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Effects of Recycled Concrete Aggregate Surface Treatments on Drying Shrinkage of Recycled Aggregate Concrete

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EFFECTS OF RECYCLED CONCRETE AGGREGATE SURFACE TREATMENTS ON DRYING SHRINKAGE OF RECYCLED AGGREGATE CONCRETE

by

ANDREW EVAN GEISTER

B.S., University of Colorado, 2008

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This thesis entitled:

Effects of recycled concrete aggregate surface treatments on drying shrinkage of recycled aggregate concrete

written by Andrew Evan Geister

has been approved for the Department of Civil, Environmental, and Architectural Engineering

Yunping Xi

Mettupalayam Sivaselvan

Nevis Cook

Date________________

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

Geister, Andrew Evan (M.S., Civil Engineering)

Effects of recycled concrete aggregate surface treatments on drying shrinkage of recycled aggregate concrete

Thesis directed by Professor Yunping Xi

The use of recycled concrete aggregate (RCA) in concrete construction is a practice that is increasing in use with a general movement toward more sustainable and environmentally responsible construction practices. The environmental benefits include reducing landfill use from building construction and reducing effects of mining for new aggregates. The surface characteristics of RCA differ from natural aggregates due to the remaining cement paste adhered to the original aggregate which result in lower aggregate density and higher absorption. An experimental study was carried out to determine the effects on concrete of various RCA surface treatments, which included a silica-cement mixture, acrylic coating, surfactant solution, and water saturation, intended to alter RCA surface characteristics. The effects on aggregate properties, fresh concrete properties, and hardened concrete properties were examined. The use of RCA at a 25% substitution rate for natural aggregate appears effective at reducing drying shrinkage and increasing compressive strength using untreated, acrylic treated, and water saturated RCA, depending on the intended use of the final concrete product.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The use of recycled materials in construction is a practice that is becoming increasingly more important and also more common as a general movement towards more sustainable building practices takes place. With an increased emphasis on recycling, reduction of mining and landfill use, and an increased use of local materials, reusing concrete as aggregate is a concept that that makes sense. Construction waste management is a very important economical and environmental impact on our society (Courard, Michel, & Delhez, 2010). The problem facing many urbanized nations is the decline of available waste disposal sites. These sites are decreasing for a variety of reasons, especially environmental. In many urban areas in the United States, existing disposal sites are being exhausted. Also, sources of good quality aggregates are rapidly becoming depleted (ACI Committee 555, 2001). The use of recycled aggregate concrete offers a sustainable solution to these problems. Furthermore, buildings seeking LEED certification can benefit greatly from the material and resources opportunities afforded by recycled-content concrete. Availability of RCA is increasing along with production of this material coming from construction, renovation, and demolition (Courard, Michel, & Delhez, 2010).

Past research has found the drying shrinkage of concrete containing RCA to be greater than conventional concrete (Hansen, 1986). This effect has been attributed to the greater water absorption potential of the adhered cement paste of RCA, as well as an overall larger proportion of mortar paste in the concrete, including both new paste from the mix and old paste from the RCA (ACI Committee 555, 2001).

1.1.1 Recycled Concrete Aggregate

A background of RCA concrete as a construction material is presented, including environmental benefits and credit for designers, the process of RCA production, and important properties of RCA that establish its difference from natural aggregates.

1.1.1.1 Environmental Factors

Although figures vary by source, some studies have reported that concrete waste contributes approximately 50% of total waste generated. Recycling concrete helps to divert material from landfills, reduce the effects of mining for new aggregates, and also reduces transportation effects associated with both processes. One study showed that the concrete recycling process produces a net cost benefit compared to landfill disposal (Tam, 2008).

Support for green building practices has increased over the last several years, and many jurisdictions offer tax credits or grants for construction which meet LEED or other similar program guidelines. Some government agencies have even required a minimum level of certification in these types of programs for new construction of public buildings. Program requirements tend to change over time, however currently as of this writing, concrete containing RCA is eligible to earn points through LEED in the categories of Construction Waste Management, Recycled Content, Regional Materials, Innovation, and indirectly through other categories (PCA, 2005).

1.1.1.2 RCA Production

To obtain RCA suitable for use in concrete construction, source concrete must be demolished, and reinforcing as well as other materials or contaminants must be removed. A common source of concrete for RCA is pavements (Courard, Michel, & Delhez, 2010) which, after reinforcing is removed, is generally free from most deleterious materials often found in typical construction demolition such as plaster, wood, plastic, glass, and other materials. However, pavement concrete that has been contaminated with salt should not be used as aggregates for reinforced concrete exposed in a moist environment (Hansen, 1986). The plant processes for producing RCA are similar to those for producing natural aggregates. Jaw type crushers remove reinforcing and reduce the particle size. Further crushing and grading produces the size distribution of aggregates suitable for concrete production (ACI Committee 555, 2001).

The resulting aggregate appearance is similar to that of natural aggregate, with the most important difference being the presence of the layer of mortar paste adhered to the original aggregate, illustrated in Figure 1-1.

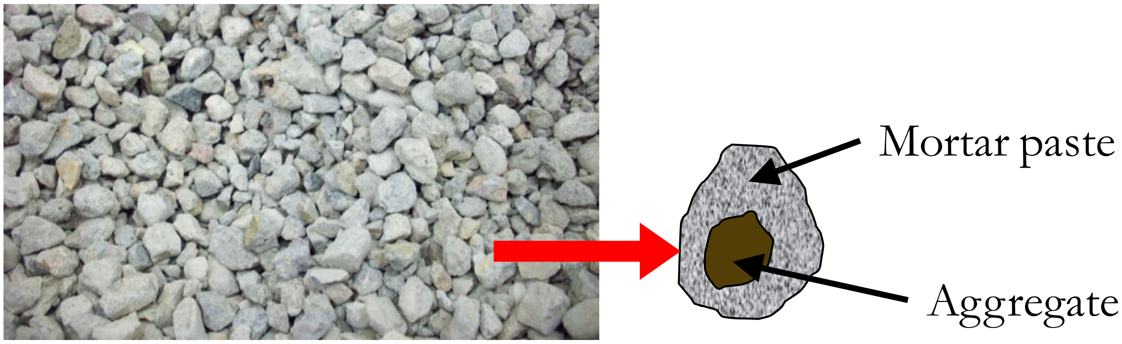

Figure 1-1. Appearance of RCA with adhered mortar paste.

1.1.1.3 RCA Properties

When old concrete is crushed, a certain amount of mortar from the original concrete remains attached to the original stone particles in the recycled aggregates. The difference in aggregate properties caused by this adhered cement layer is the reason special considerations need to be made when using this material in concrete. Many researchers have concluded that the water absorption of coarse recycled aggregates is much higher than the water absorption of original aggregates, due to the higher water absorption of old mortar attached to original aggregate particles (ACI Committee 555, 2001). The adhered mortar paste is also responsible for RCA generally having less density than natural aggregates. These differences have been reported to result in concrete containing RCA having lower compressive strength, elastic modulus, and higher creep and shrinkage deformation as well as higher permeability (Meyer, 2009). Further study of these properties is presented in Chapters 2 and 3. For these reasons, RCA concrete is generally limited to use in road construction, but further study with the use of quality testing suggests that its use can be extended (Desai S. , 2008).

The other main difference in recycling construction and demolition products as a source of aggregate is the presence of contaminants and various other building materials described previously. Strict enforcement of upper limit standards must be maintained to avoid deleterious effects of these materials and secure the integrity of RCA concrete as a viable building material (Meyer, 2009).

1.1.2 Drying Shrinkage Strain

Long term strains in concrete are critical to many types of structures including structural members, precast, prestressed members, and containment vessels (Benboudjema & Torrenti). Many authors have studied the various types of length and volume change experienced by concrete as it matures. These types of volume change include autogenous shrinkage, drying shrinkage, carbonation shrinkage, basic creep, drying creep, and swelling. Each type of length/volume change induces strain in the concrete. Shrinkage is characterized as strain measured on a load-free concrete specimen, while creep is characterized as strain measured on a concrete specimen under sustained stress (ACI Committee 209, 2005).

1.1.2.1 Drying Shrinkage Basic Principles

Concrete is a composite material made up of cement paste and aggregate, and bond interfaces between materials (Al-Attar, 2008). Concrete is treated as a two phase material where the aggregate is modeled as a perfectly elastic material, while the cement paste is idealized as a solidifying material due to the process of hydration (Asamoto, Ishida, & Maekawa, 2008). Examples of these types of models are illustrated in Figure 1-2.

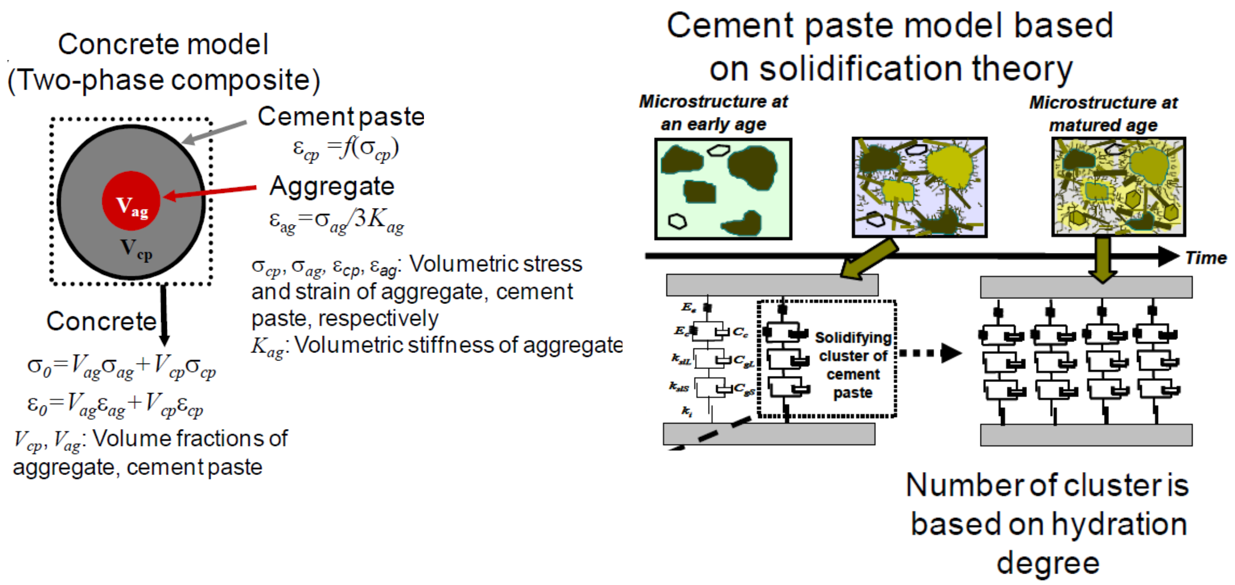

Figure 1-2. Examples of separate models for concrete aggregates and solidifying cement paste (Asamoto, Ishida, & Maekawa, 2008).

An inherent complication with concrete materials is that water is initially required for the hydration reaction with cement, but more water is needed for workability purposes than is needed for cement hydration. The remaining water held within the concrete after hydration is complete is evaporated to the surrounding environment, resulting in the volume reduction characterized as drying shrinkage (Al-Attar, 2008). The paste phase, containing cementitious and powdered materials, water, and admixtures, is the phase considered to undergo shrinkage, while the aggregate phase, containing coarse and fine aggregates, resists shrinkage. Both phases, however, are considered fully bonded and develop equal deformation and internal stresses from each other in equilibrium (Tangtermsirikul & Tatong, 2001).

Experiments have been developed to separate and observe the mechanisms involved with concrete shrinkage, and reasonably accurate results have been obtained from models describing this behavior (Bažant & Xi, 1994).

1.1.2.1.1 Capillary Tension

Capillary tension is an important phenomenon in the drying of porous media. In the case of concrete, the hardened cement paste contains capillaries in which a meniscus forms during drying (Idiart, 2009). The drying process is driven by a difference in moisture level at the concrete interior and surface. The Kelvin equation shown in (Equation 1-1) represents the relationship between relative humidity and the surface tension force produced inside the material pores.

$$\ln H = \frac{M_v}{RT}\gamma\left(\frac{1}{r_1}+\frac{1}{r_2}\right) \qquad \text{(Equation 1-1)}$$

Where H is relative humidity, γ is the surface tension force, r_1 and r_2 are radii of meniscus in pores, T is temperature, M_v is the molar volume of water present and R is the universal gas constant.

Equilibrium between pore fluid pressure and vapor pressure is disrupted by this process and results in the formation of negative pressure in the pore fluid (Grasley & Lange, 2002). Figure 1-3 presents an illustration of this mechanism.

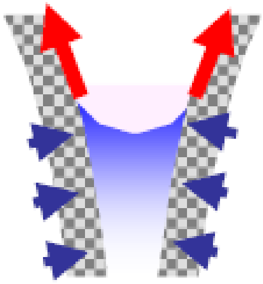

Figure 1-3. Schematic illustration of capillary forces within material pores (Asamoto, Ishida, & Maekawa, 2008).

1.1.2.1.2 Surface Tension

The formation of menisci within the pores produces surface tension resisted by the pore walls. The Laplace equation shown in (Equation 1-2) describes the fluid pore pressure, σ.

$$\sigma = \gamma \left(\frac{1}{r_1}+\frac{1}{r_2}\right) \qquad \text{(Equation 1-2)}$$

The resulting internal compressive stresses required to balance the negative pore pressure produce shrinkage within the concrete (Grasley & Lange, 2002).

1.1.2.1.3 Absorption/Desorption (Interlayer Water Movement)

One of the mechanisms affecting shrinkage is movement of water within the layers of the cement gel. At low relative humidity, liquid water within the C-S-H grain may migrate out from between these layers, reducing the space between sheets, and producing considerable shrinkage strains (Idiart, 2009). Schematic illustrations of this mechanism are shown in Figure 1-4.

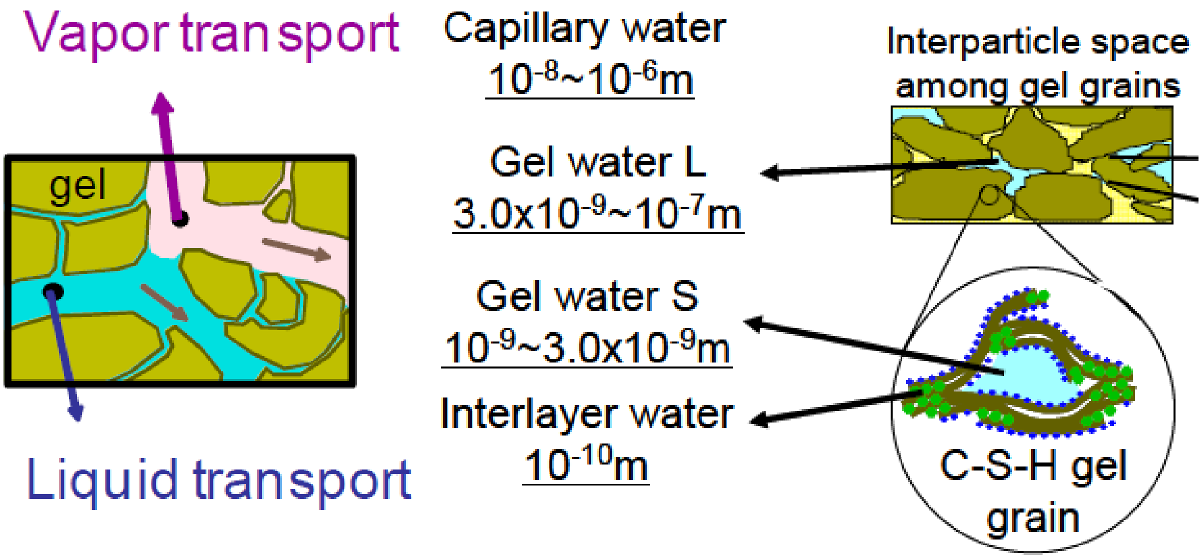

Figure 1-4. Schematics of interlayer water movement in C-S-H gel (Asamoto, Ishida, & Maekawa, 2008).

1.1.2.1.4 Drying

Drying is modeled by the moisture flux, (Equation 1-3) and (Equation 1-4) in terms of water content gradient, or by (Equation 1-5) and (Equation 1-6) in terms of the pore relative humidity gradient (Xi, Bažant, & Jennings, 1994).

$$J=-D_w \,\mathrm{grad}\, W_e \qquad \text{(Equation 1-3)}$$

$$\frac{\partial W}{\partial t}=\frac{\partial (W_e+W_n)}{\partial t}=-\mathrm{div}(J)=\mathrm{div}(D_w \,\mathrm{grad}\, W_e) \qquad \text{(Equation 1-4)}$$

$$J=-D_h \,\mathrm{grad}\, H \qquad \text{(Equation 1-5)}$$

$$\frac{\partial W}{\partial t}=\frac{\partial W}{\partial H}\frac{\partial H}{\partial t}=-\mathrm{div}(J)=\mathrm{div}(D_h \,\mathrm{grad}\, H) \qquad \text{(Equation 1-6)}$$

Where H is pore relative humidity, t is time, W is total water content, W_e is evaporable water content, W_n is nonevaporable water content, D_w is moisture diffusivity, and D_h is permeability, or humidity diffusivity.

The use of (Equation 1-5) and (Equation 1-6) in terms of pore relative humidity is considered more practical due to only small effects of cement hydration on H, compared to $\partial W_n/\partial t$ and that H can still be considered a driving force of diffusion when generalized to variable temperature, whereas grad W or grad W_e cannot (Xi, Bažant, & Jennings, 1994). Pore humidity is initially 100%, but exposure to the environment produces a long term drying process described in the diffusion equation below (Bažant Z. , 2000).

The relationship between humidity and water content is given by (Equation 1-7) (Benboudjema & Torrenti).

$$h(C)=1-0.5\left(\frac{C-C_0}{C_0-C_{eq}}\right)^2 \qquad \text{(Equation 1-7)}$$

The water content in the concrete is calculated by solving the diffusion equation, (Equation 1-8).

$$\begin{gathered}\frac{\partial C}{\partial t}=\mathrm{div}\big(D(C)\,\mathrm{grad}(C)\big)\\ t\leq t_0\Rightarrow C=C_0\ \ \forall \boldsymbol{x}\in\Omega \qquad \text{(Equation 1-8)}\\ (\text{for } t\geq t_0 \text{ and } \boldsymbol{x}\in\partial\Omega)\Longrightarrow C=C_{eq}\end{gathered}$$

The initial water content is determined by cement composition and the amount of water needed for the hydration of all the chemical components in the cement. The free water content of a given cement composition is given by $C_0(\underline{x},t)$ and varies with time throughout the process of hydration (Granger, Torrenti, & Acker, 1997).

The hydration reaction given by $\alpha_i(\underline{x},t)$ ranging from 0 to 1 is defined by(Equation 1-9).

$$\alpha_i(t)=1-\frac{m_i(t)}{m_i(0)} \qquad \text{(Equation 1-9)}$$

Where m_i is the mass of compound A_i of the chemical substance i being considered. The four chemical substances in the cement which undergo the hydration reaction are: C_2S, C_3S, C_3A, and C_4AF. (Equation 1-10) presents the calculation of the free water content in concrete based on the degree of hydration, α (Granger, Torrenti, & Acker, 1997).

$$C_0(\underline{x},t)=w_0-\left(\sum_{i=1}^{4} m_i \alpha_i(\underline{x},t) p_i\right) c_0 \qquad \text{(Equation 1-10)}$$

Where w_0 is the amount of water added to the mix, m_i is the proportion of A_i in the cement, p_i is the amount of water needed for total hydration of component of cement, and c_0 is the amount of initial cement in the mix. For simplicity, α_i is considered to be the same for each chemical substance in the cement, resulting in (Equation 1-11).

$$\alpha_i(\underline{x},t)=\alpha(\underline{x},t) \quad \forall i \in \{1 \cdots 4\} \qquad \text{(Equation 1-11)}$$

Beyond 28 days, the hydration reaction may be assumed to have advanced, as well as slowed that for α, 0.9 is considered a close approximation (Granger, Torrenti, & Acker, 1997). C_0 is then calculated for a particular cement by (Equation 1-8) through (Equation 1-11), and C_{eq} is determined from experimental results.

1.2 MOTIVATION AND OBJECTIVE

Many different mechanisms have been found to affect concrete drying shrinkage, often which are coupled and interrelated. These include temperature, humidity, porosity, and absorption. A relationship also exists between aggregate water content and ultimate drying shrinkage. (Ayano, Fujii, & Sakata, 2009).

The focus of this study is on some of the effects of these mechanisms on shrinkage behavior of RCA concrete in an experimental program in which aggregate characteristics are modified by the use of surface treatments. Specifically, the aggregate moisture absorption properties and their respective effects on concrete shrinkage are presented.

1.2.1 Effect of RCA Amount

The basis for studying the effects of varying the amount of RCA used in mix designs is from studies showing that the amount of RCA substituted for natural coarse aggregate has a significant impact on concrete properties. Several authors have reported that mechanical properties such as compressive strength, tensile strength, modulus of elasticity, creep, and shrinkage of concrete containing RCA vary with the amount of RCA used.

1.2.2 RCA Surface Treatments

The basis for the use of RCA surface treatments is the attempt to alter those surface characteristics which are thought to lead to undesirable properties in concrete containing RCA. This attempt is made through the use of materials which will fill pores and coat the surface of the RCA, reduce surface tension and capillary effects, or simply saturate the RCA to prevent the suction of water from the fresh concrete mix. A brief overview and basis for selection of each of these materials is presented below.

1.2.2.1 Silica Cement

The motivation for using a silica-cement mixture as a coating for RCA is based on the results of studies in which silica solution or silica fume was used as a surface treatment or directly added to the concrete mix with improved compressive strength results. As a surface treatment, a solution of water and silica fume was used to impregnate the surface of RCA by saturation for 24 hours. Compressive strength was shown to increase 23% to 33% at 7 days and 13% to 15% at 28 days (Katz, 2004). As an addition to the concrete mix of 8% by weight of cement, silica fume improved the shear strength of beams cast using RCA to the same level as that of conventional concrete (González-Fonteboa, Martínez-Abella, Martínez-Lage, & Eiras-López, 2009).

The method of surface treatment for this study consisted of coating RCA with a mixture containing Type I/II cement, colloidal silica solution containing 8% silica by weight of cement, and a 0.5 water/cement ratio. RCA was coated by stirring within the silica cement mixture, and the particles were separated and spread out to cure without binding together. All tests and mixing were performed after the mixture was allowed to cure for a minimum of 28 days.

1.2.2.2 Acrylic Coating

Because many of the negative results related using RCA in concrete have been reportedly due to the high absorption characteristics of the adhered cement paste, one of the surface treatments included an acrylic paint product intended to reduce or prevent water penetration through concrete. The commercially available paint is marketed as a concrete and masonry waterproof coating intended for walls including those subjected to hydrostatic pressure.

This method of surface treatment consisted of coating RCA with as much of the acrylic paint as needed to cover the surface, and excess material was allowed to drip off. Despite the vast majority of the aggregate surface being covered by the paint, very small uncoated spots remained visible on some RCA surfaces. RCA particles were separated and spread out to cure without binding together. Product manufacturer data states that full cure occurs in 7 to 14 days, therefore all tests and mixing were performed after a minimum 14 days cure time.

1.2.2.3 Surfactant Wetting Agent

The category of surfactants called wetting agents work by imparting a film to particle surfaces of the media in which they are used to reduce water repellency, lower surface tension, and allow more efficient and consistent water penetration into the media (Aquatrols, 2009). The primary industries using these types of surfactants are the well drilling and rehabilitation industry, and the agricultural industry. In well drilling and rehabilitation, the product is intended to act as a dispersant for other fluids and allow deeper penetration into pores and cracks (CETCO, 2011). In soils, wetting agents are used to allow better water penetration for agriculture (Aquatrols, 2009).

The motivation for the use of a wetting agent as a surface treatment for RCA is based on the concept of its film forming and surface tension reducing qualities. If the wetting agent could be effective at reducing the water absorption characteristics of RCA, it may also reduce the resulting capillary tension that produces larger shrinkage strains.

The method of application of the wetting agent as a RCA surface treatment was to add a solution of 1 part surfactant to 4 parts water to the RCA directly in the mixer and allowed several turns in the mixer to allow all surfaces to become coated. The amount of solution used was equal to the tested 24 hour aggregate absorption.

1.2.2.4 Water Saturation

Although results by many researchers have shown concrete containing RCA to produce higher shrinkage values than conventional concrete, some have shown that presoaking can actually produce concrete with lower shrinkage values than conventional natural aggregate concrete due to a hypothesized internal curing effect from the additional water held within the RCA (Corinaldesi, 2010).

The method of application was to presoak the RCA after measuring the proportion to be used in the mix batch by adding water equal to the tested 24 hour absorption value and leaving the wet RCA covered for 24 hours to allow the water to fully penetrate the surface.

1.3 SCOPE OF WORK AND ORGANIZATION

Although other forms of strain-producing shrinkage exist during and after cement hydration, and are likely inter-related and happen simultaneously, the focus of this study is on the shrinkage effects caused by the evaporation of excess water which is present after cement hydration takes place. The properties of the various types of aggregates used are studied, with and without surface treatments, to determine their effects on fresh and hardened concrete properties.

1.3.1 Chapter 1

Chapter 1 contains an introduction to the topic of recycled aggregate concrete and the process by which this material is produced, and also a background on the concept of concrete drying shrinkage. The primary difference in RCA from natural aggregates is discussed as the presence of a layer of adhered cement paste over the original aggregate. This layer is generally more absorptive and porous than natural aggregate and is also considered a point of weakness in the new concrete. Drying shrinkage is generally accepted as the loss of excess moisture to evaporation after cement hydration is complete. New concrete contains water within its pores all the way down to the microscopic level, and the movement of this water from the interior to the exterior based on the humidity gradient within the pores. The capillary tension developed in the pores as water evaporates is responsible for pore stresses and the resulting shrinkage strains.

1.3.2 Chapter 2

Chapter 2 presents a review of the literature focused on the topic of drying shrinkage of RCA concrete. Results obtained by others include the differences in aggregate properties of RCA from natural aggregates including absorption and density. The effect of RCA use in varying amounts on compressive strength of concrete is reported. Drying shrinkage results of RCA are presented with the parameters studied including amount of RCA substituted for natural aggregate, moisture condition of aggregates, total water content, water/cement ratio, and the effects of the use of admixtures.

1.3.3 Chapter 3

Chapter 3 contains a description of the experimental plan and summarizes results of testing. Descriptions of the materials are given as well as tests performed on aggregates to determine particle size, bulk density and absorption and the results for each type of aggregate. Details of mix design parameters are discussed as well as descriptions of mixing method, specimens, and curing methods. Descriptions and results are given for tests of concrete workability, compressive strength, and drying shrinkage.

1.3.4 Chapter 4

Chapter 4 contains analysis of the experimental data including comparison with results by others. Experimental results are examined for correlations of aggregate properties and surface treatments to tested concrete mechanical properties.

1.3.5 Chapter 5

Chapter 5 contains a summary of experimental results and analysis, as well as conclusions and recommendations for further work. Remarks on the use of RCA with and without surface treatments are made. Recommendations for further study are made on test methods and materials.

1.3.6 Chapter 6

Chapter 6 provides a complete list of all references used. References include standards from the American Concrete Institute, American Society for Testing and Materials, and published papers from a variety of related industry journals.

CHAPTER 2

REVIEW OF THE LITERATURE

2.1 INTRODUCTION

The study of drying shrinkage and other mechanical properties of concrete containing RCA has shown that these properties are affected by a variety of factors including aggregate characteristics, concrete mix design, curing conditions, and source of aggregates. These topics and related results are presented and discussed in this chapter.

2.2 TOPICS OF STUDY

Topics of study by others included the amount of RCA used, aggregate properties, saturating RCA before mixing, admixtures, drying shrinkage predictive models, water/cement ratio, curing conditions, original concrete source and strength of RCA, and original moisture content of aggregates. The most notable difference between natural aggregates and RCA the respective properties of each type is the 2% to 20% lower density of RCA, and absorption values as much as over 20 times those of natural aggregates. A survey of the available literature was performed to determine the magnitude of these differences in aggregate properties and also relate these properties to the mechanical performance of concrete containing RCA. A summary of this review is presented in Table 2-1, and further discussion of each property and effect is presented within this chapter.

Table 2-1. Summary of RCA physical properties and concrete strength.

Author	RCA % Change from Natural		RCA Concrete		
	Density	Absorption	w/c	%RCA Used	Compressive Strength % Change from Control
Xiao, 2005	-11%	+2300%	0.43	30	-6%
				50	-12%
				70	-10%
				100	-12%
Tavaloli, 1996	-13% to -18%	+83 to +630%			
Hansen, 1985			0.4	100	-26% to +4%
			0.7		-12% to +11%
			1.2		-15% to 0%
Casuccio, 2008	-4% to -2%	+32 to +57%	0.67	100	-15% to -1%
			0.35		-5% to -3%
			0.34		-10% to -8%
Etxeberria, 2007			0.55	25	+9%
			0.52	50	+11%
			0.50	100	+8%
Corinaldesi, 2010		+127%	0.4	30	-21%
			0.45		-18%
			0.5		-22%
			0.55		-23%
			0.6		-21%
		+317%	0.45		-16% to -4% with SP +8% with SP and SRA
Fathifazl, 2009	-18% to -12%	+73% to +1490%	0.5	63.5	+6% to +13%
				74.3	+6% to +13%
				100	+10% to 14%
Sri Ravindrajah, 1988		+1440% to +1730%	0.30	100 including fines	-9%
			0.40		-10%
			0.50		-13%
			0.57		-12%
			0.60		-14%
			0.70		-15%
Domingo-Cabo, 2009	-12%	+400%	0.5	20	+4% to +5%
				50	+5% to +9%
				100	+18% to +21%
Poon, 2004	-10%	+440%	0.57	20	-4% to +7%
				50	-17% to -1%
				100	-15% to +8%

2.2.1 Compressive Strength

Compressive strength of concrete containing RCA has often produced lower test values than conventional concrete; however, the use of RCA also produced more variability in test data, and resulted in some test values that were higher than concrete containing natural aggregates only. One study found that concrete compressive strength decreased with use of 25% RCA, increased with 50% RCA, and results were obtained with 100% RCA that were both higher and lower than the control mix. The authors concluded that the use of RCA results in much more variability in quality and larger coefficient variation in results (Etxeberria, Vǽzquez, Marǐ, & Barra, 2007). The conclusion is reasonable, as the source of concrete used for RCA is not a homogeneous material, and thus when it is crushed during processing, is subject to more variation from particle to particle than a natural aggregate obtained from a uniform source. When comparing equal water to cement ratios, results by (O'Mahony, 1990) showed that natural aggregate mixes provided 28 day compressive strengths that were 0-3.7% higher than 100% RCA mixes. When cement content was increased by 8% in RCA mixes to compensate for this effect they produced 28 day compressive strengths that were 0-5% higher than control mixes.

Results have shown that the compressive strength of concrete containing RCA is proportional to the strength of the original source concrete for RCA, and that RCA from high compressive strength concrete will produce new concrete with comparable values (Tabsh & Abdelfatah, 2009). Higher strength concrete tends to be denser, and have fewer open pores than lower strength concrete. The crushing behavior of higher strength concrete also more closely follows that of natural stone, resulting in a finished RCA product that behaves more like natural aggregate.

As an RCA surface treatment, a solution of water and silica fume increased compressive strength at 7 days by 23% to 33%, and at 28 days by 13% to 15% over conventional concrete (Katz, 2004). As an addition to the concrete mix of 8% by weight of cement, silica fume improved the shear strength of beams cast using RCA to the same level as that of conventional concrete (González-Fonteboa, Martínez-Abella, Martínez-Lage, & Eiras-Lόpez, 2009).

2.2.2 Quality of Original Concrete

Low quality of the original concrete can produce undesirable effects when using it as RCA. This type of concrete used as RCA may have high absorption and low strength that can create a zone of weakness for the new concrete. This surface between old cement paste and new is referred to the interfacial zone, and can be responsible for reducing the ability of the new concrete from achieving composite behavior. High absorption rates are an indicator of larger amounts of cement paste that remain attached to the aggregate, leading to more potential for weakness (Tam, Gao, & Tam, 2005). Also, large pores and voids can form near RCA due to inadequate mixing, voids trapped by aggregates, expansion and shrinkage of aggregates, inappropriate water/cement ratio, environmental moisture, and alkali-silica reaction. A two-stage mixing approach has been proposed by Tam to improve the strength and quality of the interfacial zone that involves coating the RCA with a layer of fresh cement paste prior to mixing.

Depending on the previous use of source concrete used to produce RCA, it may contain a number of impurities and contaminants. These materials are known to have a negative effect on the properties of concrete, as well as reinforcing. The materials contained in construction and demolition waste may include metal, wood, plastic, paper, soil, glass, ceramic, and others. In addition to these materials, it is possible that RCA may contain chemical contaminants such as oil, form release agents, deicing salts, and sulfates (Tam, Wang, & Tam, 2008). A relationship between the amount of attached cement paste and sulfate content has been observed, with the 2 factors showing positive correlation (Sánchez de Juan & Gutiérrez, 2009). Concrete is known to carbonate more quickly after crushing, which may also lead to increased corrosion risk to reinforcing if the RCA is to be used in reinforced concrete. Finally, alkali-silica reaction can cause damage to concrete, and if the RCA used contains the potential for alkali-silica reactivity, or if it is already occurring, may cause premature damage to the concrete it is used in (Tam, Wang, & Tam, 2008).

Although the source of original concrete appears to affect some properties of concrete containing with RCA, it does not appear to affect the chemical or mineral characterization of the new concrete (Limbachiya, Marrocchino, & Koulouris, 2007).

2.2.3 Amount of RCA Substituted for Natural Coarse Aggregate

A study was performed where RCA were substituted for coarse natural aggregates in amounts of 20%, 50%, and 100%, and results were compared to a control concrete mix containing all natural aggregates. The cement used was Type CEM I 42.5 N/S conforming to European standards, the recycled concrete came from construction waste and demolition, the water-cement ratio was kept constant at 0.45 for all mixes, and the superplasticizer Sikament 500 was used in all mixes, but a double dose was required for the 100% recycled coarse aggregate substitution mix. Results showed an increase in drying shrinkage with an increase in recycled aggregate content. A 50% recycled aggregate substitution produced 20% more shrinkage than the control concrete, and 100% recycled aggregate substitution produced 70% more shrinkage than the control concrete (Domingo-Cabo, Lázaro, López-Gayarre, Serrano-López, Serna, & Castaño-Tabares, 2009).

In one study, drying shrinkage of concrete containing 20% RCA was found to be nearly identical to the mix containing only natural aggregates at an age of 182 days. Concrete containing 100% RCA was found to have approximately 7.5% larger shrinkage strain at 182 days than the control mix (Tam & Tam, 2007). Another study found drying shrinkage to increase at RCA substitution amounts of 70% and 100% (Guo, Wang, Sun, & Cheng, 2011). Drying shrinkage at 90 days was reported for 30%, 50% and 100% RCA replacement as 1%, 5%, and 13% higher than the natural aggregate mix, respectively (Dhir, Paine, & Dyer, 2004).

Authors including Gómez-Soberón, Corinaldesi, and Ng who measured drying shrinkage at RCA substitution amounts in the range of 30% or less found that drying shrinkage decreased compared to natural aggregate concrete, but increased at RCA substitution levels of 50% and higher.

2.2.4 Aggregate Density and Size

Recycled concrete aggregate was found to be less dense than natural coarse aggregate. This property had been attributed by many to the cement paste attached to the original aggregates as well as the particles containing hardened cement paste only. The lower density of the attached paste and included air content within pores are generally accepted as the reasons for the lower density of RCA. Larger size RCA has been found to contain a larger proportion of original aggregate, and thus higher density and lower overall absorption, while smaller size RCA contain a higher proportion of hardened cement paste, and thus lower density and higher absorption (Padmini, Ramamurthy, & Mathews, 2009). Although larger aggregate size may be expected to provide better resistance to shrinkage strains, due to the larger proportion of original aggregate, Tavakoli reported that larger maximum size aggregates caused an increase in drying shrinkage when dry mixing was not performed, contrary to the behavior of natural aggregate concrete (Tavakoli & Soroushian, 1996).

2.2.5 Aggregate Absorption

Numerous experiments performed on various types of natural aggregates, recycled concrete crushed in the laboratory, from building demolition, and crushed returned concrete that had never been used in service. Recycled concrete aggregate of all types was found to be more absorptive than natural aggregate and had a density and specific gravity less than natural gravel (Corinaldesi, 2010). A relationship was also found linking the amount of adhered cement paste and the absorption properties. When mortar content increased, water absorption increased as well (Sánchez de Juan & Gutiérrez, 2009).

Because recycled concrete aggregate was found to be more absorptive than natural aggregate, problems were often experienced with low degrees of workability. Presoaking aggregates or using additional mix water was found to improve workability, but the addition of water to the mix decreased compressive strength and increased drying shrinkage. (Domingo-Cabo, Lázaro, López-Gayarre, Serrano-López, Serna, & Castaño-Tabares, 2009). Experimental results and recommendations proposed that RCA replacement for natural aggregates reduces the amount of water available for workability due to the additional water absorbed by the rough and more porous surfaces of the RCA. The rate of absorption is also faster than natural aggregates, with the greatest amount of RCA absorption occurring within the first 10 minutes of saturation. In order to maintain workability, mix formulas should be adjusted by increasing the amount of mix water to account for the difference in aggregates natural water content and the amount it will absorb during mixing (Zhang, Deng, & Qin, 2007). A contradicting study reported that oven dried RCA absorbed less water than the tested amount while mixing, and RCA concrete mixes had higher workability than the conventional concrete. The explanation for this phenomenon was that if aggregate is not presoaked, it will become coated with fresh cement paste during mixing, and will not allow water to further penetrate and fully saturate the aggregate (O'Mahony, 1990). Adjusting the mix water to account for absorption of the recycled aggregates improved compressive strength and modulus of elasticity to within 98% of values for the control concrete (Domingo-Cabo, Lázaro, López-Gayarre, Serrano-López, Serna, & Castaño-Tabares, 2009).

The absorption of the recycled concrete can be used in predictive models to predict shrinkage of concrete made with the recycled material as well as its compressive strength (Ayano, Fujii, & Sakata, 2009). Such models were found to reasonably able to predict drying shrinkage of concrete mixes containing up to 20% RCA, but underestimated shrinkage for mixes containing larger amounts (Domingo-Cabo, Lázaro, López-Gayarre, Serrano-López, Serna, & Castaño-Tabares, 2009).

Studies performed compare the effects of various types of natural aggregates found that highly absorptive, lightweight natural aggregates produced higher final drying shrinkage than normal weight, low absorption natural aggregates (Al-Attar, 2008).

2.2.6 Presoaking Aggregates

Because of the additional water absorbed by RCA, presoaking was necessary to maintain workability of fresh concrete, especially at higher replacement amounts. Presoaking was done by adding a fixed additional amount of water to selected mixes or by saturating aggregates prior to mixing. The presoaking reduced the amount of shrinkage in the concrete containing recycled concrete aggregate. This phenomenon was explained by the "internal curing effect" hypothesis, where the higher porosity of the recycled aggregate can store water to be used during cement hydration (Corinaldesi, 2010).

Other studies have found that presoaking aggregates increases the amount of drying shrinkage. One of these studies concluded that the air dry condition is the optimal condition for aggregate properties rather than saturated surface dry or oven dried (Poon, Shui, Lam, Fok, & Kou, 2004). Another reported that using saturated aggregates produces higher shrinkage strains than dry aggregate, and the use of lightweight, high absorption aggregate produces about 10% more shrinkage strain and lower compressive strength than smooth, low absorption aggregates. Rounded, dense aggregates were also found to reduce shrinkage compared to crushed gravel and lightweight aggregate (Al-Attar, 2008).

2.2.7 Superplasticizing and Shrinkage Reducing Admixtures

Many experimental studies utilized water reducing admixtures as necessary for workability purposes and to maintain the desired water to cement ratio of the concrete mix, but some studied the direct effect of admixture use on the mechanical properties of RCA concrete. The addition of superplasticizing admixtures was found to improve workability and increase compressive strength. The direct effect of dose rate on shrinkage was not reported, but a higher dose was needed to increase slump and maintain workability while using 100% recycled aggregate substitution (Domingo-Cabo, Lázaro, López-Gayarre, Serrano-López, Serna, & Castaño-Tabares, 2009). Others reported that the addition of water reducing agent increased the amount of drying shrinkage. The use of an expansive agent was effective at inhibiting drying shrinkage, as was the use of fly ash, to a lesser extent (Guo, Wang, Sun, & Cheng, 2011).

Without presoaking, the use of admixtures caused a decrease in workability in addition to strength loss when only the superplasticizer was used, compared to natural aggregate concrete and to the mix utilizing both superplasticizer and shrinkage reducing admixtures. Shrinkage of recycled aggregate concrete was found to be less than natural aggregate concrete, even when admixtures were used (Corinaldesi, 2010).

2.2.8 Water / Cement Ratio

One study demonstrated that despite utilizing a consistent amount of mix water in each concrete mix, the effective water to cement ratio decreases with the addition of recycled aggregate content due to the more absorptive adhered cement paste (Domingo-Cabo, Lázaro, López-Gayarre, Serrano-López, Serna, & Castaño-Tabares, 2009). Ultimate drying shrinkage strain was found to increase with the total water content that was required for presoaking aggregates to maintain mix workability (Ayano, Fujii, & Sakata, 2009). Similar to conventional natural aggregate concrete, the relationship observed was that drying shrinkage increased with increasing water/cement ratio (Tavakoli & Soroushian, 1996). Similar behavior was observed in experiments by (O'Mahony, 1990), where drying shrinkage generally increased with water to cement ratio, however the relationship was more linear in the case of natural aggregate mixes than with RCA mixes.

2.2.9 Use of Recycled Concrete Fines

The use of recycled concrete fines has generally not been recommended due to the high specific surface area, absorption, and corresponding water demand on the concrete mix (Hansen, 1986). Experimental results have shown that the use of these fines as replacement increases the capillary effect and sorptivity of concrete containing 100% fine recycled aggregate replacement compared to the reference concrete. The more porous structure of the fine recycled aggregate increased the absorption of the mix nearly linearly with replacement ratio. Carbonation resistance was also found to decrease with the use of recycled fines. Blends of 50% natural sands and 50% recycled fine aggregates produced concrete with 10% to 20% lower strength than recycled concrete made with all natural sands. Despite these effects, the use of recycled fine aggregates at smaller replacement ratios, up to 30% was reported as feasible (Evangelista & de Brito, 2010).

The use of high levels of natural fines caused an increased use of water reducing admixtures to compensate for the increased water demand, but also produced approximately 30% higher compressive strengths as well. When the smallest fines, less than 5 μm were used, an increase in drying shrinkage behavior and plastic shrinkage cracking were both observed (Katz & Baum, 2006).

2.3 SUMMARY

Several properties of natural aggregates and RCA have been studied and compared along with the effects each of these properties have on RCA concrete. The main difference between RCA and natural aggregate involves the cement paste adhered to the surface of the old aggregate. This layer is attributed to lower density and higher absorption by RCA, and also for creating a zone of weakness at the interface between old paste and new paste. The weakness of this zone and the additional paste present in RCA concrete are reasons presented by others for lower compressive strength and higher shrinkage results than concrete using only natural aggregates, however conflicting studies have shown that higher compressive strength and less shrinkage than control mixes are possible using RCA.

The properties studied in regard to RCA use and its effects included compressive strength, quality of original concrete, and amount of RCA substituted for natural aggregates. The effects of aggregate properties including size, density and absorption on RCA concrete were also examined. Finally, the effects of using admixtures, water to cement ratio, and recycled concrete fines in concrete mixes were examined.

Most studies showed a decrease in compressive strength with the use of RCA, but other studies have shown that RCA use can increase compressive strength. Results have also shown that material variability is an important factor, with coefficients of variation, when reported, increasing with greater RCA use. RCA produced from higher strength concrete generally resulted in concrete that approached the strength of the original concrete.

In relation to compressive strength, the quality of the original concrete was shown to be critical to producing new concrete without undesirable effects. Concrete that is very porous, absorptive, or has low strength may produce weak zones at the interface with the new cement paste, reducing its ability to act as a composite material. Additionally, depending on the previous use of the original concrete, contaminants such as other building materials, chemicals, or reactions such as carbonation or alkali-silica may be a concern for a source of weakness.

The effects of the amount of RCA replacement for natural aggregate on drying shrinkage varied among different studies. Several studies concluded that replacement of natural aggregate with RCA increased drying shrinkage, while others found that RCA concrete experienced less drying shrinkage at substitution amounts of 30% or less, and more drying shrinkage at greater amounts.

The physical properties of RCA including shape and density and absorption appear to produce similar effects on concrete as natural aggregates with the same properties, but the effect of aggregate size appears to produce the opposite effect. RCA that have more angular shape, lower density, and higher absorption tended to produce higher values of drying shrinkage, similar to natural aggregates with the same characteristics compared to smooth, rounded, dense aggregates. The difference however, is than in natural aggregate concrete larger maximum aggregate size tends to reduce overall shrinkage, while in RCA concrete larger maximum size aggregates produced higher levels of drying shrinkage despite a smaller proportion consisting of adhered cement paste.

Conflicting studies exist on the effects of presaturating RCA, use of admixtures, and total water content on concrete containing RCA. Some have found improved results from RCA presoaking due to more complete curing from the additional moisture held within the RCA pores. Others have found the increased moisture available to be lost increases the potential for shrinkage as well. The use of superplasticizing admixtures was found to be beneficial to concrete mix workability and compressive strength, but appeared to increase shrinkage as well. The use of shrinkage reducing admixtures appeared to be effective at reducing drying shrinkage. Drying shrinkage was also generally found to increase with increasing total water content.

The use of recycled concrete fines is not generally recommended due to higher water demand, reduced compressive strength, and higher shrinkage. Despite these effects, the use of recycled concrete fines was reported as feasible using low substitution amounts, and limiting the smallest size fraction.

CHAPTER 3

EXPERIMENTAL PROGRAM

3.1 INTRODUCTION

According to some research, concrete containing RCA has exhibited increased drying shrinkage compared to conventional natural aggregate concrete (Tavakoli & Soroushian, 1996). Researchers have found higher absorption properties of the RCA due to old concrete mortar that remains adhered to stones after crushing (Hansen, 1986). This study investigates the use of different types of surface treatments on absorption characteristics of RCA and potential effects on concrete made with RCA.

3.2 EXPERIMENTAL PLAN

The effects of surface treatments and amount of recycled coarse aggregate substitution on drying shrinkage of RCA concrete was investigated through a series of experiments. Tests were performed to determine characteristics of aggregates, fresh concrete, and hardened concrete.

3.2.1 Materials

The materials used in the experimental study included conventional concrete components of cement, sand, and natural aggregates, as well as recycled concrete aggregates and surface treatments.

3.2.1.1 Concrete Materials

The cement used is a commercially available Type I/II portland cement conforming to ASTM C150, fine aggregates consisted of natural sand, natural coarse aggregates consisted of crushed granite. Recycled coarse aggregates consisted of crushed concrete obtained from a local company which performs demolition, and processing of recycled concrete, and also supplies ready mix concrete containing the recycled aggregates.

3.2.1.2 RCA Surface Treatments

The materials used for recycled aggregate surface treatments included a silica-cement mixture, a commercially available acrylic paint, and a surfactant wetting agent. The silica-cement mixture was mixed and applied to the recycled aggregates and allowed to cure a minimum of 28 days prior to being used in concrete mixes. The acrylic product is a commercially available paint that is marketed by the manufacturer as a waterproof coating for concrete. The acrylic coating was applied a minimum of 7 days prior to concrete mixing. The wetting agent is a liquid surfactant that is used in water well development and rehabilitation. The wetting agent acts as a dispersant for other well rehabilitation products by increasing their ability to enter the pores and cracks of the well. The wetting agent was applied immediately prior to mixing.

3.2.2 Aggregate Properties

Tests performed on coarse and fine aggregates included sieve analysis, bulk density and absorption.

3.2.2.1 Sieve Analysis

Sieve analysis of fine aggregates was performed in accordance with ASTM C136, *Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates*. Results of sieve analysis of fine and coarse aggregates are presented in Figure 3-1.

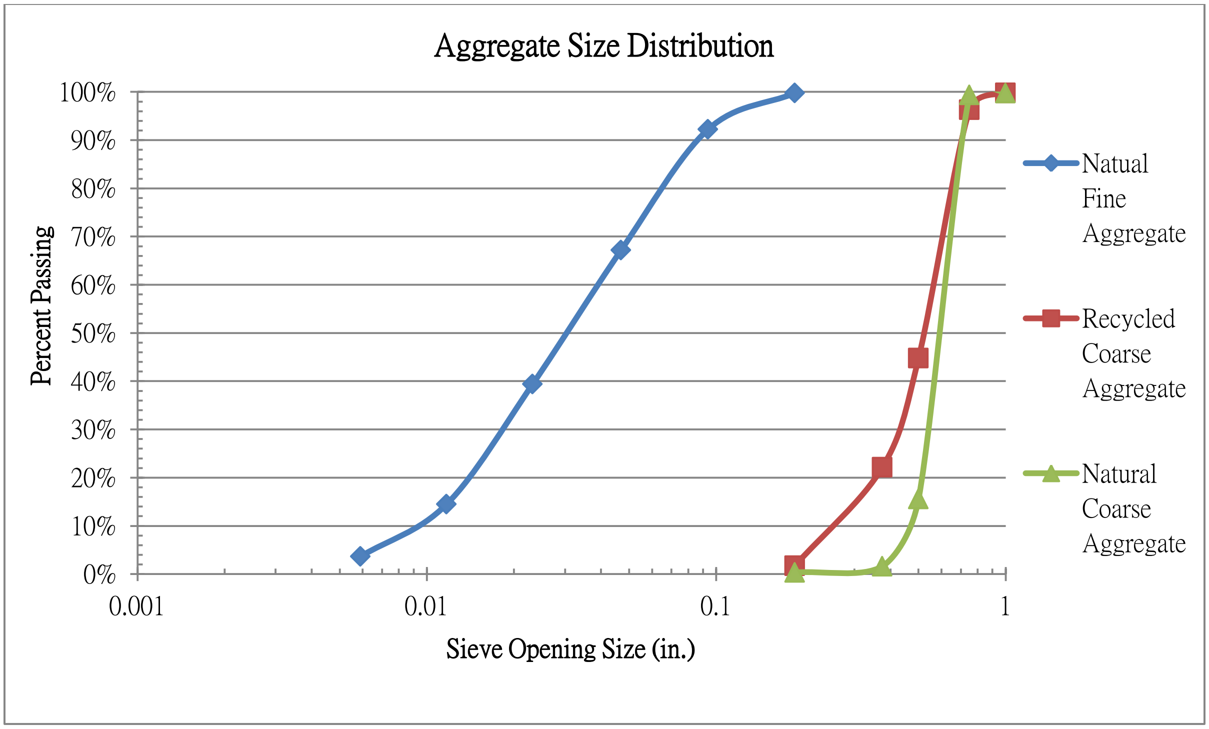

Figure 3-1. Results of aggregate sieve analysis.

Because of the relatively uniform size of the natural coarse aggregate, 30% pea gravel passing the ½ inch sieve was added by weight to match the gradation of the recycled aggregate. All other measured natural coarse aggregate properties included this addition.

3.2.2.2 Bulk Density

Bulk density of aggregates was measured in accordance with ASTM C29, *Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate*. The mass of a predetermined volume of aggregates was measured to determine its bulk density. The bulk density of each type of aggregate was determined in natural moist and oven-dried conditions, and is presented in Table 3-1.

Table 3-1. Measured bulk densities of aggregates.

Aggregate Condition	**Aggregate Bulk Density, lb/ft^3 (kg/m^3)**		
	Natural Fine	Recycled Coarse	Natural Coarse
Natural Moist	104.9 (1681)	75.5 (1210)	95.5 (1530)
Oven-dried	103.8 (1652)	73.7 (1181)	93.1 (1491)

3.2.2.3 Absorption

Absorption of coarse aggregates was measured in accordance with ASTM C 127, *Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate*, and absorption of coarse aggregates was measured in accordance with ASTM C 128, *Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate*. After recording the oven dry mass, the aggregates were submerged in water for 24 hours, and then rolled over an absorbent cloth until achieving a saturated surface-dry condition. This test was also performed on each type of surface-treated aggregate, with the exception of the surfactant, as this type of treatment was applied in liquid form immediately before concrete mixing. Table 2-1 lists the measured oven-dry and saturated surface-dry mass, as well as the calculated absorption percentage of each type of coarse aggregate.

Table 3-2. Measured absorption of coarse aggregates.

	Natural Coarse	RCA Coarse	RCA Silica Treated	RCA Acrylic Treated
Oven-dry mass, lb (g)	18.28 (8290)	14.47 (6567)	15.45 (7008)	12.98 (5889)
Saturated surface-dry mass, lb (g)	18.49 (8386)	15.51 (7034)	16.84 (7636)	13.58 (6158)
Aggregate absorption (%)	1.1 %	7.1 %	9.0 %	4.6 %

3.2.3 Mix Design

Mix proportions for each batch were determined using the absolute volume method of ACI 211.1, "*Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete.*" Five total groups of mixes were tested based on the type of RCA surface treatment used. Table 3-3 lists the group designations for each RCA surface treatment type. RCA substitution for natural coarse aggregate in each group was tested at amounts of 0, 25%, 50%, and 100%.

Table 3-3. Test group designations.

RCA surface treatment type	None	Silica-Cement	Acrylic	Surfactant Wetting Agent	Water Saturated
Group designation	N	Si	A	W.A.	W.S.

Volumetric proportions of components were kept identical throughout each test mix and water/cement ratio was kept constant at 0.5 for all batches. The component volumetric proportions for each recycled aggregate substitution amount are shown in Table 3-4. Measured bulk densities for aggregates and the ASTM standard density for cement were used to convert volume proportions to mass proportions so that materials could be portioned by mass.

Table 3-4. Mix component volumetric proportions.

Coarse Recycled Concrete Aggregate Substitution	**0%**	**25%**	**50%**	**100%**
Component	Component parts by volume			
Cement	1	1	1	1
Fine Aggregate	2.32	2.32	2.32	2.32
Coarse Natural Aggregate	3.15	2.36	1.57	0
Recycled Coarse Aggregate	0	0.79	1.57	3.15
Water/Cement Ratio	0.5	0.5	0.5	0.5

Because sand water content was found to vary with depth in the supply, the mass of a known volume of sand was measured before combining ingredients in each batch, and compared to the oven dry mass of the same volume. Thus, the water content of sand used with each mix batch was determined and taken into account when proportioning the mix water for the batch. Mix water for each batch was reduced by the amount contained in the sand.

3.2.4 Mixing Method

The mixing procedure followed the Machine Mixing method of ASTM C192 "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory." Prior to starting mixer rotation, the coarse aggregate and approximately 1/3 of the mix water was added. The mixer was then started, and after a few revolutions, the fine aggregates, cement, and remaining water were added while the mixer was running. The mixer was run for 3 minutes after all ingredients had been added, followed by a 3-minute rest, followed by 2 minutes of final mixing. The open end was covered after all ingredients were added to avoid evaporation during mixing and the rest period. After mixing, the concrete was discharged into a wheelbarrow, where it was remixed by hand trowel to ensure uniformity and eliminate segregation.

3.2.5 Tests on Concrete

The tests performed on fresh and hardened concrete included slump, compressive strength, and length change.

3.2.5.1 Slump

Concrete slump was tested for each mix according to ASTM C143 "*Standard Test Method for Slump of Hydraulic-Cement Concrete*." The damp mold was filled in 3 lifts, and each layer was rodded 25 times after placement. After filling the mold and rodding the 3rd lift, the excess concrete was struck off flush with the top of the mold. The mold was then immediately lifted off the concrete sample and placed next to the slumped concrete. The measured distance between the top of the mold and the center of the slumped concrete was measured as pictured in Figure 3-2.

Figure 3-2. Concrete slump test.

3.2.5.2 Compressive Strength

Compressive strength of concrete was tested using 4 inch diameter cylinder specimens made using the method of ASTM C192 "*Making and Curing Concrete Test Specimens in the Laboratory.*" Cylinder specimens were prepared in 2 lifts, and each layer was rodded 25 times after being placed. The top of the concrete specimen was struck flush with the top of the mold. Specimens were moist room cured and molds were removed after 24 hours. Moist room curing continued until the specified age for compressive strength testing.

Concrete cylinder specimens were capped at a minimum of 8 hours prior to compressive strength testing using sulfur mortar following the method of ASTM C617 "*Standard Practice for Capping Cylindrical Concrete Specimens*" to ensure top and bottom surfaces were straight and parallel.

Concrete compressive strength was tested in accordance with ASTM C39 "*Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.*" A set of 3 specimens from each mix was tested at an age of 7 days and 28 days. An example of the compressive strength test is shown in Figure 3-3.

Figure 3-3. Concrete cylinder compression test.

Testing was performed using the MTS test machine at a prescribed loading rate to produce a stress rate near 35 psi per second. Preliminary testing was performed prior to specimen testing to determine the prescribed displacement controlled loading to produce this rate. Displacement-controlled loading at three times the required rate produced compressive strengths 12% higher for specimens at an age of 7 days, and 15% higher for specimens at an age of 28 days, than those produced by the required loading rate. Figure 3-4 illustrates the effect of the increased loading rate producing a higher compressive strength test result.

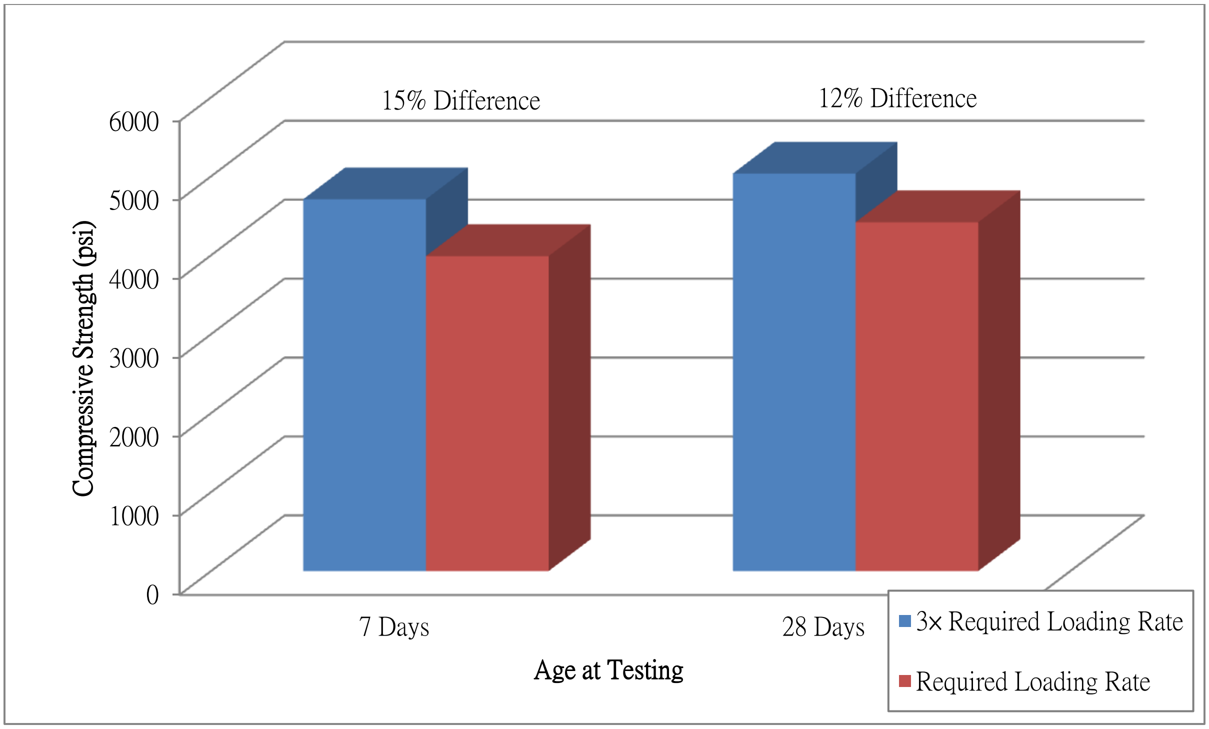

Figure 3-4. Comparison of compressive strength test results based on loading rate.

3.2.5.3 Length Change

Concrete shrinkage was measured by the method of ASTM C157 "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete" using 3 in. by 3 in. by 11.25 in. long rectangular prism specimens. 6 specimens were cast for each mix formula in 2 layers, each consolidated by rodding. Gauge studs were cast into each end for use in measuring length change. Excess material above the top of the mold was struck flush, and the top surface was smoothed with a trowel. Figure 3-5 (a)-(d) shows the process of casting the length change specimens.

Figure 3-5(a). Molds with gauge studs. (b). Tamping to consolidate specimens. (c). Smooth top surface formed by trowel. (d). Demolded specimens.

After demolding, specimen lengths were immediately measured and recorded as the initial measurement. For measurement purposes, one end was labeled “A” and the other labeled “B.” Subsequent measurements were compared to the initial measurement, and concrete shrinkage was considered a decrease in length from the initial measurement according to ASTM C 157. Specimens were measured vertically by taking the average of a set of 3 measurements with end “A” oriented upward and then a set of 3 measurements with end “B” oriented upward. An example of the length change specimen measurement is shown in Figure 3-6.

Figure 3-6. Concrete length change measurement.

3.2.6 Curing Time & Method

After casting, both types of specimens were moist room cured and demolded at an age of 24 hours. Cylinder specimens were moist room cured until the specified age of testing. 2 sets of length change specimens for each mix were studied under separate conditions to compare shrinkage behavior produced by different conditions. The first set was exposed to ambient conditions in laboratory air after demolding at an age of 24 hours. This set was designated as "Air." The second set was cured in lime-saturated water at ambient laboratory temperature for 28 days. This set of specimens was designated "Lime." At an age of 28 days, specimens were removed to laboratory air for the remainder of the study. The aim of this comparison was to study the difference in concrete shrinkage effects with a relatively short curing time, and harsher environmental conditions, as may be experienced by concrete on construction projects, compared to that of the method described in the standard.

3.3 EXPERIMENTAL RESULTS

Experimental results are presented below for concrete slump, compressive strength, and concrete length change.

3.3.1 Concrete Slump

Slump tests performed on freshly mixed concrete showed that varying recycled aggregate surface treatments and amounts of coarse aggregate replacement had an effect on concrete workability. Table 3-5 summarizes the results of this testing.

Table 3-5. Summary of concrete slump test results.

Surface Treatment	Coarse RCA Replacement			
	0	25%	50%	100%
	Concrete Slump, in.			
None	3.5	2.5	1.5	1.0
Silica-Cement	3.5	2.0	1.5	0
Acrylic	3.5	3.0	3.0	4.5
Wetting Agent Surfactant	3.5	3.5	8.5	8.75
Water Saturated	3.5	4.0	4.5	5.5

Without any surface treatment, an increase in recycled aggregates caused a decrease in concrete slump. A similar decrease occurred with concrete mixes containing silica-cement treated RCA. Concrete containing acrylic coated RCA showed very little change in slump, with no clear trend relating slump to an increase of the treated RCA, although a substitution of 100% produced a somewhat larger slump than any other RCA replacement amount. The use of the surfactant wetting agent on the RCA surface produced a large increase in slump at higher substitution amounts. Finally, the use of presoaked recycled aggregates produced small increase in slump with larger substitution amount.

3.3.2 Compressive Strength

Compressive strength properties were measured by testing 4 inch diameter cylinders at 7 and 28 days. Additionally, the rate of strength gain was examined by comparing test values at the two ages.

3.3.2.1 7-Day Compressive Strength

Concrete compressive strength testing showed the effect of RCA use with and without surface treatment on early age concrete strength. The results of compressive strength testing on cylinder specimens at an age of 7 days are presented in Table 3-6.

Table 3-6. Summary of 7-day compressive strength results.

7 Day Compressive Strength, psi				
Surface Treatment	Recycled Aggregate Content			
	0%	25%	50%	100%
None	4570	5180	4490	4320
Silica-Cement	4570	4610	4730	3200
Acrylic	4570	4650	4110	3400
Wetting Agent Surfactant	4570	3490	4100	2730
Water Saturated	4570	4950	4780	3970

With no surface treatment, concrete containing 25% recycled aggregates experienced the highest 7 day compressive strength. Silica cement treated aggregates experienced slightly higher compressive strength at 25% and 50% substitution for natural coarse aggregate. No clear trend in 7 day compressive strength was experienced by the aggregates treated with the surfactant wetting agent. Recycled aggregates saturated with water prior to concrete mixing experienced a strength increase at 25% and 50% substitution similar to RCA with no surface treatment. At 25% substitution, RCA with no surface treatment experienced the highest 7 day compressive strength, followed by water saturated

RCA. The acrylic and silica cement treated produced similar 7 day strengths, with the surfactant treated aggregate producing the lowest 7 day strength results with 25% substitution. At 50% substitution, water-saturated and silica cement treated aggregates produced the highest compressive strengths, followed by no surface treatment. Both acrylic and surfactant treated aggregates produced the lowest 7 day compressive strengths at 50% substitution. At 100% RCA substitution, concrete with no surface treatment experienced the highest 7 day compressive strength, followed by water saturated RCA. Silica cement and acrylic treated recycled aggregate produced similar results, and surfactant treated RCA concrete produced the lowest 7 day compressive strength results.

3.3.2.2 28-Day Compressive Strength

Concrete compressive strength testing showed the effect of RCA use with and without surface treatment on concrete strength after being allowed to cure for 28 days. Compressive strength results at an age of 28 days are summarized in Table 3-7.

Table 3-7. Summary of 28-day compressive strength results.

28 Day Compressive Strength, psi				
Surface Treatment	**Recycled Aggregate Content**			
	0%	**25%**	**50%**	**100%**
None	4630	5330	5040	5500
Silica-Cement	4630	4840	5090	5760
Acrylic	4630	5910	4680	4470
Wetting Agent Surfactant	4630	3550	5050	3120
Water Saturated	4630	5160	5080	4710

With no surface treatment, concrete containing 100% recycled aggregate experienced the highest tested average 28 day compressive strength. Similarly, the highest 28 day strength was achieved at 100% RCA substitution with the silica cement treated aggregate. Acrylic treated aggregate concrete experienced the overall highest compressive strength at 25% substitution, as did the water saturated RCA. Surfactant treated aggregate concrete experienced the highest 28 day compressive strength at 50% RCA substitution. At 25% substitution, acrylic treated recycled aggregates had the highest tested 28 day compressive strength, followed by the mix containing no surface treatment, water saturated RCA, and silica cement coated aggregates. RCA treated with the surfactant produced the lowest 28 day strength results at 25% substitution. 28 day strength test results for 50% RCA substitution were nearly identical for all mixes with the exception of the acrylic treated RCA which produced an average of 8% lower compressive strength. At 100% RCA substitution, silica cement treated aggregate produced the highest 28 day compressive strength, followed by no surface treatment, water saturated RCA, and acrylic. The surfactant treated RCA mix produced the lowest 28 day compressive strength at 100% substitution.

3.3.2.3 Compressive Strength Gain

The effects of RCA use and surface treatments on the rate of strength gain was examined by listing the tested 7 day compressive strength of each concrete mix as a percentage of tested 28 day strength of the same concrete mix. The strength gained by each concrete mix at an age of 7 days expressed as a percentage of its 28 day strength is summarized in Table 3-8.

Table 3-8. Compressive strength gain by 7 days.

% of 28 Day Compressive Strength Obtained at 7 Days				
Surface Treatment	Recycled Aggregate Content			
	0%	25%	50%	100%
None	99%	97%	89%	79%
Silica-Cement	99%	95%	93%	56%
Acrylic	99%	79%	88%	76%
Wetting Agent Surfactant	99%	98%	81%	88%
Water Saturated	99%	96%	94%	84%

Concrete with no RCA experienced the fastest strength gain, with specimens reaching 99% of the tested 28 day strength by an age of 7 days. Similar results were seen at 25% RCA substitution, with 7 day compressive strengths in the range of 95% to 98% of tested 28-day compressive strengths, with the exception of the acrylic treated RCA, which was lower at 78% of its 28 day strength. At 50% RCA substitution, the strength gain was slightly slower, with 7 day strengths between 81% and 94% of tested 28 day strengths. The slowest overall strength gain occurred with 100% RCA, with 7 day compressive strengths between 56% and 84% of 28 day compressive strength.

3.3.3 Length Change

The effects of RCA and the use of surface treatments on measured drying shrinkage strains over time were studied using a set of 3 specimens from each mix cured in lime saturated water for 28 days and a set of 3 from each mix which were cured for 1 day in the curing chamber and then removed to laboratory air for the remainder of testing.

3.3.3.1 Specimens Cured in Lime Saturated Water

The results of length change measurements taken on specimens cured in lime saturated water are presented in Figure 3-7 through Figure 3-11.

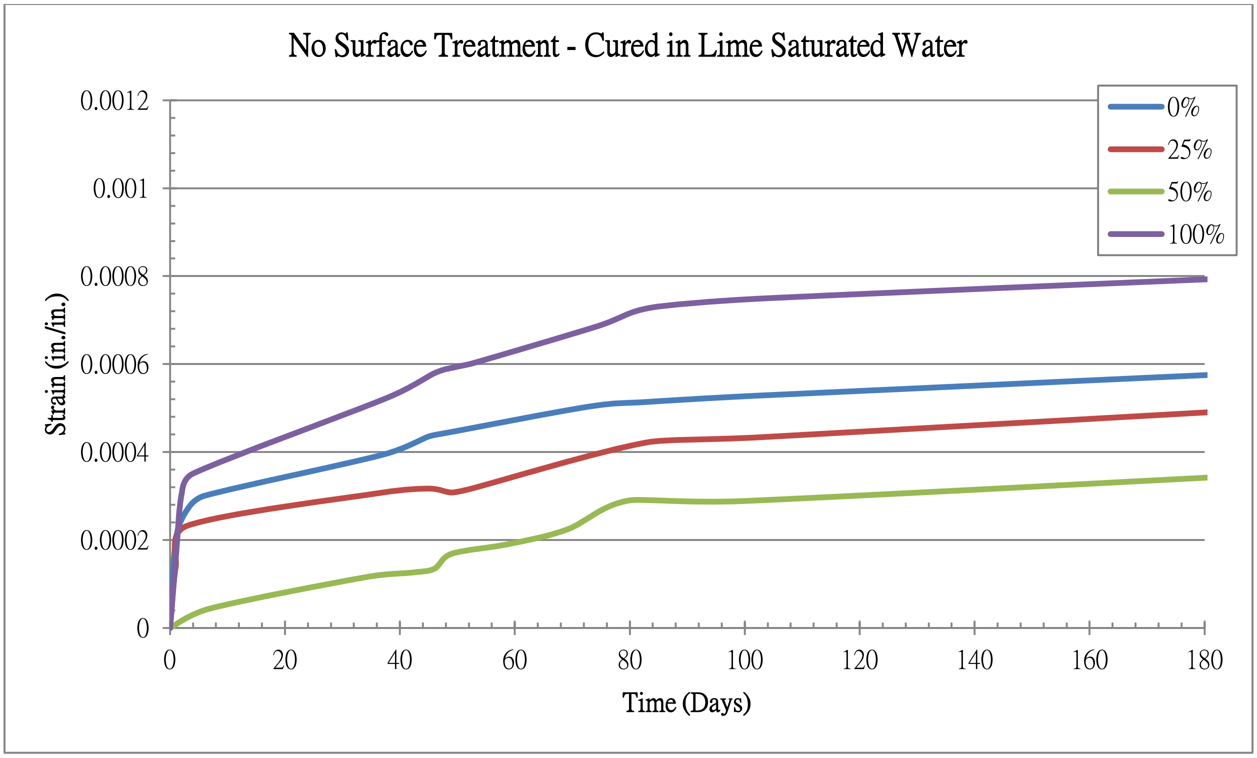

Figure 3-7. Drying shrinkage of RCA concrete with no surface treatment cured in lime saturated water.

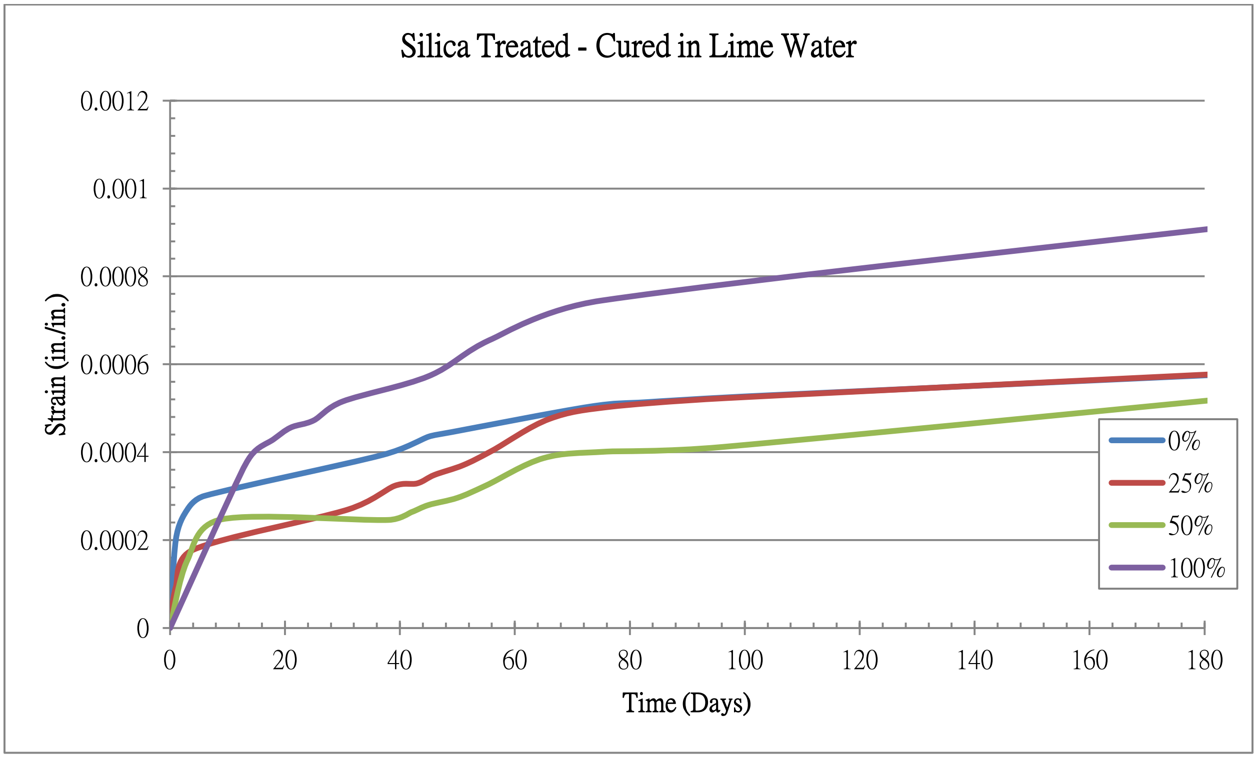

Figure 3-8. Drying shrinkage of silica-cement treated concrete cured in lime saturated water.

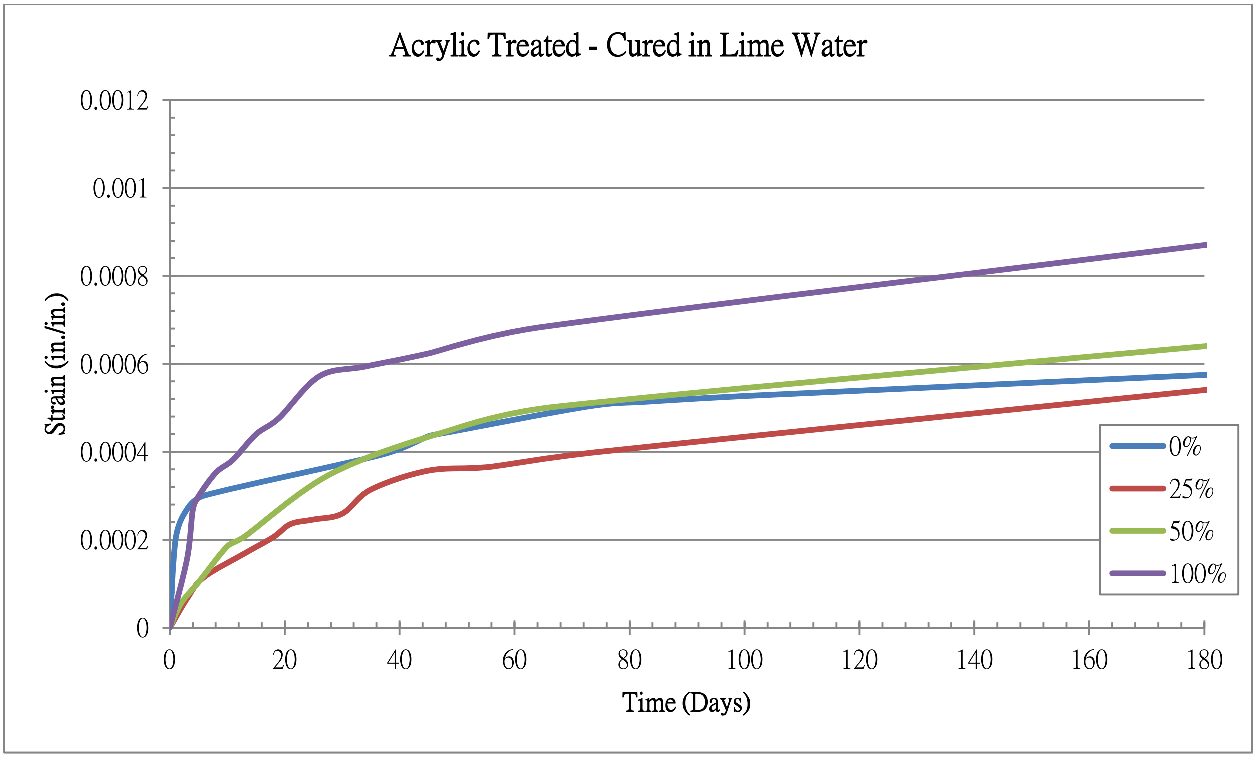

Figure 3-9. Drying shrinkage of acrylic treated RCA concrete cured in lime saturated water.

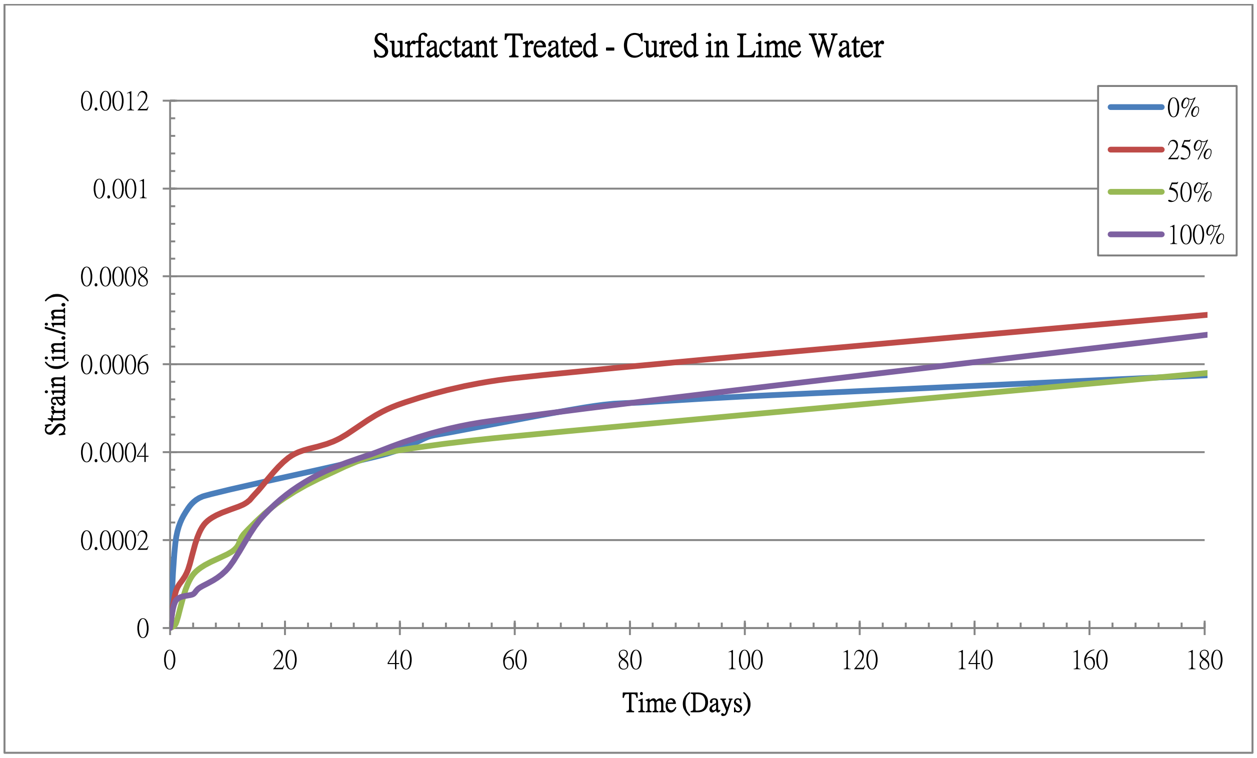

Figure 3-10. Drying shrinkage of wetting agent surfactant treated RCA concrete cured in lime saturated water.

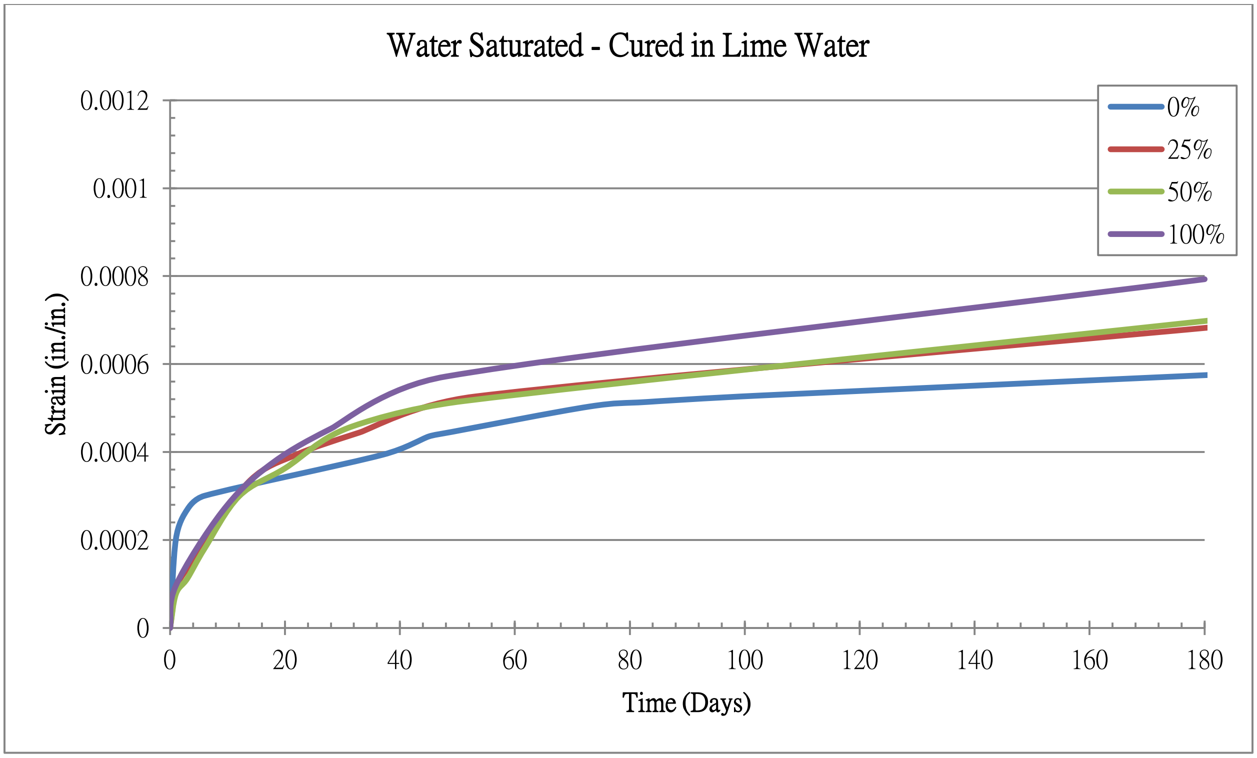

Figure 3-11. Drying shrinkage of water saturated treated RCA concrete cured in lime saturated water.

Concrete specimens cured in lime saturated water initially remain saturated while curing takes place, and after specimens are removed from the water at an age of 28 days, moisture loss begins to take place. The initial measurement after specimen removal from the lime saturated water corresponds to Day 0 on the shrinkage plot. The difference in subsequent length measurements is compared to the initial reading when the specimen was removed from the lime saturated water.

After removal from the lime saturated water, concrete containing RCA with no surface treatment experienced the highest amount of drying shrinkage from the 100% RCA mix. The second most drying shrinkage was experienced by the control mix. The 50% RCA mix began with the least amount of shrinkage at an early age, and by the age of 180 days, remained the least, resulting in the 25% mix having the second lowest long term drying shrinkage of group N.

In the silica cement treated group, the control mix initially exhibited the most shrinkage strain; however, the 100% RCA mix had exceeded all others clearly by an age of 10 days and continued to increase in the time beyond. The 25% RCA mix initially experienced less drying shrinkage strain than the control mix through 70 days of measurements, but remained almost identical to the values of the control mix. Shrinkage strains of the 50% RCA mix remained the lowest through 180 days of measurements, but the trend appears to be approaching those of the control mix and 25% RCA mix.

In the acrylic treated RCA group, the 100% RCA mix experienced the largest drying shrinkage strains. The 25% and 50% RCA mixes both initially experienced less shrinkage strain than the control mix. The shrinkage strain of the 50% RCA mix exceeded that of the control mix by an age of 30 days. The 25% RCA mix shrinkage strain remained the lowest throughout the duration of testing, but the trend appeared to be closely approaching that of the control mix.

The results of the surfactant group were somewhat more closely grouped around the values of the control mix, compared to other groups cured in lime saturated water. In this group, the 25% RCA mix, unlike other groups, exhibited the largest amount of drying shrinkage strain throughout 180 days. The 100% RCA mix, while initially exhibiting shrinkage strains lower than the control mix until an age of 24 days, and then very close to the control mix until 90 days, began to approach those of the 25% RCA mix by 180 days. Similarly, the 50% RCA mix shrinkage strains remained below the control mix for most of the testing, but began to exceed those of the control mix at an age of 170 days.

The most notable difference in the water saturated RCA group from others is that all three substitution amount mixes experienced higher values of shrinkage strains than the control mix. By the age of 16 days, the RCA mix shrinkage strains had exceeded that of the control mix. Beyond that, the 100% RCA mix experienced the largest amount of drying shrinkage. The values of shrinkage strains in both the 25% and 50% RCA mixes remained very similar throughout testing, but by an age of 120 days, the strain of the 50% RCA mix had surpassed that of the 25% mix.

Among all groups, the no surface treatment 50% RCA mix showed the least amount of shrinkage strain, while the silica-cement treated 100% RCA mix experienced the most for specimens cured in lime saturated water. By the age of 180 days, the 50% RCA substitution mix experienced the least amount of shrinkage in 2 of the 5 groups, the control mix experienced the least shrinkage in 2 groups as well, the 25% RCA mix showed the least amount of shrinkage in group A only.

3.3.3.2 Specimens Cured in Laboratory Air

A second curing method was used for length change specimens with the goal of comparing the effects of RCA and surface treatment use on drying shrinkage specimens that were allowed to fully cure and become fully saturated before testing with specimens that received a very short curing time and exposed to a dry environment. The results of length change measurements taken on specimens exposed to and remaining in laboratory air after being allowed to cure for 1 day in the curing room are presented in Figure 3-12 through Figure 3-16.

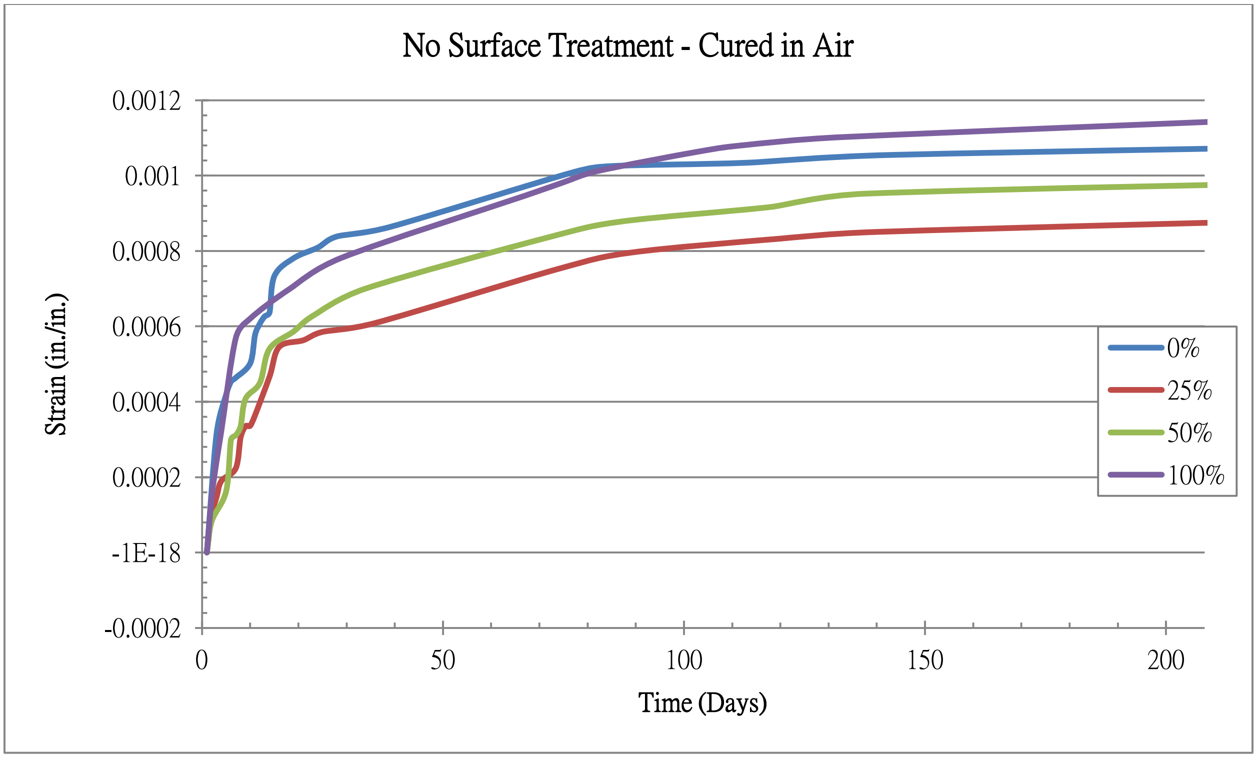

Figure 3-12. Drying shrinkage of RCA concrete with no surface treatment cured in laboratory air.

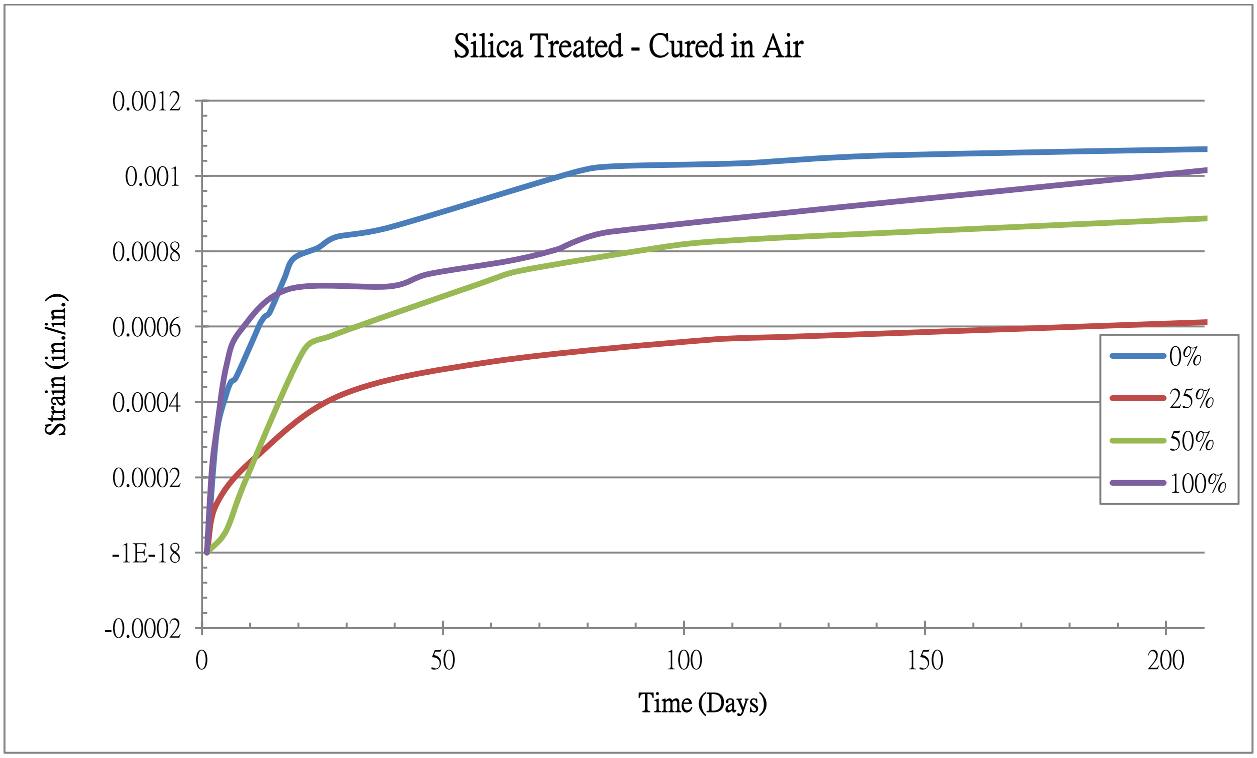

Figure 3-13. Drying shrinkage of silica-cement treated RCA concrete cured in laboratory air.

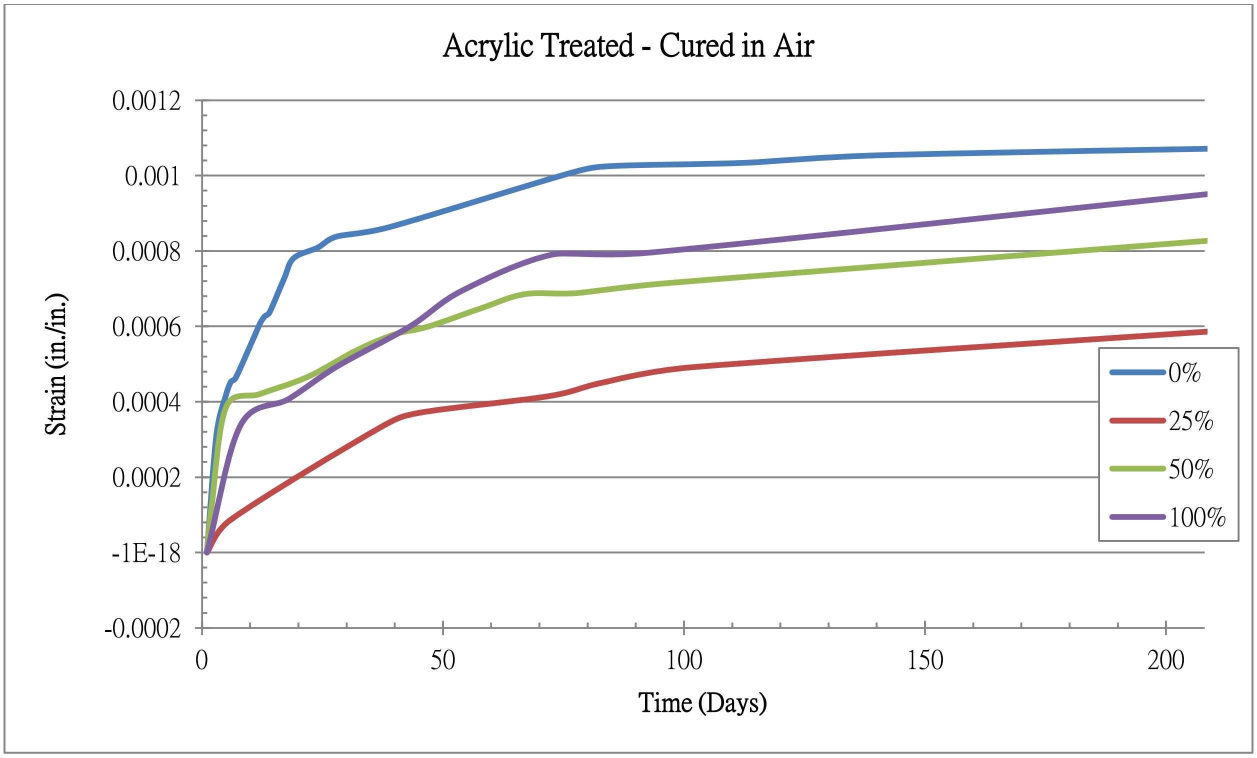

Figure 3-14. Drying shrinkage of acrylic treated RCA concrete cured in laboratory air.

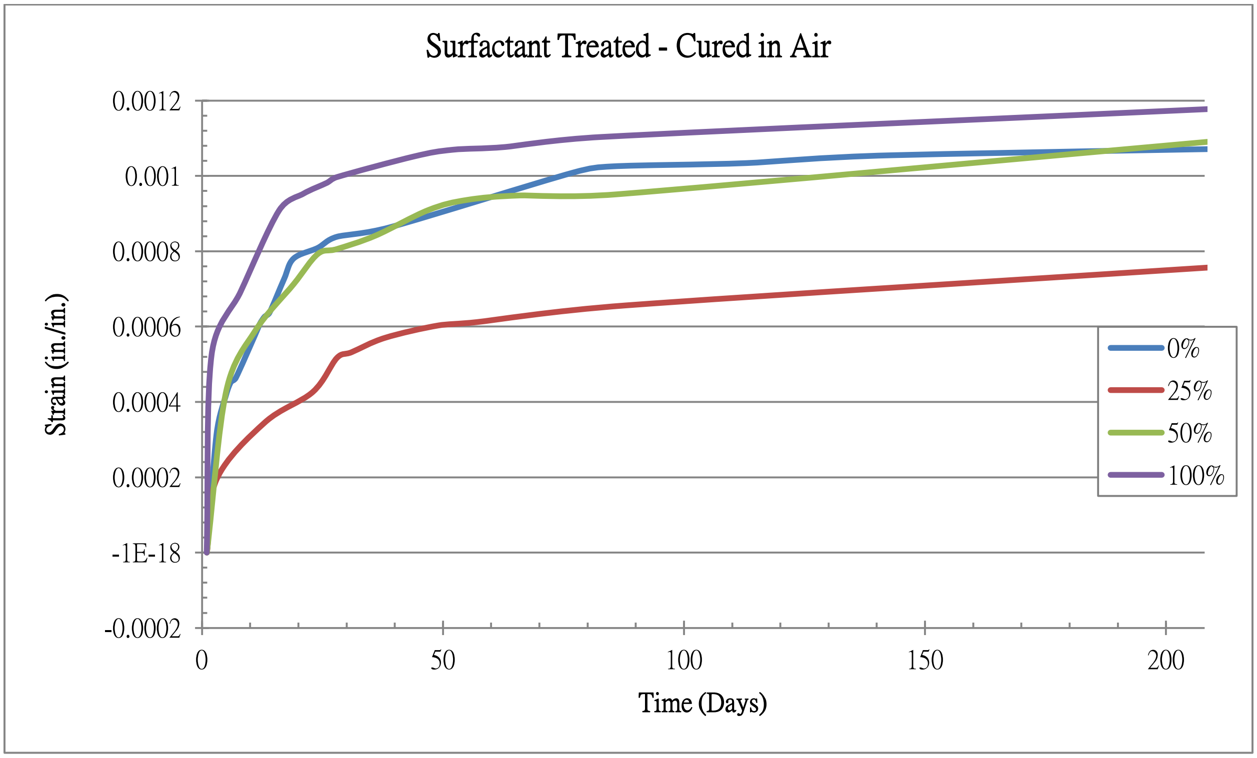

Figure 3-15. Drying shrinkage of wetting agent surfactant treated RCA concrete cured in laboratory air.

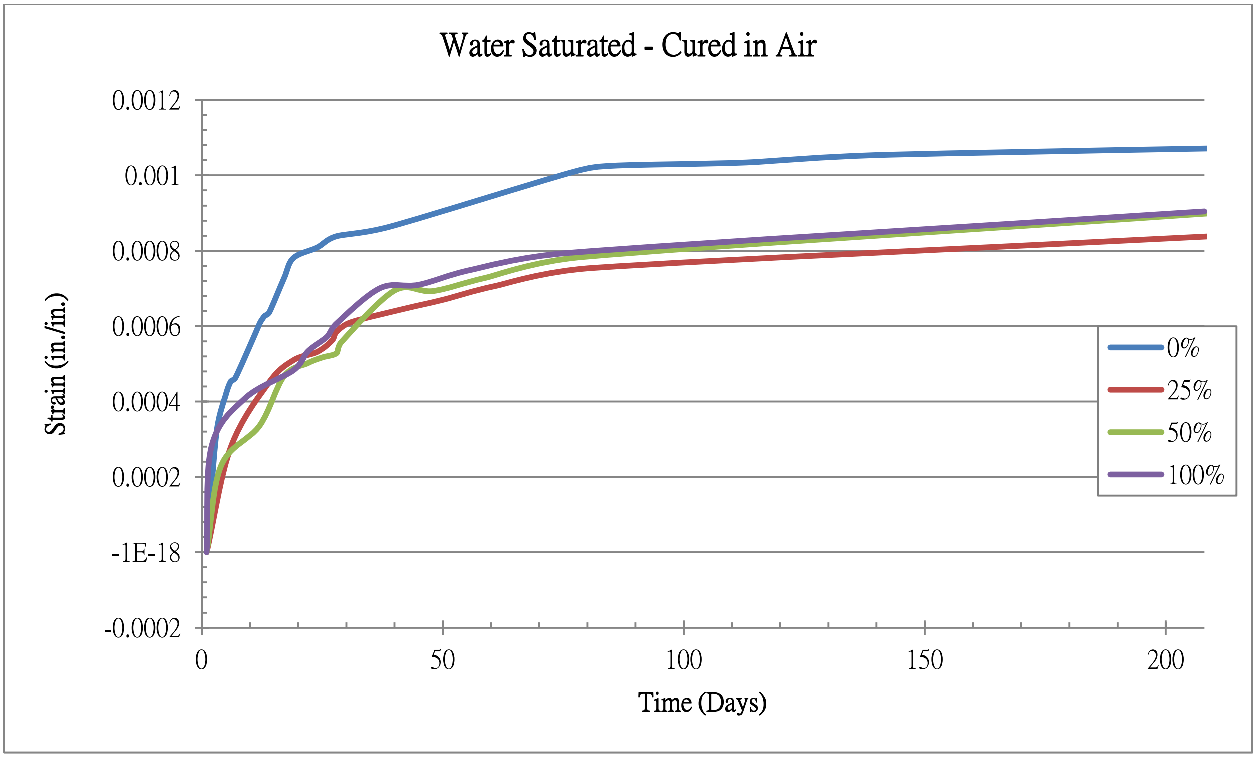

Figure 3-16. Drying shrinkage of water saturated RCA concrete cured in laboratory air.

Concrete containing RCA with no surface treatment experienced the least amount of shrinkage strain from the 25% RCA mix, followed by the 50% RCA mix. The 100% RCA and control mix experienced very similar levels of strain from the beginning of the test, but beyond the age of 80 days, the 100% RCA shrinkage strain exceeded that of the control mix.

In the silica cement treated RCA group, the control mix experienced the largest amount of shrinkage strain through an age of 100 days, followed by the 100% RCA mix. The shrinkage strain values of the 50% RCA mix are slightly below those of the 100% RCA mix, and the 25% RCA mix experienced the lowest values of shrinkage strain in this group.

The control mix experienced the highest values of shrinkage strain in the acrylic treated RCA group, followed by the 100% RCA mix. The 50% RCA mix had shown larger shrinkage strain values than the 100% RCA mix until the age of 28 days, when the 100% RCA mix surpassed it. The 25% RCA mix continued to exhibit the least amount of shrinkage strains throughout testing.

The group of RCA treated with the wetting agent surfactant experienced the most shrinkage strain from the 100% RCA mix, while the control mix and 50% RCA mix showed nearly identical results. Similar to other groups, the 25% RCA mix experienced the lowest values of drying shrinkage strain.

Concrete containing water saturated RCA showed reduced shrinkage strains compared to the control mix as well. The 100% RCA mix experienced the next greatest shrinkage strain values, followed by 50% RCA and 25% RCA. The strain values of each of the RCA substitution amounts are considerably close to one another, differing by only as much as 40 microstrains.

For specimens exposed to laboratory air with only 1 day in curing room conditions, the use of 25% RCA reduced shrinkage strains for all types of treatment methods, including none. The method which produced the lowest values of shrinkage strain was using 25% acrylic treated RCA. For all groups cured in air, the use of 100% untreated and surfactant treated RCA mixes produced the highest values of shrinkage strain.

3.3.4 Observations

Nearly all mix batches in the experimental program exhibited typical fresh and hardened concrete appearance, however, special observations were noted for the silica cement treated and acrylic treated RCA at 100% natural aggregate replacement. The 100% silica-cement treated RCA mix, which had a tested slump of 0 inches, provided difficulty consolidating in sample molds, and also exhibited numerous voids in compressive strength specimens and in length change specimens, visible in Figure 3-17.

Figure 3-17.Voids present in 100% silica cement treated RCA due to reduced workability.

The use of surfactant treated RCA appeared to significantly improve workability, with the measured slump of the 100% RCA mix being 8.75 inches, however the presence of many small bubbles was observed throughout mixing and casting the fresh concrete as well as in hardened specimens. A close-up view of this effect is shown in Figure 3-18.

Figure 3-18. (a.) Increased concrete slump using surfactant. (b.) Bubbles present in fresh concrete (c.) Bubbles present in hardened specimens.

3.4 CONCLUSIONS

3.4.1 Concrete Workability

The addition of RCA to concrete mixes affected the workability of freshly mixed concrete. A general trend of reduced workability was experienced with an increase in untreated and silica cement treated RCA. No clear trend was observed in workability with an increase of acrylic treated RCA. An increase in workability was observed with an increase of both surfactant treated and water saturated RCA.

A direct relationship was observed between the replacement of natural aggregates with RCA with no surface treatment and reduced concrete workability. The higher absorption rate of the RCA understandably appeared to reduce the slump of concrete with increased use. A similar result was observed using the silica cement treated RCA, having an even higher rate of absorption and generally less workability.

The addition of acrylic treated RCA, despite having a higher absorption rate than natural aggregate, did not cause a significant decrease in workability. In fact, the mix containing 100% acrylic RCA showed a slight increase in slump, suggesting that the 24 hour absorption capacity of this type of treated aggregate probably does not occur quickly enough to reduce workability while mixing. The 1 inch increase in slump at 100% RCA substitution from the control mix also suggests that the acrylic coating reduces absorption initially during the mixing process despite exhibiting greater 24 hour absorption than natural aggregate.

A relationship between an increase in concrete slump and an increase in both surfactant treated and water saturated RCA substitution was observed. The increased workability in the surfactant treated mixes was most likely due to the reduced surface tension of water at the RCA surface provided by the surfactant. In the case of water saturated RCA, the aggregates were used in a saturated surface dry condition and the additional water provided an increase in workability.

Without the use of water-reducing or superplasticizing admixtures, the use of 100% untreated RCA coarse aggregate substitution is not recommended with a water to cement ratio of 0.5 for workability purposes, however, experiments have shown the use of these additives to have an undesirable effect on concrete shrinkage properties (Domingo-Cabo, 2009). Similarly, 100% silica cement treated RCA mixes using a water to cement ratio of 0.5 is not recommended for the same reason. Both untreated and silica cement treated RCA concrete mixes may produce acceptable results using lower RCA substitution amounts or slightly higher water to cement ratios depending on project requirements.

From a concrete workability standpoint, the use of surfactant treated and water saturated RCA is feasible. Both of these types of treatments increased workability with increased recycled aggregate substitution. By adding an amount of surfactant solution equal to the difference between RCA natural and saturated surface dry conditions, the concrete slump increased much more than by adding water only. This effect suggests that the surfactant is effective as a dispersing agent and also at reducing the amount of water drawn out of the mix by aggregates through capillary suction. A lower dose of surfactant solution would likely be effective at maintaining fresh concrete workability.

3.4.2 Compressive Strength

The use of both untreated and surface treated RCA affected the compressive strength of concrete at ages of 7 and 28 days, as well as the rate of strength gain. For each surface treatment group, there appeared to be an optimal RCA substitution amount which produced the maximum value of compressive strength.

Compressive strength at an age of 7 days benefitted the most from the use of 25% RCA substitution with no surface treatment, however other treatment methods were able to improve 7 day compressive strength over the control mix, while other combinations decreased 7 day compressive strength. Group W.S. produced the highest overall 7 day compressive strength with a 13% increase over the control mix. Both silica cement treated and water saturated RCA improved the tested 7 day compressive strength over the control mix at 25% and 50% substitution. Group Si had the highest 7 day compressive strength using 50% RCA, while group W.S. had the highest 7 day strength using 25%. The use of acrylic treated aggregate improved 7 day compressive strength at 25% replacement only. While all mixes decreased 7 day compressive strength when 100% RCA was used, group W.A. produced the lowest overall 7 day compressive strength, with a 40% decrease from the control mix.

Compressive strength at an age of 28 days was able to be improved over the control mix using RCA with and without surface treatments, while fewer combinations resulted in a decrease in compressive strength compared to 7 day tests. All amounts of RCA substitution increased 28 day compressive strength using no surface treatment, silica cement treated, and water saturated aggregates, with the highest 28 day compressive strength for groups N and Si occurring with 100% RCA substitution. Acrylic treated RCA increased 28 day compressive strength the most at 25% replacement, producing an improvement of nearly 28% over the control mix. Wetting agent treated RCA showed an improvement in 28 day strength at 50% replacement only, and similar to 7 day tests, showed the lowest overall 28 day result with a 33% decrease from the control mix.

The increased use of RCA increased the length of time required for concrete to gain strength. With the only exceptions being 25% acrylic treated RCA and 50% surfactant treated RCA, a direct correlation between amount of RCA used and percentage of 28 day strength developed by 7 days was observed. This may be due to water absorbed and held within the RCA being released more slowly during the hydration process compared to natural aggregates.

3.4.3 Concrete Length Change

Concrete specimens that were allowed to cure for 28 days in lime saturated water benefitted most from the use of 25% RCA substitution using either no treatment, silica-cement, or acrylic for reducing shrinkage. The use of acrylic with 25% RCA provided the most effective shrinkage reducing performance.

Concrete specimens exposed to a dry environment after 1 day in the curing room similarly experienced the greatest reduction in shrinkage strain through the use of 25% acrylic treated RCA, however all surface treatments and RCA substitution amounts reduced shrinkage with the exception of 100% RCA with no treatment, or treated with surfactant.

Concrete specimens removed from curing room conditions to laboratory air tended to experience larger amounts of drying shrinkage without RCA. This effect may be due to the very low absorption properties of natural aggregates that water in the concrete mix is more readily evaporated from the cast specimens. Alternatively, the higher absorption RCA draws more water from the mix which may be held within the adhered cement paste and then released gradually as evaporation takes place, thus slowing and also possibly reducing the rate of concrete volume change.

3.4.4 Summary

An experimental program was carried out to evaluate the effects of varying amounts of RCA and corresponding surface treatments on properties of fresh and hardened concrete. Aggregate properties tested included particle size distribution, bulk density and absorption. Tests performed on fresh and hardened concrete included slump, compressive strength, and length change.

The test groups included no surface treatment, silica cement mixture, acrylic paint, wetting agent surfactant, and water saturation. Each group was tested using 0, 25%, 50% and 100% RCA substitution for natural aggregate.

RCA was found to have lower density and higher absorption than natural coarse aggregates. The silica cement surface treatment was found to increase aggregate absorption, and the acrylic treatment was found to reduce absorption. The surfactant and water saturation treatments were used to provide moisture to the RCA before mixing to reduce the amount of mix water absorbed by RCA.

Concrete workability was reduced with an increase in RCA use with higher absorption properties including no treatment and silica cement treatment. Concrete workability increased with the increased use of RCA and treatments that lowered absorption characteristics including surfactant and water saturation. Workability was not significantly affected by the acrylic treated RCA.

Compressive strength at an age of 7 days experienced the largest increase through use of 25% RCA with no surface treatment. The use of 25% and 50% water saturated RCA provided significant increases in 7 day compressive strength as well. The use of 100% surfactant treated RCA provided the biggest decrease in 7 day compressive strength and none of the mixes containing 100% RCA provided an increase in compressive strength from the control mix.

Compressive strength at an age of 28 days improved with several combinations of RCA use and surface treatments. The largest increase in compressive strength was with the use of 25% RCA treated with acrylic, followed by 100% silica treated RCA. The largest decrease in 28 day compressive strength was due to the 100% RCA mix treated with surfactant.

The rate at which concrete gains strength was examined by comparing results of 7 day and 28 day compressive strength results. The use of RCA slowed the development of compressive strength gain in concrete.

Length change was studied to determine the effects of RCA and surface treatments on drying shrinkage on specimens cured in lime saturated water and on specimens exposed to dry laboratory air. The largest reduction in drying shrinkage of specimens cured in lime saturated water was due to the 25% RCA acrylic treated mix. The largest reduction in drying shrinkage of specimens exposed to laboratory air was 100% untreated and surfactant treated RCA.

CHAPTER 4

ANALYSIS OF DATA

4.1 INTRODUCTION

The results of testing presented in Chapter 3 are examined to determine if relationships exist between the various measured properties and the experimental results.

4.2 AGGREGATE PROPERTIES

Experiments were performed on aggregates to determine how they were affected by the various surface treatment methods. The properties examined included aggregate bulk density and absorption.

4.2.1 Aggregate Density and Absorption

The measured bulk density of treated and untreated RCA was compared to natural aggregate as a percentage difference. A summary of this comparison is presented in Table 2-1.

Table 4-1. Comparison of coarse aggregate properties.

Aggregate Property	% Change from Natural Coarse Aggregate		
	RCA Coarse	RCA Silica Treated	RCA Acrylic Treated
Bulk dry density	-21%	-8%	-29%
Aggregate absorption	+525%	+685%	+300%

The measured value of 24 hour absorption for coarse RCA was over 5 times the value measured for natural aggregate. The higher absorption results and lower RCA density values agree with those of

Zhang, Domingo-Cabo, Poon, and others who studied aggregate absorption. The silica cement treatment increased the aggregate density from the value of the untreated RCA to only 8% less than natural aggregate, however, the absorption value increased as well, possibly due to the large surface area of silica fume mixture. The use of acrylic surface treatment slightly lowered aggregate density, and significantly lowered absorption, although absorption remained higher than the value for natural aggregates.

4.3 FRESH CONCRETE PROPERTIES

The properties of freshly mixed concrete were examined to determine the effects of RCA and the various surface treatments. The properties examined included total mix water content and concrete slump.

4.3.1 Water Content

Using the known aggregate absorption properties measured in Chapter 3, the resulting effective water/cement ratio was determined by the method described by (Zhang, Deng, & Qin, 2007), where the water absorbed by aggregates was assumed to be unavailable for cement hydration and subtracted from the original water/cement ratio. The calculation of the amount of water absorbed by coarse aggregates is shown in (Equation 1-1).

$$\Delta W = m_{RA} \times (s_{RA} - w_{RA}) + m_{NA}(s_{NA} - w_{NA}) \qquad \text{(Equation 4-1)}$$

Where m_{RA} is the mass of RCA, s_{RA} is the specific 24 hour absorption of RCA, and w_{RA} is the existing water content of RCA. Similarly, m_{NA}, s_{NA}, and w_{NA} represent the mass, specific 24 hour absorption, and existing water content of natural aggregate, respectively.

Resulting effective water/cement ratios for each mix formula accounting for aggregate absorption are presented in Table 4-2.

Table 4-2. Resulting effective water/cement ratio accounting for aggregate absorption.

Surface Treatment	Coarse RCA Replacement			
	0	25%	50%	100%
	Effective Water/Cement Ratio			
None	0.48	0.45	0.43	0.40
Silica-Cement	0.48	0.45	0.42	0.36
Acrylic	0.48	0.47	0.46	0.43
Wetting Agent Surfactant	0.48	0.48	0.49	0.50
Water Saturated	0.48	0.48	0.49	0.50

The resulting values of the available water after coarse aggregate absorption correlate well with the recorded values from the slump test in Chapter 3. A summary of this relationship is presented in Figure 4-1.

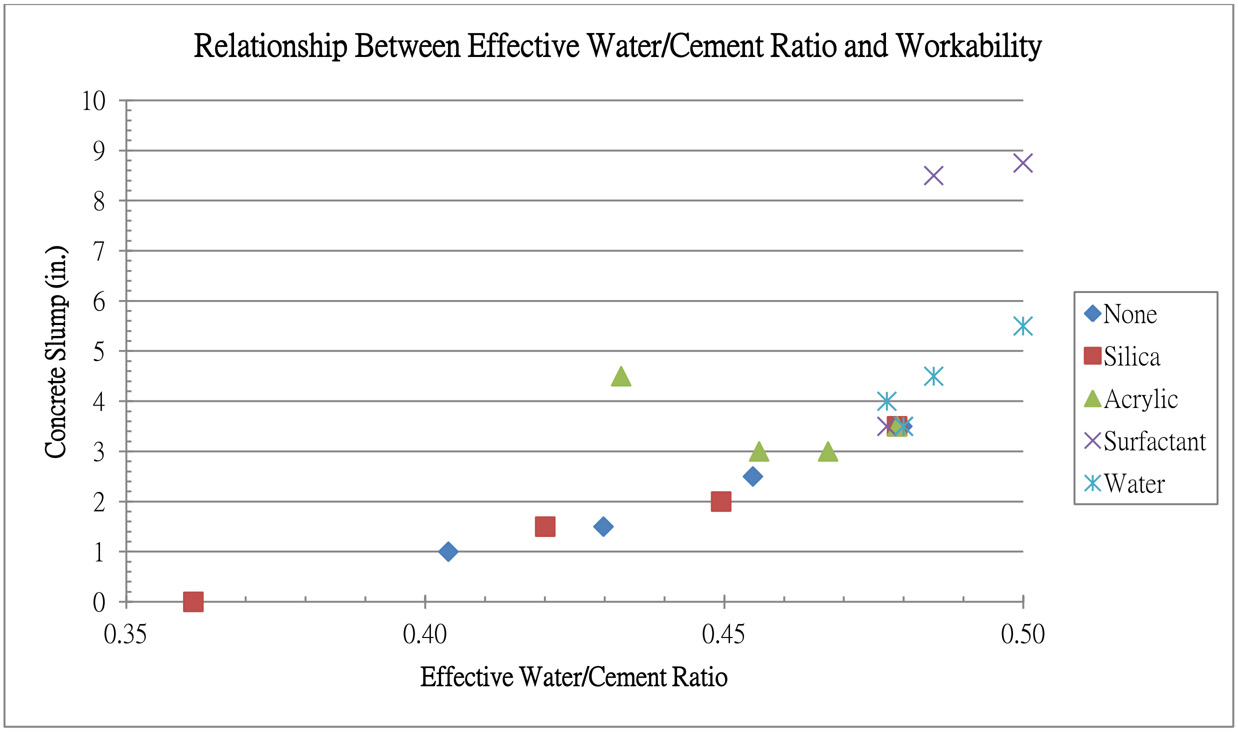

Figure 4-1. Relationship between effective water/cement ratio and concrete slump.

Although a clear relationship exists between the remaining water in the concrete mix after coarse aggregate absorption and concrete workability, the presence of outliers for the 100% acrylic treated RCA, 50% surfactant treated and 100% surfactant treated RCA mixes suggests these types of treatments produce different behavior. The 24 hour absorption capacity of acrylic treated RCA most likely does not occur quickly enough to reduce workability while mixing. The increase in concrete workability at 100% acrylic RCA substitution, despite producing a lower effective water cement ratio, also suggests that the acrylic coating reduces the rate of absorption initially during the mixing process. The surfactant wetting agent, as observed in Chapter 3, produced a much more viscous concrete mixture at 50% and 100% RCA replacement without using additional water. This effect is most likely attributed to the ability of the wetting agent to act as a dispersant for the water particles and also lower the capillary tension in the pores of RCA.

4.4 HARDENED CONCRETE PROPERTIES

Hardened concrete properties were analyzed to determine the effects of RCA replacement amount with and without the use of surface treatments. The properties examined included compressive strength at ages of 7 and 28 days, and length change.

4.4.1 Compressive Strength

Results of compressive strength tests performed at 7 days and 28 days indicate that RCA produces different effects on different types of surface treated or untreated RCA, as well as the time required for compressive strength to develop in each type of mix. The results of compressive strength testing as a function of RCA replacement amount are represented graphically for concrete ages of 7 days and 28 days in Figure 4-2 and Figure 4-3, respectively.

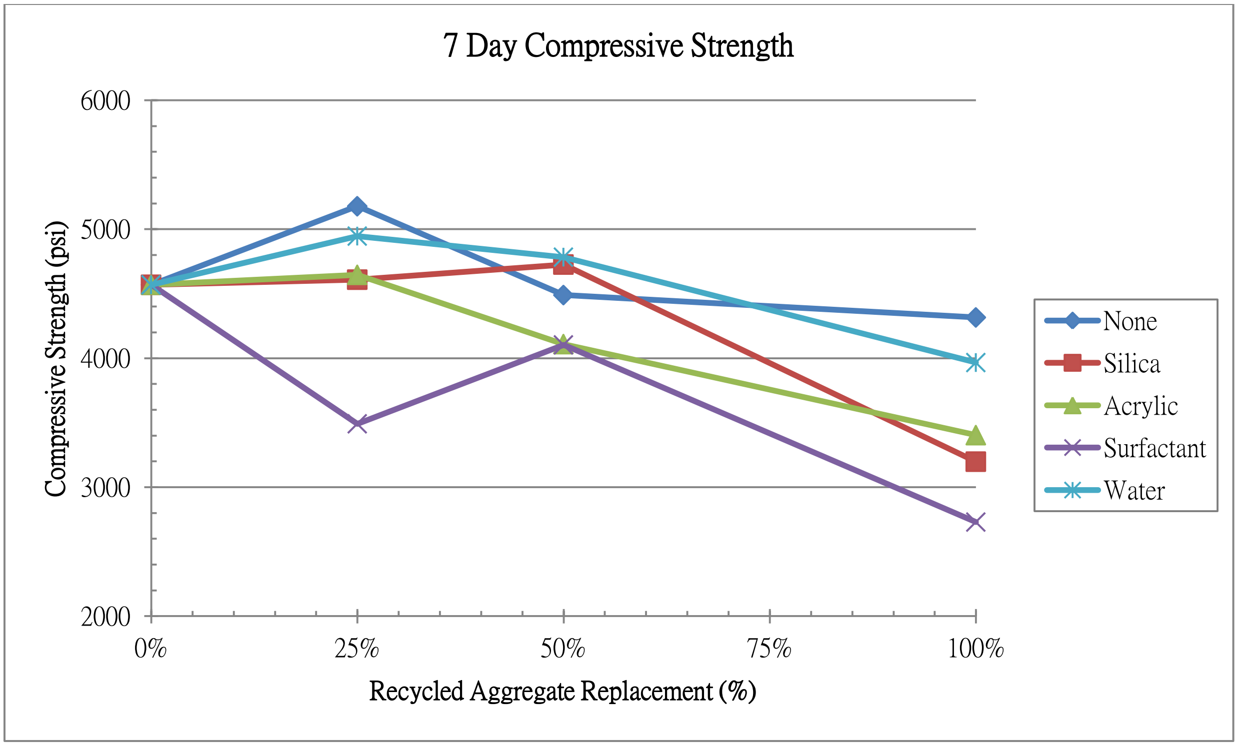

Figure 4-2. 7 day compressive strength as a function of RCA replacement.

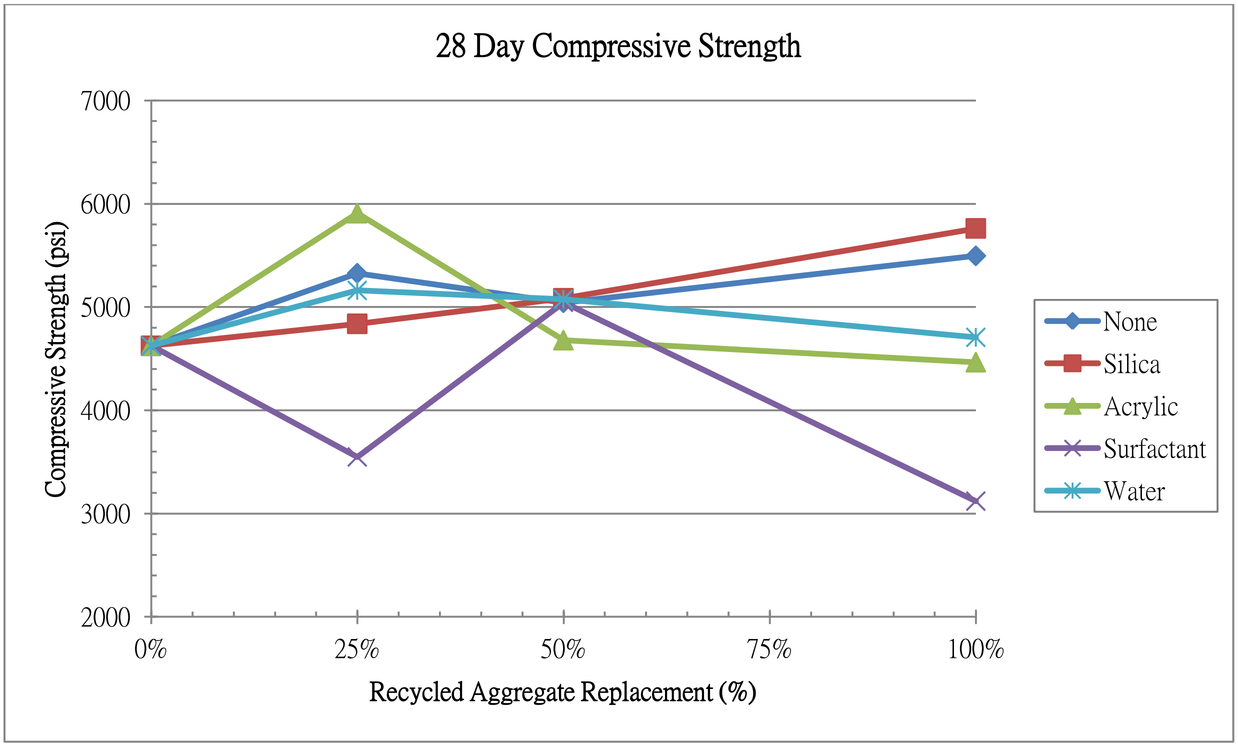

Figure 4-3. 28 day compressive strength as a function of RCA replacement.

7 day compressive strength increased at 25% RCA replacement for all mixes except the wetting agent treated mix. At 50% RCA replacement, all mixes had slightly higher compressive strength than the control mix except the acrylic treated mix. At 100% RCA replacement, compressive strength results of all mixes were lower than the control.

At 28 days, similar results were achieved using 25% RCA as observed at 7 days. Using 50% RCA replacement, test results were nearly identical for all mixes except the acrylic treated RCA mix, which had slightly lower compressive strength than the control mix. Using 100% RCA replacement, the mixes using silica cement and no surface treatment experienced higher compressive strength than the control mix, while the remaining mixes generally improved as well. Because of this, an examination of strength development from 7 days to 28 was conducted. The proportion of 28 day strength developed by 7 days is presented in Figure 4-4.

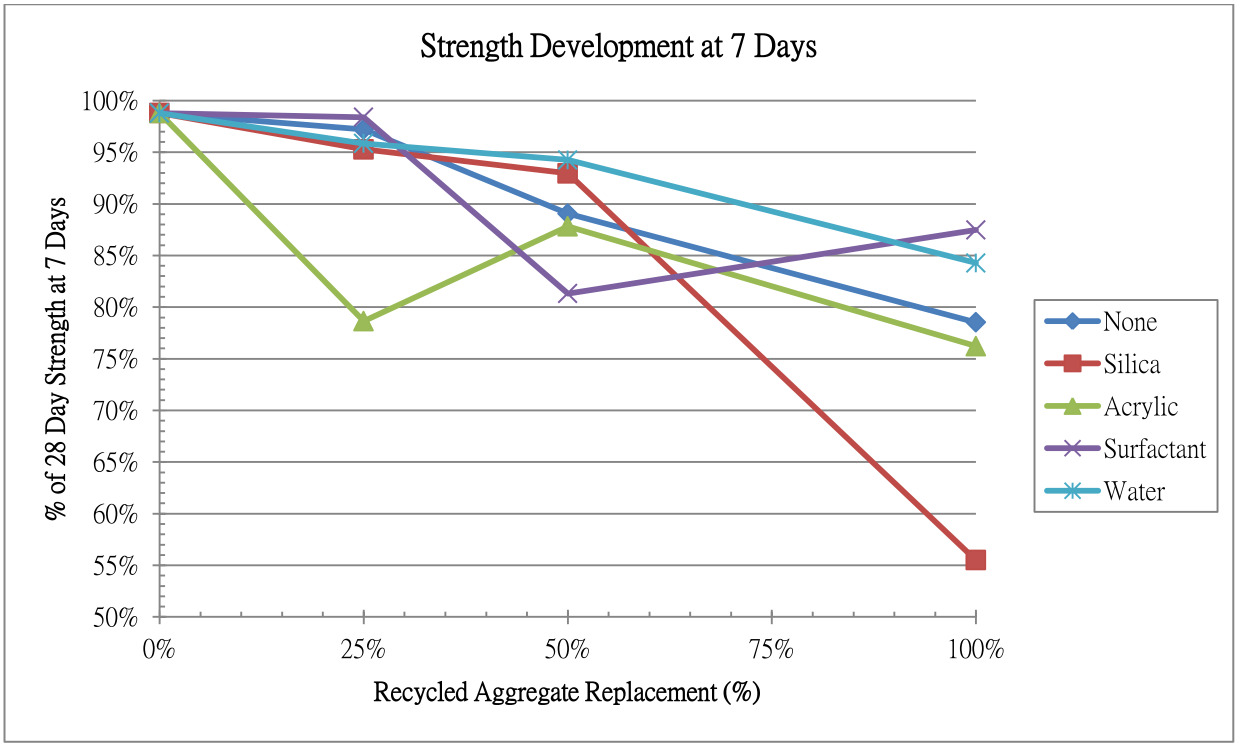

Figure 4-4. % of 28 day strength gained by 7 days

The general trend in compressive strength development was that an increased use of RCA caused compressive strength to develop more slowly. These results agree with similar results by (O'Mahony M. M., 1990).

4.4.1.1 Compressive Strength Variation

Compressive strength tests by others reported higher variation in results with an increased use of RCA (Etxeberria, Vázquez, Marí, & Barra, 2007). Results of compressive strength testing as part of this experimental program, however, did not show a general increase in variation with RCA use. Rather, coefficient of variation remained relatively steady throughout testing, with the exception of a large increase at 100% silica cement treated RCA that is most likely due to low casting quality and the presence of voids associated with a zero slump mix. Plots of the coefficient of variation for compressive strength data at 7 and 28 days are presented in Figure 4-5 and Figure 4-6, respectively.

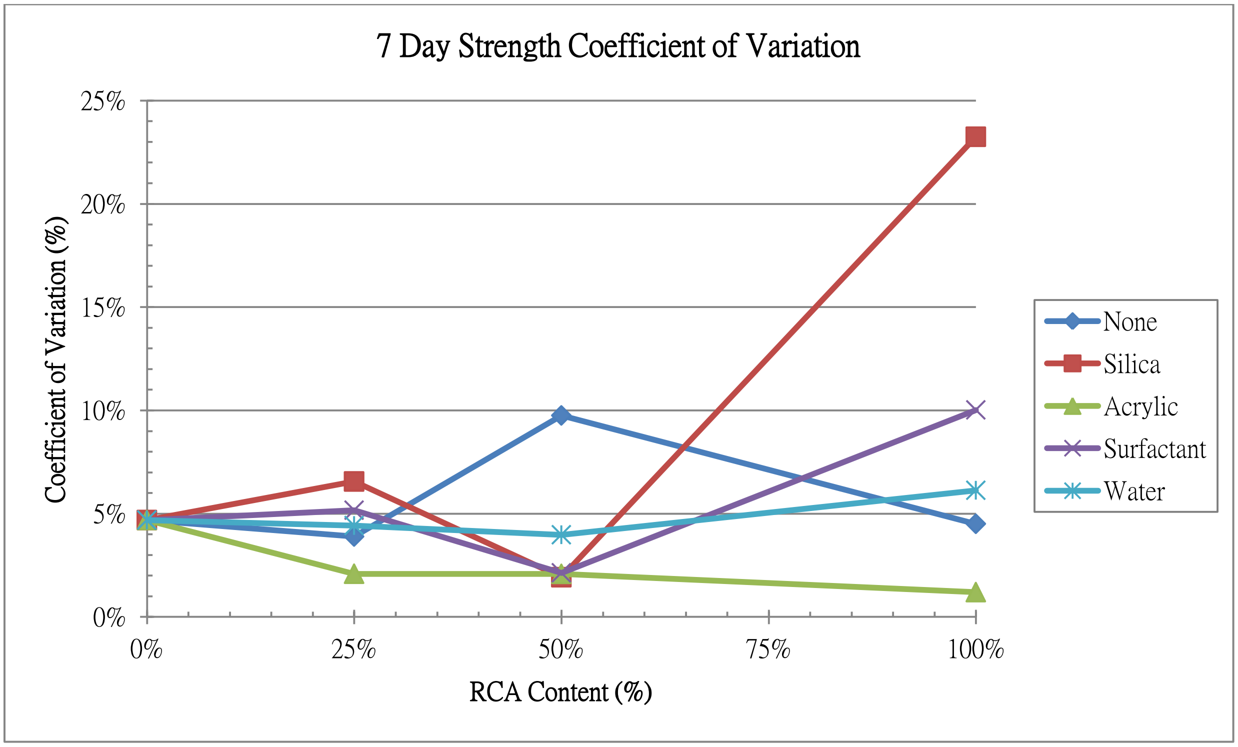

Figure 4-5. Coefficient of variation for 7 day compressive strength results.

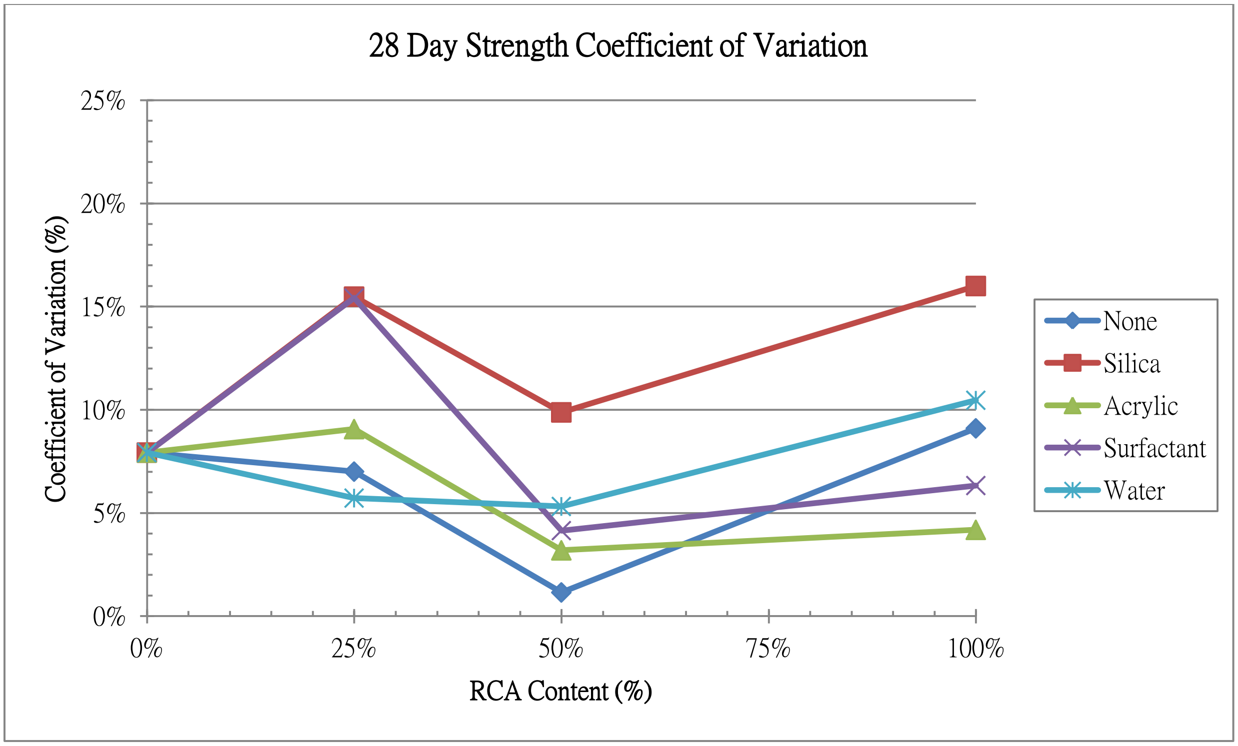

Figure 4-6. Coefficient of variation for 28 day compressive strength results.

4.4.2 Drying Shrinkage

Drying shrinkage was measured for a duration of 180 days for specimens cured in lime saturated water and in laboratory air. The values of shrinkage strain for each mix were compared for both curing methods to determine the effects of RCA replacement as well as surface treatments on drying shrinkage strain. For specimens cured in lime saturated water, 50% RCA replacement with no surface treatment provided the lowest amount of drying shrinkage strain at 180 days. For specimens exposed to laboratory air, 25% RCA replacement improved 180 day drying shrinkage for all surface treatment types, with the acrylic treatment providing the lowest overall drying shrinkage. Full development of drying shrinkage is illustrated in Figure 4-7 and Figure 4-8. Results based on RCA replacement and surface treatment type are shown in Figure 4-9 and Figure 4-10.

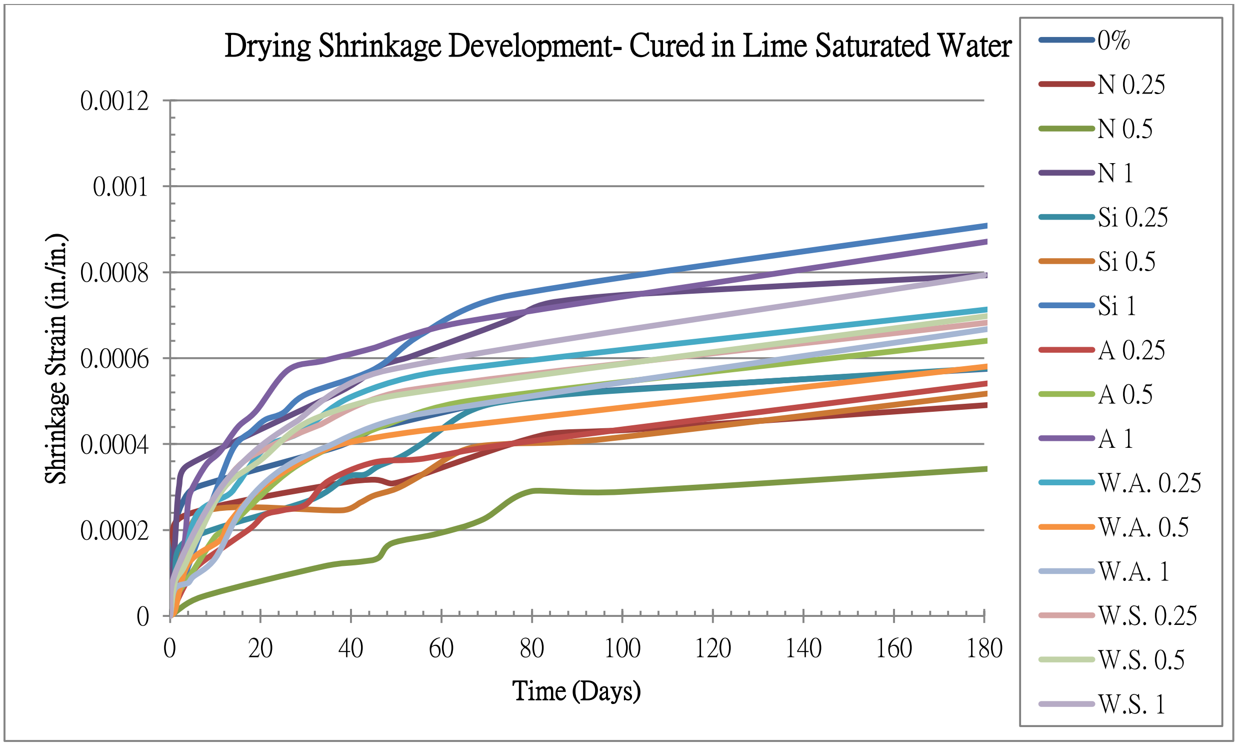

Figure 4-7. Development of drying shrinkage of specimens cured in lime saturated water.

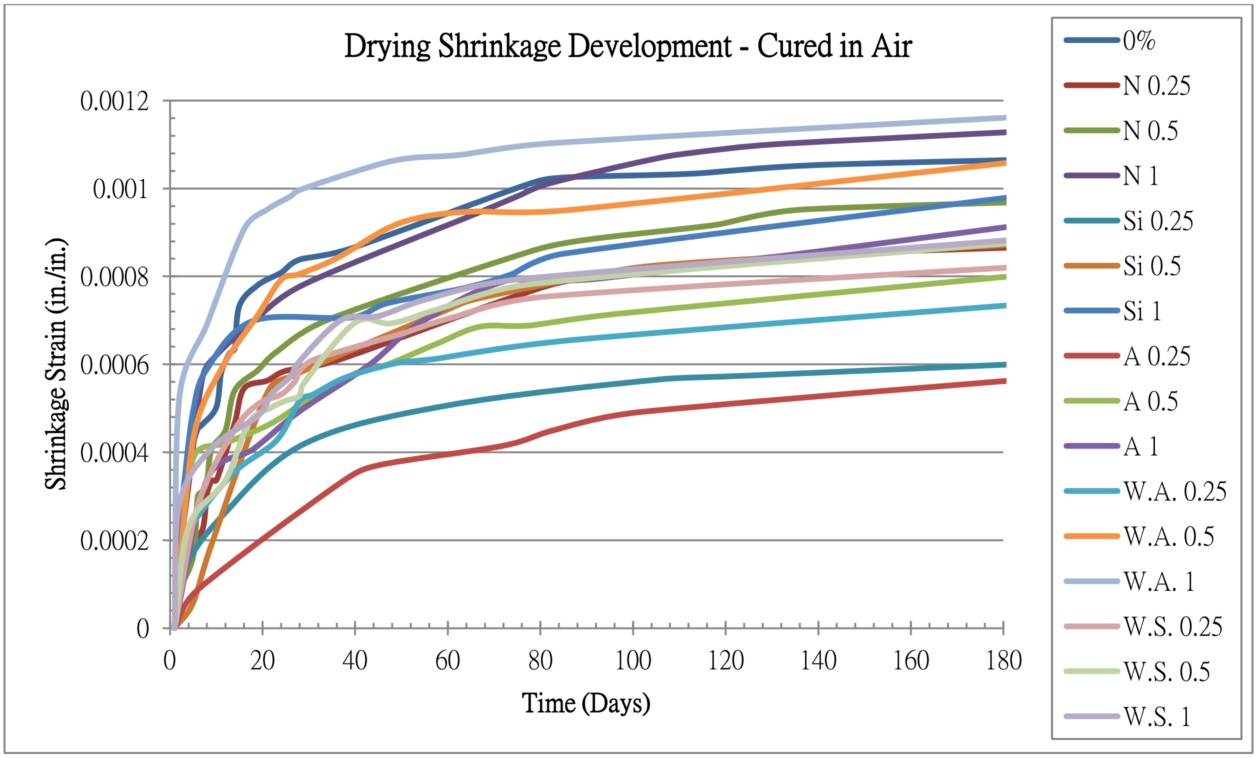

Figure 4-8. Development of drying shrinkage for specimens exposed to laboratory air.

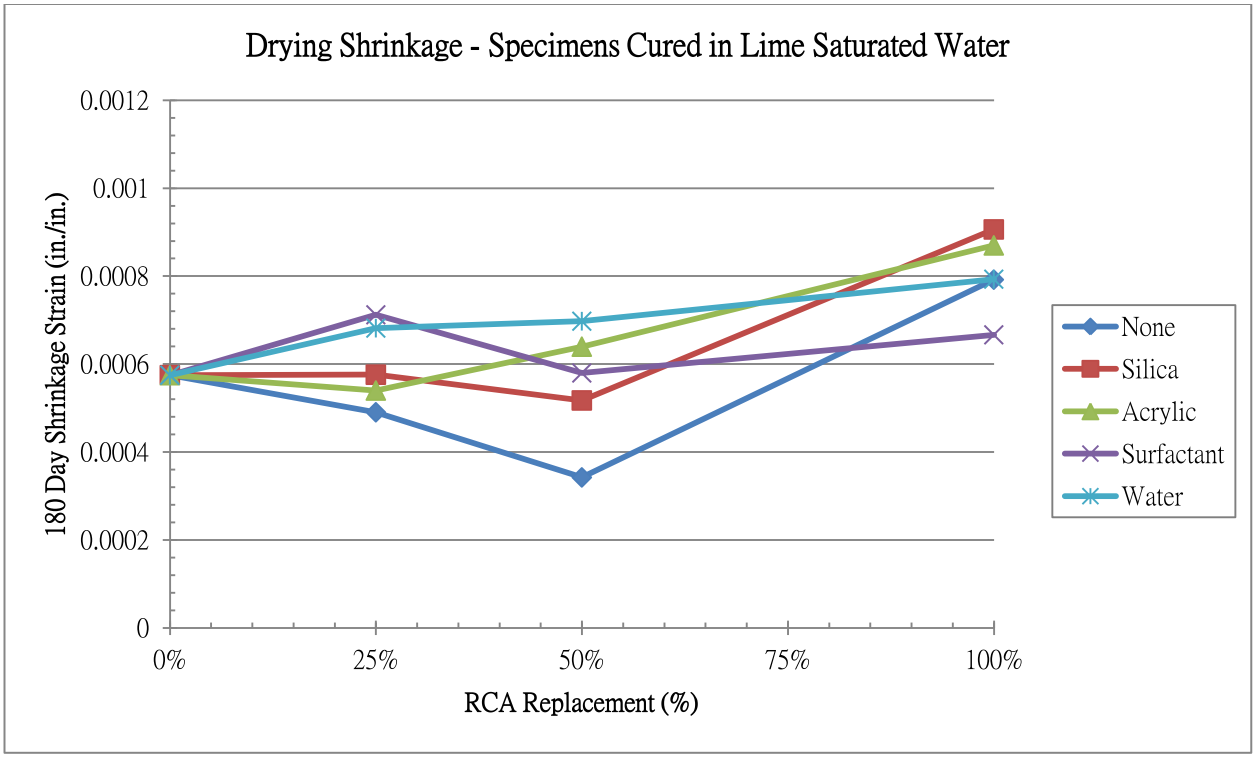

Figure 4-9. 180 day drying shrinkage of specimens cured in lime saturated water.

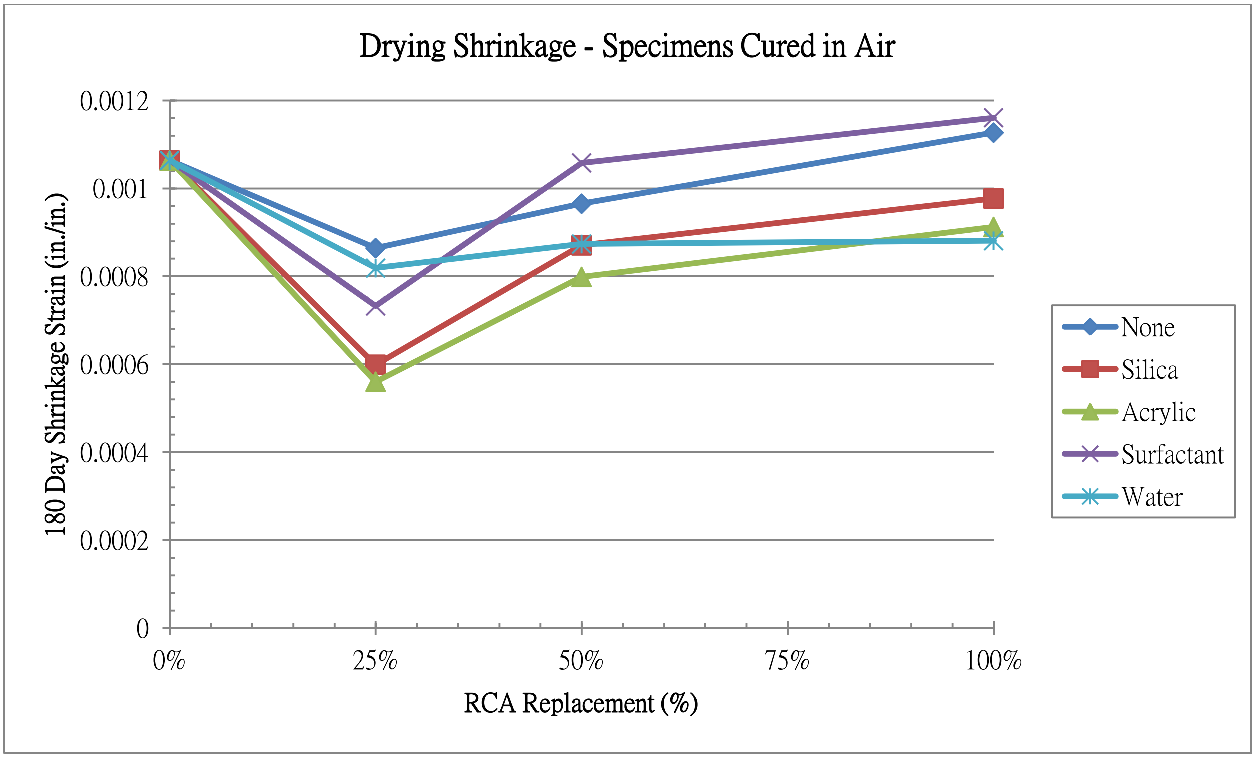

Figure 4-10. 180 day drying shrinkage of specimens cured in air.

4.5 COMPARISON OF CURING METHODS

The effect of curing method on drying shrinkage was examined for each mix combination. For specimens cured in lime saturated water, shrinkage strains were always less than those exposed to laboratory air after only 1 day in the curing room. The increase in drying shrinkage caused by exposure to laboratory air ranged from 3% to 185%, with an average increase of 44%. In each group, using 50% RCA produced the largest difference between curing methods, but the reason for this phenomenon is not clear. This effect is illustrated in Figure 4-11.

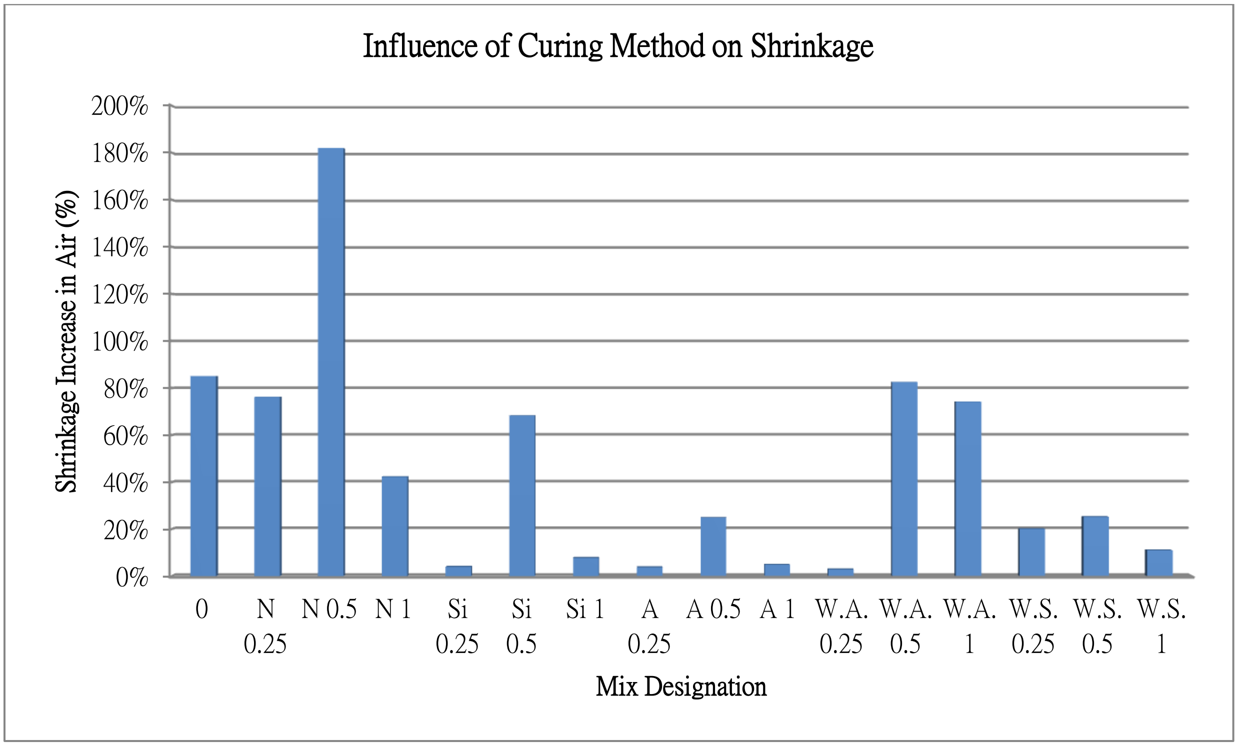

Figure 4-11. Drying shrinkage increase for specimens cured in air compared to lime saturated water.

A comparison of the effect of curing method on measured drying shrinkage at 180 days for each group is presented in Figure 4-12 through Figure 4-16.

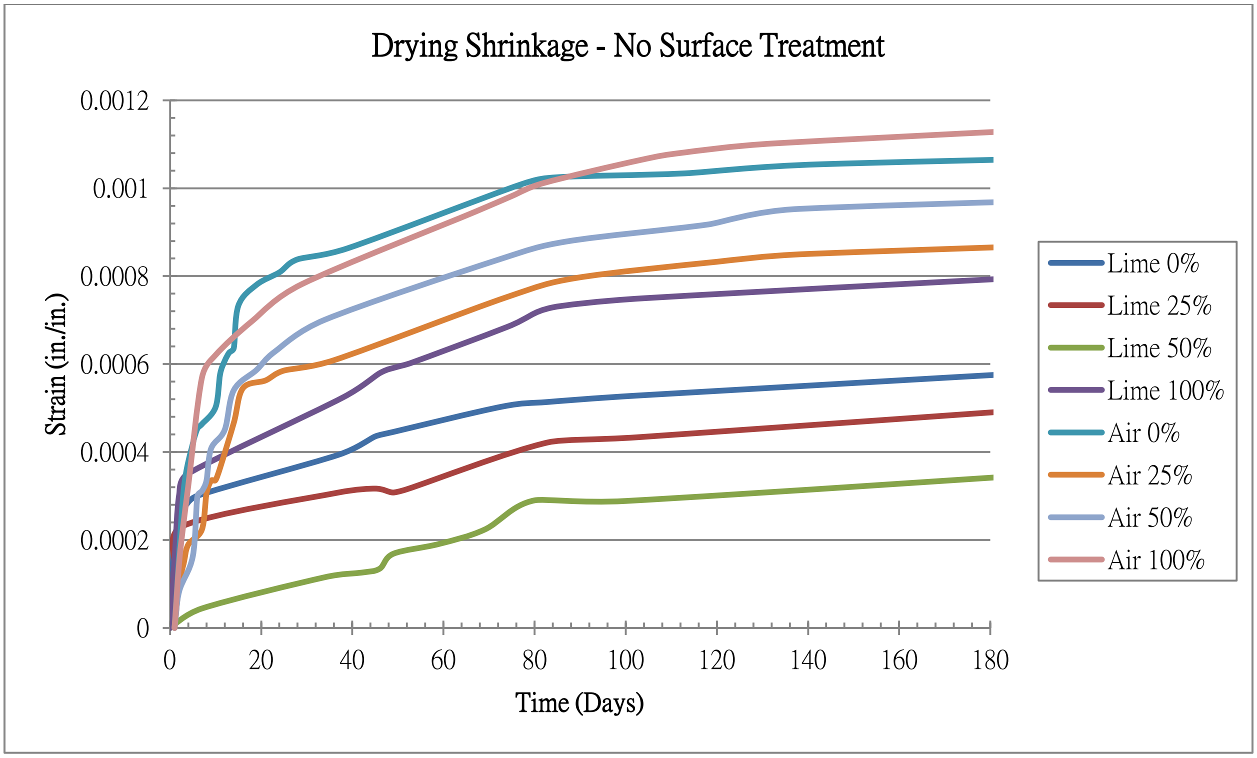

Figure 4-12. Comparison of curing method on drying shrinkage for RCA with no surface treatment.

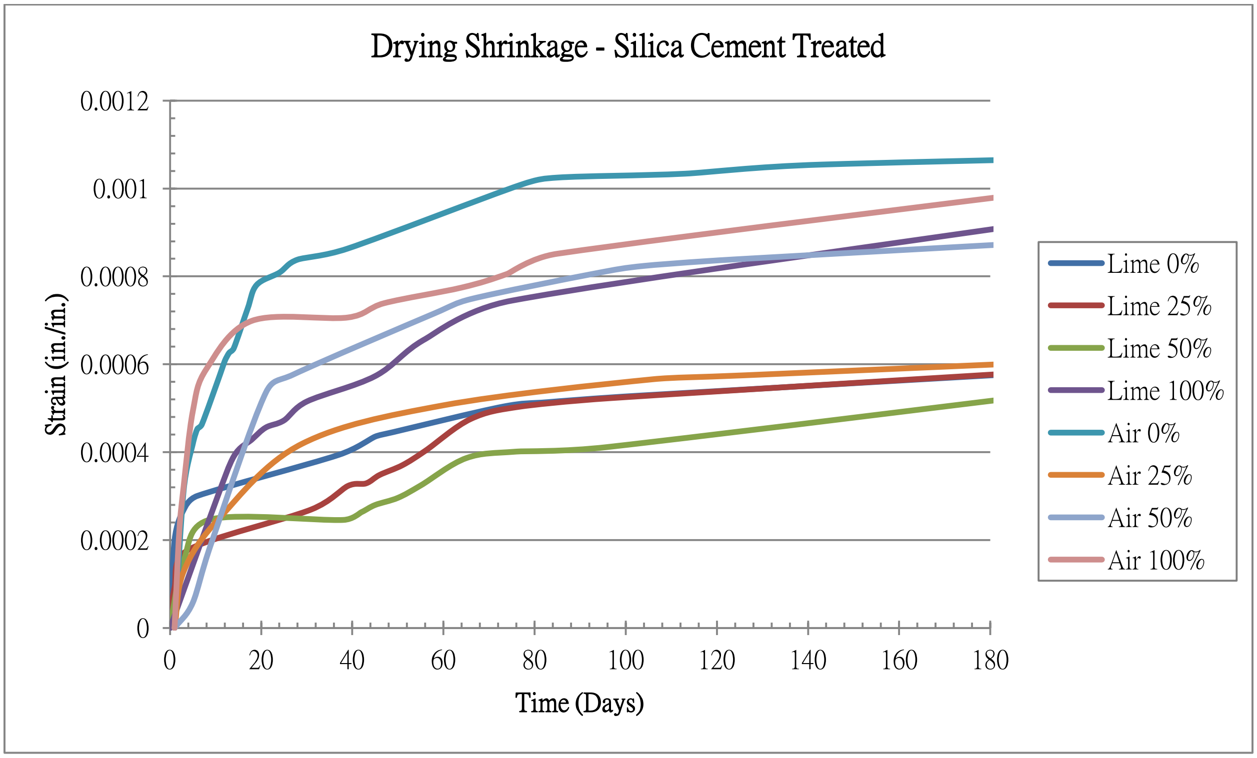

Figure 4-13. Comparison of curing method on drying shrinkage for RCA treated with silica cement.

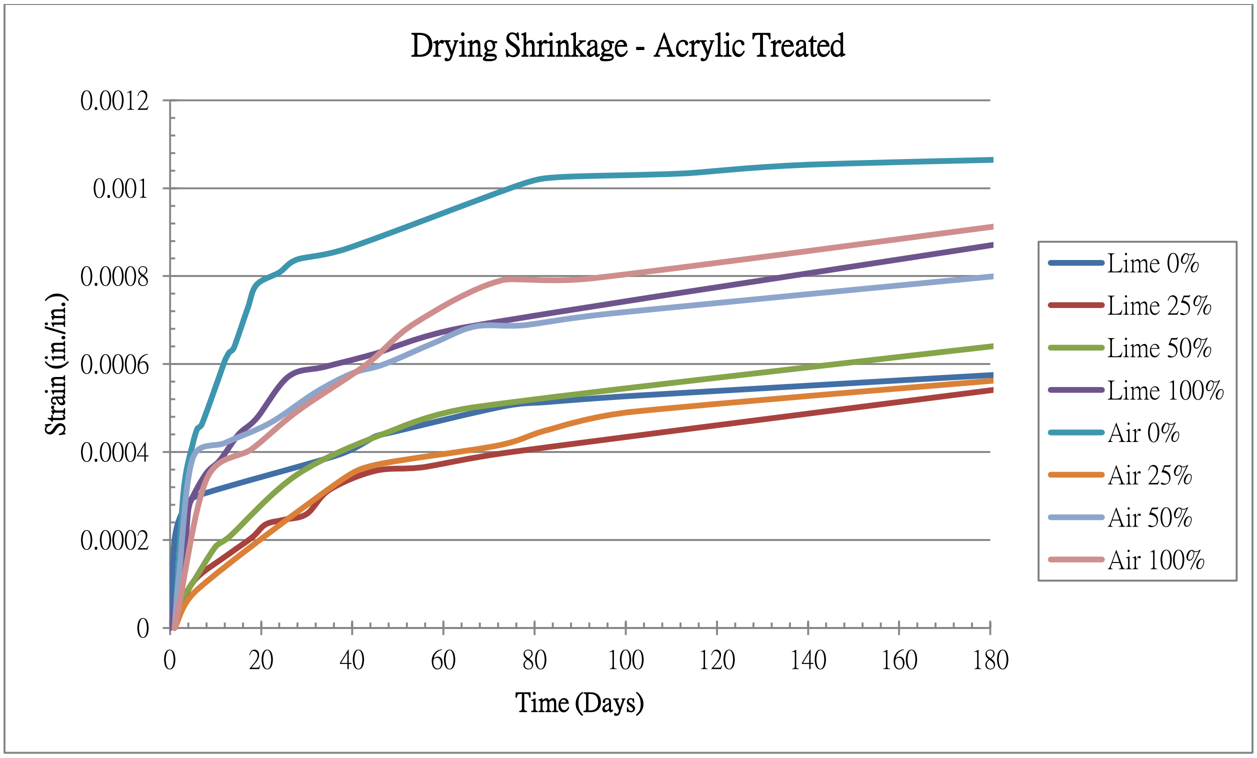

Figure 4-14. Comparison of curing method on drying shrinkage for RCA treated with acrylic.

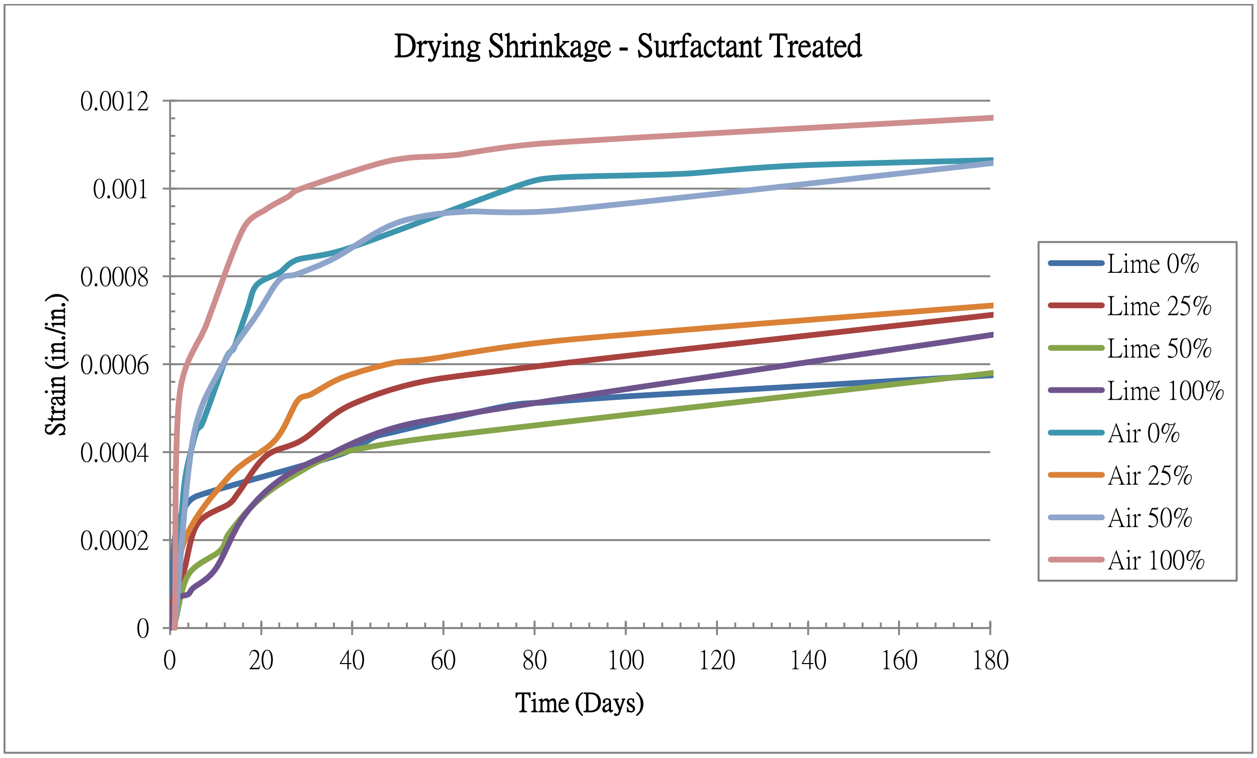

Figure 4-15. Comparison of curing method on drying shrinkage for RCA treated with surfactant.

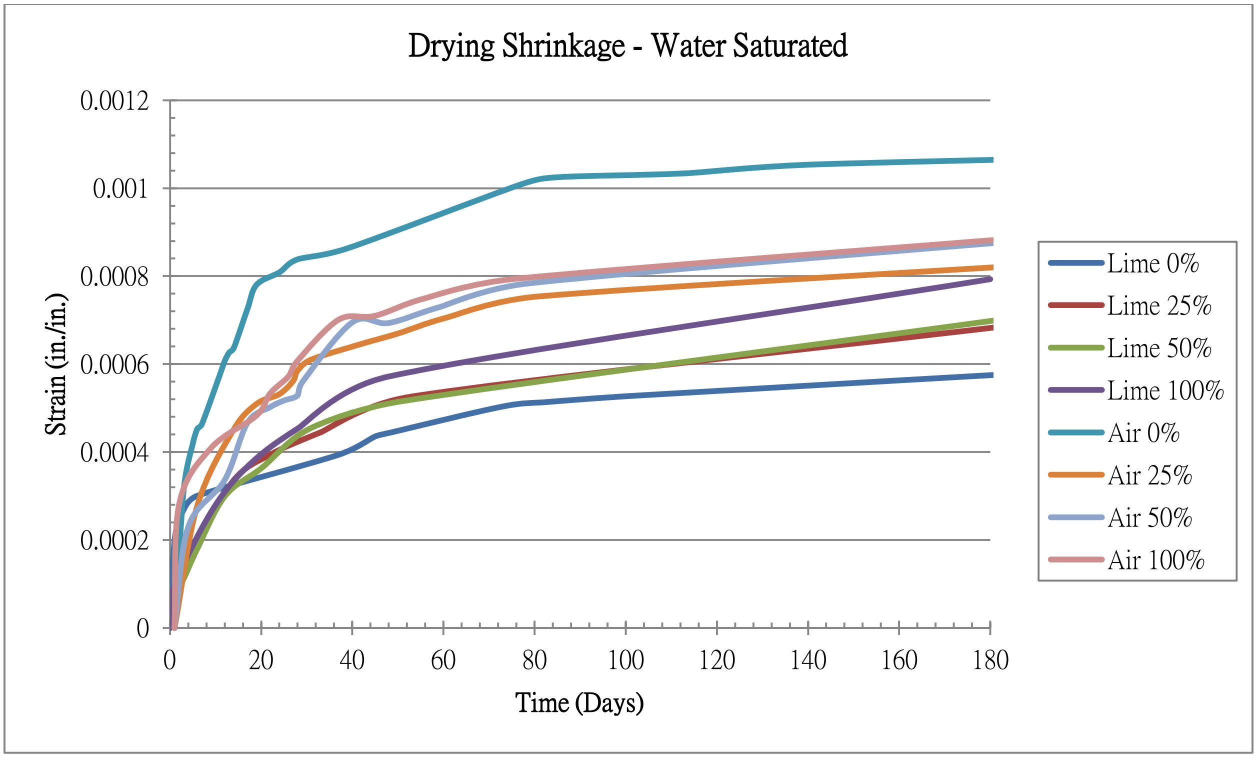

Figure 4-16. Comparison of curing method on drying shrinkage for saturated RCA.

4.6 SUMMARY

The effect of aggregate absorption was observed to produce a lower effective water to cement ratio than by only considering the amount of water added to the concrete mix. The relationship between this effect and concrete workability was clearly observed in the slump test results. The absorption of water by the recycled aggregates appeared to increase the amount of time required for compressive strength development, as the percentage of 28 day strength developed by an age of 7 days generally decreased with increasing RCA content. Coefficient of variation did appear to correlate directly with increasing RCA content, contrary to results by others, however the 100% silica cement treated RCA mix batch with very low slump values experienced poor casting quality and higher variation in compressive strength results.

Results of drying shrinkage testing were affected by the amount of RCA used, treatment method and curing method. Specimens cured in lime saturated water generally experienced similar strain values as the control mix, with an overall increase at 100% RCA replacement. Specimens containing 50% RCA replacement with no surface treatment produced the least amount of drying shrinkage of all specimens. A comparison of curing methods demonstrated that samples exposed to laboratory air produced 3% to 185% more shrinkage than when cured for 28 days in lime saturated water.

CHAPTER 5

CONCLUSIONS

5.1 INTRODUCTION

An experimental study was carried out with the purpose of examining the effects of surface treatments for recycled aggregate concrete (RCA) on drying shrinkage of concrete. The study included a background introduction on RCA for use in concrete, a review of the available literature related to the topic, an experimental testing and measurement program, and interpretation of the experimental results.

5.1.1 Recycled Concrete Aggregate

There are several environmental benefits of RCA, and include reducing landfill use due to construction and demolition waste, reducing the effects of mining for aggregates, and reducing transportation related to both. Credit is also available to designers from green building guideline programs for utilizing recycled and local materials for their projects (PCA, 2005).

RCA is produced from concrete that is demolished from structures, pavements or may be returned from a project and discharged from the truck at the plant. Accordingly, materials such as metal reinforcing, wood, plastic, and other building materials must be removed. The concrete must also contain less than acceptable amount of contaminants such as chlorides, sulfates, oil, carbonation and alkali-silica reaction (Meyer, 2009).

While RCA contains the original aggregates used in the source concrete, the distinguishing difference between RCA and natural aggregates is the layer of cement paste that remains attached to the aggregate. This paste is often much more absorptive than natural aggregate, can be weakened by the crushing process, and can contain fine material that is only loosely attached (Tam, Gao, & Tam, 2005).

5.1.2 Drying Shrinkage

The mechanisms of drying shrinkage in concrete involve the loss of excess water from the pores within the cement paste that does not react during cement hydration. The additional water is needed for workability, but water that remains after hydration takes place will begin to evaporate at a rate that depends on the environmental conditions at the concrete surface (Al-Attar, 2008). As water evaporates from concrete pores, a meniscus forms that creates capillary tension and produces stress in the concrete. This stress leads to shrinkage, and although paste and aggregate are considered fully bonded and composite, the paste phase is considered to undergo all shrinkage while the aggregate is considered stiff enough to resist shrinkage (Asamoto, Ishida, & Maekawa, 2008).

5.1.3 Surface Treatments

The experimental program involved 5 separate groups of aggregates including a control and 4 types of surface treatments. The surface treatment groups included a mixture of colloidal silica solution and cement, an acrylic waterproofing paint, a surfactant wetting agent, and the last group consisted of presaturating RCA for 24 hours prior to mixing the concrete batch.

5.2 AGGREGATE PROPERTIES

The most important difference between RCA and natural aggregates is that the adhered cement paste lowers density and increases absorption. The maximum size of aggregate tends to have an effect on these properties because larger size RCA tends to have a larger portion consist of original aggregate, while smaller sizes tend to consist of hardened cement paste (Padmini, Ramamurthy, & Mathews, 2009).

5.2.1 Aggregate Size

Particle size distribution was measured by sieve analysis, and additional natural aggregate passing the ½ inch sieve was added at a rate of 30% by mass so the distribution would match that of the RCA, a Type 57 following ASTM C33 Specifications.

5.2.2 Aggregate Density

The density of RCA has been found by other studies to be 2% to 18% less dense than natural aggregates. Measurements in the experimental program of this study found similar results with the RCA density 21% lower than natural aggregate. The silica cement mixture increased the density of RCA to only 8% below that of natural aggregate, while the acrylic treatment reduced RCA density slightly further.

5.2.3 Aggregate Absorption

The measured absorption of RCA by others ranged from 32% higher to over 23 times higher than natural aggregate. Experimental results in this study found RCA to have 5.25 times higher absorption than the natural aggregate used in the study. The silica cement treatment increased absorption to 6.85 times the value of natural aggregate, and the acrylic treated RCA still had a measured absorption value of 3 times greater than the natural aggregate.

5.3 FRESH CONCRETE PROPERTIES

The concrete mix formula was designed following the guidelines of ACI 211.1 using Type I/II cement, an initial water to cement ratio of 0.5, and RCA substitutions in the amounts of 0, 25%, 50%, and 100% of coarse aggregate in the mix. The mix water was adjusted by the measured water content of the fine aggregate to maintain a constant water to cement ratio in all mixes, however the available water was reduced by aggregate absorption and was reflected in the slump test.

5.3.1 Effective Water to Cement Ratio

The most important property regarding concrete strength is water to cement ratio. To determine the effect of aggregate absorption, the remaining free water available was calculated. The amount of water left after aggregate absorption was used to determine the effective water to cement ratio, and as expected, this value decreased with increasing RCA substitution.

5.3.2 Workability

Results of the concrete slump test showed that aggregate absorption had a significant effect on concrete workability. A clear relationship between concrete slump test results and effective water to cement ratio was observed, with the exceptions of 100% acrylic treated RCA, 50% and 100% surfactant treated RCA. These results suggested that the acrylic coating slows the rate of absorption to the extent that it does not reduce workability during mixing. Surfactant treatments appeared to be effective in increasing workability as well, probably more than necessary with slump test values of over 8 inches. The 100% untreated RCA mix and the 100% silica cement treated RCA mixture, which increased absorption, produced concrete mixes with very low slump values, and also provided difficulty casting specimens. Their use at this level of water to cement ratio is not recommended.

5.4 HARDENED CONCRETE PROPERTIES

The important concrete mechanical properties studied in this program were concrete compressive strength and drying shrinkage. The effects of surface treated and non-surface treated RCA on these properties were observed and compared.

5.4.1 Compressive Strength

Different types of surface treatments in varying RCA substitution amounts had different effects on concrete compressive strength. 7 day strengths increased from the control mix for 25% RCA replacement amounts except for the surfactant treated mix, and then generally decreased in strength from 25% to 50% RCA substitution. All mixes containing 100% RCA had lower 7 day compressive strength results than the control mix. Compressive strength results at 28 days showed improved results for most mixes, even at 50% and 100% RCA substitution, except for acrylic and surfactant treated batches.

5.4.1.1 Compressive Strength Gain

Compressive strength was found to develop more slowly with the increasing use of RCA. The control mix containing no RCA reached 99% of its 28 day strength by an age of 7 days, and the percentage of 28 day strength developed by 7 days decreased with increasing RCA content.

5.4.1.2 Compressive Strength Variation

Although other studies found variation in compressive strength results to increase with an increase in RCA content, results of this experimental program did not show a direct increase related to

RCA use. Rather, the largest increase in variability appeared related to low casting quality producing increased voids in the 100% silica cement treated RCA mix.

5.4.2 Drying Shrinkage

Drying shrinkage was measured for each batch using 2 different methods of curing. One set of specimens was cured in lime saturated water according to the method described in ASTM C157, and the other set was exposed to laboratory air after one day in the curing room. Specimens cured in lime saturated water experienced the least shrinkage from untreated RCA specimens at 25% and 50% replacement, and surfactant treated RCA specimens experienced the least shrinkage at 100% replacement.

5.4.2.1 Comparison of Curing Methods

Specimens cured in lime saturated water experienced less shrinkage than specimens exposed to laboratory air. Those cured in lime saturated water as a group generally experienced the least amount of drying shrinkage at 50% RCA replacement, while the group exposed to laboratory air experienced the least amount of shrinkage at 25% RCA replacement. The largest increase in shrinkage between the types of curing methods occurred in the 50% RCA replacement group. The difference in results between methods is most likely due to water held within RCA pores being available to slow the evaporation process in specimens exposed to a dry environment.

5.5 EFFECTS OF RCA SURFACE TREATMENTS

Each type of surface treatment was selected with the aim of altering the surface characteristics of the RCA. The effects of surface treatments were evaluated based on concrete workability, compressive strength, and drying shrinkage results.

5.5.1 No Treatment

The control mix, which did not contain any RCA or surface treatments, contained an angular crushed granite coarse aggregate with 30% pea gravel added by weight to match the size distribution of the RCA. The higher absorption rate of RCA with no surface treatment caused a resulting decrease in effective water to cement ratio, which was apparent in the decreased workability with increasing RCA content.

The 7 day compressive strength was slightly lower than the control mix except at 25% RCA replacement which was higher. Compressive strength at an age of 28 days improved for all substitution amounts. Drying shrinkage of untreated RCA improved over the control mix under both types of curing methods for 25% and 50% RCA replacement, but increased at 100% RCA in both methods. Based on these results, the use of untreated RCA at replacement amounts of 25% seems feasible if the decrease in workability can be tolerated. RCA Replacement amounts above 25% are not recommended due to casting problems caused by reduced workability.

5.5.2 Silica Cement

A mixture containing colloidal silica and cement was used to coat the surface of RCA with the intended purpose of filling pores of the old cement paste and providing a suitable bonding surface for the new cement paste. The use of this treatment increased the RCA density, but also increased absorption as well. This behavior was evident in the results of concrete slump tests and casting quality of specimens.

Compressive strength of silica treated RCA mix increased over the control mix, with the exception of the 7 day strength of the 100% RCA mix. The 28 day strength of the 100% RCA mix however, was the highest of the group, and also had the slowest developing compressive strength in the group, and the highest coefficient of variation in compressive strength data. Drying shrinkage decreased from the control mix for both types of curing methods at 25% and 50% RCA replacement using this treatment. Drying shrinkage also decreased for 100% RCA specimens exposed to air after 1 day, but increased from the control mix for specimens cured in lime saturated water. Based on these results, this surface treatment is effective at increasing compressive strength and reducing shrinkage, however, a higher water to cement ratio would need to be used for the mix to be practical to use. The poor casting quality experienced, especially by using 100% RCA, was due to the higher absorption caused by the surface treatment. The many voids present in specimens were also likely to contribute to faster drying and development of shrinkage in these specimens.

5.5.3 Acrylic

An acrylic based concrete waterproofing paint was applied as an RCA surface treatment with the intent of reducing the absorption characteristics of the RCA. The treatment did reduce absorption, but not to the level of natural aggregate. The reduction helped improve workability compared to untreated and silica cement treated aggregates, with a slight increase in slump with increased RCA use.

This treatment increased compressive strength only at 25% RCA replacement to the highest tested value of all groups, while it decreased compressive strength at all other replacement amounts. Compressive strength behavior may have been affected by a loss of bond between the new cement paste and acrylic surface of RCA. Drying shrinkage decreased from the control mix only for 25% RCA replacement specimens exposed to air, while it decreased to the lowest level of all groups at the

25% and 50% replacement levels for specimens cured in lime saturated water. Based on these results, this type of treatment was effective at producing the highest compressive strength and lowest drying shrinkage at the 25% replacement level, but actually produced negative effects at other replacement levels. The cost of this type of treatment, however, may be too high to be practical in a large-scale production environment.

5.5.4 Surfactant

A type of surfactant known as wetting agent was used to pre-treat the surface of RCA to reduce the surface tension of water in the pores of the old cement paste. This type of treatment caused a large increase in concrete workability and also a large increase in the number of bubbles in the fresh concrete.

Compressive strength decreased for all RCA substitution amounts using this treatment method except 50% which increased slightly. This method produced the lowest compressive strength at 25% and 100% RCA replacement for all groups. For specimens cured in lime saturated water, the surfactant increased shrinkage strains for all substitution amounts. For specimens exposed to air, this treatment only improved shrinkage at the 25% replacement level. Based on these results, this particular treatment is likely not effective as an RCA surface treatment due to the negative effects on compressive strength and shrinkage.

5.5.5 Water Saturated

The effects of soaking aggregates prior to mixing were studied to counteract the effects of RCA absorbing more water from the mix than natural aggregates. This type of treatment was effective at improving concrete workability, and the available water available for cement hydration was not reduced by absorption of RCA.

Compressive strength increased slightly at 25% replacement, and decreased slightly with increasing RCA replacement. This result is reasonable as the effective water to cement ratio increases slightly with each increase in RCA content. The drying shrinkage of water saturated RCA specimens cured in lime saturated water experienced higher shrinkage than the control mix, but those exposed to laboratory air experienced less shrinkage than the control mix. Based on these results, the use of water saturated RCA may be effective, but if concrete receives complete curing in a moist environment, it will likely experience greater shrinkage strains than in if exposed to a dry environment.

5.6 EFFECT OF RCA QUALITY

Although water to cement ratio is considered the most important factor in determining concrete strength, there are several other factors involved when using RCA in concrete, one of the most important being the quality of the RCA used. The water assumed to be available for cement hydration after aggregate absorption takes place may be calculated and accordingly adjusted, however the properties of strength, air content, and shrinkage potential of RCA may also depend on the attached cement paste. If there is a large amount of fine material loosely attached to the surface of RCA, then bond to the new cement paste may be reduced. Similarly, a large number of voids or high air content of the adhered old cement paste may reduce strength, creating a zone of weakness.

Drying shrinkage can similarly be affected by the quality of RCA used. The cement paste is the phase of concrete that is considered to shrink, while the aggregate is considered to resist shrinkage. When using RCA, a portion of the aggregate also contains paste, and if the RCA contains a large portion of cement paste, a larger proportion of the new concrete will consist of the paste phase as well. This may contribute to more shrinkage susceptibility of the concrete. Besides limiting contaminants and foreign materials in RCA, specific quality requirements should be made that take into consideration the intended use of the new concrete in the project, including acceptable tolerances.

5.7 RECOMMENDATIONS FOR FURTHER STUDY

There are many opportunities for improvement in the field of studying RCA concrete including materials, testing and analysis. Because quality of RCA is critical to the performance of RCA concrete, further testing on the material properties would be valuable. Such testing would potentially include compressive strength of the aggregate, proportion of adhered cement paste, and evaluation of how angular aggregates are.

Several types of materials including concrete additives or cement replacements are available and currently used that further promote the concept of using waste materials in concrete. If additional water is required for workability as shown in this study and others, the opportunity would exist to explore the use of more supplementary cementitious materials such as fly ash, slag, silica fume, and pozzolanic materials. RCA fines have also been given limited study, and although their use has been largely dismissed, but there may be applications where some portion of fine aggregate may be replaced with RCA fines with acceptable results.

Further testing would be useful to determine the exact properties of RCA that cause different effects in RCA concrete, as well as helping to establish RCA property requirements. More long term study on RCA concrete will help determine whether it could also be used for higher quality applications. Testing on RCA concrete would potentially include more long term shrinkage study, freeze-thaw durability, air content and permeability testing. A similar study using the same effective water to cement ratio, or using the necessary amount of water to maintain a constant slump for all mixes would help determine properties of RCA concrete that would be more practical for construction use.

5.8 SUMMARY

An experimental study was carried out to determine the effects of increasing amounts of recycled concrete aggregate (RCA) and surface treatments on the properties of concrete containing RCA. The benefits of this material include both environmental and economic factors regarding reducing landfill use, mining, and transportation.

The experimental program included cement, fine aggregate, natural and recycled coarse aggregate in varying amounts, and surface treatments. Surface treatments used included none, silica cement mixture, acrylic, surfactant solution, and water. Tests and measurements were conducted to determine aggregate, fresh concrete, and hardened concrete properties.

The aggregate properties studied included size distribution, density, absorption. The density of RCA was found to be 21% lower than natural aggregate, while absorption was found to be 5.25 times higher. The use of surface treatments was studied as a means to alter these characteristics. The silica cement mixture raised density and absorption, acrylic lowered both, and the two liquid treatments were assumed to prevent further absorption without affecting density.

Fresh and hardened concrete properties examined included slump, compressive strength and length change. The use of some of these methods appears feasible based on the experimental results, while others are not due to negative effects. The use of untreated RCA at 25% replacement appears feasible due to improved compressive strength and drying shrinkage results, however a reduction in workability was experienced due to the increased aggregate absorption. The use of the silica cement mixture at a water to cement ratio of 0.5 is not recommended because of the poor workability due to the increased absorption. The use of acrylic as a surface treatment may be effective at 25% RCA replacement because of improved compressive strength and shrinkage results, however this method may not be cost effective in large scale use. The use of surfactant does not appear to be effective in this application at this particular dose, despite improved workability, due to negative effects on concrete strength and shrinkage. The use of water saturated RCA may be feasible if it is used in a dry environment, but may experienced larger shrinkage strains if it receives proper curing.

The quality of RCA is critical to achieving desirable properties in RCA and must be considered along with intended use, purpose, and environment of the final product. Additional testing may be needed in order to determine the quality of concrete to be used in higher quality applications. Additional testing may potentially include tests on aggregates such as compressive strength, shape, and amount of adhered mortar. Tests on concrete may potentially include more long term shrinkage study, freeze-thaw durability, and permeability.

CHAPTER 6

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