity, which is larger than the decrease in the density of concrete and the specific heat. In structures exposed to day/night cycles with important temperature fluctuations, a concrete with a lower thermal diffusivity is desirable because increases the dynamic thermal performance of concrete, acting as a buffer that absorbs/releases heat at a slower rate.

$$\alpha = \frac{k}{\rho * c_p} \quad (2)$$

Where α is the thermal diffusivity (mm^2/s), ρ is the density (kg/m^3) and $c_p$is the specific heat (J/kg*K).

The thermal diffusivity decreased with the increase of the lightweight aggregate volume (Table 4-7). It is also lower than that of the mortar matrix. The concrete with 20% of expanded clay volume presented a lower thermal diffusivity than their counterparts with 27.5% and 35% of expanded clay.

Table 4-7: Thermal properties of lightweight concretes at equilibrium density

Mix	Thermal conductivity (W/mK)	Thermal diffusivity (mm^2/s)	Specific heat (J/kg K)
M	1.44	0.62	971
ES20	1.19	0.56	1059
ES27.5	1.07	0.56	1006
ES35	1.03	0.55	1014
ES42.5	0.96	0.51	1050
ES50	0.93	0.51	1029
EC20	1.12	0.48	1192
EC27.5	1.03	0.60	927
EC35	0.88	0.53	992
EC42.5	0.79	0.44	1115
EC50	0.73	0.46	976
EPS10	1.22	0.59	1019
EPS15	1.14	0.56	1039
EPS20	1.04	0.53	1110
EPS25	1.03	0.54	1052
EPS30	0.80	0.52	961
FEC16	1.30	0.55	1112
FEC45	1.02	0.52	1067
FEC75	0.75	0.43	1131

4.3.3. Analysis of mechanical and thermal properties of LWA

The work of Moreno et. al. proposed a methodology to assess the impact of coarse LWA in the mechanical properties (Moreno et al., 2014; Moreno, 2011). This methodology was applied to the coarse LWA concretes of this research but cannot be extended to the fine LWA due the changes in the matrix composition.

Two-phase models were validated (Moreno et al., 2014) for the compressive strength and the elastic modulus. The compressive strength model is presented in Equation 2. The LWA are considered as air containers. An upper bound of 3.84 is proposed to represent entrapped air in the concrete. A reduction of the aggregate weakness factor (θ) implies a decrease in air content and an increase in the contribution of the LWA to the compressive strength of concrete. The apparent elastic modulus of the LWA is calculated from the Hirsch's model represented in Equation 3. This model corresponds to the harmonic mean of the series and parallel models for elastic modulus of composite materials.

$$f_c = f_m * 10^{-\theta V_a} \quad (3)$$

Where f_c is the compressive strength of the lightweight concrete, V_a is the lightweight aggregate volume and θ is the aggregate weakness factor.

$$E_c = \frac{1}{0.5 * \left[\frac{V_a}{\beta} + \frac{(1 - V_a)}{E_m}\right] + 0.5 * \left[\frac{1}{V_a * \beta + (1 - V_a) * E_m}\right]} \quad (4)$$

Where E_c the elastic modulus of the lightweight is concrete, V_a is the LWA volume and β is the apparent elastic modulus of the lightweight aggregate.

The aggregate weakness factor (θ), and the apparent elastic modulus (β) of the aggregates were obtained from non-linear analysis in the software STATA. Coefficients of determination, R^2, were higher than 0.993. Expanded shale, as Figure

4-2 a) shows, presented the lowest aggregate weakness factor in compressive strength and was more than 3.1 and 4.4 times lower than expanded clay and EPS, respectively. The apparent elastic modulus of expanded shale was 2.7 and 3.4 times larger than those obtained using expanded clay and EPS, respectively.

The apparent elastic modulus is influenced by the properties of the mortar matrix (Moreno et al., 2014). It was concluded that β increases with the increase of E_m. The latter explains that the apparent elastic modulus of expanded clay is 26% higher than EPS. Apparent elastic modulus of 4.2 GPa for expanded clay and 2.2 GPa for EPS, for a mortar matrix of 23.3 GPa was previously reported (Moreno et al., 2014), compared to 38.9 GPa in the present research.

Table 4-8: Apparent aggregate weakness factor LWA

Lightweight Aggregate	θ	t	P>|t|	95% C.I. (±)	R^2
Expanded shale	0.50	23.0	0.00	0.08	0.998
Expanded clay	1.57	10.3	0.00	0.18	0.996
Expanded polystyrene	2.18	37.2	0.00	0.34	0.994

Table 4-9: Apparent elastic modulus of LWA

Lightweight Aggregate	β (MPa)	t	P>|t|	95% C.I. (±) (MPa)	R^2
Expanded shale	14335	15.2	0.00	1605	0.999
Expanded clay	5253	22.1	0.00	1313	0.993
Expanded polystyrene	4160	11.9	0.00	899	0.997

The proposed methodology (Moreno et al., 2014) for mechanical properties can be extended for assessing the apparent thermal conductivity of LWA. Nguyen calculated the thermal conductivity of aggregates based on an inverse calculation approach and validated three multiphase models: Differential Multiphase, Mori Tanaka, and Self-Consistent. The three models presented similar results, but the

Differential Multiphase provided more conservative results (Le Hung Nguyen, 2013). The Differential Multiphase (DM) model considers n types of randomly oriented ellipsoidal inclusions into a matrix and is presented in Equation 4 (Phan-Thien & Pham, 2006). For two-phase materials with spherical inclusions, the DM model presents the implicit solution of Equation 5 (Hochstein, 2013).

$$\frac{d\lambda}{dt} = \frac{\lambda}{1 - v_T t} \sum_{i=1}^{n} v_I \frac{\lambda_i - \lambda}{3} \sum_{j=1}^{3} \frac{1}{\lambda_i A_i^j + \lambda(1 - A_i^j)} \, , \lambda(0) = \lambda_m \, , 0 \le t \le 1 \qquad (5)$$

Where v_T is the total volumetric fraction of the inclusions, v_i is the volumetric fraction of the i inclusion, λ_i is the apparent thermal conductivity of the i inclusion and A_i^j $(j = 1, 2, 3)$ are the solutions of the elliptic integral based in the shape of the i inclusion.

$$1 - v_1 = \left(\frac{\lambda_1 - \lambda_c}{\lambda_1 - \lambda_m}\right)\left(\frac{\lambda_m}{\lambda_c}\right)^{1/3} \qquad (6)$$

Where v_1 is the volumetric fraction of lightweight aggregate, λ_1 is the apparent thermal conductivity of the lightweight aggregate and λ_C and λ_M are the experimental thermal conductivity of concrete and mortar matrix, respectively.

Table 4-10 shows that the apparent thermal conductivity of the expanded shale is two times the apparent thermal conductivity of the expanded clay and 26 times that of the expanded polystyrene. The apparent thermal conductivity of EPS (0.018 W/mK) was not significant and lower than experimental results of EPS (0.04 W/mK) (Bjørn Petter Jelle, 2011).This model seems to be less accurate to estimate the thermal conductivity of inclusion materials with very low thermal conductivity.

Table 4-10: Apparent thermal conductivity of LWA

Lightweight aggregate	λ (W/mK)	t	P>|t|	95% C.I. (±) (W/mK)	R^2
Expanded shale	0.47	17.0	0.00	0.07	0.993
Expanded clay	0.23	15.3	0.00	0.04	0.998
Expanded polystyrene	0.018	0.38	0.72	0.12	0.986

As an analytical assessment, the apparent elastic modulus and apparent thermal conductivity of LWA were used to compare their efficiency in the concrete. That is, the elastic modulus and thermal conductivity of the composite can be estimated and the performance of a particular lightweight aggregate assessed. The parallel and series composite models were considered as upper and lower bounds for elastic modulus and thermal conductivity. A previous study proposed the Hashin-Shtrikman (HS) upper bound model (Hashin & Shtrikman, 1962) and the Effective Medium Theory (EMT) model as bounds for thermal conductivity of internal porosity materials (Carson, Lovatt, Tanner, & Cleland, 2005). Lightweight concretes are internal porosity materials, where the matrix phase forms a continuous heat pathway through the composite. These bounds are also considered for thermal conductivity.

$$P_{series} = \frac{1}{\frac{V_a}{P_a} + \frac{(1 - V_a)}{P_m}} \qquad (8)$$

$$P_{par} = V_a * P_a + (1 - V_a) * P_m \qquad (9)$$

Where P_s is the property (either elastic modulus or thermal conductivity) of the lightweight aggregate P_m is the property (either elastic modulus or thermal conductivity) of the mortar matrix and V_a is the lightweight aggregate volume.

Figure 4-3 shows the effect of LWA in elastic modulus and thermal conductivity of the composite. To maximize elastic modulus and minimize thermal conductivity, it is desired the elastic modulus behaving closer to a parallel model and the thermal conductivity closer to a series model. Nevertheless, LWA concretes tend to behave oppositely; that is, closer to a series model for elastic modulus, and closer to the parallel model for thermal conductivity. The proposed bounds for Carson et. al. (2005) are in well agreement with the experimental thermal conductivity results. It must be pointed out that the larger the difference in elastic modulus and thermal conductivity between the mortar matrix and LWA, the less the improvement rate in the concrete.

Figure 4-3 shows that decreasing the thermal conductivity of the aggregate is not as effective as expected in reducing the thermal conductivity of the concrete. Comparing expanded polystyrene with expanded clay, the effect of using a LWA with a thermal conductivity of about 10% of that of expanded clay reduced the thermal conductivity of concrete in less than 15%, for 30% of LWA volume.

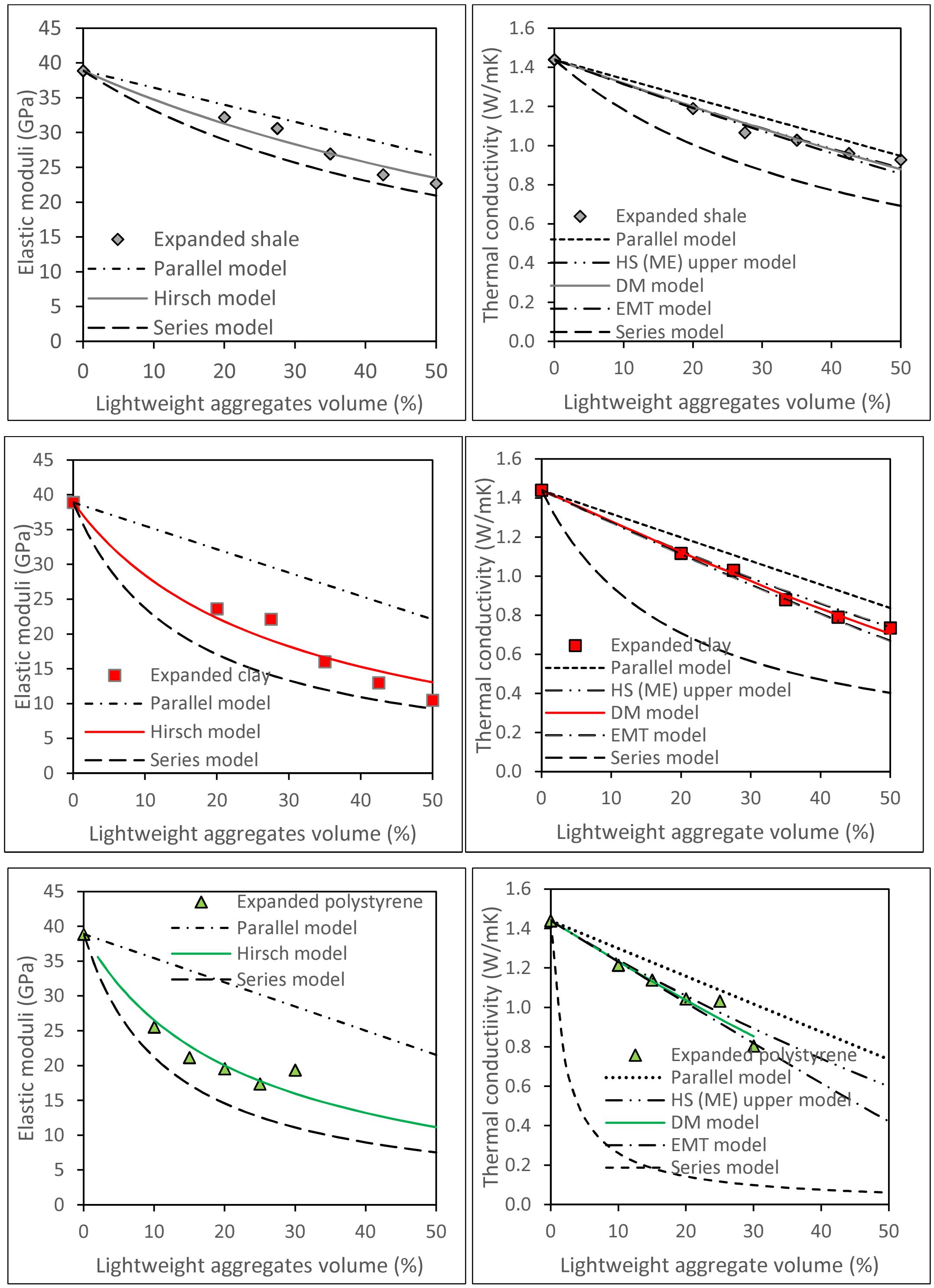

Figure 4-3: Experimental thermal conductivity and elastic modulus of lightweight concretes compared to the proposed models and bounds

Figure 4-4 shows the trade-off between the apparent thermal conductivity, apparent elastic modulus and the aggregate weakness factor. The relationship tends to be inversely proportional between aggregate weakness factor and the apparent thermal conductivity and directly proportional between the latter and the apparent elastic modulus. These factors are mainly influenced by the porosity of the aggregates (Table 4-1). Expanded shale presents a high mechanical performance with the lowest weakness factor (θ), highest apparent elastic modulus (β) but the lowest thermal performance with the highest apparent thermal conductivity (λ_1). On the other hand, EPS leads to the lowest apparent thermal conductivity (λ_1) with the lowest mechanical performance (θ, β).

The compressive strength, elastic modulus and thermal conductivity of concrete depend of the porosity of the LWA. The pores are the dispersed phase whose strength is negligible compared to the stress of the matrix (ACI Committee 213, 2013). Nevertheless, the thermal conductivity of the air (0.025 W/mK) (Lienhard IV & Lienhard V, 2015) is also negligible compared to the mortar matrix (1.44 W/mK). This leads to a different behavior of stress concentration and heat flux in LWA concrete. The pores of LWA act as the weak locations of LWA concrete for mechanical strength. There is stress concentration in the vicinity of LWA pores, triggering crack formation and propagation and ultimately failure. On the contrary, the heat flux lines flow through the mortar, avoiding the pores of LWA. This would explain the relative low effect of increasing the porosity of the aggregate in the thermal conductivity of concrete. For instance, the expanded polystyrene porosity (99%) does not help to decrease thermal conductivity significantly because the heat flux lines avoid the LWA, working similar to a parallel model (see Figure 3). These results suggest that achieving a low thermal conductivity of the composites necessarily requires a reduction in the thermal conductivity of the matrix; otherwise, matrix is going to remain as the main heat conductor.

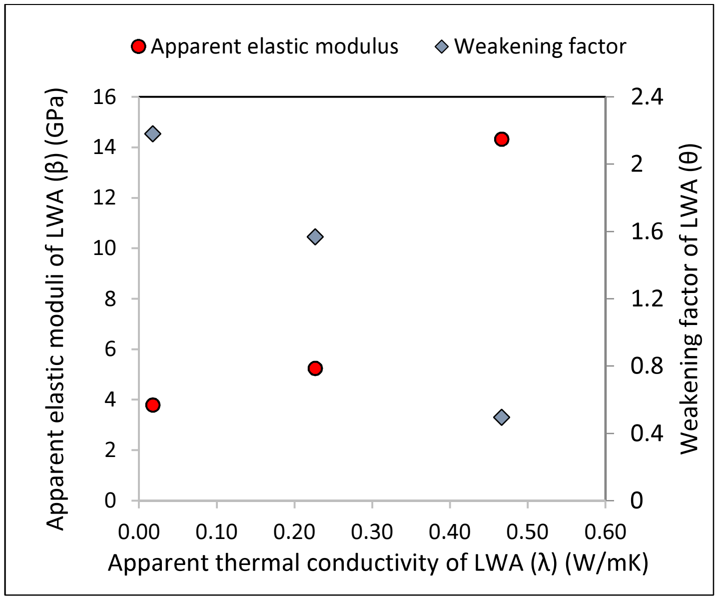

Figure 4-4: Aggregate weakness factor and apparent elastic modulus as function of apparent thermal conductivity

4.3.4. Interaction of mechanical properties and thermal properties

The three modifications in the constituents presented similar trends in compressive strength and thermal conductivity since both properties decrease as the constituent material (FA, coarse LWA and fine LWA) increased. The slope of the linear trends between compressive strength and thermal conductivity in Figure 4-5 would represent the efficiency of a certain new constituent; that is, a large slope would mean a large change in compressive strength with a small change in thermal conductivity. On the contrary, a small slope would mean small changes in compressive strength with large changes in thermal conductivity.

Consequently, FA presents the largest slope, so the highest decrease in compressive strength for a given decrease in thermal conductivity. For instance, a reduction of 0.1 W/mK in thermal conductivity will bring a reduction of 13 MPa in 28-day compressive strength. Among the LWA, expanded shale and fine expanded clay presented the highest slopes meaning that a reduction of 0.1 W/mK in thermal conductivity will bring a reduction of 9.4 and 8.6 MPa in 28-day compressive strength, respectively. On the other hand, coarse expanded clay and expanded polystyrene presented the lowest slopes meaning that a reduction of 0.1 W/mK in thermal conductivity will bring a reduction of 5.8 and 5.6 MPa in 28-day compressive strength, respectively.

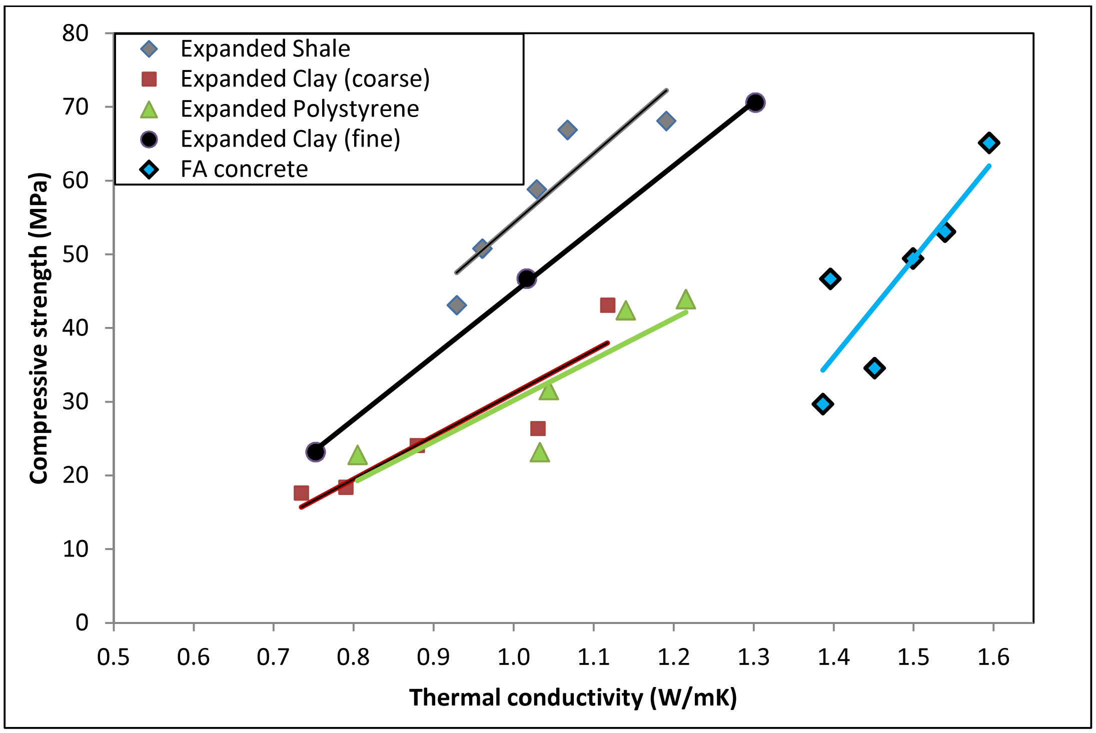

Figure 4-5: Relationship of compressive strength and thermal conductivity of concretes

The apparent thermal conductivity and aggregate weakness factor of expanded clay and expanded polystyrene (Figure 4-4) tend to a balance in the properties of concrete. Expanded polystyrene presents the advantage of a smaller maximum aggregate size, which increases the compressive strength of concrete (Le Roy et al., 2005; Miled et al., 2007). This suggests that expanded clay of similar porosity and smaller aggregate size must present a higher compressive strength than the results of the present study. It would be more efficient than expanded polystyrene.

Figure 4-6 show the compressive strength-to-thermal conductivity ratio (fc/k) for the FA and LWA mixtures in the study. The increase of FA ratio reduced thermal conductivity and compressive strength, but since the reduction in compressive strength is greater, the fc/k decreases. High FA replacement levels in concrete with NWA present a lower efficiency in the balance of fc/k.

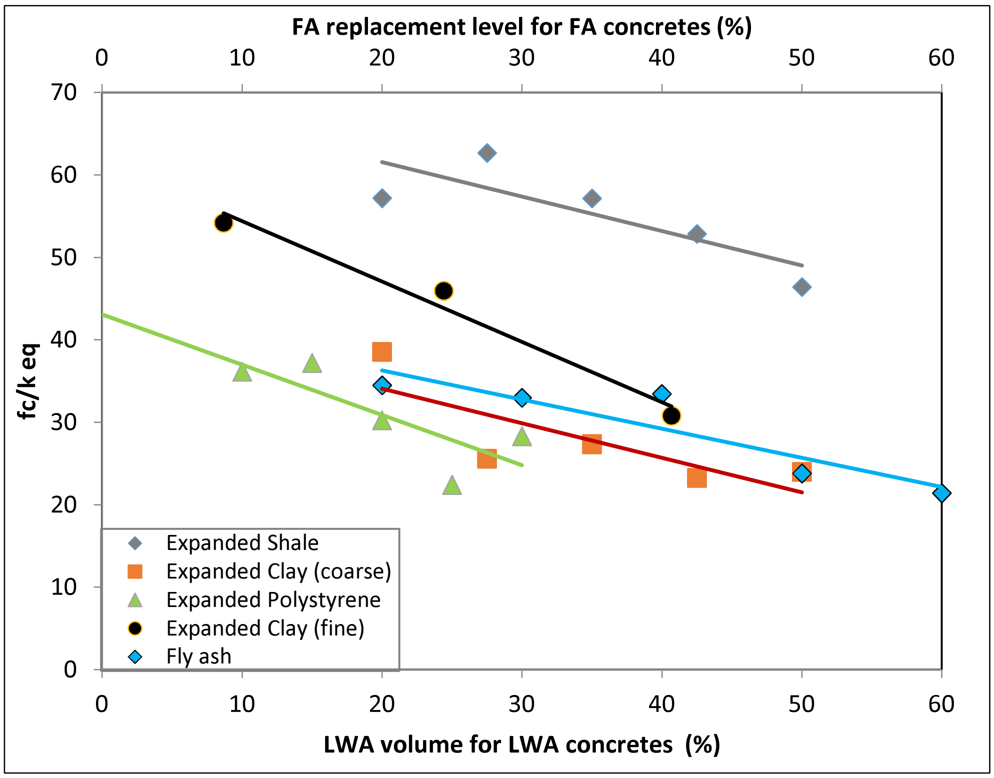

Figure 4-6: Ratio of compressive strength to equilibrium thermal conductivity of concretes

According to Figure 4-1, the thermal conductivity of concrete, under these curing conditions, is not affected for FA replacement levels higher than 40%. As discussed earlier, there is an optimum FA replacement level for compressive strength (Oner et al., 2005). The fraction of FA that behaves as inert aggregate decreases the mechanical properties because there are less hydration products and the pozzolanic reaction decreases. Also, this fraction contributes to decrease the thermal conductivity. These results suggest that there is an optimum volume of FA replacement level that minimizes the thermal conductivity: a balance between the changes in the microstructure (transformation of CH to CSH) and the reaction degree of FA. This optimum is also influenced for the curing conditions. With the increase of curing in a high relative humidity ambient, there will be an increase of the hydration products and the pozzolanic reaction and therefore further increase in the fc/k.

For LWA concretes, the fc/k tends to decrease with the increment of LWA volume. Expanded shale with 27.5% LWA volume has a more efficient fc/k than the mortar, with an increase from 58 to 62 MPa/W/mK. For a higher LWA volume, the fc/k reduces up to 46 MPa/W/mK for 50%. The fc/k decreases with the increment of LWA volume for the other two LWAs. Expanded clay and EPS concretes also present a lower fc/k for the same LWA volume caused for the higher sensitivity of compressive strength. For expanded clay concrete with volume ranging 27.5%-50%, fc/k tends to diminish its reduction rate to 27-24 MPa/W/mK. The fc/k is very sensitive to the compressive strength because is reduced at a higher rate than the thermal conductivity. While Figure 4-6 shows that FA concretes present a higher fc/k than expanded clay and polystyrene concretes, Figure 5 shows that these LWA are more efficient in decreasing the thermal conductivity for structural strength concretes.

The inclusion of LWA in the high strength mortar matrix causes a reduction in compressive strength of up to four times, while the thermal conductivity reduces in less than two times the mortar. The higher porosity of LWA has a greater reduction effect on the compressive strength than in the thermal conductivity. The lower porosity of expanded shale benefits the mechanical behavior but limits the thermal conductivity that can be reached. On the other hand, the mechanical strength is highly reduced for expanded clay and EPS. This effect reduces the fc/k for EPS and expanded clay, compared to expanded shale.

Figure 4-5 and Figure 4-6 confirm that the coarse expanded clay and expanded polystyrene presents a similar balance between thermal conductivity and compressive strength. Both materials seem to be equivalent to obtain a structural concrete with low thermal conductivity. Expanded shale presents higher fc/k efficiency, but is limited to a thermal conductivity higher than 0.9 W/mK. Previous research shows that the combination of coarse and fine LWA increases the fc/k (L H Nguyen et al., 2014). The combined effect of coarse LWA, fine LWA and FA might decrease the thermal conductivity of concrete beyond the limits of the present study. The thermal conductivity of all the constituents of the concrete must be reduced and balanced to avoid thermal bridges.

This article investigated the mechanical and thermal properties of concrete with the independent modifications of three constituents: (i) Fly ash (FA) in the binder (ii) coarse lightweight aggregate (LWA), and (iii) fine LWA. The compressive strength, elastic modulus, thermal conductivity, thermal diffusivity and specific heat were measured. The impact of the type of coarse LWA (expanded shale, expanded clay, expanded polystyrene) was evaluated with two-phase models for compressive strength, elastic modulus and thermal conductivity. These results were used to compare the efficiency of the type of coarse LWA in concretes. The interaction of compressive strength and thermal conductivity was analyzed for the three constituents' modifications. The main conclusions are listed as follows:

- FA presented a higher impact in the reduction of compressive strength (56%) than thermal conductivity (14%). The effect on thermal conductivity is limited by the low paste volume (34%) and the higher thermal conductivity of the aggregates when using normal weight aggregates. The balance between the CH to CSH transformation, pore size distribution and anhydrate FA leads to a decrease in thermal conductivity and to the optimum compressive strength to thermal conductivity ratio.

- The three coarse LWA presented a higher impact in the reduction of compressive strength than the thermal conductivity of concrete. Expanded shale is more suitable to a high strength LWA concrete but the thermal conductivity of concrete is limited to values higher than 0.9 W/mK. Expanded clay and expanded polystyrene concretes presented structural strength, with a lower thermal conductivity down to 0.74 W/mK.

Coarse expanded clay and expanded polystyrene present a similar balance between thermal conductivity and compressive strength. Both materials seem to be suitable to obtain a structural concrete with low thermal conductivity.

- The LWA porosity affects differently the mechanical and thermal properties. The pores of LWA are the weak locations for mechanical performance, where the stress concentration initiates the failure of the concrete. Porosity acts similarly for elastic modulus concentrating deformations around it. The elastic modulus of concrete when using LWA is better represented by a series composite model. Contrarily, the heat flux lines flow through the mortar (higher thermal conductivity phase), avoiding the pores of LWA. The thermal conductivity of concrete using LWA is better represented by a parallel composite model. This explains the relative low effect of increasing the porosity of the aggregate in the thermal conductivity of concrete. The expanded polystyrene porosity (99%) does not help to decrease significantly the thermal conductivity because the heat flux lines avoid the LWA.

- The increase in LWA volume up to 50% for expanded shale and expanded clay and up to 30% for expanded polystyrene did not increase the thermal conductivity efficiency because the thermal conductivity of the concrete is mostly governed by the mortar matrix. The reduction of thermal conductivity of LWA is not as effective as expected in reducing the thermal conductivity of the concrete. The effect of the replacement of expanded clay for expanded polystyrene with a thermal conductivity of only 10% of the first, reduced the thermal conductivity of concrete in less than 15%, for 30% of LWA volume.

4.4. Acknowledgments

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5. TOWARDS AN IMPROVED BALANCE OF MECHANICAL AND THERMAL RESISTANCE FOR LIGHTWEIGHT CONCRETES WITH HIGH VOLUME FLY ASH CONTENT

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Highlights

- Fine expanded clay allows a higher reduction of thermal conductivity with a lower reduction of compressive strength compared to coarse expanded clay.
- Fine expanded clay presented: (1) better pore spatial distribution in the concrete which explain the thermal conductivity, (2) smaller maximum pore size which explain the compressive strength and (3) more refined pores which also affects the thermal conductivity.
- The combination of constituents generates a higher tortuosity effect in the thermal conductivity with the reduction of thermal bridges within the concrete.

Abstract

Energy efficient concrete houses demand cement based materials with reduced thermal conductivity. This paper evaluates the interaction of three constituents on the compressive strength and thermal conductivity: (i) coarse expanded clay (CEC), (ii) fine expanded clay (FEC), (iii) and fly ash (FA). The three constituents combined reduced the compressive

strength and thermal conductivity to 9.3 MPa and 0.43 W/mK. FEC produced a greater reduction in thermal conductivity and a lower reduction in compressive strength than CEC for the pore size distribution refinement, decrease in maximum pore size and increase in spatial distribution of FEC within the concrete.

Keywords: Expanded clay, fly ash, compressive strength, thermal conductivity, porosity properties, pore size distribution, CT scan.

5.1. Introduction

Space heating and cooling of residential sector account over 10% of total primary energy consumption in United States, Europe and Chile(Corporacion de Desarrollo Tecnológico, 2010; DOE, 2012; Pérez-Lombard et al., 2008). Concrete is the most used building material and excels in mechanical properties and constructability; nevertheless, cast in place concrete houses share is 14% in Chile (Remesar & Lopez, 2012) and less than 2% in USA (Portland Cement Association, 2012). The relatively low thermal resistance of concrete compared to timber and masonry construction contributes to the low use of cast in place concrete in houses. Building codes demand a minimum thermal resistance for the wall envelope of houses in most populated areas of Chile (MINVU, 2011) and worldwide (EURIMA, 2007) which are difficult to reach using conventional concrete construction. Concrete houses with walls of 15 cm width in Santiago, Chile demand a thermal conductivity of 0.42 W/mK, whereas the thermal conductivity of conventional concrete ranges 1.4-2.3 W/mK (Khan, 2002; K.-H. Kim et al., 2003; Lamond & Pielert, 2006). Therefore, concrete construction requires the addition of insulating panels that increases the direct costs (labor, material) and limits its use compared to the other construction systems.

Literature review shows two strategies that reduce thermal conductivity of concrete: (i) replacement of normal weight aggregates by lightweight aggregates (LWA) (Gündüz, 2008; L H Nguyen et al., 2014; Q.L. Yu et al., 2013) and (ii) replacement of Ordinary Portland Cement (OPC) for supplementary cementing materials (SCM) (Bentz et al., 2010; Demirboga, 2003b). Nevertheless, these strategies also present collateral effects on the mechanical performance of concrete (Chandra & Berntsson, 2002; Holm & Bremner, 2000; Metha & Monteiro, 2014).

LWA present a cellular pore structure and a lower particle density than normal weight aggregates (Holm & Bremner, 2000). Several studies have shown that LWA decreases the thermal conductivity of concrete (Chen & Liu, 2013; Gündüz, 2008; H. K. Kim et al., 2012; Mateos et al., 2000; L H Nguyen et al., 2014; Q L Yu et al., 2013; Yun et al., 2013). The LWA air-dry density, ranges from 60 to over 1000 kg/m^3, depending of its total porosity (Chandra & Berntsson, 2002). In general terms, the lighter the aggregate particle, the lower its intrinsic strength (ACI Committee 213, 2013; Holm & Bremner, 2000; Videla & Lopez, 2001) , therefore, all LWA are not suitable for making concrete with structural strength. Expanded clay is among the LWA that allows production of LWA structural concrete with low thermal conductivity at oven-dry state, ranging from 0.35 to 0.43 W/mK when using 100% OPC as cementitious material (L H Nguyen et al., 2014; Zareef, 2010). A study developed structural LWA concretes with thermal conductivity at oven-dry density of 0.28 W/mK for cenospeheres as LWA (Wu et al., 2015).

Fly ash (FA), a by-product of coal power plants, has been used as a partial replacement of OPC in order to meet a sustainable development (Bilodeau & Malhotra, 2000). The OPC production industry is responsible of the 7% of the world's CO_2 emissions (Metha, 2004). Previous studies have shown that the thermal conductivity of cement paste is reduced when using SCM (Demirboga, 2003b; Fu & Chung, 1997). Among the SCM, FA is one of the most effective in reducing thermal conductivity of concrete (Demirboga, 2003a, 2003b). The FA effect in mechanical properties and durability of normal weight concrete have been widely studied for FA ratios up to 80% (Berry & Malhotra, 1981; Bilodeau & Malhotra, 2000; Bouzoubaâ et al., 2001; Langley et al., 1990; Megat Johari et al., 2011; Metha, 2004; Oner et al., 2005; Siddique, 2004; Toutanji, Delatte, Aggoun, Duval, & Danson, 2004; A. Wang et al., 2003). Literature have shown that the increase of replacement level of OPC by fly ash (i.e. replacement level) up to 70% decreases the thermal conductivity in binder (Demirboğa & Gül, 2003; Demirboga, 2003a, 2003b; M. Y. J. Liu, Alengaram, Jumaat, & Mo, 2014) and decreases the strength gain rate (Guo, Shi, & Dick, 2010; Siddique, 2004; A. Wang et al., 2004).

In despite of the effects of LWA and FA in thermal properties of concrete, there is a lack of studies analyzing their effects simultaneously. Demirboğa & Gül (Demirboğa & Gül, 2003) showed that the combination of fine LWA (expanded perlite, pumice) with FA replacement level of 10%-30% decreased the dry thermal conductivity of concrete to 0.15 W/mK, but also decreased the 28-day compressive strength to 3 MPa (Demirboğa & Gül, 2003). Therefore, the resulting mixture was not suitable for structural concrete walls. To the authors knowledge there are not previous studies focused on developing an insulating structural concrete using FA and LWA specially focused on housing applications.

One limitation of the previous studies is that they generally measure the thermal conductivity of oven-dry density (L H Nguyen et al., 2014; Q.L. Yu & Brouwers, 2012), but this is not the actual moisture condition in the field. In fact, the equilibrium density (ASTM, 2014c; Holm & Bremner, 2000) is used to represent the in-service ambient density of LWA concretes, which contains a moisture content of approximately 4% by volume (Valore Jr., 1980). In fact, the term equilibrium density is used for LWA concretes (ASTM, 2014c) which contains more water, compared to the oven-dry density. This additional water increases the thermal conductivity up to 20% (Holm & Bremner, 2000; Khan, 2002; Lamond & Pielert, 2006). Therefore, it is required to use the equilibrium density for better represent the actual performance of the mixtures.

This study aims to understand and assess the effect and interaction of three constituents in the thermal and mechanical properties of concrete in order to develop an insulating concrete for external bearing walls houses. The constituents are coarse expanded clay aggregate, fine expanded clay aggregate, and fly ash. The measured mechanical and thermal properties were compressive strength, elastic modulus, thermal conductivity, thermal diffusivity and specific heat. The porosity properties of the coarse and fine expanded clay were analyzed with micro-CT scan. Multiple linear regression models for compressive strength and thermal conductivity were assessed to evaluate the impact of each component. The analysis of the interaction between compressive strength and thermal conductivity allowed to select the strategies that most reduced the thermal conductivity with the lowest impact in the compressive strength.

5.2. Experimental program

5.2.1. Materials and mix proportion

Concrete mixtures were produced using an Ordinary Portland Cement (OPC) with a specific gravity of 3.14 and Blaine fineness of 410 m^2/kg and Fly ash (FA) with specific gravity of 2.37. A siliceous normal weight aggregate and an expanded clay lightweight aggregate were used. The physical properties of normal weight aggregates and lightweight aggregates (LWA) are shown in Table 4-1. LWA were submerged for 72 hours prior to mixing to achieve an adequate pre-wetted condition (ACI Committee 213, 2013) . This condition was used for water absorption measurement (ASTM, 2013). Also, high range water reducer was used in a dose of 0.2% by cement weight for all mixtures.

The total porosity, P, of both coarse and fine LWA was estimated from equation 1. The oven-dry density, ρ_{OD}, was measured (ASTM, 2013) and the density of the solid portion of expanded clay, ρ_{solid}, was considered as 2650 kg/m^3, as reported in previous studies (ACI Committee 213, 2013; Bogas et al., 2012; Holm & Bremner, 2000).

$$P = 1 - \frac{\rho_{OD}}{\rho_{solid}} \quad (1)$$

Table 5-1 Physical properties of aggregates

Aggregate	Origin	Size (mm)	Oven-dry density (kg/m^3)	SSD density (kg/m^3)	Abs. (%)	Total porosity (%)
Lightweight coarse expanded clay	Rotatory kiln produced in Spain	5 /0	885	1260	42.3%	67%
Lightweight fine expanded clay	Crushed from coarse expanded clay	20 /10	784	941	20.0%	70%
Normal weight fine aggregate	Natural sand from river	5 /0	2658	2679	0.8%	-
Normal weight coarse aggregate	Crushed	20 /10	2617	2662	1.7%	-

The objective was to understand and assess the effect and interaction of the three mentioned constituents for the development of an insulating concrete with the minimum effect in the compressive strength. Figure 1 presents the experimental design, which considers three factors: (F1) coarse expanded clay relative volume, (F2) fine expanded clay to total fine aggregate ratio and (F3) FA replacement level. F1 represented the LWA volume fraction in the total concrete volume. F2 represented the volumetric replacement rate of normal weight fine aggregate for fine expanded clay and was limited to 75% due segregation problems for higher replacement in a trial mixture. F3 was the volumetric replacement level of OPC for FA.

The experimental design corresponds to a fractional factorial (“NIST/SEMATECH e-Handbook of Statistical Methods,” 2012; Serpell & Lopez, 2013). It consists in two binary models: (1) two factors (F1, F2) at two levels each with an intermediate mixture having the average levels of each factor; and (2) three factors (F1, F2, F3) at two levels each with an intermediate mixture. The two models are represented in

Figure 5-1: Experimental program mixtures, where the model 1 corresponds to the mixtures with 0% of FA replacement level and model 2 corresponds to the mixtures with FA. The levels are presented in Table 5-2. A mortar and a concrete with normal aggregates and OPC were elaborated as control mixtures. The water-to-cementitious material ratio was fixed at 0.4 for all the mixtures. The mixture proportions of factorial (1) (CF) and factorial (2) (CFFA) are presented in Table 5-3.

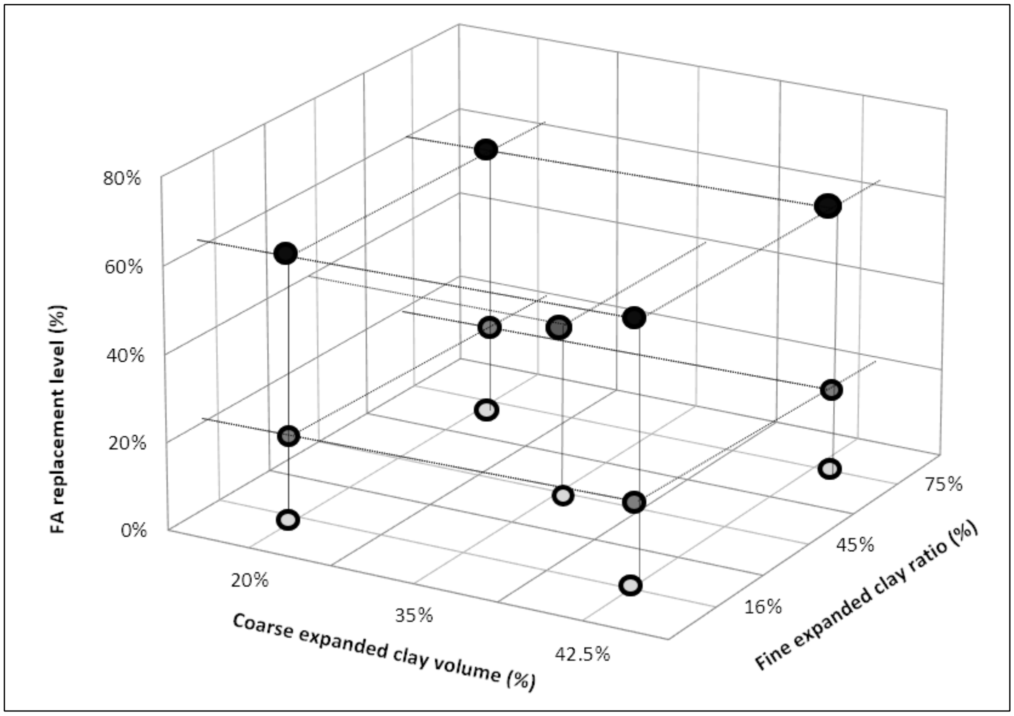


Figure 5-1: Experimental program mixtures

Table 5-2: Levels and factors of the experimental program

Experimental factors		Levels		
Name	Description	-1	0	1
F1	Coarse expanded clay relative volume	20%	35%	43%
F2	Fine expanded clay to total fine aggregate ratio	16%	45%	75%
F3	FA replacement level of OPC	20%	40%	60%

Mixtures were produced in a 100 liter vertical axis mixer. Coarse and fine LWAs were submerged in water for 72 hours and drained in a No. 50 sieve for 10 minutes before the mixing. Moisture content of lightweight aggregates was considered in the mixing water. Nine 100x200-mm cylindrical specimens were cast for mechanical tests and two 1150-mm cubic specimens were cast for thermal properties. Concrete was compacted by rodding, according to ASTM C192 (ASTM, 2006).

Specimens were left in their molds for 24 hours and submerged in water at 20 °C (±1) for 7 days after demolding. Two 150x150x75 mm prismatic specimens were saw-cut from each cubic specimen. The cut was perpendicular to the filling face of the specimen. Then, the specimens (prisms and cylinders) were stored in a chamber at 22°C (±2) and 50% (±3) R.H., until the age of the mechanical and thermal tests.

Table 5-3: Mix proportions of the lightweight concretes

Mix	OPC (kg/m^3)	FA (kg/m^3)	Water (kg/m^3)	Coarse expanded clay (kg/m^3)	Coarse normal weight aggregate (kg/m^3)	Fine expanded clay (kg/m^3)	Fine normal weight aggregate (kg/m^3)	HRWA (Kg/m^3)
Concrete	390	0	156	0	870	0	890	0.78
Mortar	600	0	240	0	0	0	1470	1.20
CF1	464	0	184	188	0	88	999	0.93
CF2	334	0	132	400	0	64	717	0.67
CF3	377	0	150	329	0	202	532	0.75
CF4	464	0	184	188	0	414	297	0.93
CF5	334	0	132	400	0	297	214	0.67
CFFA1	371	70	176	188	0	88	995	0.88
CFFA2	267	50	127	400	0	64	715	0.63
CFFA3	186	210	158	188	0	88	995	0.79
CFFA4	133	151	114	400	0	64	715	0.57
CFFA5	226	114	136	329	0	202	530	0.68
CFFA6	371	70	176	188	0	414	296	0.88
CFFA7	267	50	127	400	0	297	214	0.63
CFFA8	186	210	158	188	0	414	296	0.79
CFFA9	133	151	114	400	0	297	214	0.57

5.2.2. Test procedures

a) Mechanical properties

Compressive strength was measured at 7, 28 and 120 days while elastic modulus was measured only at 28 days; both properties were assessed based on the average of three specimens. Elastic modulus was measured applying up to 33% of the maximum compressive strength and the strain was registered with three extensometers. Elastic modulus was calculated according to ASTM C469 (ASTM, 2014b).

b) Thermal properties

The thermal properties were measured with a Hot Disk TPS1500 in the single side mode. This is a state of the art transient technique that measures thermal conductivity and thermal diffusivity of materials (Gustafsson, 1991). The volumetric specific heat is calculated from these two properties. The thin sensor acts both as a heat source and a temperature sensor. In the single side mode, the sensor was located over the sample and the other side was covered with polyurethane (thermal conductivity = 0.025W/mK, thermal diffusivity = 0.25 mm^2/s). The maximum increase of temperature during the test was 5 °C for all the samples. The sensor model was 4922, with diameter of 29.2 mm. The penetration depth in horizontal and perpendicular direction from the sensor was at least 23 mm. The measurement time was 320 seconds. The tests were developed under laboratory conditions at 20° C (±1). The prismatic specimens were measured one time.

The thermal properties were registered for specimens at equilibrium moisture condition at 120 days and also at oven-dry condition. The equilibrium moisture condition was determined when specimens reached the so called equilibrium density which occurs when the mass of the specimens presented less than 0.5% change in successive measurements 28 days apart (ASTM, 2014c). The oven dry condition was obtained by drying the specimens at 105°C for 48 hours (time to reach constant mass), and cooled for 5 hours until reaching 20°C. The heating and cooling rates were 0.5°C/min to minimize the temperature gradients and therefore thermal cracking.

c) Micro-CT Analysis

Micro computed tomography scans of coarse and fine expanded clay were performed to analyze their porosity. A representative sample of the fine expanded clay particle size distribution was enclosed in a polyethylene test tube of 20 mm long and 6 mm in diameter. One coarse expanded clay aggregate was selected based in the median oven-dry density of 20 individual aggregates.

Scans were performed in the MicroCT Core Laboratory (Texas, USA) in a Skyscan1172 desktop micro-CT system. The samples were scanned in air for 1 hour with the following settings: 60 kV, 133 μA, 1.0 mm aluminum filter, 0.7° rotation step, 360° rotation, 6 frame averaging, 2240 x 2240 CCD, 1000 millisecond exposure and 10 μm voxel size.

5.3. Results and discussion

The results of mechanical properties and thermal properties at equilibrium moisture conditions are presented in Table 5-4. Multiple linear regression analyses were performed for the 120-day compressive strength and thermal conductivity at equilibrium density. The 120-day compressive strength was selected to match the age at which the equilibrium condition was reached, so both results represent the concrete under the same age, curing and hydration conditions and are representative of actual conditions in the structure.

Table 5-4: Mechanical properties, thermal properties and density of concretes.

Mix	ρ_{eq} (kg/m^3)	ρ_{OD} (kg/m^3)	fc 7 days (MPa)	fc 28 days (MPa)	fc 120 days (MPa)	E 28 days (GPa)	κ_{eq} (W/mK)	α_{eq} (mm2/s)	c_{eq} (J/kgK)
Concrete	2391	2350		81.4		48.3	1.59	0.76	888
Mortar	2304	2222		84.6		38.9	1.44	0.62	971
CF1	1792	1728	28.2	28.8	28.5	26.0	1.04	0.59	1055
CF2	1560	1500	18.0	19.3	19.0	15.9	0.78	0.52	980
CF3	1483	1404	15.6	16.6	17.0	17.3	0.68	0.46	1140
CF4	1461	1363	18.0	19.9	22.4	12.6	0.63	0.47	936
CF5	1213	1142	11.7	12.9	14.4	11.1	0.52	0.44	963
CFFA1	1837	1773	23.4	27.7	27.0	23.7	0.90	0.54	956
CFFA2	1499	1436	16.9	18.9	17.5	18.0	0.77	0.45	1127
CFFA3	1726	1638	15.7	23.0	25.8	18.1	0.83	0.51	987
CFFA4	1479	1435	12.4	16.4	15.9	15.9	0.71	0.50	962
CFFA5	1429	1355	14.7	17.0	17.6	16.3	0.66	0.46	999
CFFA6	1399	1342	14.6	14.3	15.2	12.5	0.59	0.45	950
CFFA7	1240	1172	11.1	12.8	13.3	11.3	0.50	0.44	907
CFFA8	1232	1167	6.9	11.9	13.7	12.2	0.48	0.43	889
CFFA9	1174	1102	6.1	9.3	9.3	10.0	0.43	0.43	837

Note: $\boldsymbol{\rho_{eq}}$*: equilibrium density,* $\boldsymbol{\rho_{OD}}$*: oven-dry density, fc: compressive strength, E: elastic modulus,* $\boldsymbol{\kappa_{eq}}$*: thermal conductivity at equilibrium density,* $\boldsymbol{\alpha_{eq}}$*: thermal diffusivity at equilibrium density,* $\boldsymbol{c_{eq}}$*: specific heat at equilibrium density*

Figure 5-2 shows the effect of the concrete's density in the thermal conductivity for equilibrium and oven-dry density. The combined effect of coarse expanded clay, fine expanded clay and FA decreased the thermal conductivity in 74%, when compared to the normal weight concrete. Concretes without FA (CF mixtures) presented a higher thermal conductivity than concretes with FA (CFFA mixtures). The interaction of constituents allowed achieving concretes with similar total LWA volume (48-53%), where the equilibrium density varied in 6%, but with differences in thermal conductivity up to 19%. It is observed that each factor contributes differently in decreasing the thermal conductivity. The impact of each factor will be analyzed in sections 3.1 and 3.2.

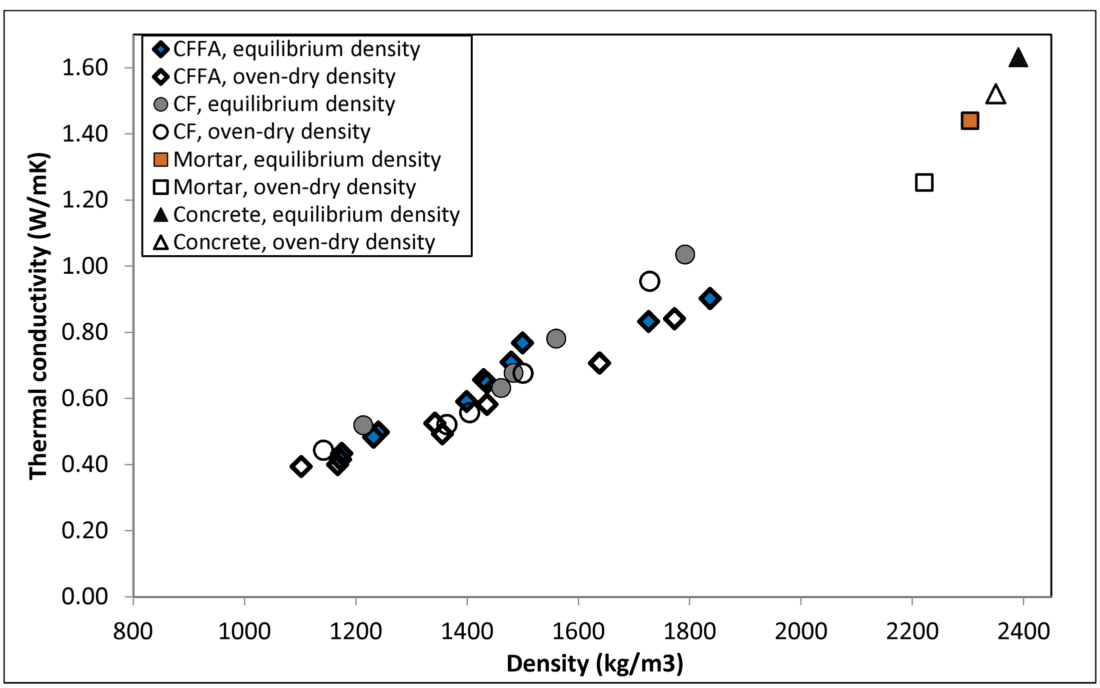


Figure 5-2: Thermal conductivity and density of concretes for equilibrium density and dry density

Figure 5-2 also shows the effect of the equilibrium moisture content in the thermal conductivity. The equilibrium moisture content of concretes increased the thermal conductivity at equilibrium density compared to the oven-dry density in 7-33% with an average of 18%. This effect is caused by the higher thermal conductivity of water compared with the air, which is 15 times higher (Ghoshdastidar, 2012). Even though concrete structures are not at oven dry conditions during its service life, the effect of the moisture content in the thermal conductivity found herein can be considered to estimate properties in the actual moisture conditions when the oven dry conductivity is known.

5.3.1. Multiple linear regression models for compressive strength and thermal conductivity

Multiple linear regression (MLR) models were developed for compressive strength and thermal conductivity in order to assess the contribution of mixture design factors on each property. MLR allows evaluating the effect of independent variables (i.e., the constituents used) in one dependent variable (i.e., compressive strength and thermal conductivity). Thus, the independent variables represent the effect of: coarse expanded clay relative volume, fine expanded clay to total fine aggregate ratio and FA replacement level. The coarse expanded clay relative volume is the only variable that represent the actual volume of the concrete while the volume of the other two depend on the coarse expanded clay relative volume. Therefore, the fine expanded clay to total fine aggregate ratio ($S_{EC(F)}$) was transformed to fine expanded clay volume ($V_{EC(F)}$) (Equation 2) while the FA replacement level (S_{FA}) was transformed to the FA paste volume (V_{FA}) (Equation 3).

$$V_{EC(F)} = V_s * S_{EC(F)} \qquad (2)$$

$$V_{FA} = V_p * S_{FA} \qquad (3)$$

where $V_{EC(F)}$ is the fine expanded clay volume, V_s is the total fine aggregate volume and $S_{EC(F)}$ is the fine expanded clay to total fine aggregate ratio. Additionally, V_{FA} is the FA paste volume, V_p is the binder volume and S_{FA} is the FA replacement level.
Fine aggregates and OPC volumes were also considered as independent variables on the analysis, but were found to be not significant. The results obtained are valid within the limit of the ratios and volumes defined in the experimental program. The proposed models are represented in Equation 4 and Equation 5.

$$f_{est} = \beta_0 + \beta_1 * \ V_{FA} + \beta_2 * V_{EC(F)} + \beta_3 * V_{EC(C)} \quad (4)$$

$$k_{est} = \gamma_0 + \gamma_1 * \ V_{FA} + \gamma_2 * V_{EC(F)} + \gamma_3 * V_{EC(C)} \quad (5)$$

Where f_{est} is the estimated compressive strength, k_{est} is the estimated thermal conductivity, $V_{EC(C)}$ is the coarse expanded clay volume, $V_{EC(F)}$ is the fine expanded clay volume and V_{FA} is the fly ash paste volume. Additionally, β_i and γ_i are the MLR coefficients($i = 0,1,2,3$).

a) MLR model for compressive strength

Table 5-5 present the model summary and coefficient results. When the MLR model is estimated for compressive strength, the β_1, β_2, and β_3 parameters in Equation 4 become the values shown in Table 5-5. These values represent the individual contribution of each constituent on the compressive strength of concrete for a level of significance of 0.05. The fact that the β parameters are negative implies that an increase in the volume results in a decrease of the concrete compressive strength. The three constituents explained the 92% of the variability of the compressive strength at 120 days of the concrete.
The constituent that least reduced the compressive strength is the FA volume, followed by the fine expanded clay volume and the coarse expanded clay volume. From Table 5-5, an increase of 10% each of the constituents decrease the

compressive strength in: 2.3 MPa FA volume, 3.5 MPa for fine expanded clay volume, and 4.4 MPa for coarse expanded clay volume.

Table 5-5: Model summary and coefficient results of the compressive strength regression analysis

	Coefficients	Standard Error	t Statistic	P-value	95% C.I. (±)
β_0	39.9	2.0	19.6	2.6E-09	4.5
β_1	-23.9	6.8	-3.5	5.5E-03	15.1
β_2	-35.0	4.6	-7.7	1.7E-05	10.1
β_3	-43.7	4.7	-9.2	3.3E-06	10.5

R^2=0.924, Adjusted R^2=0.902

The increase of FA volume reduced the 120-day compressive strength because the increment of FA replacement level decreases the CH content produced by the OPC upon hydration. Additionally, the 50% relative humidity used for conditioning the samples between 7 and 120 days possibly reduced the degree of hydration of the binder and therefore the strength gain rate. Previous studies reported that the hydration of the cement paste stops for internal relative humidity (R.H.) below 80% (Patel et al., 1988). The decrease in the hydration process is related to reduction of water activity by the negative capillary pressure in the pores for R.H. below 80% (Flatt et al., 2011).

The inclusion of coarse expanded clay presented a higher decrement in the compressive strength than the inclusion of fine expanded clay. This effect of the LWA size has been seen previously (K. G. Babu & Babu, 2003; Holm & Bremner, 2000; Le Roy et al., 2005). The increase of coarse and fine expanded clay reduced the compressive strength because their intrinsic strength is lower than normal weight aggregates and the mortar phase. This effect was also evidenced in previous research (ACI Committee 213, 2013; Moreno et al., 2014; Videla & Lopez, 2001; Y. Kea, A.L. Beaucour , S. Ortola , H. Dumontetb, 2009) . The weakening effect of lightweight aggregates is related with their porosity which will be discussed in section 3.2.

b) MLR model for thermal conductivity

Table 4-6 shows that the individual increase of the three constituents also decrease the thermal conductivity of concrete for a level of significance below 0.05 (Table 6). The three constituents explained the 98% of the variability of the thermal conductivity at 120 days and equilibrium moisture. The constituent that most reduced the thermal conductivity is the fine expanded clay volume, followed by the coarse expanded clay volume and the FA paste volume. From Table 6, the increase of 10% decreases the thermal conductivity in: 0.14 W/mK for fine expanded clay volume, 0.10 W/mK for coarse expanded clay volume and 0.07 W/mK for FA paste volume.

Table 5-6: Model summary and coefficient results of the thermal conductivity regression analysis

	Coefficients	Standard Error	t Statistic	P-value	95% C.I. (±)
γ_0	1.29	0.03	43.8	9.3E-13	0.07
γ_1	-0.70	0.10	-7.2	3.1E-05	0.22
γ_2	-1.40	0.07	-21.3	1.2E-09	0.15
γ_3	-1.00	0.07	-14.6	4.5E-08	0.15

R^2=0.983, Adjusted R^2=0.978

The reduction of thermal conductivity due the increase of coarse and fine expanded clay is associated with their high porosity, which is consistent with the literature (ACI Committee 213, 2013; Holm & Bremner, 2000; L H Nguyen et al., 2014). In a previous study, the total replacement of siliceous coarse aggregate for coarse expanded clay decreased the thermal conductivity in 48%, from 1.8 to 0.94 W/mK (Sacht, Rossignolo, & Santos, 2010) while other study reported a 36% decrease in the thermal conductivity with a 100% replacement ratio of fine expanded clay (L H Nguyen et al., 2014). The influence of porosity will be discussed in section 3.2.

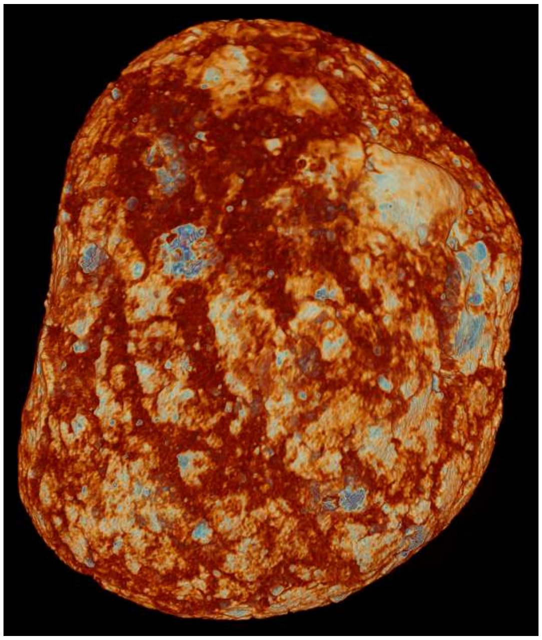
The FA paste volume effect on the thermal conductivity is related with the increase on the porosity due a higher degree of hydration (Demirboğa, 2007; A. Wang et al., 2004; Z. Yu & Ye, 2013). Anhydrate FA also presents a lower thermal conductivity than anhydrate OPC due the amorphous structure of FA (Demirboga, 2003a). The pore refinement effect of FA and the transformation of the crystalline CH to the more amorphous CSH due to the pozzolanic reaction of the FA contribute to the decrease of thermal conductivity (Chapter Four). Previous research showed that a 30% of FA weight replacement decreased the thermal conductivity in 12% for pumice and 14% for expanded perlite concrete (Demirboğa & Gül, 2003). FA paste also presents lower thermal conductivity than Portland cement paste (Demirboga, 2003a; K.-H. Kim et al., 2003).

5.3.2. Effect of porosity on compressive strength and thermal conductivity

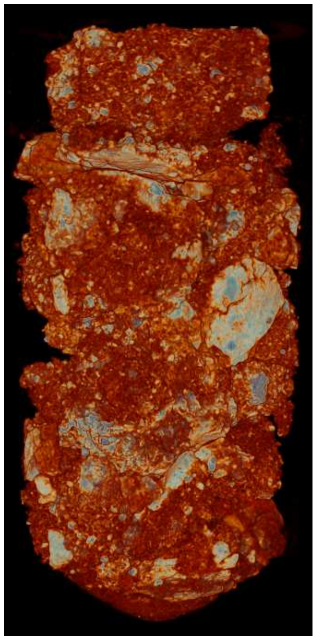
The MLR results indicate that fine expanded clay produced a greater reduction in thermal conductivity and a lower reduction in compressive strength than coarse expanded clay. These results are influenced by: (1) pore spatial distribution of the LWA pores within the concrete, (2) maximum pore size of expanded clay and (3) refinement of pore size distribution in the LWA particles. The porosity properties of coarse and fine expanded clay were measured in a CT scan and are presented in Table 5-7. The measured total porosity (Table 5-7) is lower than the estimated total porosity (Table 4-1) because the CT scan visualizes pores bigger than 10 µm. Figure 5-3 shows density distribution images for coarse and fine expanded clays, where white represent the most dense and red the least dense. The red color predominates the images, which is related with the high porosity of LWA, as expected.

Table 5-7: Porosity properties of coarse and fine expanded clays from CT scan analysis

Sample	Closed porosity (%)	Open porosity (%)	Total porosity (%)	Surface area/Volume ratio (mm^{-1})
Coarse expanded clay	0.2%	54.4%	54.5%	0.653
Fine expanded clay	0.3%	52.6%	52.8%	8.12



(a)



(b)

Figure 5-3: Density distribution image from CT scan from: (a) Coarse expanded clay; (b) Fine expanded clay

The higher reduction of thermal conductivity by fine expanded clay is also explained by the pore spatial distribution of the pores in the concrete. For the same LWA volume, a smaller aggregate size increases the total surface area. Fine expanded clay presented more than 12 times the surface area than coarse expanded clay. This means that fine expanded clay allows a more homogeneous pore spatial distribution than coarse expanded clay, for the same volume of LWA. Then, the improvement of LWA spatial distribution also decreases the paste distance between LWA particles. A better distribution of the pores (the dispersed phase) decreases linear pathways of binder paste (the continuous phase) in the concrete. This force the heat flux pathways to pass through the smaller size aggregates. The improvement in pore spatial distribution allows to reduce the thermal conductivity for the same total porosity. In a previous research, numerical simulations indicated that the size and the spatial distribution of the bigger pores influenced the effective thermal conductivity of porous media (Huai, Wang, & Li, 2007). Our results show that the pore spatial distribution must be considered in order to further reduce the thermal conductivity of concrete.

The maximum pore size also influenced the compressive strength. Literature shows that the decrease of the maximum aggregate size increased the compressive strength for expanded polystyrene LWA concrete (Le Roy et al., 2005; Miled et al., 2007). Holm and Bemmer also showed the same effect for expanded shale with the increase of the ceiling strength (Holm & Bremner, 2000). Nevertheless, the air pores of LWA behave as stress concentrators for LWA concrete under compressive stress. The stress concentration in the vicinity of LWA pores triggering crack formation and propagation and ultimately failure (Popovics, 1998). Coarse LWA presented a higher maximum pore size (1.81 mm) than fine expanded clay (0.83 mm). A smaller pore size decreases the stress concentration within the LWA. The 7.6% of the porosity volume of coarse expanded clay is present in pores larger than 0.83 mm, the maximum size of fine expanded clay. Based in the CT scan results, the decrease of the maximum pore size of LWA with similar porosities should increase the compressive strength of LWA concretes.

The refinement of pore size distribution affects the thermal conductivity. Coarse expanded clay presented a slightly higher total porosity than fine expanded clay, but the latter presented more refined pores, as shown in Figure 5-4. The 90% of the porosity volume is present in pores smaller than 0.28 mm for fine expanded clay and

0.50 mm for coarse expanded clay. Previous research showed that the refinement of pore size distribution decreased the thermal conductivity, for the same pore volume (Pia & Sanna, 2013).

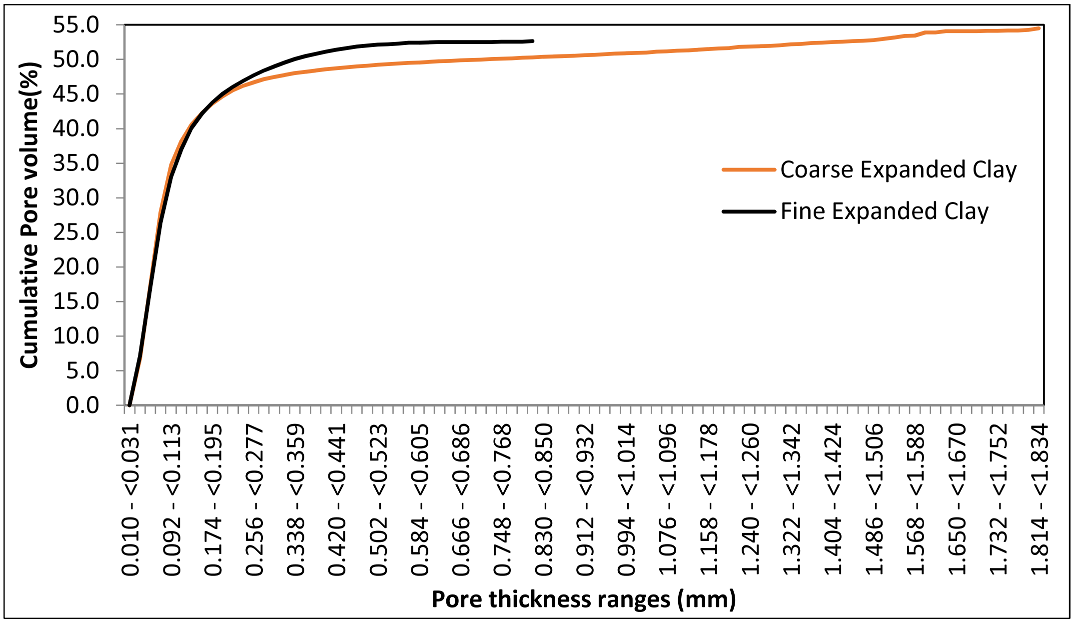


Figure 5-4: Cumulative pore volume of the total porosity of fine and coarse expanded clays

5.3.4 Interaction of thermal conductivity and compressive strength

The present development demands a strategy that decreases the thermal conductivity with a minimum negative impact of the compressive strength. Figure 5-5 shows that the combined effect of coarse expanded clay, fine expanded clay and FA allows achieving a lower thermal conductivity than each constituent used independently. The slopes in Figure 5-5 represent the “cost” in compressive strength of lowering the thermal conductivity. A more inclined slope means that the reduction in thermal conductivity requires an important decrease in compressive strength. Similarly, a less inclined slope means that the reduction in thermal conductivity has a minor reduction in compressive strength.

The combined effect of constituents also show the lowest slope compared to the constituents used independently meaning that is a more efficient strategy. The independent effect of the constituents was obtained from a previous study (Chapter Four). For a decrease of 0.1 W/mK there was a loss in compressive strength of: 10.7 MPa for FA, 8.6 MPa for fine expanded clay, 5.8 MPa for coarse expanded clay and only 2.2 MPa for combination of coarse and fine expanded clay. When FA is also included with the combination of coarse and expanded clays, the reduction in compressive strength was 3.3 MPa.

The combination of constituents enables to decrease simultaneously the thermal conductivity of the different phases of concrete: aggregates (coarse, fine) and binder. Then, the heat flux through the concrete presents a higher tortuosity effect with the reduction of thermal bridges formed by higher thermal conductivity components. The higher decrease rate in thermal conductivity causes a smaller cost in compressive strength. In despite of the higher rate in compressive strength reduction, the use of FA allows to achieve lower values of thermal conductivity, reducing the heat flux through the binder.

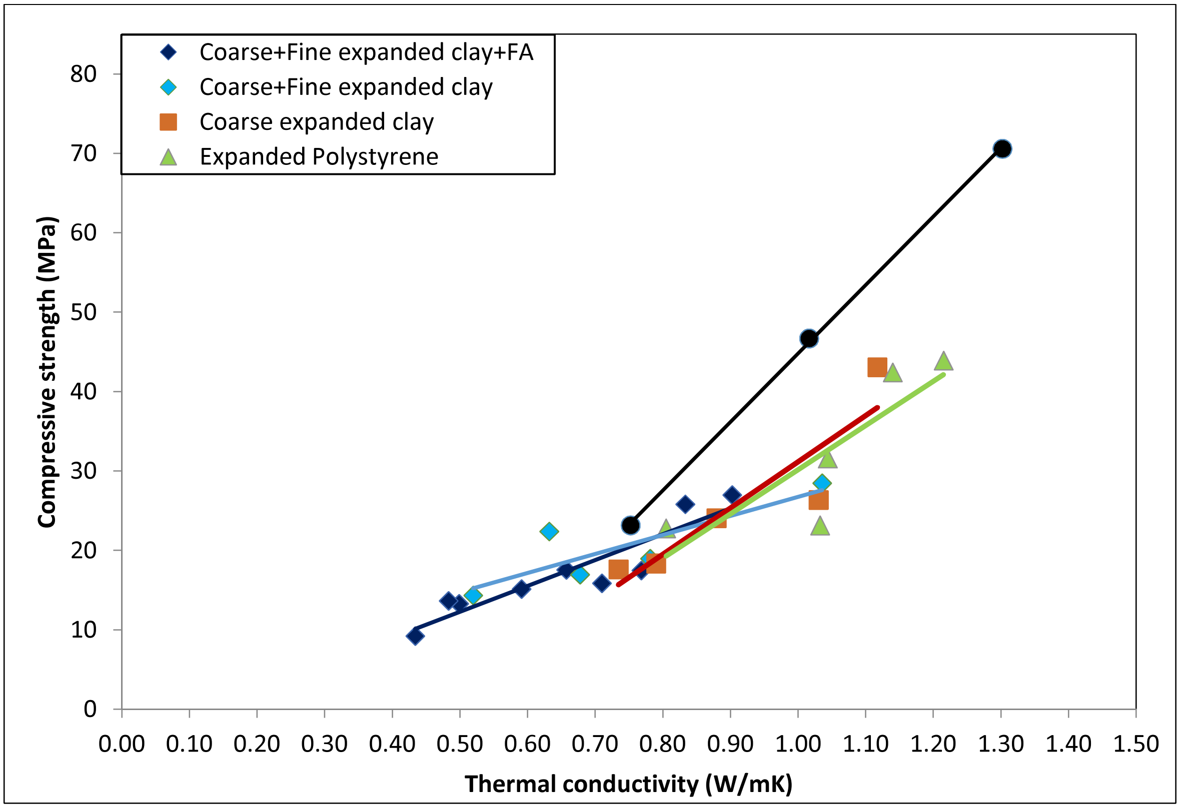


Figure 5-5: Relationship of compressive strength and thermal conductivity.

Note: FAC: FA concrete, FEC: Fine expanded clay concrete, CEC: Coarse expanded clay concrete, CF: Coarse LWA and Fine LWA combined, CFFA: Coarse LWA, Fine LWA and FA combined

The reduction of maximum size aggregate of the LWA, which is related with a reduction of the maximum pore size, is recommended to enhance the compressive strength and further reduce the thermal conductivity due to two different effects: the more refined pore size distribution within the LWA particle and the more homogeneous spatial distribution of pores in the concrete. Then, the compressive strength of concretes with the lowest thermal conductivity can be further increased to structural strength reducing the maximum aggregate size (Holm & Bremner, 2000; Le Roy et al., 2005; N. Liu & Chen, 2014; Miled et al., 2007).

5.4. Conclusions

This study reports mechanical and thermal properties of LWA concrete with coarse expanded clay, fine expanded clay and fly ash combined in different levels. Lightweight concretes with compressive strength and thermal conductivity ranging 28.8-9.3 MPa and 1.04-0.43 W/mK, respectively were obtained. The impact of each constituent on the compressive strength and thermal conductivity of concrete was evaluated. The main conclusions are listed as follows:

- The combined effect of coarse expanded clay, fine expanded clay and fly ash allows achieving a 74% decrease in the thermal conductivity at equilibrium density of concrete, up to 0.43 W/mK, with a compressive strength of 9.3 MPa.
- The fine expanded clay allows for a larger reduction of thermal conductivity with the lower reduction in the compressive strength compared to coarse expanded clay. Fly ash presents the smallest effect in both compressive strength and thermal conductivity.
- The porosity properties of expanded clay particles explain the better compressive strength and thermal conductivity performance of the fine expanded clay aggregate, compared to coarse expanded clay. Based on the CT scan results, fine expanded clay presented: (1) better pore spatial distribution in the concrete which explain the thermal conductivity performance, (2) smaller maximum pore size which explain the compressive strength performance and (3) more refined pores which also affects the thermal conductivity performance.
- The combination of constituents generates a higher tortuosity effect in the thermal conductivity with the reduction of thermal bridges within the concrete. The higher decrease rate in thermal conductivity causes a smaller cost in compressive strength. In despite of the higher rate in compressive strength reduction, the use of FA allows to achieve lower values of thermal conductivity, reducing the heat flux through the binder.

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6. THERMAL AND MECHANICAL PROPERTIES OF NORMAL WEIGHT AND LIGHTWEIGHT PERVIOUS CONCRETE

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Abstract

Building codes demand a reduction in the thermal conductivity of cement based materials. This study explored the mechanical and thermal properties of pervious concretes. The effect of paste volume, aggregate type (normal weight, lightweight) and the aggregate size of lightweight aggregates were analyzed. The lightweight aggregate used was expanded shale. The interaction between the compressive strength and thermal conductivity were analyzed. The centrifuge method was adapted and developed to determine the effective and internal porosities of pervious concretes. The replacement of normal weight aggregate for expanded shale is more efficient than the increase of effective porosity in normal weight aggregate pervious concrete and allowed a higher reduction in thermal conductivity. This effect showed that the thermal conductivity of pervious concretes is governed by the heat flow through the aggregates.

Keywords: pervious concrete, porous concrete, no-fines concrete, lightweight aggregates, expanded shale, thermal conductivity, compressive strength

6.1. Introduction

Concrete, the most used building material, excels in mechanical properties and constructability but lacks of thermal resistance. Over 10% of total primary energy consumed in United States, Europe and Chile is for heating and cooling of residential sector (Corporacion de Desarrollo Tecnológico, 2010; Pérez-Lombard et al., 2008). The building codes demand an increment of the thermal resistance of normal concrete wall houses. This opens the opportunity to explore the combination of concrete technologies that reduces the thermal conductivity of concrete

Pervious concrete, also known as porous or no-fines concrete is composed of paste and gap-graded coarse aggregates, where the components form an internal pore structure, with the porosity ranging 15-30% (Deo & Neithalath, 2011; J. Kevern et al., 2009; J. T. Kevern et al., 2008; Sumanasooriya et al., 2013; K. Wang et al., 2006). Pervious concrete have been used in pavement for water runoff management (Manahiloh et al., 2012; Sansalone et al., 2008), air purifying (Asadi et al., 2012) and noise reduction (H. K. Kim & Lee, 2010). It was also used for external walls in buildings (Short & Kinniburgh, 1963) and its durability has been assessed (Carsana et al., 2013).

It has been reported that the increase of porosity in pervious concrete decrease the thermal conductivity of concrete (Short & Kinniburgh, 1963; Valore Jr. & Green, 1951; Wong et al., 2007) Nevertheless, it is still higher than the demanded for external walls and the mechanical properties were not measured in the same study. The thermal and mechanical properties of pervious concretes have not been assessed yet, with most of studies focusing on the mechanical properties.

Lightweight aggregates (LWA) present a higher porosity than normal aggregates that produce a decrease in the compressive strength and the thermal conductivity of LWA concretes (ACI Committee 213, 2013; Chandra & Berntsson, 2002). There has been more interest in assessing the mechanical and thermal properties of LWA concrete for expanded clay (L H Nguyen et al., 2014; Mike Schlaich & Zareef, 2008; Yun et al., 2013), expanded shale (L H Nguyen et al., 2014; Yun et al., 2013) and other LWA's (Gündüz, 2008; Mateos et al., 2000; Uysal et al., 2004; Q.L. Yu et al., 2013). Nevertheless, there are limited results of pervious concretes with LWA. One study evaluated the mechanical and thermal properties of LWA pervious concretes, with compressive strength ranging 2.5-6.0 MPa and thermal conductivity ranging 0.16-0.25 W/mK (Zaetang et al., 2013). The LWA used were not suitable for structural concrete and limited the compressive strength for no structural application. It is desired to explore the mechanical and thermal properties of pervious concretes with LWA suitable for structural concretes. Expanded shale have been highly used for LWA structural concrete (H.Z. Cui et al., 2012; Y. Kea, A.L. Beaucour , S. Ortola , H. Dumontetb, 2009; Yun et al., 2013). It seems suitable to increase the compressive strength of LWA pervious concretes.

The total porosity of pervious concretes affects the mechanical and thermal properties. Current methods for determine pervious concrete porosity are based in a volumetric approach and allow measuring the total effective porosity for a specific drying method (ASTM, 2014a; Montes et al., 2005). Nevertheless, this method cannot quantify the porosity formed in the internal structure in a LWA pervious concrete. The LWA porosity increases the total effective porosity of a LWA pervious concrete. There was not found a method that allows bring a pervious concrete to SSD. It is desired to determine the surface-dry porosity of pervious concrete in order to quantify the effective porosity at SSD and the internal porosity of LWA pervious concretes.

This article aims to explore the mechanical and thermal properties of pervious concretes. The effect of the paste volume and the type of aggregates (NWA and LWA) were assessed. A novel test method was developed to determine the internal porosity of pervious concrete with NWA or LWA. The compressive strength, elastic modulus, thermal conductivity, thermal diffusivity and specific heat were reported. The interaction between the compressive strength and thermal conductivity were analyzed to select the strategies that most impacted the balance of both properties.

6.2. Experimental program

6.2.1. Materials and mix proportions

Concrete mixtures were produced using an Ordinary Portland Cement (OPC) with a specific gravity of 3.14 and Blaine fineness of 410 m^2/kg. Normal weight aggregate (NWA) were produced in Chile. Expanded shale from USA was used as lightweight aggregate (LWA). The LWA were submerged for 72 hours and the absorption was obtained according to ASTM C1761 (ASTM, 2013). The aggregates properties are presented in Table 6-1.

Table 6-1: Physical properties of aggregates

Aggregate	Size (mm)	OD density (kg/m^3)	SSD density (kg/m^3)	Abs., 72 hr (%)
Coarse expanded shale	12.5 /10	1267	1430	12.9%
Coarse expanded shale	10 /5	1257	1423	13.2%
Normal weight coarse aggregate	10 /5	2679	2700	0.8%

The experimental design consists in a fractional factorial (“NIST/SEMATECH e-Handbook of Statistical Methods”). It consists in a binary model of two factors (paste volume, Type of aggregate) and two levels, with and intermediate mixture (Table 6-2). The objective of varying the paste volume was to vary the effective porosity of pervious concretes. These five mixtures presented aggregate size #4 (passing 10 mm sieve and retained in 5.0 mm sieve). Two mixtures were added for LWA with aggregate size 3/8” (passing 12.5 mm sieve and retained in 10 mm sieve) to evaluate the increase in LWA size. The water-to-cement ratio (W/C) and the aggregate volume were fixed at 0.32 and 58% respectively for all the mixtures. The mixture proportions are shown in Table 6-3.

Table 6-2: Levels and factors of the experimental program

Experimental factors		Levels		
Name	Description	-1	0	1
TA	Type of aggregate	100% NWA	50% NWA, 50% LWA	100% LWA
PV	Paste volume	20%	24%	28%

Concrete was mixed in an 80-liter vertical axis mixer. Expanded shale was submerged in water for 72 hours and drained in a No. 50 sieve for 10 minutes before the mixing. Moisture content was considered in the mixing water. The compaction method was based in a previous research (Castro, 2004). Concrete samples were cast in three layers by rodding 25 times each layer. The compaction was completed by dropping the molds from 5 cm height three times after rodding the last layer.

Three 10x20 cm cylindrical specimens were cast for each batch for mechanical testing and two 10x20 cm cylindrical specimens were cast for thermal properties and porosity testing. Four 10x10 cm cylindrical specimens were saw-cut from the two cylindrical specimens for thermal properties and porosity testing. Specimens were left in their molds for 24 hours and submerged in water at 20(±1) °C for 7 days after demolding. Then, the specimens were stored in a chamber at 22°C (±2) and 50% (±3) R.H., until the age of the mechanical, thermal and porosity tests.

Table 6-3: Mix proportions of pervious concretes

Mix	W/C	OPC (kg/m^3)	Water (kg/m^3)	Coarse NWA (kg/m^3)	Coarse LWA (kg/m^3)
NW28%, #4	0.32	439	140	1514	0
NW20%, #4	0.32	313	100	1514	0
(NW,LW)25% ,#4	0.32	392	125	757	433
LW28%, #4	0.32	439	140	0	842
LW20%, #4	0.32	313	100	0	842
LW28%, 3/8"	0.32	439	140	0	829
LW20%, 3/8"	0.32	313	100	0	829

6.2.2. Mechanical and thermal procedures

d) Mechanical properties

Compressive strength and elastic modulus were measured on 3 specimens at 28 days. Elastic modulus was measured applying up to 33% of the maximum compressive strength and the strain was registered with 3 extensometers. Elastic modulus was calculated according to ASTM C469 (ASTM, 2014b).

e) Thermal properties

The thermal properties were measured with a Hot Disk TPS1500 in the double side mode. This is a state of the art transient technique that measures thermal conductivity and thermal diffusivity of materials (Gustafsson, 1991). The volumetric specific heat is calculated from these two properties. The thin sensor acts both as a heat source and a temperature sensor. The maximum increase of temperature during the test was 5 °C for all the samples. The sensor model was 4922, with diameter of 29.2 mm. The penetration depth in horizontal and perpendicular direction from the sensor was at least 23 mm. The measurement time was 320 seconds. The tests were developed under laboratory conditions at 20° C (±1). Each double sample was tested once.

The thermal properties were registered in equilibrium moisture condition at 90 days and in oven-dry condition. The equilibrium moisture condition was determined when specimens reached the so called equilibrium density which occurs when the mass of the specimens presented less than 0.5% change in successive measurements 28 days apart (ASTM, 2014c). The oven dry condition was obtained by drying the specimens at 105°C for 48 hours (time to reach constant mass), and cooled for 5 hours until reaching 20°C. The heating and cooling rates were 0.5°C/min to minimize the temperature gradients and therefore thermal cracking.

6.2.3. Porosity measurement methods

a) Centrifuge method

The centrifuge method was proposed to determine the moisture properties of LWA at SSD (A. E. Miller, Barrett, Zander, & Weiss, 2014; A. Miller et al., 2014). The basis of the method is the balance between the centrifugal force that extracts the water and the capillary force that holds the pores. Miller et. al. (2014) showed that there is a minimum time necessary for the water flow from the LWA surface. This centrifuge method was extended to pervious concrete samples, as Figure 6-1 shows. Two cylindrical samples were measured simultaneously. It was applied up to 720 seconds (12 minutes) for all the samples.

The vacuum saturation method was applied to the pervious concretes before the centrifuge method to saturate most of permeable pores. A previous research showed that the vacuum method is the most efficient saturation method for measuring the effective porosity (Safiuddin & Hearn, 2005). The saturation method was applied to four specimens for each pervious concrete, based on ASTM C1202 (ASTM, 2012).The centrifuge method was run at a centrifuge speed of 2800 rpm.

Figure 6-1: Centrifuge setup for porosity measurement

Figure 6-2 shows the apparent effective porosity of LWA pervious concrete with paste volume of 20% and aggregate size #4. Most of the water content was lost during the first 30 seconds of spinning. After a few minutes, the effective porosity of all pervious concretes rapidly stabilized. The test time selection criteria was when the apparent effective porosity decreased less than 0.1% for extra 60 seconds (1 minute) of centrifuge spinning. The test time was 360 seconds (6 minutes) for all pervious concretes. The apparent effective porosity just decreases 0.5% for an extra 360 seconds (6 minutes) of spinning.

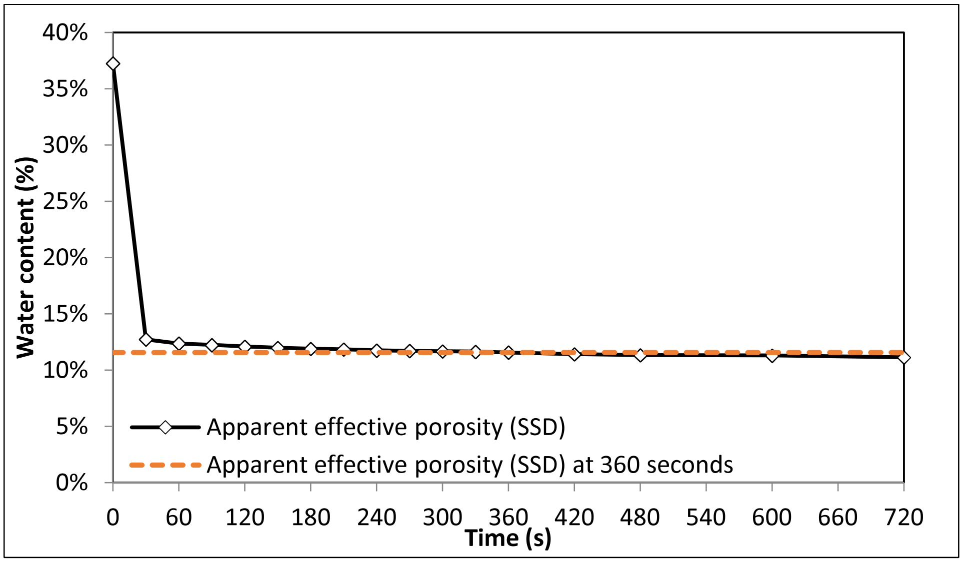

Figure 6-2: Effect of test time of centrifuge method in the apparent effective porosity

b) Micro-CT scan analysis for porosity measurement

Micro computed tomography scans of expanded shale of size 3/8” and NWA pervious concrete with paste volume of 20% and aggregate size #4 were performed to analyze their porosity properties. One expanded shale aggregate was selected based in the median oven-dry density of 20 individual aggregates. A cube of 5 cm side was saw cut from a cylinder for the scan.

Scans were performed in a Skyscan1172 desktop micro-CT system, at UTHSCSA Micro-CT Core Laboratory (Texas, USA). The samples were scanned in air with the following settings: 60 kV, 133 μA, 1.0 mm aluminum filter, 0.7° rotation step, 360° rotation, 6 frame averaging, 2240 x 2240 CCD and 1000 millisecond exposure. The voxel size for expanded shale and pervious concrete was 10 μm and 35 μm respectively. Scan time for expanded shale and pervious concrete was 1 hour and 1:45 hours respectively.

6.3. Results and discussion

6.3.1. Porosity methods

Table 6-4 shows that the effective porosity of pervious concretes increased for vacuum saturation compared to water submerged procedure of ASTM C1754 (ASTM, 2014a). The vacuum saturation method allows saturating more permeable pores because the air is removed before the water access them. A significant amount of pores are smaller than the voxel size and were not detected. The expanded shale presented open porosity and total porosity of 3.4% and 10.5%, but the estimated porosity was 53% (Paper 1). The absorption rate of the scanned expanded shale was 12.7%, which is higher than the open porosity. Capillary pores within the expanded shale (Figure 6-3) that connect the detected closed porosity must be smaller than 10 μm. The same results were presented for the pervious concrete. The total porosity measured from the CT scan analysis was 17.7% and resulted less than both effective porosities.

Table 6-4: Porosity properties of pervious concrete

Mix	Effective porosity ASTM1754, oven-dry (%)	Effective porosity vacuum, oven-dry (%)	Effective porosity vacuum, SSD (%)	Internal porosity centrifuge (%)
NW28%,#4	15%	20%	9%	10%
NW20%,#4	25%	31%	24%	7%
(NW+LW)25%,#4	23%	26%	11%	15%
LW28%,#4	21%	31%	15%	16%
LW20%,#4	36%	39%	20%	19%
LW28%,3/8"	25%	29%	11%	18%
LW20%,3/8"	34%	38%	21%	17%

Table 6-5: Porosity results of pervious concretes

Sample	Closed porosity (%)	Open porosity (%)	Total porosity (%)
NW20%,#4	0.2%	17.6%	17.7%
Expanded shale	7.3%	3.4%	10.5%

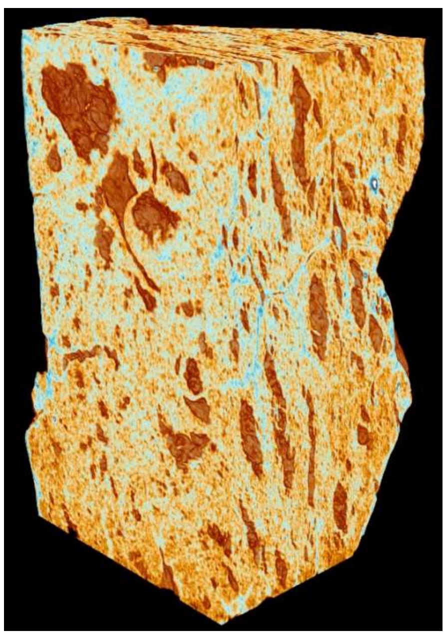

Figure 6-3: Density distribution image of expanded shale

Figure 6-4 presents the pore volume distribution of expanded clay and pervious concrete with paste volume of 20% and aggregate size #4. The expanded shale pores are more refined than the pervious concrete pores. The median pore volume size for expanded shale and pervious concrete correspond to 0.44 mm and 1.94 mm.

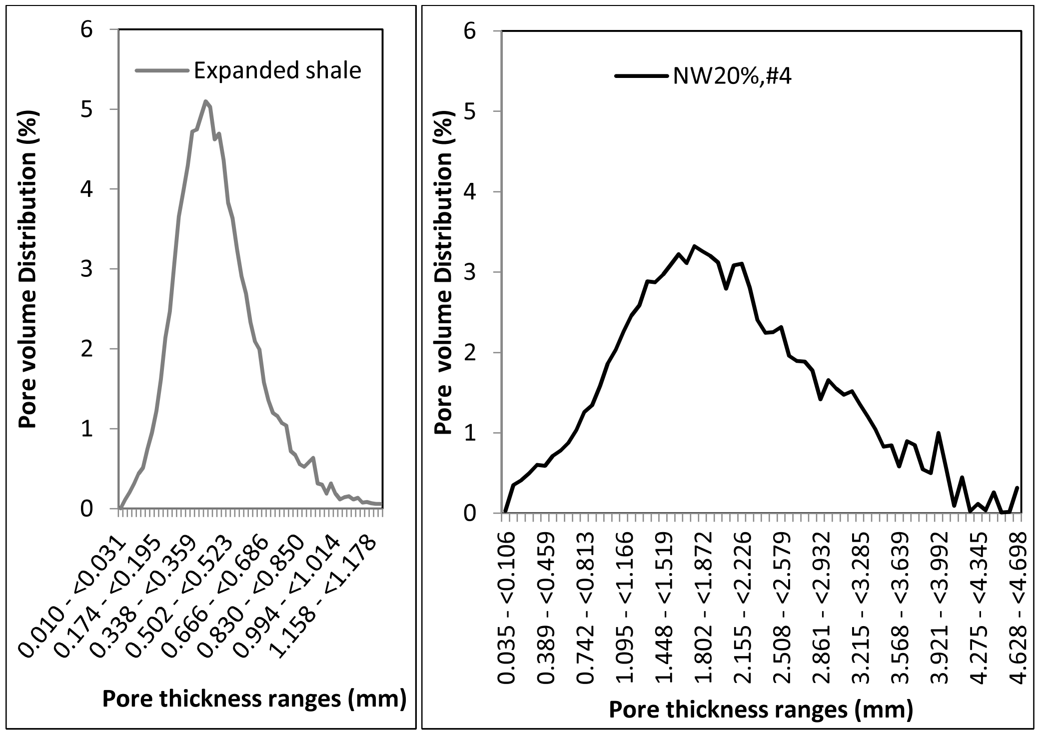

Figure 6-4: Pore volume distribution of expanded shale and pervious concrete

Figure 6-5 shows that the total effective porosity at OD condition increases with the substitution of NWA for LWA. The increment is influenced by the higher porosity of LWA. The internal porosity increased from 7-10% for NWA to 16-19% for LWA pervious concretes. Figure 6-5 also shows that the effective porosity at SSD increased from 9-15% to 20-24% with the decrement of cement paste from 28% to 20%. The effective porosity at SSD condition is a better indicator of the permeable pores formed within the concrete structure. It is more suitable to represent the hydraulic properties. These pores are a fraction of the total porosity that affects the mechanical and thermal properties. The total porosity of concretes could be estimated if the total porosity of the paste, aggregates and non-connected pores within the concrete are assessed.

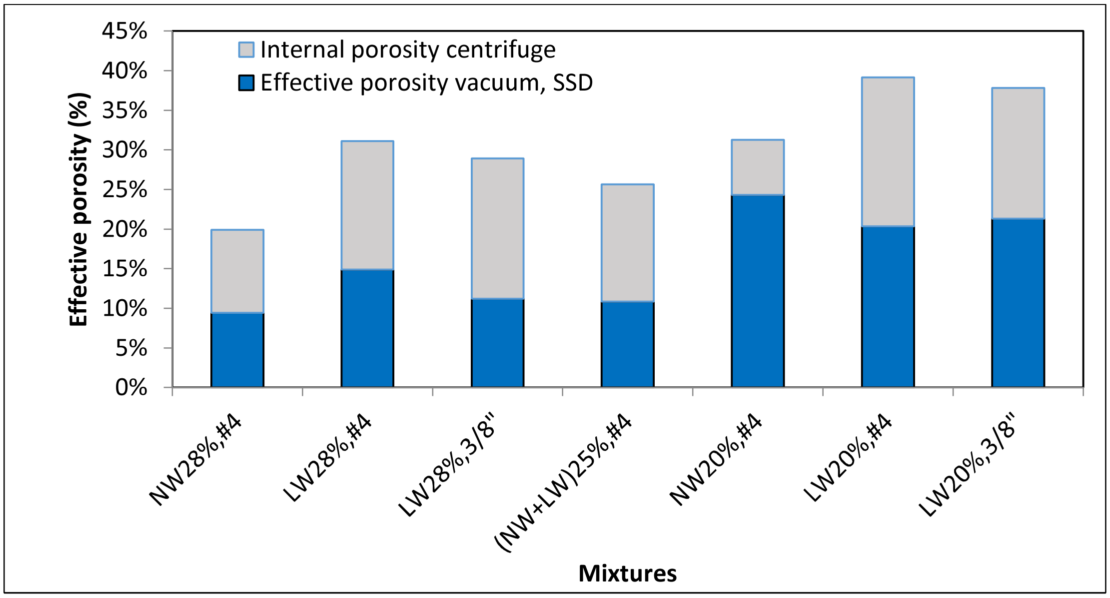

Figure 6-5: Effective porosity of pervious concretes

6.3.2. Mechanical and thermal properties

Figure 6-6 and Table 6-6 show that the replacement of NWA for LWA reduced the compressive strength. The LWA aggregates present a higher porosity than NWA. From the mechanical standpoint, the pores in the LWA act as stress concentrators under compressive strength and cause an earlier failure in the pervious concrete. The decrease of paste volume resulted in a higher decrement of the mechanical properties than the replacement of NWA for LWA. With the decrease of the paste volume, there is an increment of porosity and a decrement in the contact surface between the aggregates, which increases the stress concentration in the paste. The paste volume influence in the mechanical properties was also previously reported (Deo & Neithalath, 2011).

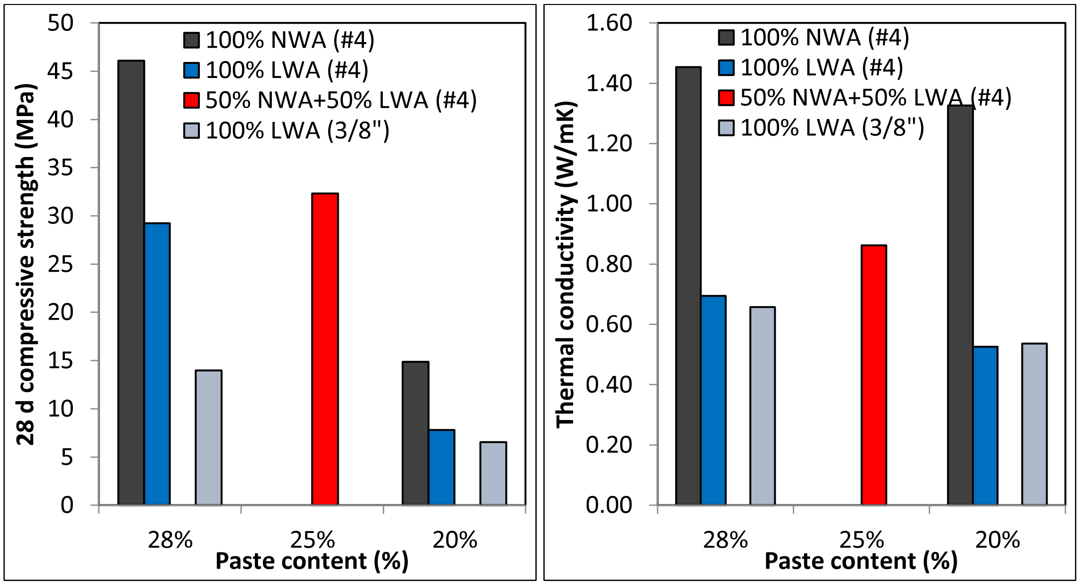

Figure 6-6: Compressive strength at 28 days and thermal conductivity at equilibrium density

Figure 6-6 also shows that the increase of aggregate size in LWA pervious concrete decreased the compressive strength. The decrement was higher for high paste volume. This effect was previously reported for NWA (Deo & Neithalath, 2011). They attributed the decrement in the compressive strength to the differences in the internal pore structure caused by the aggregate sizes. The range of aggregate size is larger for #4 (4.75-9.5 mm) than for 3/8” (9.5-12.5 mm). This creates a more homogeneous pore structures when using a smaller aggregate size (Deo & Neithalath, 2010).

Table 6-6: Density and mechanical properties of pervious concretes

Mix	ρ_{eq} (kg/m^3)	ρ_{OD} (kg/m^3)	f_c 28 days (Mpa)	E 28 days (Gpa)
NW28%,#4	2186	2116	46.1	40
NW20%,#4	1925	1881	14.9	20
(NW+LW)25%,#4	1831	1760	32.3	23
LW28%,#4	1499	1411	29.2	20
LW20%,#4	1266	1215	7.8	12
LW28%,3/8"	1450	1369	14.0	14
LW20%,3/8"	1262	1207	6.5	13

Figure 6-6 shows that the reduction of paste volume decreased the thermal conductivity for NWA pervious concretes in a 9%, for LWA with aggregate size #4 in 18% and for LWA with aggregate size 3/8" in 24%. NWA pervious concrete presented a higher increment in the internal porosity (9% to 24%) than in the effective porosity (OD) (20% to 31%). The interconnected pores are less efficient for the reduction of the thermal conductivity. As Figure 6-7 shows, the NWA and the paste form continuous linear pathways through the pervious concrete structure for the heat flow.

Table 6-7: Thermal properties of pervious concretes at equilibrium and oven-dry density

Mix	Equilibrium density			Oven-dry density		
	k (W/mK)	α (mm^2/s)	c (J/kg K)	k (W/mK)	α (mm^2/s)	c (J/kg K)
NW28%,#4	1.45	0.58	1145	1.31	0.71	884
NW20%,#4	1.33	0.54	1276	1.07	0.51	1124
(NW+LW)25%,#4	0.86	0.43	1087	0.78	0.45	990
LW28%,#4	0.69	0.46	1016	0.60	0.47	910
LW20%,#4	0.53	0.46	924	0.53	0.41	957
LW28%,3/8"	0.66	0.42	1095	0.48	0.46	850
LW20%,3/8"	0.54	0.38	1135	0.45	0.35	1066

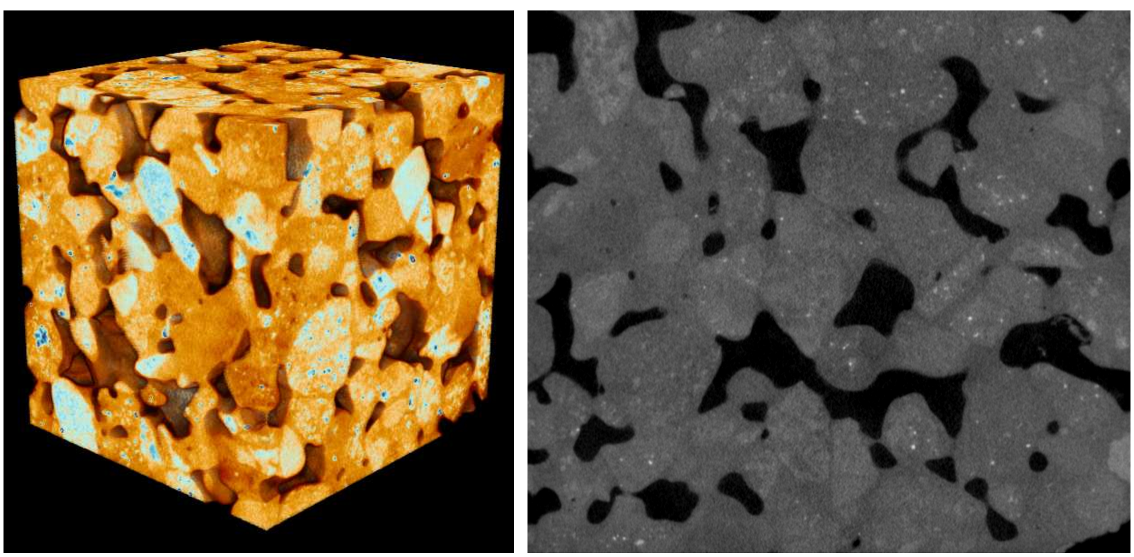

Figure 6-7: CT scan density distribution image and orthogonal cross sectional image of NW20%, #4 pervious concrete

The replacement of NWA for LWA is more efficient to decrease the thermal conductivity; the reduction ranged 50-52%. The LWA present a high porosity, which reduces the thermal conductivity of the aggregate compared to NWA. The replacement of NWA for LWA forces the heat flow through the LWA. Figure 6-6 shows that the replacement of NWA for LWA and the decrease in paste volume decreased the thermal conductivity in a 63%.

Figure 6-8 presents the relationship between compressive strength and thermal conductivity of the pervious concrete and compares it with LWA concretes with expanded clay and expanded shale as coarse aggregates (Paper1, Paper 2). The internal porosity of expanded shale pervious concrete decreases the compressive strength and thermal conductivity when compared to the expanded shale concrete.

Figure 6-8 show that the decrease of the paste volume triggered a higher decrement in the compressive strength than in the thermal conductivity of NWA and LWA pervious concretes. The replacement of NWA for LWA is more efficient than the reduction of the paste volume in NWA pervious concrete and allowed a higher reduction in thermal conductivity than the latter. This effect showed that the thermal conductivity of pervious concretes is governed by the heat flow through the aggregates. The reduction of aggregate size is efficient to increase the compressive strength of concrete while maintaining a similar thermal conductivity.

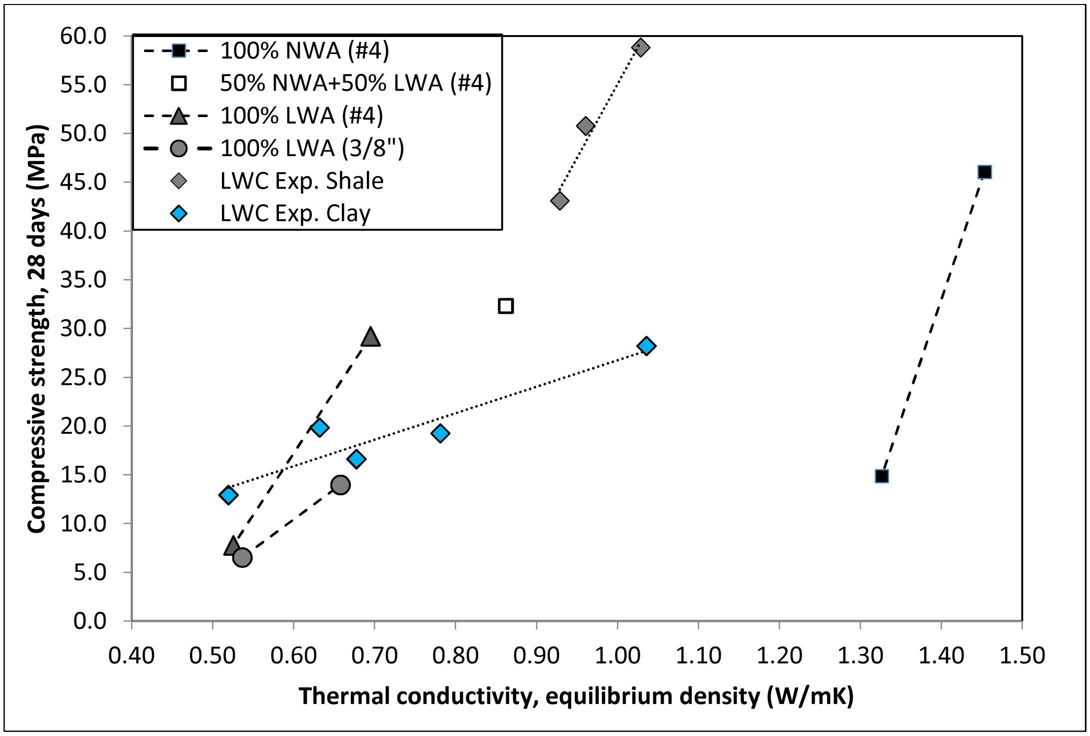

Figure 6-8: Compressive strength and thermal conductivity of pervious concretes and LWA concretes

The pervious concrete with 50% of NWA and 50% of LWA present a higher reduction in the thermal conductivity than in the compressive strength when compared to the decrease of the paste volume in NWA concretes. The partial replacement of LWA decreases the thermal conductivity. A random distribution of LWA and NWA limits linear pathways of paste and NWA, forcing the heat to flow through LWA. Nevertheless, the full replacement of NWA for LWA allowed decreasing the thermal conductivity more than the partial replacement, while obtaining a compressive strength of 29 MPa.

These results suggest that the balance between the compressive strength and thermal conductivity might be enhanced with the decrease of the aggregate size and a paste with lower thermal conductivity. Literature shows that cement paste with supplementary cementing materials decrease the thermal conductivity (Demirboga, 2003a; Fu & Chung, 1997). This study does not allow assessing the relationship between the compressive strength and thermal conductivity, but allows exploring the effect in the range of paste volume examined.

6.4. Conclusions

This article presents an exploratory study of the effect of paste volume and the type of aggregates (NWA, LWA) in the mechanical and thermal properties of pervious concrete. A novel test for pervious concretes, the centrifuge method, was adapted and developed to determine the effective and internal porosities of pervious concretes. The main conclusions are listed as follows:

- The reduction of paste volume presented a higher decrement in compressive strength than the replacement of NWA for LWA. On the other hand, the replacement of NWA for LWA presented a higher decrement in thermal conductivity than the reduction of paste volume. This effect showed that the thermal conductivity of pervious concretes is governed by the heat flow through the aggregates.
- Results from the centrifuge method confirm that the decrease of paste volume (increase of porosity) due a lower paste volume generates an increase of interconnected pores, which is less efficient for heat transfer and compressive strength.
- The increase of aggregate size in LWA pervious concrete presented a higher decrement of compressive strength for high paste content. The increase of aggregate size generates a less homogeneous pore structure. The thermal conductivity varied in less than 5%.

The replacement of NWA for LWA and the reduction of aggregate size are efficient to increase the compressive strength of concrete while maintaining a similar thermal conductivity.

6.5. Aknowledgements

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7. CONCLUSIONS AND RECOMMENDATIONS

This research assessed the effect of the internal structure of concrete in their mechanical and thermal properties. Chapter Four evaluated the independent intervention of three constituents: (i) Fly ash (FA) in the binder (ii) coarse lightweight aggregate (LWA), and (iii) fine LWA. The impact of the type of coarse LWA (expanded shale, expanded clay, expanded polystyrene) was evaluated with two-phase models for compressive strength, elastic modulus and thermal conductivity. These results were used to compare the efficiency of the type of coarse LWA in concretes.

The combined effect of coarse expanded clay, fine expanded clay and fly ash was evaluated in Chapter Five, in order to understand and asses their interaction in the mechanical and thermal properties of concrete. The porosity properties of the coarse and fine expanded clay were analyzed with micro-CT scan for assess their effect in mechanical and thermal properties. Multiple linear regression models for thermal conductivity and compressive strength were assessed to evaluate the impact of each component.

Chapter Six presented an exploratory study of the effect of paste volume and the type of aggregates (NWA, LWA) in the mechanical and thermal properties of pervious concrete. A novel test, the centrifuge method, was developed for determine the effective and internal porosities of pervious concretes.

FA presented a higher impact in the reduction of compressive strength (56%) than thermal conductivity (14%). The effect on thermal conductivity is limited by the low paste volume (34%) and the higher thermal conductivity of the aggregates when using normal weight aggregates. The changes that generates FA in the microstructure of the binder influence the mechanical and thermal properties. The balance between the CH to CSH transformation, pore size distribution and anhydrate FA leads to a decrease in thermal conductivity and to the optimum compressive strength to thermal conductivity ratio.

The three coarse LWA presented a higher impact in the reduction of compressive strength than the thermal conductivity of concrete. Expanded shale is more suitable to a high strength LWA concrete but the thermal conductivity of concrete is limited to values higher than 0.9 W/mK. Expanded clay and expanded polystyrene concretes presented structural strength, with a lower thermal conductivity down to 0.74 W/mK. Coarse expanded clay and expanded polystyrene present a similar balance between thermal conductivity and compressive strength. Both materials seem to be suitable to obtain a structural concrete with low thermal conductivity.

The LWA porosity affects differently the mechanical and thermal properties. The pores of LWA are the weak locations for mechanical performance, where the stress concentration initiates the failure of the concrete. Porosity acts similarly for elastic modulus concentrating deformations around it. The elastic modulus of concrete when using LWA is better represented by a series composite model. Contrarily, the heat flux lines flow through the mortar (higher thermal conductivity phase), avoiding the pores of LWA. The thermal conductivity of concrete using LWA is better represented by a parallel composite model. This explains the relative low effect of increasing the porosity of the aggregate in the thermal conductivity of concrete. The expanded polystyrene porosity (99%) does not help to decrease significantly the thermal conductivity because the heat flux lines avoid the LWA. These results accept the hypothesis 1, which stated that the increment of lightweight aggregates total porosity does not increment the efficiency of the compressive strength, elastic modulus and thermal resistance of lightweight aggregates concretes.

The increase in LWA volume up to 50% for expanded shale and expanded clay and up to 30% for expanded polystyrene did not increase the thermal conductivity efficiency because the thermal conductivity of the concrete is mostly governed by the mortar matrix. The reduction of thermal conductivity of LWA is not as effective as expected in reducing the thermal conductivity of the concrete. The effect of the replacement of expanded clay for expanded polystyrene with a thermal conductivity of only 10% of the first, reduced the thermal conductivity of concrete in less than 15%, for 30% of LWA volume.

The combined effect of coarse expanded clay, fine expanded clay and fly ash allows achieving a 74% decrease in the thermal conductivity at equilibrium density of concrete, up to 0.43 W/mK, with a compressive strength of 9.3 MPa. The fine expanded clay allows for a larger reduction of thermal conductivity with the lower reduction in the compressive strength compared to coarse expanded clay. Fly ash presents the smallest effect in both compressive strength and thermal conductivity.

The combination of constituents generates a higher tortuosity effect in the thermal conductivity with the reduction of thermal bridges within the concrete. The higher decrease rate in thermal conductivity causes a smaller cost in compressive strength. In despite of the higher rate in compressive strength reduction, the use of FA allows to achieve lower values of thermal conductivity, reducing the heat flux through the binder. These results accept hypothesis 2.

The porosity properties of expanded clay particles explain the better compressive strength and thermal conductivity performance of the fine expanded clay aggregate, compared to coarse expanded clay. Based on the CT scan results, fine expanded clay presented: (1) better pore spatial distribution in the concrete which explain the thermal conductivity performance, (2) smaller maximum pore size which explain the compressive strength performance and (3) more refined pores which also affects the thermal conductivity performance. These results accept hypothesis 3.

For pervious concretes, the reduction of paste volume presented a higher decrement in compressive strength than the replacement of NWA for LWA. On the other hand, the replacement of NWA for LWA presented a higher decrement in thermal conductivity than the reduction of paste volume. This effect showed that the thermal conductivity of pervious concretes is governed by the heat flow through the aggregates. These results accept hypothesis 4.

Results from the centrifuge method confirms that the decrease of paste volume (or increase of porosity) due a lower paste volume generates an increase of interconnected pores, which is less efficient for heat transfer and compressive strength. The increase of aggregate size in LWA pervious concrete presented a higher decrement of compressive strength for high paste content. The increase of aggregate size generates a less homogeneous pore structure. The thermal conductivity varied in less than 5%.

This study propose that the effect of FA in thermal conductivity is caused by factors not considered in previous studies. These factors, such as the porosity, the pore size distribution and the hydration products were not measured. The effects of FA on these factors were based on previous studies that confirm these effects. The obtained results are also limited by the constant water to binder ratio; its variation affects the porosity and pore size of the paste. It is recommended a study that measures these factors and the mechanical and thermal properties in order to confirm their effect with experimental results.

A pore size distribution of LWA was achieved from a CT scan analysis. Nevertheless, the cost of the CT scan limited to one sample per LWA. The size of the LWA also limited the maximum resolution and the minimum pore size up to 10 µm. The total porosity achieved in the CT scan indicates that there are pores smaller than 10 µm. It is recommended to analyze smaller particles individually with a higher amount of samples.

The effect of the LWA size in the mechanical and thermal properties, which is related with the porosity properties, is one of the most important results of this research. This effect was widely known for mechanical properties but it was not previously associated with the porosity properties of LWA. Future research could evaluate this effect with other LWA and proportions.

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APPENDIX

APPENDIX A: IMAGES OF EXPERIMENTAL WORK

Figure A-7-1: Fine expanded clay (left) and coarse expanded clay (right)

Figure A-7-2: Mixing of lightweight aggregates concrete

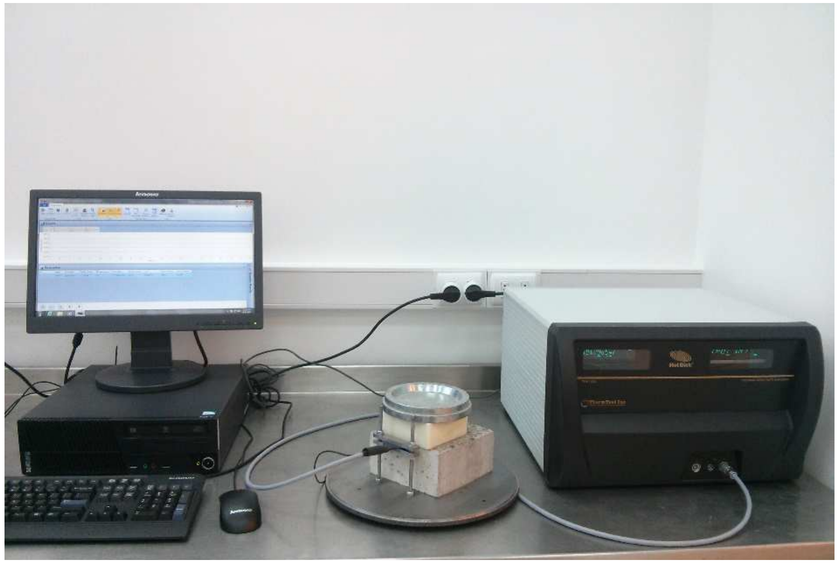

Figure A-7-3: Hot Disk TPS 1500 system

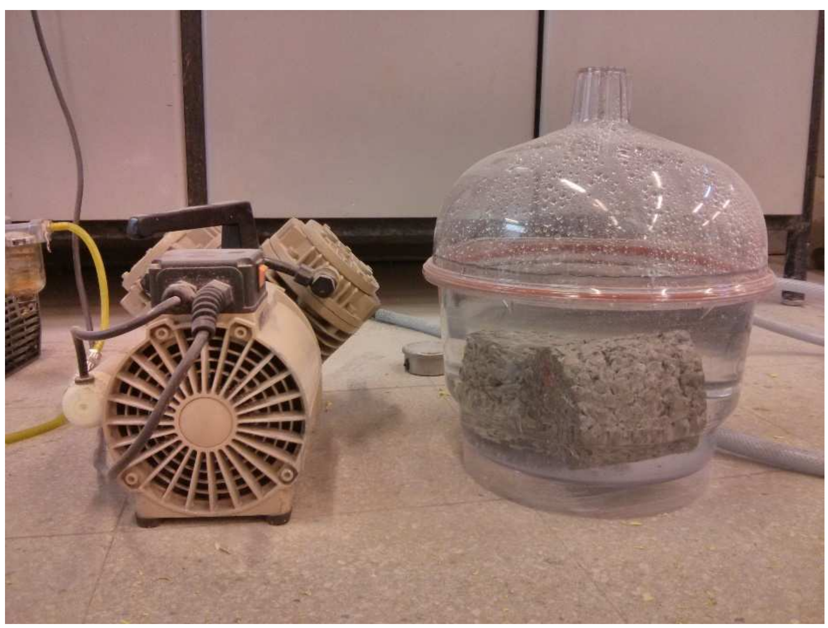

Figure A-7-4: Vacuum saturation method for pervious concretes

Figure A-7-5: Compressive strength test for cylindrical specimens

APPENDIX B: EFFECT OF DRY CHAMBER IN COMPRESSIVE STRENGTH

Figure A- shows that the decrease rate in moisture content was higher in the early ages. The “dry chamber” curing conditions promoted the water loss in the lightweight concrete. All of the lightweight concretes presented the same behavior. This water loss could generate drying shrinkage and induces tensions on the paste (Metha & Monteiro, 2014). The water loss of the porous aggregates might also weaken the compressive strength at later ages. A significant portion of the pores were empty at 120 days. When concrete is under compressive strength and the pores are 100% saturated, the water, as an incompressible fluid, produce an opposite pressure inside the pores that might increase the concrete strength.

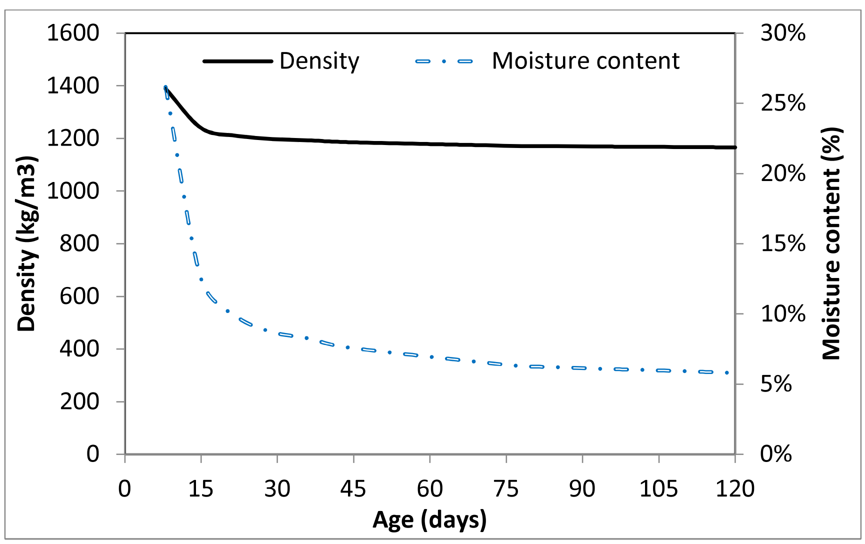

Figure A-6: Effect of drying conditions on density and moisture content for CFFA9

The water loss also affected the compressive strength gain rate at later ages. The loss of water also stops the hydration degree of the binder, which affected the compressive strength gain rate. Previous studies reported that the hydration of the cement paste stops for an interior relative humidity (R.H.) below 80% (Patel et al., 1988). The decrease in the hydration process is related to reduction of water activity by the negative capillary pressure in the pores for R.H. below 80% (Flatt et al., 2011). The water loss evidenced in Figure A- also affected the pozzolanic reaction of fly ash. The pozzolanic reaction depends of the CH content and water content (Oner et al., 2005; A. Wang et al., 2004). The increase of fly ash ratio also decreased the cement content and the CH content produced by its hydration.