THE EFFECTS OF LIMESTONE POWDER PARTICLE SIZE ON THE MECHANICAL PROPERTIES AND THE LIFE CYCLE ASSESSMENT OF CONCRETE

by

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ABSTRACT

The major environmental impact of concrete comes from the CO_2 emissions during cement production. The main goal of this research project is to develop an optimized cement replacement to reduce energy consumption and CO_2 emissions. This is tested by replacing cement with limestone powder and the implementation of limestone powder in concrete to meet construction specifications. This study utilizes limestone powders with different particle sizes to replace a part of portland cement in various replacement levels. Studying the microstructure of the limestone powder in concrete with a petrographic examination can provide a visual understanding of the distribution within the cement paste. Due to the dilution effect, partially replacing cement, there is a reduction in the physical properties of concrete. To assess the dilution effect, a modification to Féret's equation is used to calculate an efficiency factor of the limestone powder in comparison to cement. To measure the environmental impact, a life cycle assessment is conducted on concrete with limestone powder. This allows for an evaluation that maximizes the environmental benefit and with minimal reduction in concrete strength.

I. INTRODUCTION

1.1 Overview

The major environmental impact of concrete comes from the CO_2 emissions during cement production. The manufacturing of cement contributes to the third largest source of carbon emission in the United States and is responsible for the approximately 5% of global CO_2 emissions (Huntzinger & Eatmon, 2009). As the focus on sustainable construction is increasing in North America, replacing a portion of the ordinary portland cement (OPC) with pozzolans, or environmentally friendly filler materials can be used to reduce the effects on the environment. By optimizing the mixture design, both the cost and the environmental impact of concrete can be reduced (Proske, Hainer, Rezvani, & Graubner, 2014).

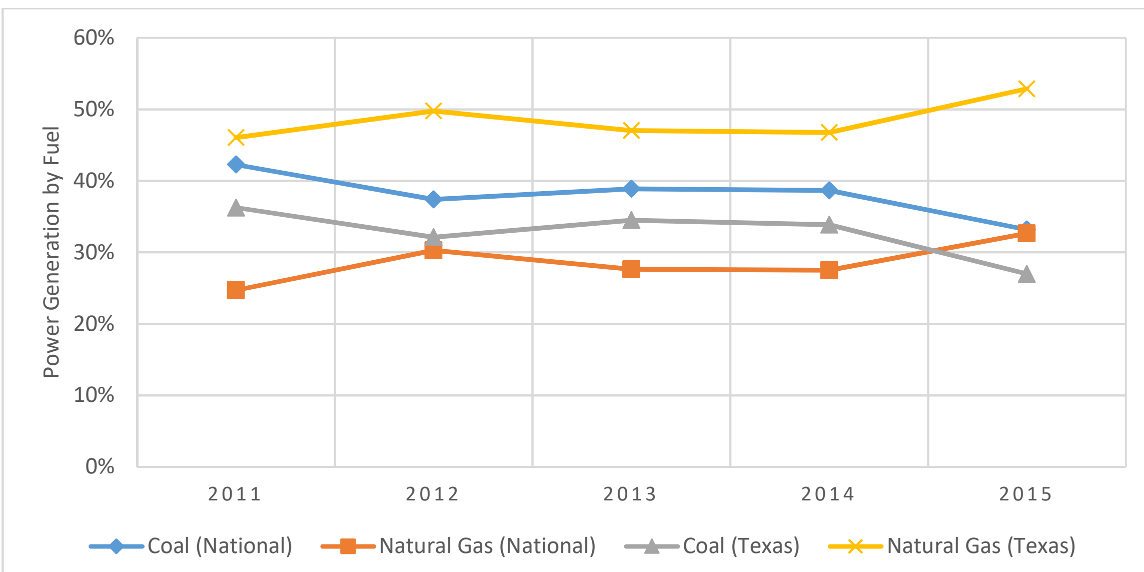

Figure 1. Percentage of Power Generation by Fuel.

Fly ash is widely used as a cement replacement because of the cementitious and pozzolanic properties. The combustion of coal produces fly ash for power generation and depending on the source of coal used it might have different properties. Class C fly ashes typically have a higher calcium oxide (CaO) content that has cementitious and pozzolanic properties and is normally produced from burning lignite or subbituminous coal. Class F fly ash is typically produced from burning anthracite or bituminous coal and contains more silicon dioxide (SiO_2), aluminum oxide (Al_2O_3) and iron oxide (Fe_2O3) (ASTM C618, 2015). The use of natural gas for power generation has reduced the availability of fly ash. Power generation from coal as a fuel has been reduced by 9% in the United States from 2011 to 2015, and by 10% in Texas, as indicated by Figure 1 (U.S. Energy Information Administration, 2016). The demand for cement and concrete is continuing to rise resulting in a 37% increase in Texas from 2011 to 2014. This demand is expected to continue to rise, as numbers indicate an additional increase for a demand of 24% between 2014-2018. With a current production capacity of 17.2 million tons, the cement demand in Texas is expected to exceed the production capacity during in the projected timeframe (Prusinski, 2014).

1.2 Problem Statement

As urban expansion continues to grow, the increasing demand for concrete may exceed the cement production capacity. The use of supplementary material in concrete to replace portions of cement is important to meet demand and reduce the environmental impact of cement production. The use of fly ash has been the long industrial standard used as a cement replacement. But as the use of natural gas for power generation and green energy gains popularity, the availability of fly ash is continuing to reduce as less coal is burned at power plants. Thus an alternate is needed. Most research focuses on inter-ground limestone, this study focuses on the mechanical properties and feasibility that calcium carbonate ($CaCO_3$) or limestone powder can be used as a cement replacement while batching concrete. The use of limestone powder during the batching process will be investigated for the mechanical and environmental effects that the particle size and replacement level have on concrete for optimal performance.

1.3 Assumptions

Cement and limestone powder used to conduct this study are materials that are manufactured, and characteristics like the composition and particle size are provided by the manufacturers. Materials are assumed to meet ASTM specification and that the manufactures specification is correct. The mixing process is done in accordance with ASTM C192, with the modification of adding limestone powder (ASTM C192, 2015). Adding all the cement to mix first to coat the aggregate is assumed to provide a better bond between aggregates and cement paste. For the purpose of conducting a life cycle assessment (LCA), all transportation is assumed to be by road and use diesel fuel. The round-trip haul distance to and from the cement manufacturing plant and the limestone powder are estimated to be 60 miles and estimated to be 30 miles for aggregates to and from the quarry. Emissions for the production of limestone powder is provided by the manufacturer. However, there is only emissions data for the 4 µm and 8 µm particle size limestone powder. Because the manufacturing of the 15 µm particle sized limestone powder requires less progressing, the emissions data is assumed to be half of 8 µm particle size.

1.4 Limitations

Materials used in the study meet ASTM standards, but are produced and sourced locally, and may not be attained in other regions. The experiment was conducted in a controlled testing environment of a laboratory. Environmental factors like humidity, temperature, and other external factors limits the validity to other settings. The particle size of the limestone powder used in this experiment is limited to the three sizes produced by the manufacturer. The particle sizes are manufactured to a nominal size of 4.5 µm, 8 µm, and 15 µm limestone particles.

1.5 Delimitations

Because concrete has a broad range of application, this study does not include details for the use for which this concrete is being created. The scope of the study covered the concrete production until it is batched and loaded ready to be delivered. The data from this study, however, can be used for any future projects or applied to case studies to conduct specific research. Due to the complexity of conducting LCA, this experiment does not cover the resources required to produce and acquire solid fuels used in the kiln, diesel used for transportation of materials, energy, water and any special additives used in the cement manufacturing and concrete production. Due to limited information available on the interaction between limestone powder and additives used in concrete, no additional additives were used.

II. LITERATURE REVIEW

Limestone, also known as calcium carbonate ($CaCO_3$), has long been used as a critical component of concrete. The use of limestone powder as a cement replacement has also been used in Europe as early as 1965. By inter-grounding limestone with cement clinker, the use of portland-limestone cement (PLC) is a common practice in Europe (Schmidt, 1992). Only in recent years has the U.S. standards incorporated the use of inter-ground limestone in the ASTM (American Society for Testing and Materials) standard and specification for portland cement. ASTM C150 allows for up to 5% limestone powder in Type I cement (ASTM C150, 2015). ASTM C595 is the standard specification for blended hydraulic cements and allows for the incorporation of up to 15% limestone by mass in the blended cement as Type IL (ASTM C595, 2015). Even with the ASTM standards allowing the use of portland limestone cements, the manufacturing of these cements are limited and not widely available in the United States.

The introduction of limestone to concrete can be done like other pozzolanic materials by incorporating the limestone powder directly in the mixing design. This process is an alternative to inter-grounding the limestone with the cement, and the limestone powder can be mixed in with the concrete while batching. Replacing cement with limestone powder, when batching concrete, means that the limestone powder and cement are made separately, and their physical properties are different. The particle size, surface area, or distribution of the limestone powder may differ, and therefore, needs to be controlled.

2.1 Mechanical Properties and Durability

By replacing part of the cement with limestone powder, it will provide additional surface for precipitation of hydration, while also decreasing the amount of water needed to keep the concrete workable (Bonavetti, Donza, Menendez, Cabrera, & Irassar, 2003). According to

Barbara Lothenbach, blending ordinary cement with limestone was found to accelerate the initial hydration reaction and also influenced the hydrate assemblage of the cement pastes. This enhanced the hydration of the clinker by the filler effect, rather than its influence on the chemistry. Thus, indicating that limestone powder has little effect on the temperature of the fresh properties of concrete (Lothenbach, Le Saout, Gallucci, & Scrivener, 2008). Limestone powder, however, is not an entirely inert filler; as there is a small interaction between tricalcium silicate (C_3S) and $CaCO_3$, there is no pozzolanic reaction and does not produce calcium silicate hydrate (CSH) gel (Ramezanianpour, Ghiasvand, Nickseresht, Mahdikhani, & Moodi, 2009). Limestone powder in the binder phase of a mixture improves the particle packing efficiency because of its particle size, which results in the reducing of water demand that improves the workability. The improved particle packing efficiency also reduces bleeding in the hardened concrete blocking capillary pores, which reduces penetrability and improving the durability (Githachuri & Alexander, 2013).

Concrete undergoes shrinkage as it dries as a result of the hydration or evaporation process. Shrinkage can lead to cracking and in severe cases can cause structural problems. The volume and gradation of aggregates in concrete contribute to the effects of shrinkage. Using larger volumes of aggregates can minimize the potential for this and provide particle-to-particle structure (Barksdale, 1991). Separate grinding of the limestone and clinker provides greater opportunity to optimize the particle size distribution.

2.2 Effects on Concrete Composition and Compressive Strength

Many models describe the relationships between mix composition and properties of concrete compressive strength. But the mix composition of concrete does not only include cement as more materials are used to replace cement in concrete. Cement concentrations are still a major factor that determines compressive strength. There are multiple popular models like Féret's equation, Bolomey's formula, and Abrams' formula that focus on the relationship between water and cement and the compressive strength. These models can also be used as predictive models based on the water and cement content to predict the compressive strength. F. de Larrard documents the accuracy of these models and compares the models to the same data sets (Larrard, 1999). Féret's equation that uses absolute volumetric proportions of cement, water and air had the lowest mean error of 1.2 MPa when compared to the data sets. Bolomey's formula that uses a linearized form of Féret's equation, which does not account for the air content, had a mean error of 1.4 MPa (Bolomey, 1935). The mean error of compressive strength for Abrams' formula was 2.1 MPa, an exponential equation that focuses on the 2 adjustable parameters and the water/cement ratio (Abrams, 1919).

All three models provide good approximations to present data. The strength of concrete is not only determined by the cement paste but also other factors. The design of the three models incorporates the use of empirical constants that varies with concrete strength for any given set of aggregates and processing equipment used (Gan, 1997). The empirical constants in the models can adjust for concrete containing additional materials, such as fly ash and limestone powder, but it does not isolate the effect on the model. Abrams' and Bolomey's formulas only focus on the relation between cement and water to determine the strength. But the strength of concrete is not just controlled by the relation of cement and water. There are other factors such as air content. The volumetric approach by Rene Féret's model incorporates more elements of concrete that determine the strength (Féret, 1892). To isolate the efficiency of limestone powder in concrete, an extension of Féret's equation can be used because it takes the air content into account and it has a mathematical form that's physically justified by the use of absolute volume.

$Féret's\ Rule:$

$$f_c = K\left(\frac{c}{c+w+a}\right)^2 \qquad \text{(Eq. 1)}$$

$Where:$

$f_c = Compressive\ stregth\ (PSI)$

$c = Cement\ (ft^3/yd^3)$

$w = Water\ (ft^3/yd^3)$

$a = Air\ (ft^3/yd^3)$

$K = Empirical\ Constant$

The general rule formulated by Rene Féret in 1896 relates the strength of concrete to the water and cement and is determined by the volumetric proportions in of the cement, water, and air. In this expression, the volume of air is also included because it is not only the water/cement ratio but also the degree of compaction, which indirectly means the volume of air filled voids in the concrete is taken into account in estimating the strength of concrete (Féret, 1892). The relation between the water/cement ratio and strength indicates that lower water/cement ratio results in stronger concrete given minimum air voids. When the water/cement ratio is below the practical limit, the strength of the concrete falls rapidly due to the introduction of air voids. If a graph is drawn between the strength and the cement/water ratio an approximately linear relationship will be obtained. (Neville, 2011).

2.3 Sustainability

Concrete is one of the most widely used construction materials, and its production impacts the environment in a number of ways. The acquisitions and quarrying of large quantities of raw materials and aggregates, to meet demand for concrete, depletes natural resources. Cement is the primary bonding material that consists of calcareous material such as limestone or chalk, and from alumina and silica found as clay or shale (Neville, 2011). Geographically these materials are found all over the world, and nearly in all countries, making it one of the most common materials used for construction.

Producing cement starts with obtaining raw materials from a quarry. The materials are processed or crushed and reduced to a fine powder that is dried. The raw material is then blended to consist of the right portions of the lime, silica, alumina, and iron oxide. Next, the raw materials are preheated before entering a large rotary kiln that is fueled by pulverized coal that is 1450 degrees Celsius. The raw materials fuse into little balls known as clinker. The clinker is cooled, and gypsum is then added to control the setting of the cement before the final grinding process that results in the final product of portland cement (Neville, 2011).

The manufacturing of cement is not very efficient. There is a release of CO_2 in cement production primarily due to the calcination of the limestone, as approximately 1.6 metric tons of raw materials are needed to make 1 metric ton of cement (Nisbet, Marceau, & VanGeem, 2002). Roughly 40% of raw materials are lost in the creation process. By implementing limestone powder as a replacement for cement, the environmental effect can be reduced. However, the reduced effects will differ based on the particle size of the limestone powder used. This is because fine limestone powder requires additional milling. Using limestone powder with a particle distribution of about 8 μm, produce approximately 54 pounds of CO_2 per ton produced. Whereas, a finer particle size of about 4.5 μm produces about 200 pounds of CO_2 per ton. (HuberCrete, 2015). That is only 3.4% to 12.5% of the CO_2 emissions compared to manufacturing a ton of cement, making it very sustainable as the major environmental impact of concrete comes from the CO_2 emissions during cement production.

III. RESEARCH DESIGN AND METHODS

The problem of this study is to experimentally analyze the effect that $CaCO_3$ or limestone powder has on the fresh and hardened properties, based on the level of replacement of cement and the particle size used in the concrete mix designs. The purpose of this study is to develop information, specifically concerning $CaCO_3$ and the effects it has on the mechanical properties. Understanding this will enable the concrete industry to utilize $CaCO_3$ as a cement replacement to offset some of the environmental effects that are associated with cement manufacturing. Separate grinding of the limestone and clinker provides greater opportunity to optimize the particle size distribution and to ascertain what levels of $CaCO_3$ and particle size used are advantageous for the physical properties and environmental effects.

The focus of this study is to evaluate both the mechanical properties and environmental effects in conjunction with each other to utilize limestone powder in concrete. Because of the dilution effect on the mechanical properties, to find an optimal solution a life cycle analysis is required. As the limestone powder is manufactured separately, the effects of the particle size also have to be considered in both the mechanical properties and environmental effect. Figure 2 shows a flow chart of the environmental and mechanical properties that are analyzed.

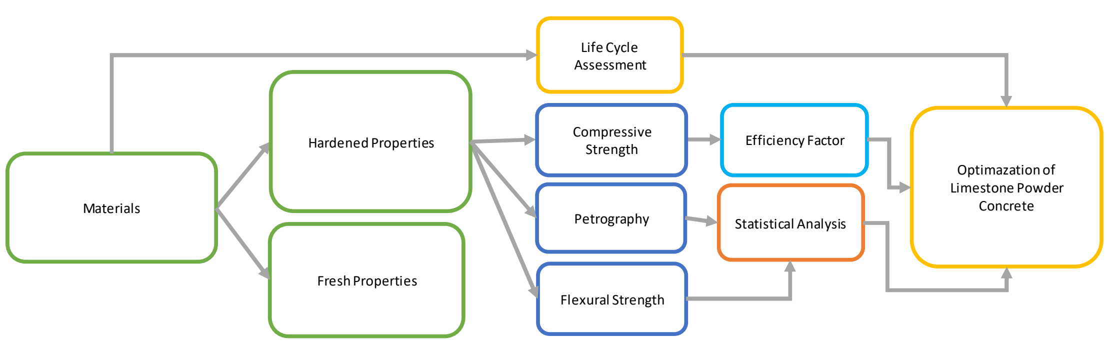

Figure 2. Research Design Flow Chart.

3.1 Materials

Type I ordinary portland cement (meeting ASTM C150 specifications) is used and replaced partially with limestone powder or calcium carbonate ($CaCO_3$) powders that differ in particle size. The percentages of limestone powder replacement are 10%, 20%, and 30% by mass of the cement. The particle size consists of 4.5 µm, 8 µm, and 15 µm limestone powder. A particle distribution is indicated by Figure 3 and shows the range of particles that are present for each nominal size. The range of the particle sizes is greater in the larger nominal sizes. The concrete mixture includes using natural river gravel, and river sand with fineness modulus of 2.68. The cement to water ratio of 0.40 is kept consistent in with all batches and is calculated from the total amount cement and limestone powder used.

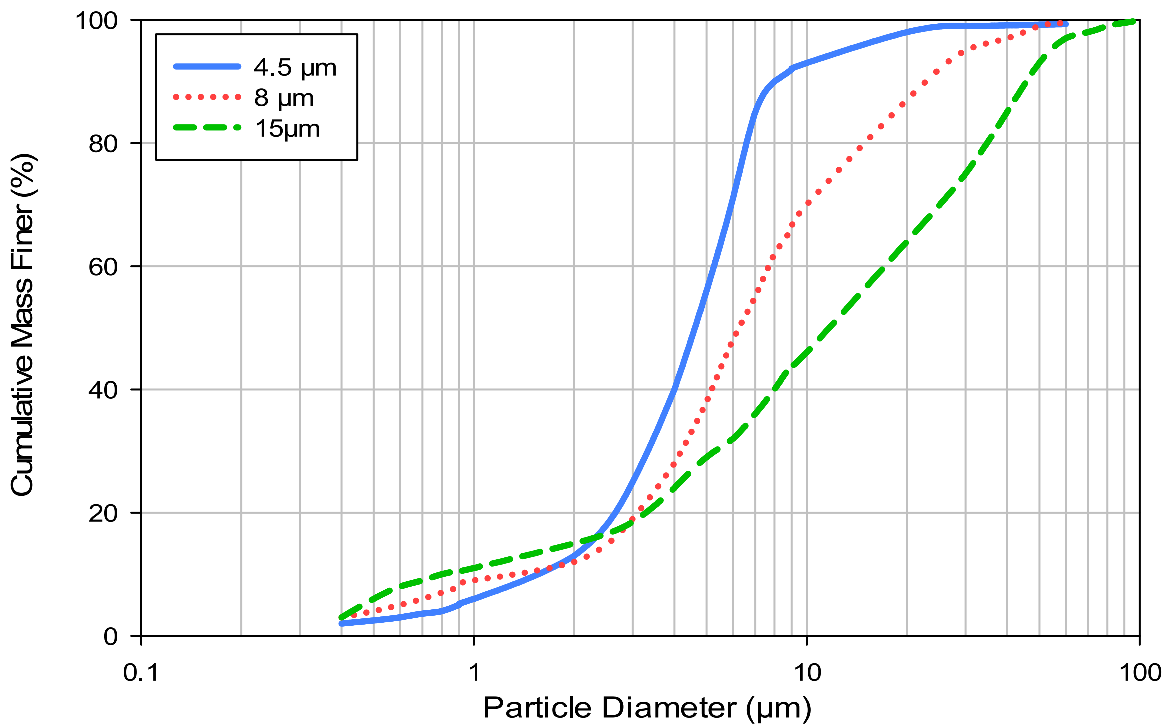

Figure 3. Limestone Powder with a Particle Distribution by Size.

In each series, cylindrical and beam specimens are produced. Three different cement intervals and different particle sizes of limestone are introduced (4.5 µm, 8 µm, and 15 µm). The mixture design is shown in Table 1. The concrete is mixed in accordance to ASTM C192, and the cement is added to the drum mixer before adding the limestone powder (ASTM C192, 2015). Once the concrete is mixed, it is then tested for fresh properties. Fresh properties include the workability along with the new density, temperature, and air content. The concrete mixtures are then cast into molds that are rodded to create uniform specimens for testing. After one day of casting, the specimens are de-molded and cured in 100% humidity at 72 degrees Fahrenheit until testing.

Table 1. Mix Design.

Mix Design (lb/yd³)	Control	Alpha-10	Beta-10	Gamma-10	Alpha-20	Beta-20	Gamma-20	Alpha-30	Beta-30	Gamma-30
Cement	587	528	528	528	469	469	469	411	411	411
Limestone Powder	-	59	59	59	117	117	117	176	176	176
Water	235	235	235	235	235	235	235	235	235	235
River Gravel	1716	1716	1716	1716	1716	1716	1716	1716	1716	1716
River Sand	1205	1205	1205	1205	1205	1205	1205	1205	1205	1205
w/c	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4

*Alpha - 4.5 µm   *Beta - 8 µm   *Gamma - 15 µm

3.2 Mixing Procedure

Both coarse and fine aggregates are retrieved from its respective barrels. Each is kept under controlled temperature conditions in a laboratory setting to keep aggregate temperatures constant. The moisture content of the aggregates present in the barrels is greater than the absorption because water was added to the aggregates. Twenty-four hours before mixing concrete, the moisture content of the aggregates is tested by oven drying to the standard of ASTM C566 (ASTM C566, 2013). This ensures the amount of free water and water added to the batch when mixed can be calculated and properly adjusted to keep the water cement ratio constant. The mixing process was done in accordance with ASTM C192 (ASTM C192, 2015). The coarse aggregate, fine aggregate, water and limestone powder were weighed into buckets according to the required batch weight. Type I portland cement, was obtained from Texas Lehigh in Buda, Texas. Coarse aggregate was added to a 6 cubic foot drum mixer with half of the water specified and mixed for thirty seconds. After the initial mix, all other materials were added, with the limestone powder last. The amount of limestone powder varies in the different mixes, depending on the particle size and the percentage of cement replacement of the batch designs. All materials were mixed for three minutes and allowed to rest for two minutes. Then, to complete the mixing process, the materials were mixed again for two minutes.

3.3 Fresh Properties

The slump is determined by following ASTM C143 (ASTM C143, 2015). The inside of the cone shaped mold is dampened and placed on a flat, level, moist, non-absorbent metal surface. The mold is filled with three layers of an equal volume of concrete. Each layer is rodded 25 times with a 5/8 inch rod with rounded ends, penetrating approximately 1 inch into the layer below the current layer. After rodding the top layer, excess concrete was struck off by a rolling motion of the tamping rod. Any concrete surrounding the base of the cone-shaped mold is cleaned up, and the mold is lifted upward in a steady motion for five seconds with no lateral motion. The entire test is performed as soon as the batch has been properly mixed. The slump is measured by determining the vertical difference between the top of the mold and the displaced concrete from the original center of the top surface of the specimen.

The temperature of the freshly mixed concrete is assessed by a temperature measuring device according to ASTM C1064 (ASTM C1064, 2013). The device was submerged 3 inches into the freshly mixed concrete and ensured that the cavity left by the placement of the tool was closed to avoid any ambient air temperature readings. The temperature measuring device is left in the mixed concrete for at least 2 minutes, and the reading was recorded to the nearest 1 °F before removing the device.

The air content of the freshly mixed concrete is measured using the pressure method, following procedure Type B in ASTM C231 (ASTM C231, 2014). A sample of the freshly mixed concrete is obtained and scooped into the measuring bowl by rodding each of the 3 layers 25 times with top layer of rodding penetrating about 1 inch into the bottom layer. After rodding and tapping the third layer, the excess concrete is struck off with the strike-off plate until the surface is even with the top of the measuring bowl. Before conducting the pressure test, the fresh density of the concrete is measured at this time by weighing the filled measuring bowl. After the apparatus is assembled, water is added with a rubber syringe through the open petcock holes until all air is expelled from the measure. Next, the air bleeder valve on the air chamber is closed, and air is pumped into the air chamber until the gauge hand is on the initial pressure line. The gauge is allowed to stabilize at the initial pressure line by pumping or bleeding off air as necessary. The petcocks are then closed, and the main air valve is opened between the air chamber and the measuring bowl tapping the sides of the measuring bowl to relieve local restraints. Once the pressure gauge is stabilized and the percentage of air on the dial is read the main air valve is released.

3.4 Hardened Properties

3.4.1 Mortar Compressive Strength

The compressive strength of mortar cubes is a common test method used to measure hardened mechanical behavior. The compressive strength of the 2 inch mortar cubes were performed at 1 day, 3 days, 7 days, 28 days and 90 days after batching in accordance with ASTM C109 (ASTM C109, 2013) Three measurements are taken on different positions and averaged. Using a Test Mark CM-4000, for testing equipment, the cylinders are compressed until failure at a load rate of 75 ± 25 psi/s. The maximum load at failure is used for each specimen and the compressive strength is calculated using the average.

3.4.2 Concrete Compressive Strength

The compressive strength of concrete, commonly considered to be its most important characteristic (especially when limestone powder is used to replace cement because it adversely affects the compressive strength), also gave an overall good quality of the concrete and the structure of the hydrated cement paste. The physical properties of testing concrete compressive strength were performed at 1 day, 7 days, 14 days, 28 days and 90 days after batching in accordance with ASTM C39 (ASTM C39, 2015). Three diameter measurements are taken on different positions on the cylinder and averaged. The length of the specimens is also measured at three locations spaced evenly around the circumference, and the cylinders are weighed to determine the hardened density. Using a Test Mark CM-4000, for testing equipment, the cylinders are compressed until failure at a load rate of 35 ± 7 psi/s. The maximum load at failure is used for each specimen and the compressive strength is calculated using the average.

3.4.3 Concrete Splitting and Flexural Strength

The splitting tensile strength was tested using the bearing plate and strips per ASTM C496 using 4 x 8 inch cylinders at 28 days (ASTM C496, 2011). The flexural strength of concrete was tested using the third-point loading test method in accordance with ASTM C78 standard (ASTM C78, 2015). The modulus of rupture for concrete was calculated using 6" x 6" x 20" beams at 28 days of aging. The average strength is calculated from three specimens that are tested to failure for flexural strength. The flexural strength will be compared to the compressive strength to see the correlation. A strong correlation of the batches containing limestone powder will be an indication the effects are similar to the modulus of rupture and compressive strength of concrete at 28 days.

3.5 Statistical Analysis

To evaluate the effects limestone powder has, a linear regression analysis is performed to establish if there is a correlation between the compressive strength of mortar and concrete. The mortar and corresponding concrete throughout the testing period are compared to mixes containing the same level of limestone powder. Using the compressive strength data collected on the effect of the particle size of limestone allows for a comparison of the effects in mortar and concrete. The compressive strength correlation for mortar and concrete is assessed to the age to show strength gain. Ages of 1 day, 7 days, 28 days and 90 days are used.

To analyze the effect the particle size of limestone produced has on mortar and concrete the compressive strength of mortar and concrete at 28 days and 90 days are assessed for statistical significance using analysis of variance (ANOVA). Analysis of variance is used to substantiate whether the measured variation was statistically significant. This inferential statistical method apportions the total variation in the results caused by the random variation and by each factor. A conventional level of significance of 0.05 is used for the analysis. This approach can test the hypothesis of whether particle size of limestone affects the mortar and concrete strength.

3.6 Petrography

Petrographic examination uses petrographic microscopes to analyze the mineral content and the texture within the concrete. Detailed examination of the cement pastes and aggregates can be used to look at the relation between the cement paste and aggregates. Petrographic examinations of concrete can provide information on multiple aspects of the composition with a forensic approach. It is used to study aggregate composition, identification of cement aggregate reactions, and to the premature failure of an existing concrete structure. Microcracks affect both the strength of concrete and the durability and are largely responsible for the low tensile strength of concrete (Neville, 2011). The use of a petrographic examination gives a visual analysis to identify the presence or existence of $CaCO_3$ in the concrete, the distribution, and for reactions with the cement paste.

3.6.1 Sample Preparation

Thin sections were cut from 4” x 8” concrete cylinders with a diamond blade. The sample section is marked and cut to fit the 24 mm x 46 mm slide. The concrete section is cleaned and vacuum impregnated with blue epoxy. Once the epoxy has cured the sample is ground by hand with 400 grit until the surface is even, then with 1000 grit for a polished finish. Frost the glass slide to produce a rough surface that enables the thin section to be cemented to it with epoxy. Ensure to wash the polished side of the thin section, so that there are no particles from the grinding in the thin concrete section. Cement the chip to the slide using epoxy and trim off the excess epoxy and label the section. Trim off the thin concrete section to the desired thickness and ensure the epoxy is present in the section. Hand grind the section using 600 grit and finish hand grinding using 1000 grit (or finer) for a polished finish. Trim off excess epoxy from around the section and wash it.

3.6.2 Petrographic Analysis

The control and concrete specimens containing 20% limestone powder in 4.5 μm, 8 μm, 15 μm particle sizes are processed into double polished thin slices that are vacuum impregnated with blue epoxy. The slides are used to evaluate the distribution of the limestone powder present in the cement paste. Measurements of the particles sizes are done with a microscope and software of three random samples of 476 x 357 μm of cement paste for each nominal particle size sample. The results of the measurements are then compared to a range of the particle distribution of the limestone powder before batched into concrete. Visual comparison of the samples of the cement paste can also be used to determine if there is a reaction between the cement and limestone powder.

3.7 Efficiency of Limestone Powder and Predictive Model

The main focus of this papers is to show that both the mechanical properties and environmental effects have to be considered in conjunction with each other to utilize limestone powder in concrete. Because of adverse effects on the mechanical properties, an optimal solution is based on the life cycle analysis results and the mechanical properties. Using the mechanical properties, the effectiveness of limestone powder as a cement replacement must be compared to properties of cement. Féret's equation can be modified to determine an efficiency factor of limestone powder in comparison to the cement based on the particle and replacement level. By using the results from testing the compressive strength at 28 days and 90 days, the modified Féret's equation can be used to calculate the efficiency of the limestone powder in each batch design.

Féret's expression relies on the volumetric relation of cement, water, and air that can be in estimating the strength of concrete. Using the results of the efficiency factor at 28 days, Féret's's modified equation can be used as concrete strength prediction model for concrete containing limestone powder using the same principles and elements from Féret's expression.

3.8 Life Cycle Assessment of Concrete

Conducting a Life Cycle Assessment (LCA) on the batch designs, data on the inputs and emissions associated with concrete can be compared and analyzed for their impact on the environment. The Life Cycle Inventory (LCI) quantifies inputs and outputs like emissions at the different stages of concrete production. Using CO_2 equivalents emissions, data from LCI can be compared and analyzed to highlight the point of production at which concrete utilizes the most resources and has the highest impact on the environment. By ranking processes in the LCI in terms of energy used and emissions emitted can determine the process in concrete production that can be modified and will yield the highest in terms of reducing the environmental impact. The LCA can also be used to evaluate concrete products and compare them to alternative construction materials. The data from this LCA will be available for incorporation into existing and future concrete batch designs. Comparing mix designs with data from this LCA can be used to improve a production process, reduce cost, or shrink the impact concrete has on the environment.

For the purpose of this LCA, the functional unit is one cubic yard (yd^3) of concrete. The concrete of specific mix designs is used in this study. The mix designs consist of cement, water, coarse aggregate, fine aggregate, and limestone powder. This composition of concrete utilized a 0.40 water to cement ratio without additional admixture used. All materials used are in bulk and do not include additional packaging. LCI inputs and outputs associated with producing concrete is documented. The LCI consists of data from the mix designs used in this study and emissions data from the Portland Cement Association Research & Development Information (Nisbet, Marceau, & VanGeem, 2002). These LCA emissions in the air include carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NOx), carbon monoxide (CO), volatile organic compounds (VOC), and methane (CH_4). However, this does not include all emissions that are produced by concrete production. For this study, the focus is the major greenhouse gasses associated with concrete production. To analyze the data from the LCI, the greenhouse gas emissions is converted to carbon dioxide equivalents, CO_2e, to standardize emissions for comparisons. In order to compare the different stages of cement production to one another, the conversion data from the LCI to CO_2e are acquired by using U.S. Environmental Protection Agency Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) to obtain the emission factors (Bare, Norri, Pennington, & McKone, 2012). Production data of the limestone powder is obtained from the manufacture. The emissions data for producing water to be used in concrete is from a review article in Nature Climate Change (Rothausen & Conway, 2011).

3.8.1 System Boundary

This LCA does not include all the inputs and outputs associated with producing concrete. The production of fuel and energy inputs are not discussed in this LCA. Due to the complexity and differences based on the region and use of concrete, there are limitations in this LCA that are outlined to show what is included and excluded in this concrete production. The line with dashes defines the boundary of the LCA in Figure 4.

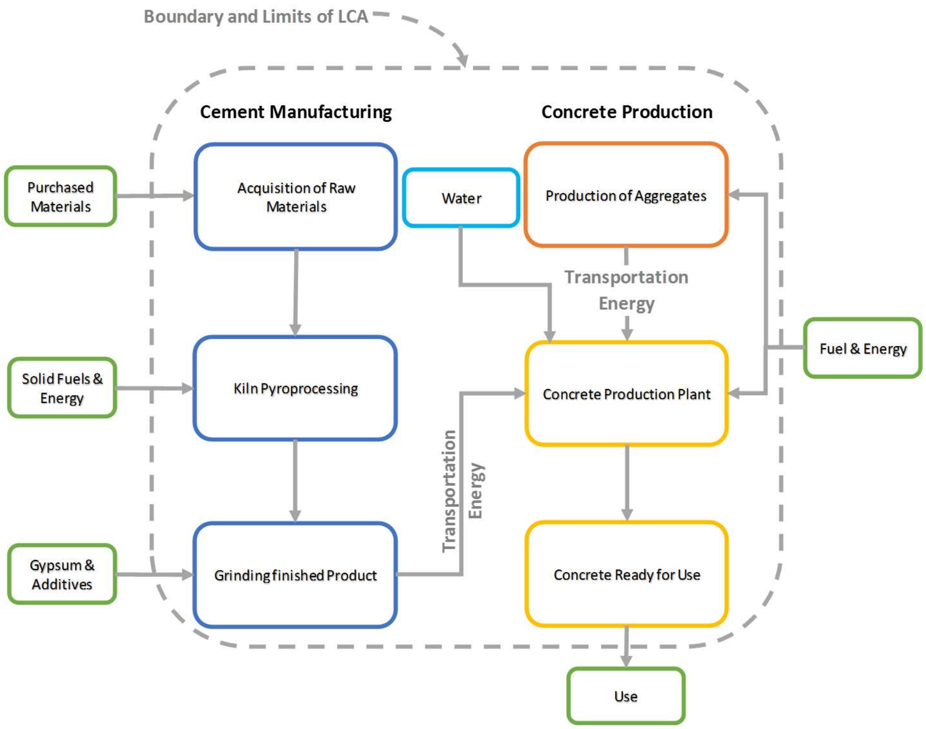

Figure 4. System Boundary of LCA.

The main processes in the scope of the LCA are the manufacturing of cement, production of aggregates, transportation of material, and the concrete production. This LCA does not cover the resources required to produce and acquire solid fuels used in the kiln, diesel used for transportation of materials, energy, water and any special additives in the cement manufacturing and concrete production. It also excludes any special additives that went into cement manufacturing and concrete production process. Another limitation of this LCA is the use for which this concrete is being created. Because concrete has a wide variety of application, this LCA does not include it in the scope.

IV. RESULTS

4.1 Fresh Properties

Table 2. Fresh Concrete Properties.

Batch Data	Control	Alpha-10	Beta-10	Gamma-10	Alpha-20	Beta-20	Gamma-20	Alpha-30	Beta-30	Gamma-30
Concrete Temperature (°f):	78.4	77.8	78.4	77.9	76.6	78.4	78.4	77.0	76.7	77.0
Slump (in):	4.0	2.5	3.5	3.3	7.5	7.0	3.3	7.0	3.0	6.0
Density (lb/ft^3):	147.4	147.4	147.4	147.1	143.7	144.2	147.4	145.2	145.2	145.2
Air Content (%):	2.4%	2.2%	2.3%	2.2%	2.1%	2.3%	2.2%	2.3%	2.1%	2.0%

*Alpha - 4.5 µm   *Beta - 8 µm   *Gamma - 15 µm

4.1.1 Temperature

The properties of fresh concrete with limestone powder are considered to be important because of the relation they have with the hydration of the concrete. Table 2 shows the test results for temperature, which ranged from 76.6 °F to 78.4 °F. The temperature slightly decreased with higher levels of limestone powder present in the concrete, with no significant differences between particle sizes. The slight change in temperature within the different mix designs indicated that no reaction was taking place between the cement and the limestone powder and that the slight change was due to the lower amount of cement present.

4.1.2 Workability

The workability of the concrete in the fresh state was measured by conducting a slump test. The results for slump are shown in Table 2. The slump, or workability, slightly increased as a result of limestone powder present in the concrete, most significantly at levels of a 20% replacement. All concrete batches had good workability throughout the process of testing the fresh properties of the concrete and placing it into molds.

4.1.3 Density

Table 2 represents the density of the fresh limestone powder concrete. Fresh density should also be considered when investigating mechanical behavior because it affects the material's elastic modulus and compressive strength. Fresh density in the range 143.7 lb/ft^3 to 147.4 lb/ft^3 decreased with limestone powder present in the concrete. The decrease in density depends on the difference in the specific gravity of cement and limestone powder. Type I OPC has a specific gravity of 3.15, while limestone powder is 2.70. Replacing the cement with limestone powder will affect the density, and since the density affects the compressive strength of concrete, it will result in lower strength (Neville, 2011).

4.1.4 Air Content

The air content of fresh concrete containing limestone powder is considered to be important due to the relation it has with durability and porosity. Table 2 shows the test results for air content that has not been modified with any air entraining admixtures, which ranged from 2.3% to 2% with the control mixture at 2.4%. The air content decreased slightly with higher levels of limestone powder present in the concrete. The change in air content within the different mix designs indicated that there was a slight filler effect and efficient particle packing. This indicated that the presence of limestone powder in concrete has positive effects on durability and porosity.

4.2 Hardened Properties

4.2.1 Mortar Compressive Strength

Table 3. Average strength of Mortar with limestone Powder.

Mix Design (PSI)	1 Day	3 Day	7 Day	28 Day	90 Day
Control	3071	3402	4365	4949	5798
Alpha-10	2852	3140	3791	4727	4993
Beta-10	2640	3161	4218	4748	5389
Gamma-10	2793	3712	4081	4285	5572
Alpha-20	2590	3226	3818	4369	4576
Beta-20	2398	3532	3249	4058	4594
Gamma-20	2591	3050	3977	4535	5025
Alpha-30	2380	2999	3418	4052	4326
Beta-30	1875	3003	3056	3476	4002
Gamma-30	2224	2808	3378	4095	4115

*Alpha - 4.5 µm   *Beta - 8 µm   *Gamma - 15 µm

The compressive strength tests were performed on 2” x 2” x 2” mortar cubes. All the samples were cured in a room with a constant temperature and humidity for the initial two days. After curing for two days, all the samples were de-molded and placed in water with a constant temperature. At the ages of 1, 3, 7, 28, and 90 days, the compressive strengths of all the samples were tested.

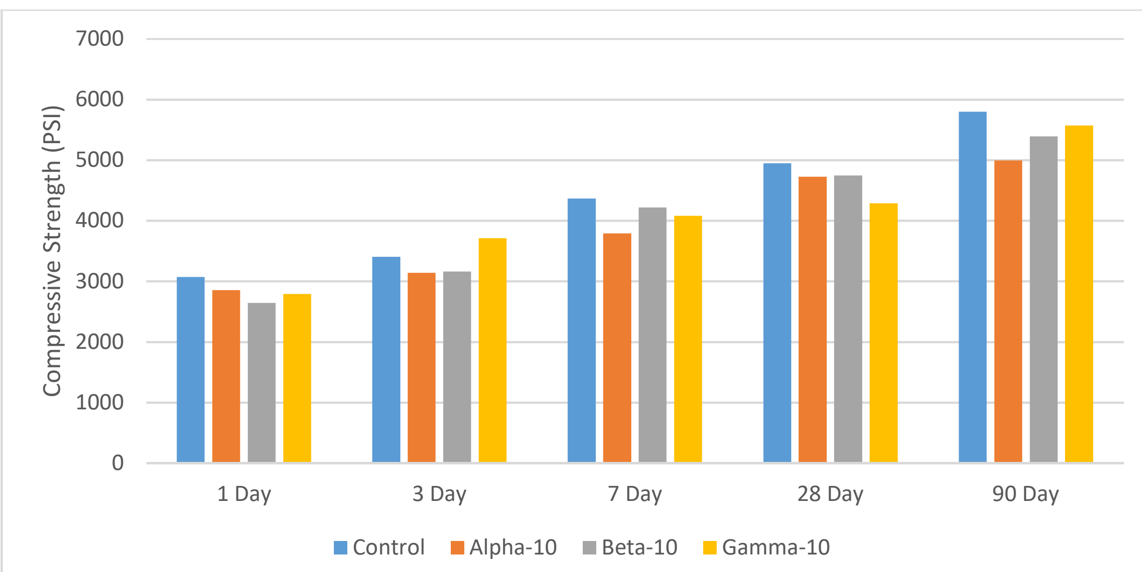

Figure 5. Effect of Age on Mortar Compressive Strength with 10% Limestone Powder.

Figure 5 illustrates how different levels and particle sizes of limestone powder in mortar affects the compressive strength of concrete. The level of cement replaced with limestone powder adversely affects the strength. A 10% replacement of cement at 28 days performs similarly to that of the control with a reducing the mortar strength by the larger limestone particle size. The results from the 90 day samples indicate that the larger limestone particle sizes performed better with a 2% reduction in strength compared to the control.

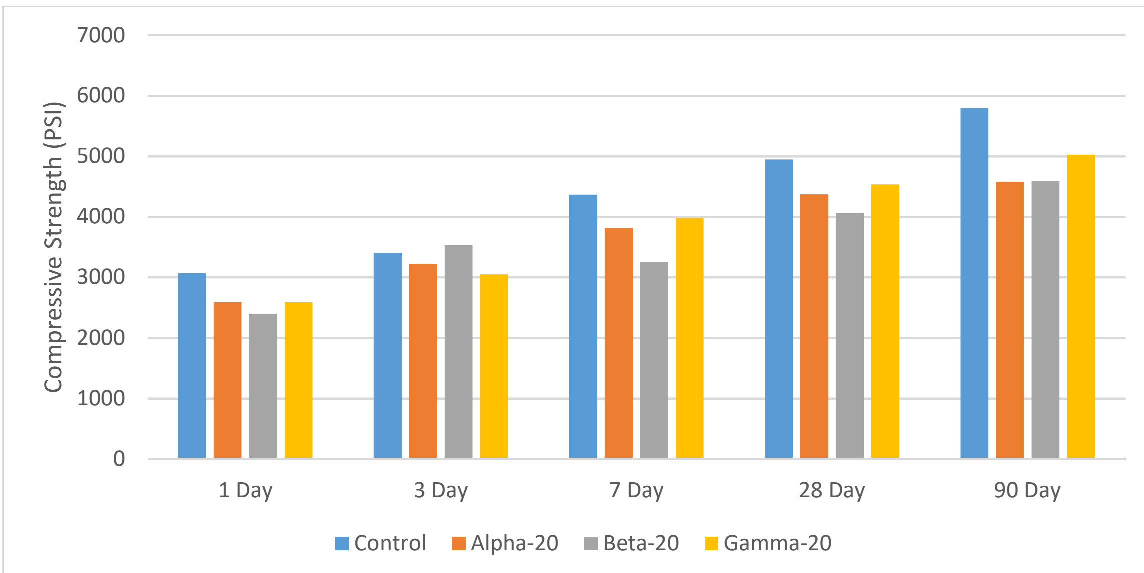

Figure 6. Effect of Age on Mortar Compressive Strength with 20% Limestone Powder.

A 20% replacement of cement at 28 days reduced the mortar strength by 6% to 16% compared to the control. That ranges from 4058 psi to 4535 psi. Figure 6 shows that the particle size of the limestone powder does not have a big effect on the compressive strength of the mortar, but that the level of replacement is starting to affect the strength of the mortar cubes negatively. Also, it’s more significant as the age increases like the 90 day results show.

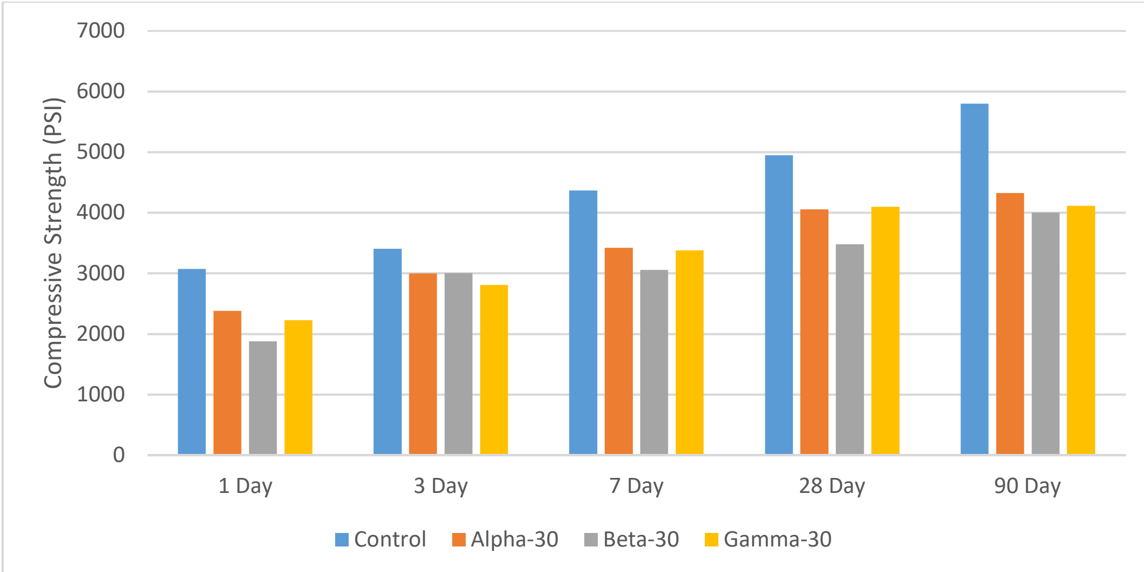

Figure 7. Effect of Age on Mortar Compressive Strength with 30% Limestone Powder.

A 15% to 28% reduction was observed with a 30% replacement at 28 days and increased to 25% to 31% at 90 days. Figure 7 shows a similar result to the 20% replacement that the replacement level is affecting the mortar strength negatively. And the particle size of the limestone powder has little to no effect on the compressive strength of the mortar ranging from 3476 psi to 4095 psi at 28 days and 4002 psi to 4326 psi at 90 days.

4.2.2 Concrete Compressive Strength

Table 4. Average strength of Concrete with limestone Powder.

Mix Design (PSI)	1 Day	7 Day	14 Day	28 Day	90 Day
Control	3052	5726	6559	6610	7536
Alpha-10	2686	4821	5392	5684	6427
Beta-10	2690	4868	5362	5722	6293
Gamma-10	2674	5108	5667	5816	6524
Alpha-20	2120	4247	4817	5454	5747
Beta-20	2004	4588	5063	5378	6011
Gamma-20	2597	4650	4988	5534	6090
Alpha-30	1932	4087	4573	5218	5576
Beta-30	1845	4311	4822	5366	5695
Gamma-30	1727	4340	4688	5197	5703

*Alpha - 4.5 µm *Beta - 8 µm *Gamma - 15 µm

The compressive strength of concrete, commonly considered to be its most important characteristic (especially when limestone powder is used to replace cement because it adversely affects the compressive strength), also gave an overall good quality of the concrete and the structure of the hydrated cement paste. Table 4 shows the calculated average PSI from 3 specimens at 1 day, 7 days, 14 days, 28 days and 90 days.

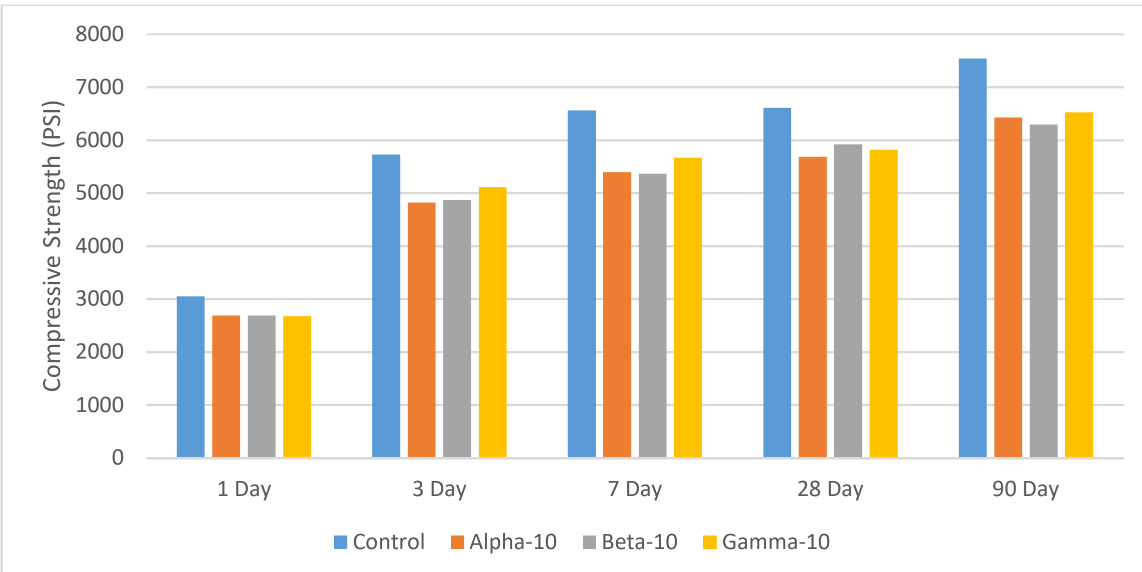

Figure 8. Effect of Age on Compressive Strength with 10% Limestone Powder.

Figure 8 illustrates the test results of the compressive strength of concrete with a 10% replacement of limestone powder compared to the control that does not contain limestone powder. As expected, the replacement of the limestone powder adversely affected the compressive strength. A 10% replacement of cement on average reduced compressive strength by 13% at 28 days, and 15% at 90 days, compared to the control. Based on Figure 8, the particle size of the limestone powder did not show that it affects the concrete strength, ranging from 5648 psi to 5922 psi at 28 days, and 6293 psi to 6524 psi at 90 days.

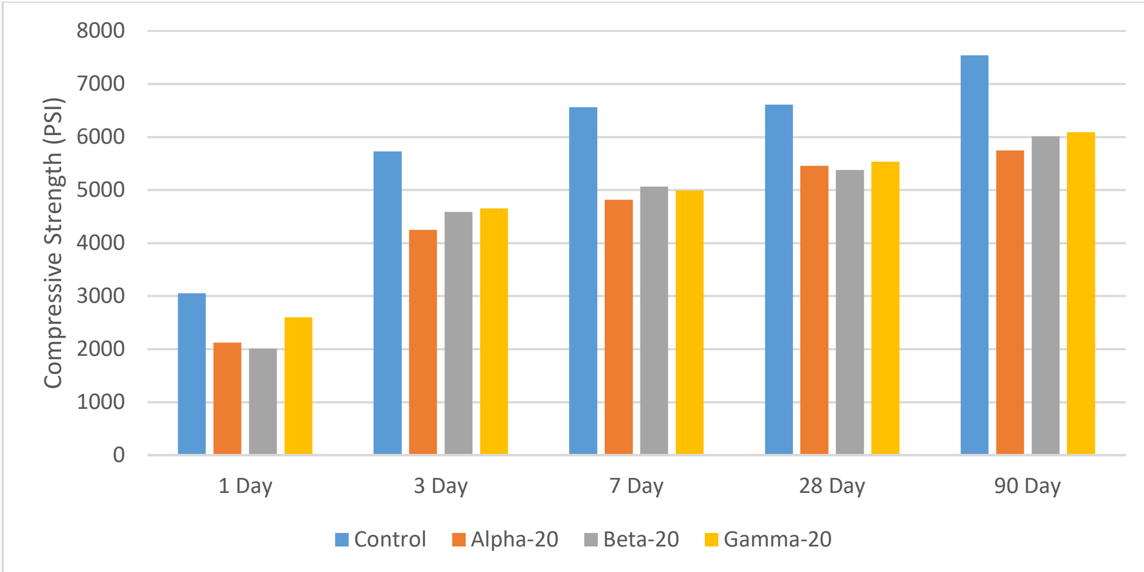

Figure 9. Effect of Age on Compressive Strength with 20% Limestone Powder.

Figure 9 illustrates the test results with a 20% replacement limestone powder compared to the control. A 20% replacement of cement reduced the compressive strength even more with an average of 19% at 28 days, and 21% at 90 days. The results follow the same pattern as Figure 8, demonstrating that the particle size of the limestone powder had little effect on concrete strength ranging from 5378 psi to 5534 psi at 28 days, and 5747 psi to 6090 psi at 90 days.

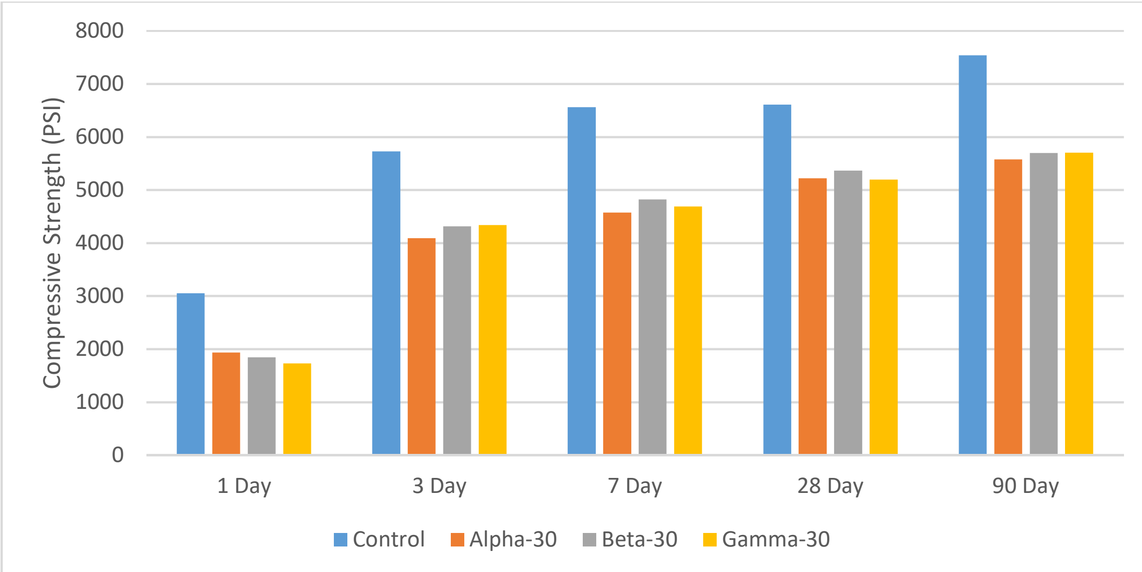

Figure 10. Effect of Age on Compressive Strength with 30% Limestone Powder.

Figure 10 illustrates the test results of a 30% replacement limestone powder compared to the control. There was an average compressive strength loss of 21% at 28 days and 25% at 90 days. The particle size of the limestone powder still had little effect on strength, even at a larger volume of limestone powder in the concrete, ranging from 5197 psi to 5366 psi at 28 days, and 5576 psi to 5703 psi at 90 days.

4.2.3 Mortar and Concrete Relation

To evaluate the effects limestone powder has, a linear regression analysis was performed to establish if there is a correlation between the compressive strength of mortar and concrete. The mortar and corresponding concrete throughout the testing period were compared to mixes containing the same level of limestone powder. Using the compressive strength data collected on the effect of the particle size of limestone allows for a comparison of the effects in mortar and concrete. The compressive strength correlation for mortar and concrete were assessed to the age to show strength gain. Ages of 1 day, 7 days, 28 days and 90 days were used.

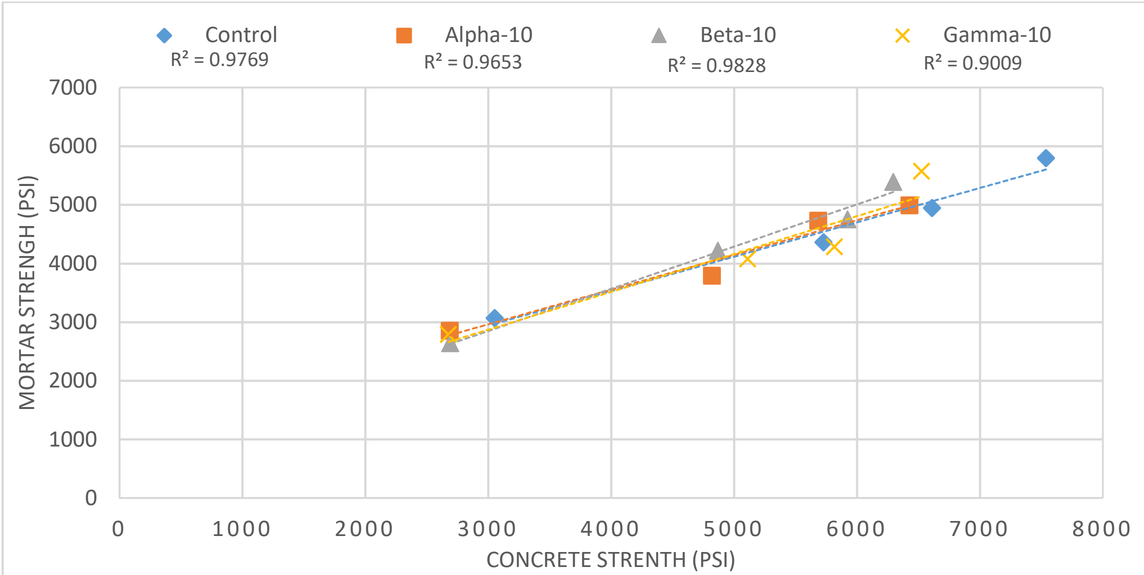

Figure 11. Correlation of Compressive Strength of Mortar to Concrete with 10% Limestone Powder.

Figure 11 compares mortar and concrete to the compressive strength to isolate the effects of the limestone powder. Mortar and concrete with a 10% replacement of limestone powder affect the compressive strength negatively. Figure 11 shows that there was a significant correlation with a R^2 value greater than 0.90 in all mixes with 10% limestone powder, indicating that the limestone powder affects the mortar and concrete in the same manner. The strength of the mortar can also be used to predict the concrete strength. The slope of the correlation curve in relation to the concrete and the mortar can be used to evaluate if the presence of limestone powder affects the rate of gain in compressive strength. A slope comparison of the mixes containing 10% limestone powder to the control shows that the addition of limestone powder does not affect the rate of strength gain. Figure 11 also indicates that the size of the limestone particle has little to no effect on the rate that strength is gained.

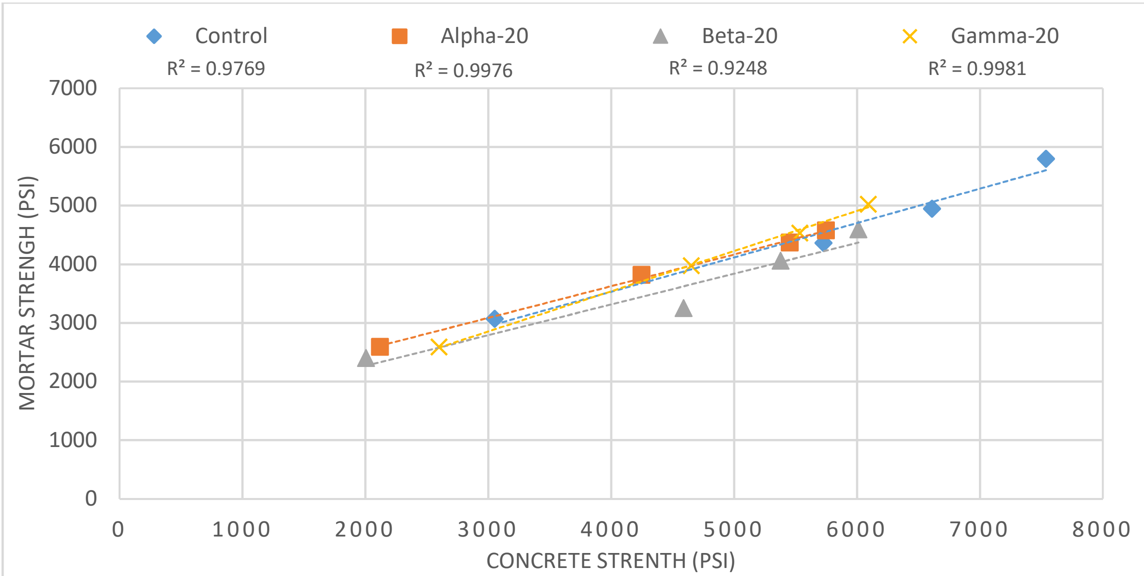

Figure 12. Correlation of Compressive Strength of Mortar to Concrete with 20% Limestone Powder.

The correlation in mortar and concrete containing 20% is also strong and shows that there is a significant correlation with a R^2 value greater than 0.92. The slope of the correlation curves represents the rate of curing in mixes contain 20% limestone powder and displays similar results to that of the 10% limestone powder mixes. Figure 12 shows that the rate of curing for all mixes containing 20% limestone powder is similar to each other and the control, indicating that the limestone powder particle size has little effects the mortar and concrete.

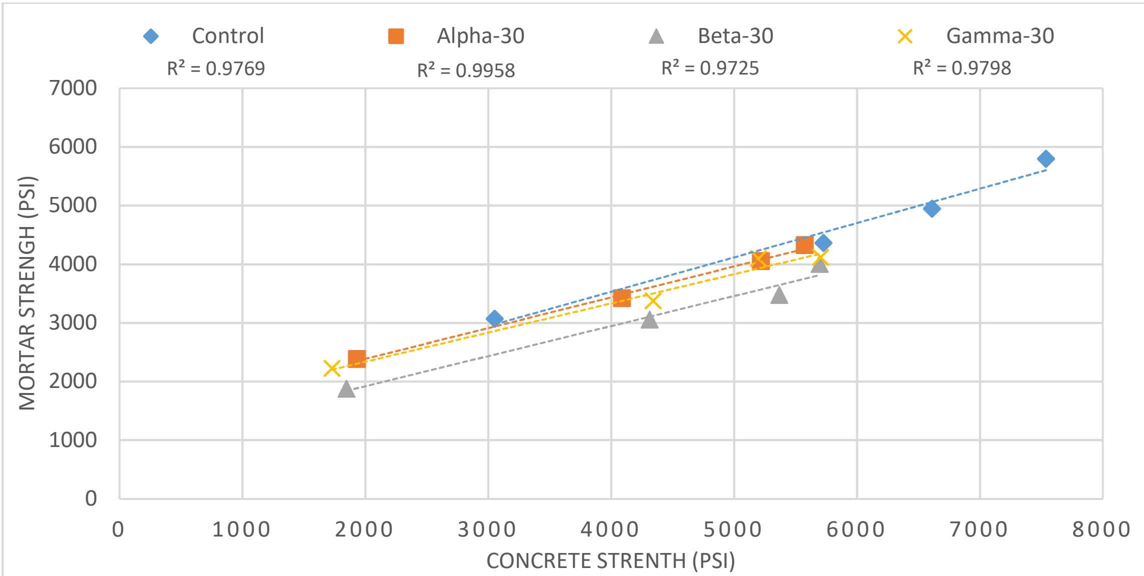

Figure 13. Correlation of Compressive Strength of Mortar to Concrete with 30% Limestone Powder.

Mixes containing 30% limestone powder show similar results as the 10% and 20% mixes as it compares mortar and concrete to the compressive strength. Figure 13 shows that there is a strong correlation with a R^2 value greater than 0.97 in all mixes containing 30% limestone powder with slopes that are similar to that of the control. All mortar mixes and concrete correlates to each other indicating that the level of limestone powder affects the mortar and concrete in the same manner, and mortar can be used predict properties of concrete containing limestone powder. The presentence of the limestone powder in mortar and concrete at all levels tested has little effect on the rate of curing in comparison to the control. The particle size of the limestone powder correlates to the strength of the mortar to the concrete but has little effect.

4.2.4 Concrete Splitting Tensile Strength and Flexural Strength

Table 5. Splitting Tensile Strength and Flexural Strength of Concrete.

Mix Design	Splitting Tensile Strength (PSI)	% Compressive Strength	Modulus of Rupture (PSI)	% Compressive Strength
Control	521	7.9%	884	13.4%
Alpha-10	499	8.8%	805	14.2%
Beta-10	494	8.3%	807	13.6%
Gamma-10	483	8.3%	780	13.4%
Alpha-20	481	8.8%	694	12.7%
Beta-20	467	8.7%	721	13.4%
Gamma-20	465	8.4%	695	12.6%
Alpha-30	458	8.8%	622	11.9%
Beta-30	459	8.6%	663	12.4%
Gamma-30	455	8.8%	648	12.5%

*Alpha - 4.5 µm   *Beta - 8 µm   *Gamma - 15 µm

The splitting tensile strength was tested using the bearing plate and strips per ASTM C496 using 4 x 8 inch cylinders (ASTM C496, 2011). The flexural strength of concrete beams was tested using third-point loading test method in accordance with ASTM C78 (ASTM C78, 2015). The modulus of rupture and splitting tensile strength for concrete was calculated after an aging period of 28 days. Table 5 illustrates the calculated average PSI from three specimens that were tested to failure for the splitting tensile strength and flexural strength.

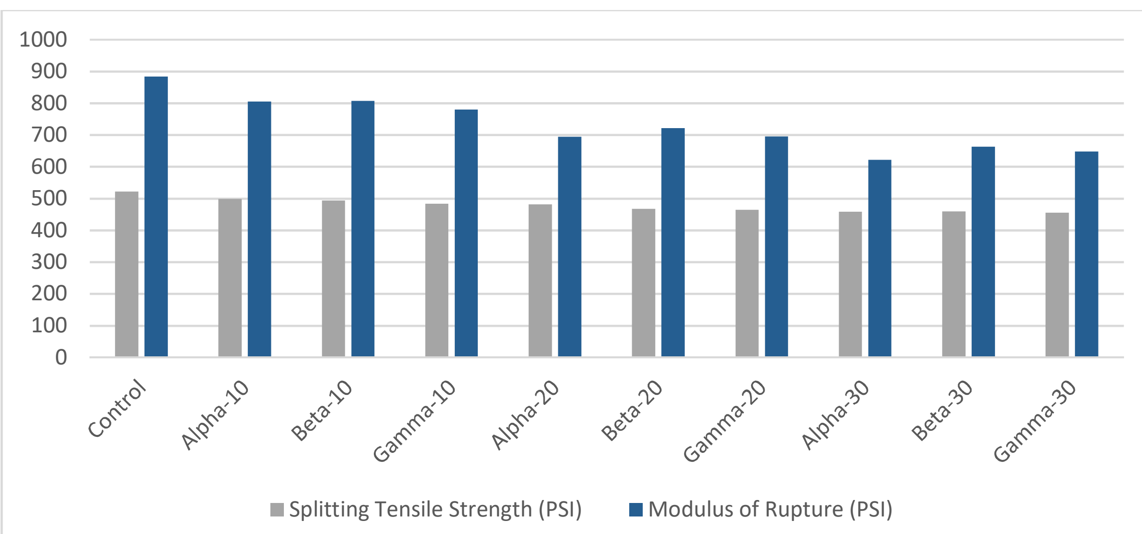

Figure 14. 28 Day Splitting Tensile Strength and Flexural Strength.

The splitting tensile strength results in Table 5 range 455 psi to 499 psi, decreasing as the limestone powder increased. The adverse effects of the limestone powder are less significant in the strength than the compressive strength. As 10% replacement of cement reduced the splitting tensile strength on average by 6%, a 20% replacement reduced the strength by 10%, and an average of 12% reduction was observed with a 30% replacement. The limestone powder particle size had little influence on the splitting tensile strength.

Figure 14 illustrates how different levels and particle sizes of limestone powder in concrete affects the flexural strength of concrete. As expected, replacement of the limestone powder adversely affects the flexural strength. A 10% replacement of cement reduced the flexural strength by 9% to 12%, a 20% replacement reduced the strength by 18% to 21%, and a 25% to 30% reduction was observed with a 30% replacement. As in the case of compressive strength and splitting tensile strength, the particle size of the limestone powder did not have a significant effect on the flexural strength.

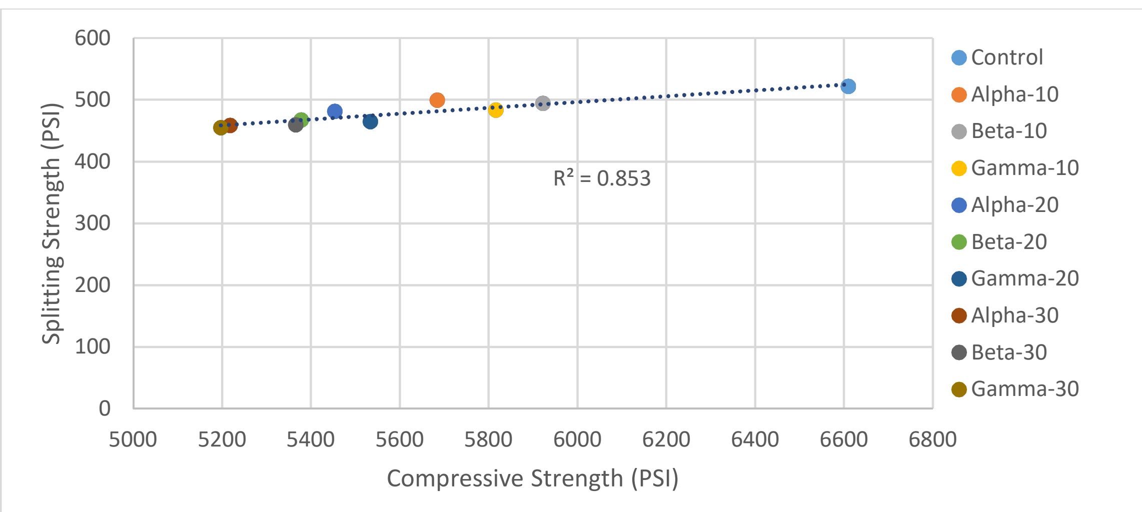

Figure 15. Correlation of Splitting Tensile Strength and Compressive Strength.

The correlation to the compressive strength is important because it can be used to estimate the splitting tensile strength. Figure 15 shows the correlation relation between the splitting tensile strength and compressive strength, with a R^2 value of 0.85. The splitting tensile strength with limestone powder is on average 8.6% of the concrete compressive strength, about a 1% increase over the control.

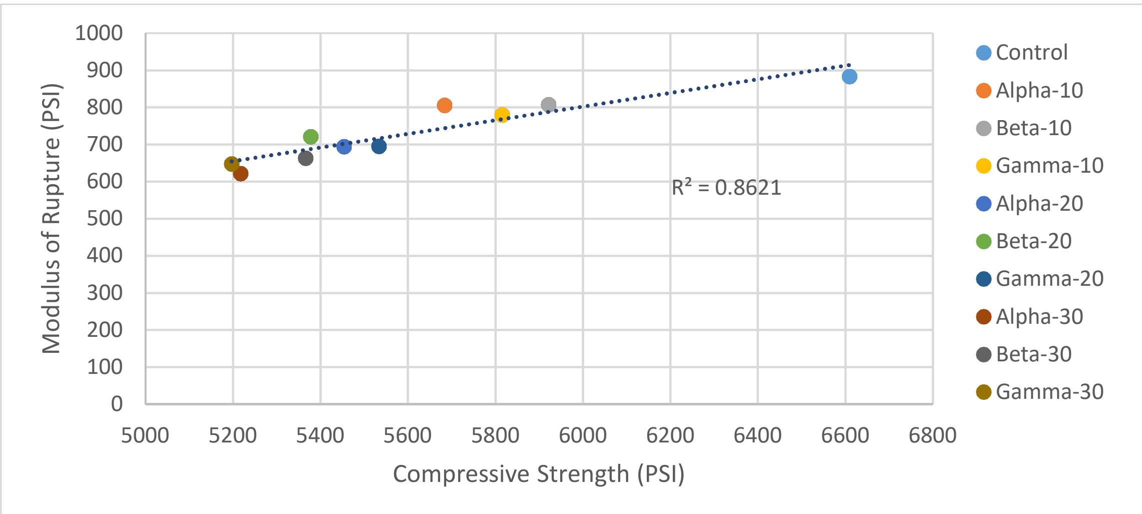

Figure 16. Correlation of Modulus of Rupture and Compressive Strength.

Figure 16 illustrates the relationship between compressive strength and flexural strength. The flexural strength values of concrete with limestone powder range from 11.9% to 14.2% to that of the compressive strength, with the control in the same range of 13.4%. A R^2 value of 0.86 indicates that a strong correlation was observed between the modulus of rupture and compressive strength of concrete at 28 days. Findings from the correlation results indicate the compressive strength could be used to estimate both splitting tensile strength and the flexural strength of concrete with limestone powder.

4.2.5 Shrinkage

Shrinkage is an important mechanical property that effects the structure of concrete and mortar. Shrinkage occurs when the internal humidity in concrete and mortar is lowered, by either the environmental factors or the hydration process. Deformation during the cement hydration process is more significant during early ages.

Table 6. Shrinkage with different limestone powder finesse.

Mix Design	Initial	7-day (%)	14-day (%)	21-day (%)	28-day (%)
Control	0	0.059	0.097	0.106	0.110
Alpha-10	0	0.052	0.086	0.098	0.110
Beta-10	0	0.047	0.095	0.102	0.110
Gamma-10	0	0.053	0.097	0.105	0.109
Alpha-20	0	0.056	0.089	0.099	0.105
Beta-20	0	0.045	0.090	0.097	0.102
Gamma-20	0	0.041	0.083	0.091	0.098
Alpha-30	0	0.043	0.081	0.091	0.097
Beta-30	0	0.044	0.082	0.088	0.095
Gamma-30	0	0.043	0.086	0.092	0.094

*Alpha - 4.5 µm   *Beta - 8 µm   *Gamma - 15 µm

The values in Table 6 represent the microstructure of the mortar and its ability to support deformation as the presence of water exchange with the external environment. Calculated average percentage of shrinkage from 3 specimens at 7 days, 14 days, and 28 days in accordance with ASTM C596 (ASTM C596, 2015).

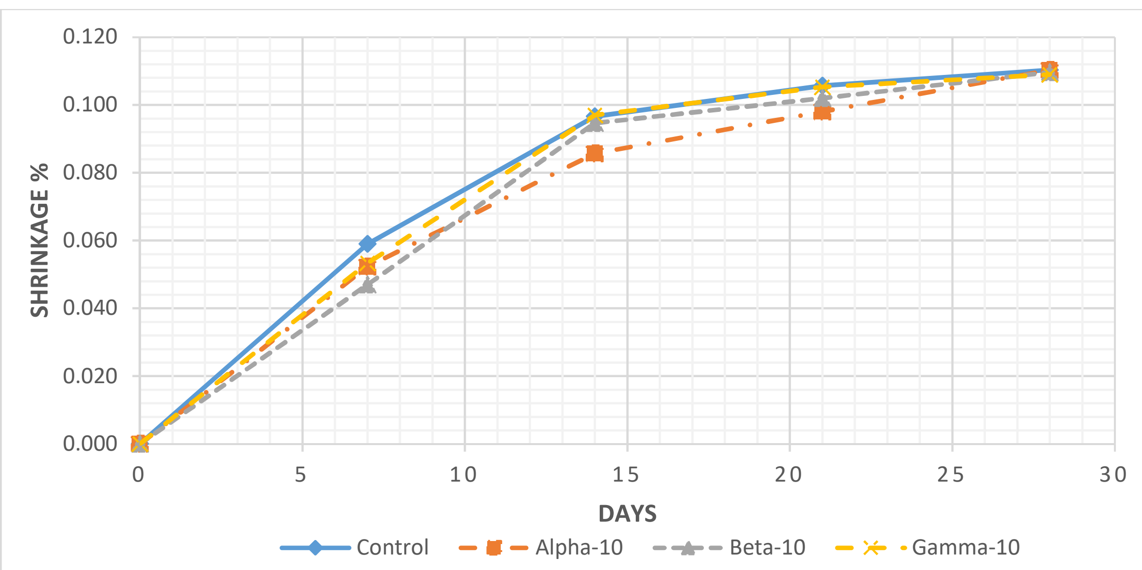

Figure 17. Effect of Age on Shrinkage with 10% Limestone Powder.

Figure 17 illustrates the test results of the shrinkage with a 10% replacement of limestone powder compared to the control that does not contain limestone powder. A 10% replacement of cement on average reduced the shrinkage at early ages. At 28 days and beyond, there is little to no change in shrinkage compared to the control. Based on Figure 17, the particle size of the limestone powder did not have a significant effect on the shrinkage and is 0.110% that is similar to the control.

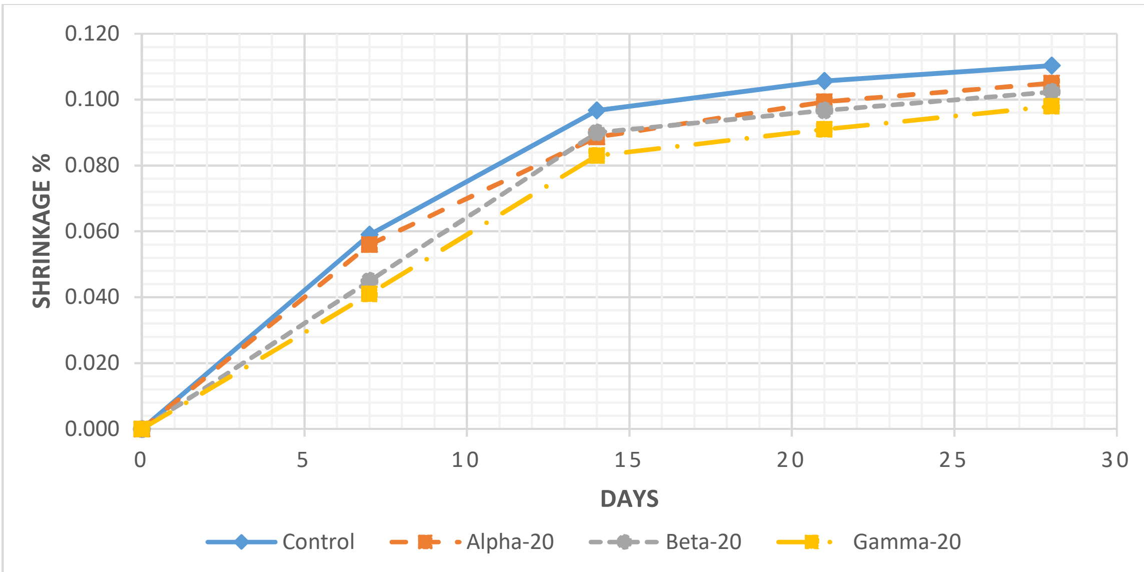

Figure 18. Effect of Age on Shrinkage with 20% Limestone Powder.

The test results with a 20% replacement limestone powder compared to the control is represented by Figure 18 showing a reduction in the shrinkage in the early stage and at 28 days is .008% less than the control. The results follow the same pattern as Figure 17 with little variances in shrinkage between the different particle sizes ranging from 0.105% to 0.098% at 28 days.

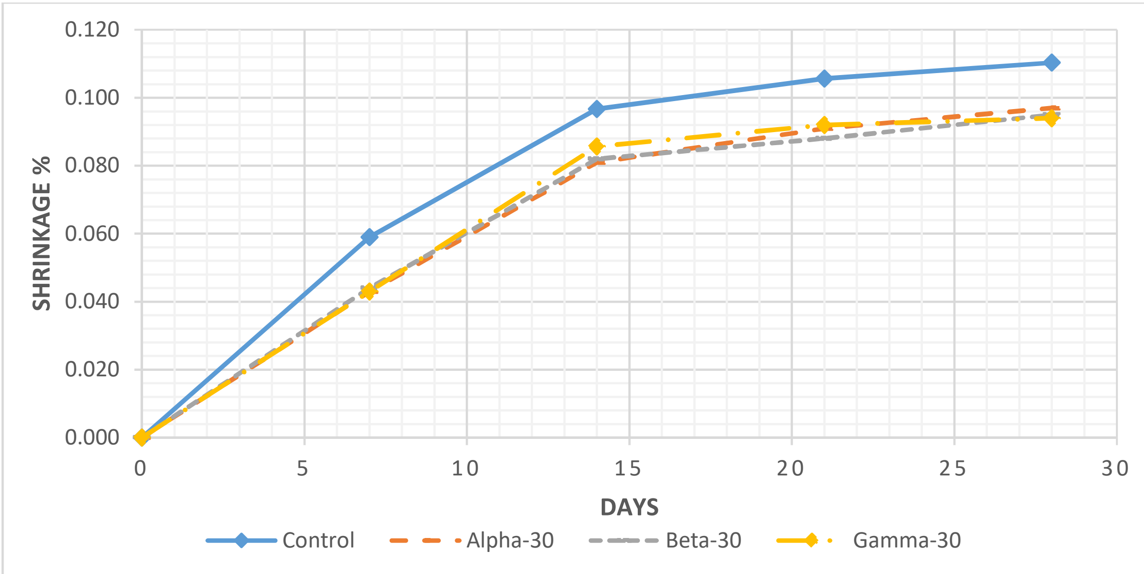

Figure 19. Effect of Age on Shrinkage with 30% Limestone Powder.

Figure 19 compares the test results of a 30% replacement limestone powder to the control. There was an average reduction in shrinkage by 0.015% at 28 days, and at the early ages of the specimens. The particle size of the limestone powder still had little effect on shrinkage, even with a larger volume of limestone powder used to replace cement. Using less cement in the specimens is the driving factor reducing the shrinkage and agrees with the compressive strength results that the particle size of limestone has little to no effect on the mechanical properties of concrete.

4.3 Statistically Significance

Data collected on the effect of the particle size of limestone powder produced with compressive strength for mortar and concrete were assessed at 28 days and 90 days for statistical significance using analysis of variance (ANOVA). Analysis of variance is used to substantiate whether the measured variation was statistically significant. This inferential statistical method apportions the total variation in the results that are caused by the random variation and by each factor. A conventional level of significance of 0.05 was used for the analysis. This approach can test the hypothesis of whether particle size of limestone affects the concrete strength. Table 7 illustrates the analysis of the effect particle size and replacement percentage has on compressive strength.

Table 7. Analysis of variance of mortar compressive strength at 28 days.

Hypothesis: 1

H_o: $\mu_1 = \mu_2$ - The particle size does not affect the Compressive Strength of Mortar

H_1: $\mu_1 \neq \mu_2$ - The particle size does affect the Compressive Strength of Mortar

ANOVA

Source of Variation	*Sum of Squares*	*Degrees of freedom*	*Mean Square*	*F-value*	*P-value*	*F-critical*
Particle Size	597232.07	2.00	298616.04	1.21	0.32	3.55
Replacement %	2798649.85	2.00	1399324.93	5.65	0.01	3.55
Interaction	1166225.93	4.00	291556.48	1.18	0.35	2.93
Error	4455958.67	18.00	247553.26			
Total	9018066.52	26.00				

Rejection Criteria Particle Size

$F_o > F\alpha\ 0.05, 2{,}18$

1.21 > 3.55

FALSE

To test if the effect on compressive strength of mortar at 28 days is significant, the null hypothesis, H_o, is that the particle size does not affect the compressive strength of concrete. The alternative hypothesis, H_1, is that the particle size does affect the compressive strength of concrete. Table 7 represents the F-values, along with P-values for the ANOVA of the concrete strength, at 28 days. Because *1.21 > 3.55,* the null hypothesis was not rejected. Thus, the particle size does not significantly affect the compressive strength of concrete at a level of 0.05. Also because 5.65 > 3.55, the null hypothesis is rejected. Consequently, the replacement percentage of limestone powder does significantly affect compressive strength of mortar.

Table 8. Analysis of variance of mortar compressive strength at 90 days.

Hypothesis: 1

H_o: $\mu_1 = \mu_2$ - The particle size does not affect the Compressive Strength of Mortar

H_1: $\mu_1 \neq \mu_2$ - The particle size does affect the Compressive Strength of Mortar

ANOVA

Source of Variation	*Sum of Squares*	*Degrees of freedom*	*Mean Square*	*F-value*	*P-value*	*F-critical*
Particle Size	534324.52	2.00	267162.26	0.73	0.50	3.55
Replacement %	6595993.19	2.00	3297996.59	9.03	0.00	3.55
Interaction	753048.59	4.00	188262.15	0.52	0.73	2.93
Error	6577529.33	18.00	365418.30			
Total	14460895.63	26.00				

Rejection Criteria Particle Size

$F_o > F\alpha\ 0.05, 2,18$

0.73 > 3.55

FALSE

Test results of the 90 day compressive strength were analyzed with similar hypotheses as before. Table 8 represents the F-values, along with P-values for the ANOVA of the mortar strength at 90 days, and results are the same as the 28 day test. Because *0.73 > 3.55,* the null hypothesis is not rejected. Thus, the particle size does not significantly affect the compressive strength of concrete at a level of 0.05. Since 9.03 > 3.55, the null hypothesis is rejected. Consequently, the replacement percentage of limestone powder does significantly affect compressive strength of mortar at 90 days.

Table 9. Analysis of variance of concrete compressive strength at 28 days.

Hypothesis: 1

H_o: $\mu_1 = \mu_2$ - The particle size does not affect the Compressive Strength of Concrete

H_1: $\mu_1 \neq \mu_2$ - The particle size does affect the Compressive Strength of Concrete

ANOVA

Source of Variation	*Sum of Squares*	*Degrees of freedom*	*Mean Square*	*F-value*	*P-value*	*F-critical*
Particle Size	200034.03	2.00	100017.02	2.85	0.08	3.55
Replacement %	1166198.52	2.00	583099.26	16.60	0.00	3.55
Interaction	256670.51	4.00	64167.63	1.83	0.17	2.93
Error	632259.91	18.00	35125.55			
Total	2255162.98	26.00				

Rejection Criteria Particle Size

$F_o > F\alpha\ 0.05, 2, 18$

2.85 > 3.55

FALSE

The same approach is used to test if the particle size has an effect on the compressive strength of concrete at 28 days using the same hypothesis of H_o, the particle size does not affect the compressive strength of concrete and the alternative hypothesis, H_1, the particle size does affect the compressive strength of concrete. The results in Table 9 represent a similar result to that of the mortar results. The F-values, along with P-values for the ANOVA of the concrete strength does not reject the null hypothesis with values of *2.85 > 3.55*. Thus, the particle size does not significantly affect the compressive strength of concrete and mortar at a level of 0.05. Since 16.60 > 3.55, the null hypothesis is rejected. Consequently, the replacement percentage of limestone powder does significantly affect compressive strength, and that is also true for mortar.

Table 10. Analysis of variance of concrete compressive strength at 90 days.

Hypothesis: 1

H_o: $\mu_1 = \mu_2$ - The particle size does not affect the Compressive Strength of Concrete

H_1: $\mu_1 \neq \mu_2$ - The particle size does affect the Compressive Strength of Concrete

ANOVA

Source of Variation	*Sum of Squares*	*Degrees of freedom*	*Mean Square*	*F-value*	*P-value*	*F-critical*
Particle Size	160602.07	2.00	80301.04	1.94	0.17	3.55
Replacement %	2622096.30	2.00	1311048.15	31.62	0.00	3.55
Interaction	143406.59	4.00	35851.65	0.86	0.50	2.93
Error	746383.33	18.00	41465.74			
Total	3672488.30	26.00				

Rejection Criteria Particle Size
$F_o > F\alpha\ 0.05, 2, 18$
1.94 > 3.55
FALSE

Test results of the 90 day compressive strength of concrete follow the same pattern as the hypotheses that were tested. Table 10 represents results that are the same as the 28 day test and the mortar test for 28 and 90 days. Since *1.94 > 3.55,* the null hypothesis is not rejected. Thus, the particle size does not significantly affect the compressive strength of concrete or mortar at ages that were tested at a level of 0.05. Because 31.62 > 3.55, the null hypothesis is rejected as in the other tests. The replacement percentage of limestone powder does significantly affect compressive strength in concrete and mortar at all ages that are tested.

4.4 Petrographic Analysis

4.4.1 Visual Examination

The use of a petrographic examination gives a visual analysis of the how the limestone powder effects the concrete. Concrete thin sections on 24 mm x 46 mm slides of 20% limestone powder in 4.5 µm, 8 µm, 15 µm particle sizes and the control shows a district visual difference. Visual comparison of the samples of the cement paste can also be used to determine if there is a reaction between the cement and limestone powder by the formation of calcium silicate hydrate gel. These images are two-dimensional representations of concrete but can give some insight to the structure of and composition of a volumetric product.

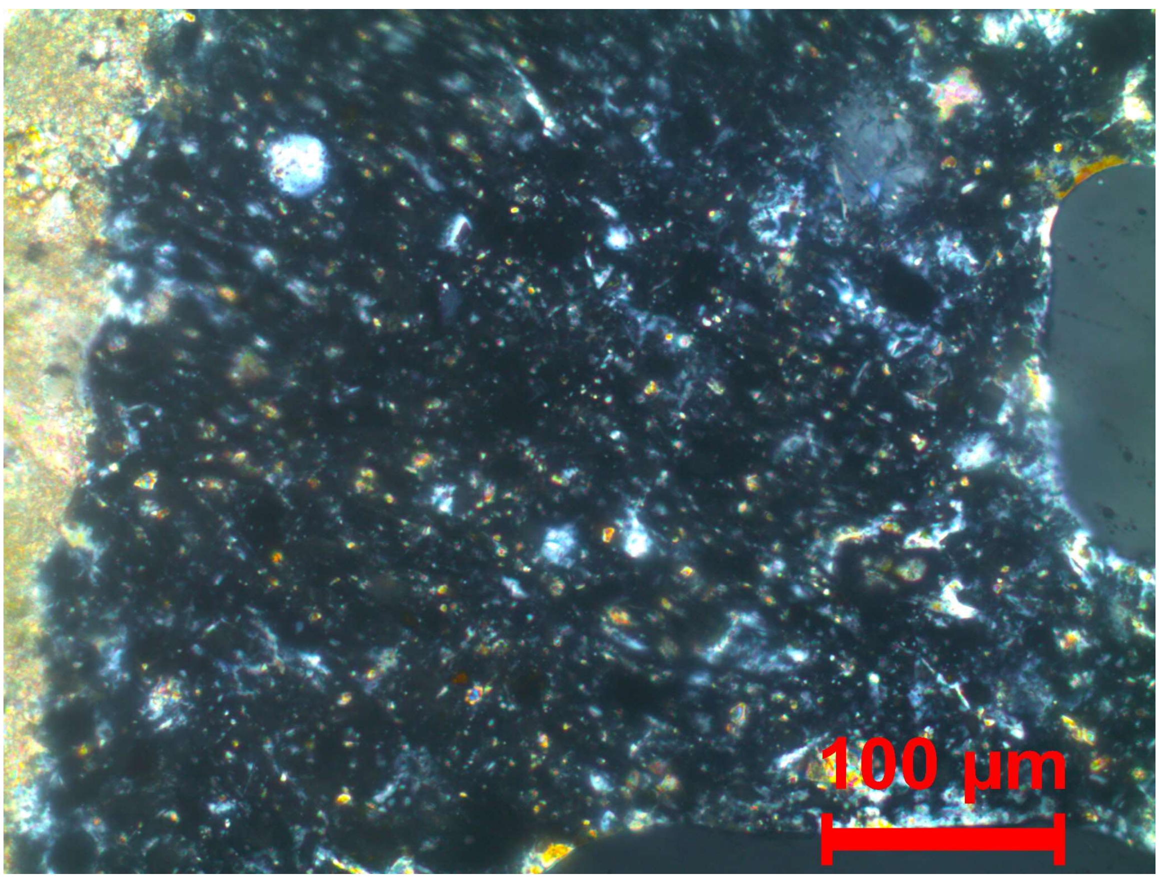

Figure 20. Control sample Image without limestone powder.

Figure 20 shows an image of the control sample that contains no additional limestone powder. The image focuses on the cement paste with the majority of the area as calcium–silicate–hydrates and calcium hydroxide reacted. There is a small presence of limestone, due to both the coarse and fine aggregates.

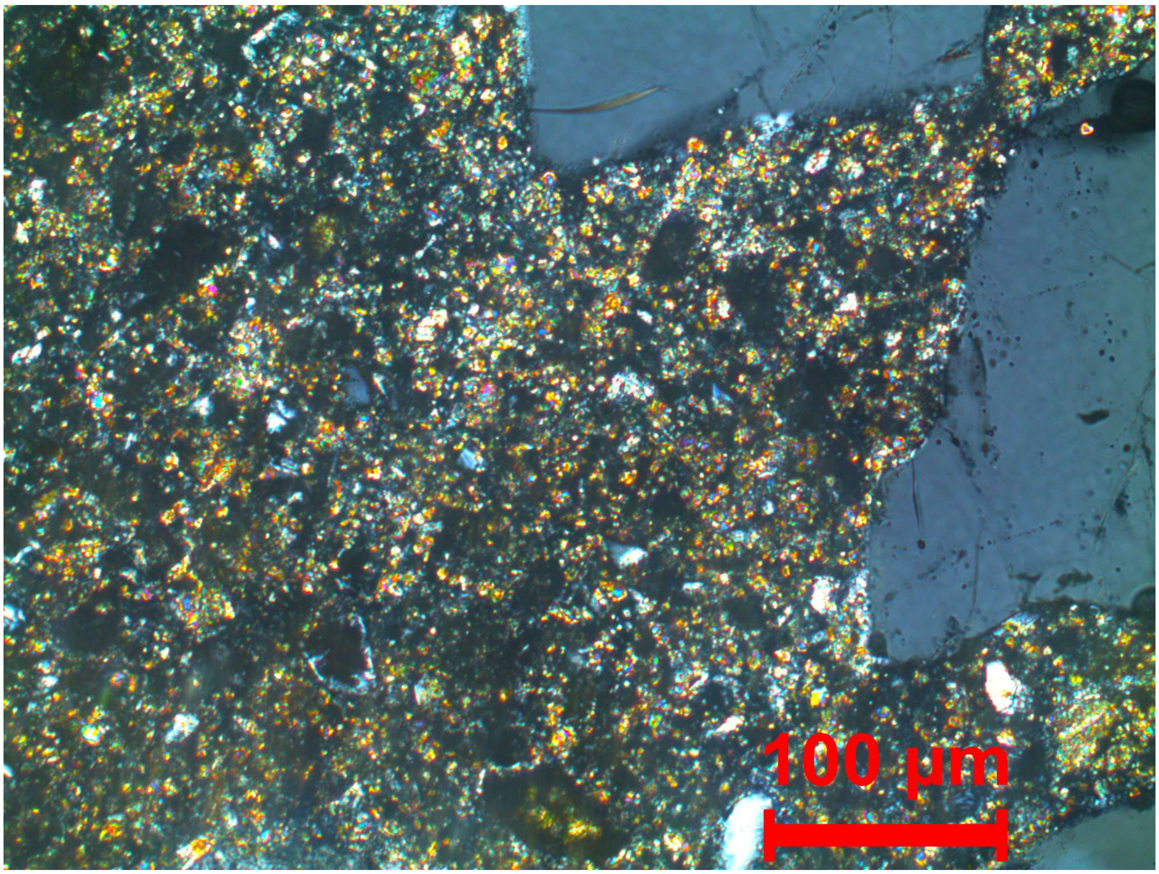

Figure 21. Sample Image of concrete with 4.5 µm Limestone Powder.

Visually there is a significant difference between Figure 20 and 21 due to the additional limestone powder. Figure 21 shows how the limestone powder is distributed relatively even within the cement paste. The affluent presence of the limestone particles indicates that a chemical reaction between the cement and limestone powder is minimal.

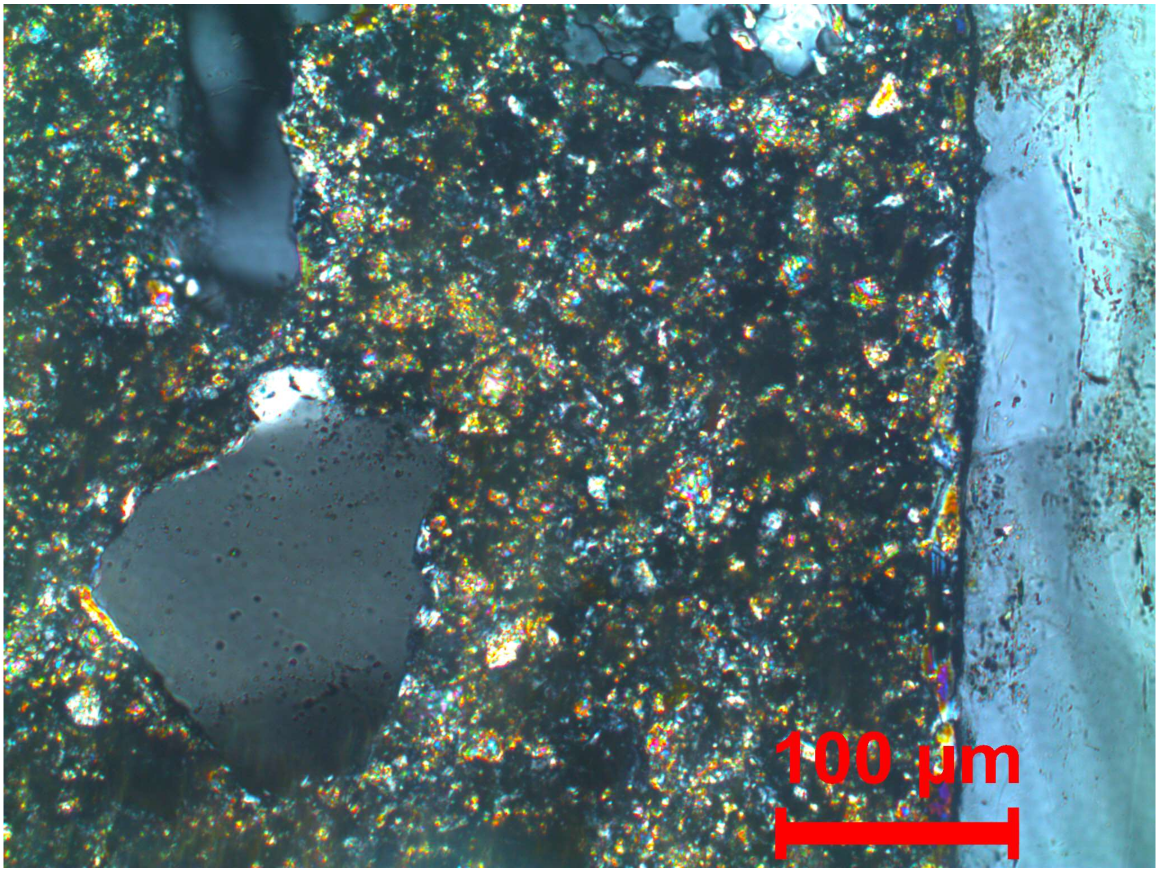

Figure 22. Sample Image of concrete with 8 µm Limestone Powder.

Figure 21 shows the 8 µm limestone particles in the cement paste. Some particles are slightly bigger, but visually it is similar to that of Figure 21. The limestone particles are still fairly evenly distributed and easily identified.

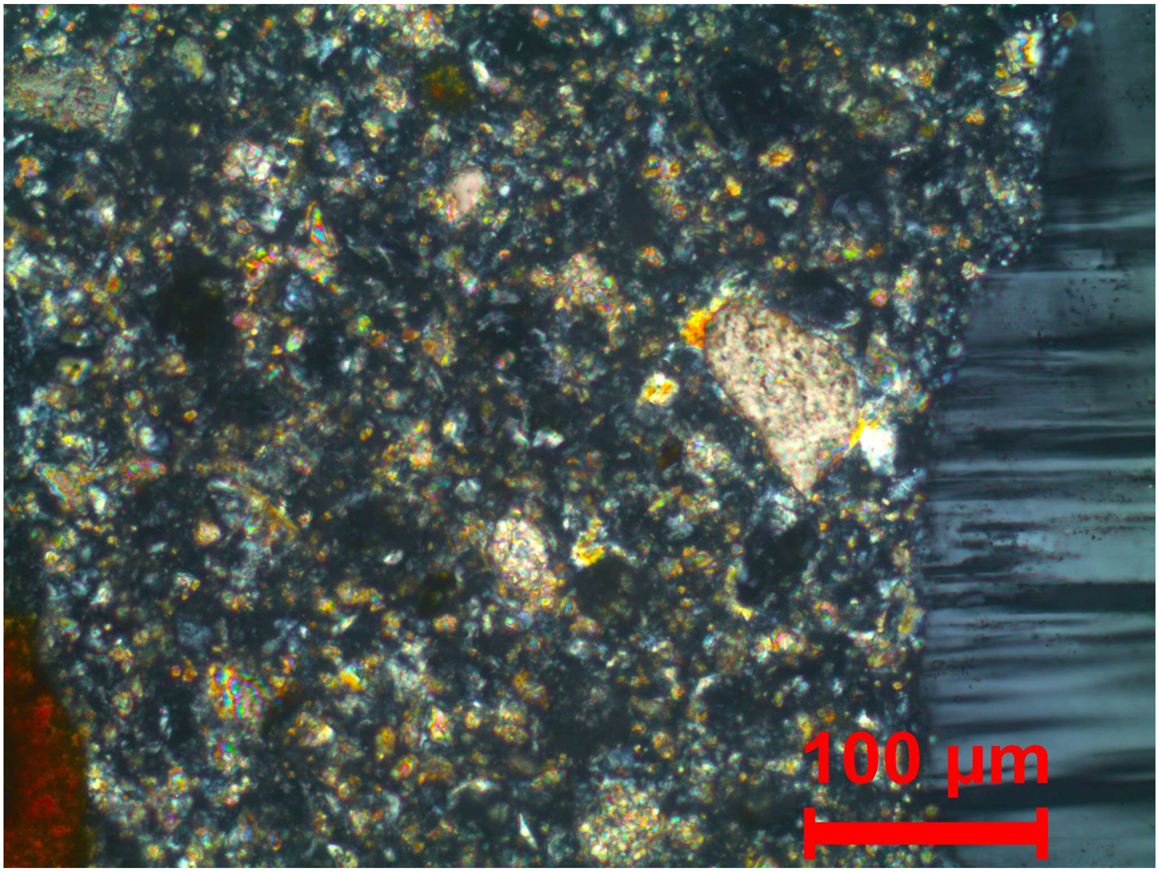

Figure 23. Sample Image of concrete with 15 µm Limestone Powder.

The visual results from Figure 23 is expressively different with large limestone particles present in the cement paste. However, the distribution of limestone particles are still similar to that of Figures 21 and 22. The majority of the particles are relatively small with a few larger particles between the paste. This might be some indication as to why the particle size does not have a significant effect on the mechanical properties. And unlike smaller cement particles that tend to react more rapidly, there is no visual chemical reaction because if there was additional formation of calcium silicate hydrate gel the images would have had a similar visual representation to that of the control.

4.4.2 Particle Size Analysis with Imaging Software

The 24 mm x 46 mm thin concrete slide images were obtained using a Leica D2500P petrographic microscope with polarizing light and analyzing filters. Each slide was used to capture three 476 x 357 µm images at magnification 200 and focus on the cement paste. Each image was analyze using ImageJ, a public domain Java image processing program that can display, edit, analyze and process images. Based on the user-defined selections and thresholds, it can count and calculate areas based on the pixel color values. Each image is analyzed selecting color threshold values of hue, saturation, and brightness that isolate the limestone particles. The values are applied to all images and processed to analyze the limestone particle to produce a count, area of the particle, and the mean color. A sample of the cement paste that did not visually contain aggregates within each image is also analyzed for the percentage of the area that is occupied by limestone particles. This is used as a reference for the particle distribution in the area because all samples contain 20% limestone powder.

Table 11. Image Software Analysis Results.

Image	Particle Count	Average Particle Area (µm²)	Average Diameter (µm)	Mean Color Threshold	Area Occupied
Alpha 2-1.jpg	2415	6.04	2.77	163.54	19%
Alpha 2-2.jpg	2088	6.15	2.80	164.09	18%
Alpha 2-3.jpg	2236	6.26	2.82	166.13	17%
Beta 2-1.jpg	1209	21.71	5.26	139.80	17%
Beta 2-2.jpg	1557	15.99	4.51	150.91	19%
Beta 2-3.jpg	1478	13.17	4.10	148.17	14%
Gamma 2-1.jpg	979	20.72	5.14	135.81	18%
Gamma 2-2.jpg	953	18.35	4.83	134.33	20%
Gamma 2-3.jpg	1172	29.29	6.11	137.45	20%

*Alpha - 4.5 µm *Beta - 8 µm *Gamma - 15 µm

Table 11 shows the collected data from each image that was analyzed. As expected, the concrete with a more fine limestone powder has a higher count of particles within the sample and less particle count as the size of the limestone particles are increased. For each particle count, an average area in µm² is also calculated. Based on the area an estimated particle size or average diameter can be determined. The area of the particle occupation within the paste is fairly consistent in all the images and is slightly less than 20%. The slight decrease below 20% of the area occupation might be an indication that a small percentage of particles might have a chemical reaction with the cement, but the decrease is most likely due to the small sample size and image distortions.

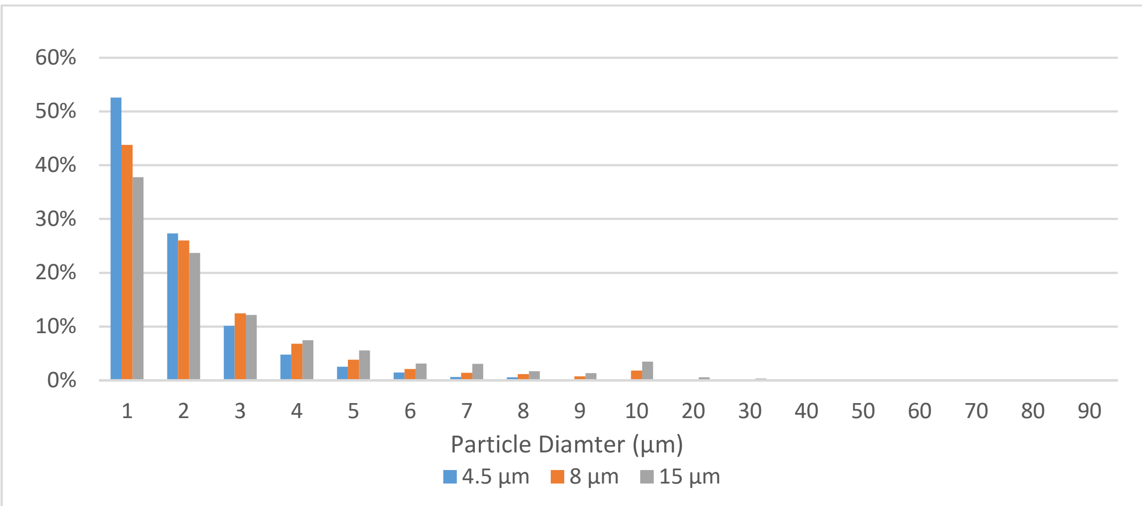

Figure 24. Particle Distribution by Diameter.

Table 11 shows the average diameter of all particles counted is less than the nominal size. This is most likely due to the two-dimensional view that displays a section of the particle, and the majority of particles are very fine as shown in Figure 24. Even though the 15 µm does contain larger particles, the percentage of particles larger the 10 µm is less than 5%. Figure 24 shows that the distribution of the particles by size are comparable and might explain why particle size has little effect on the mechanical properties.

4.4.3 Particle Distribution of Particle Size by Mass

The particle distribution of limestone powder in the concrete can be evaluated to that of the raw materials to identify if the limestone powders react with the cement or other changes in size due to clumping. The data from limestone powder is expressed by the percentage of the cumulative mass of the particle size. In order to make this comparison, data collected from the petrographic images analyzed with ImageJ are used to calculate a cumulative mass to determine the particle distribution of limestone powder in concrete. The specific gravity of limestone powder is 2.7 and can be used to determine an estimated mass equivalent sphere diameter of the particle.

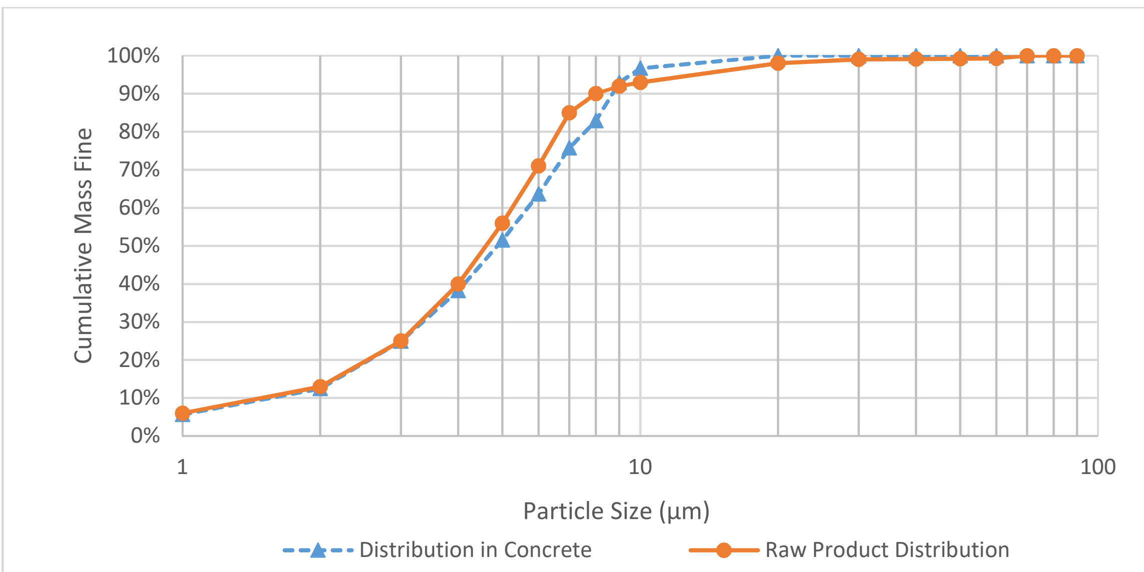

Figure 25. Limestone Powder Particle Distribution in Concrete (4.5 µm).

Figure 25 shows the particle distribution of 4.5 µm limestone powder in the concrete and compares it to the raw limestone powder product. The distribution of the limestone particles in concrete is similar to the distribution of the raw limestone powder product indicating that the distribution is homogenous and that particle do not clump together. This also indicates that there is no significant reaction occurring between the limestone particles and cement since there is little to no loss in calculated mass.

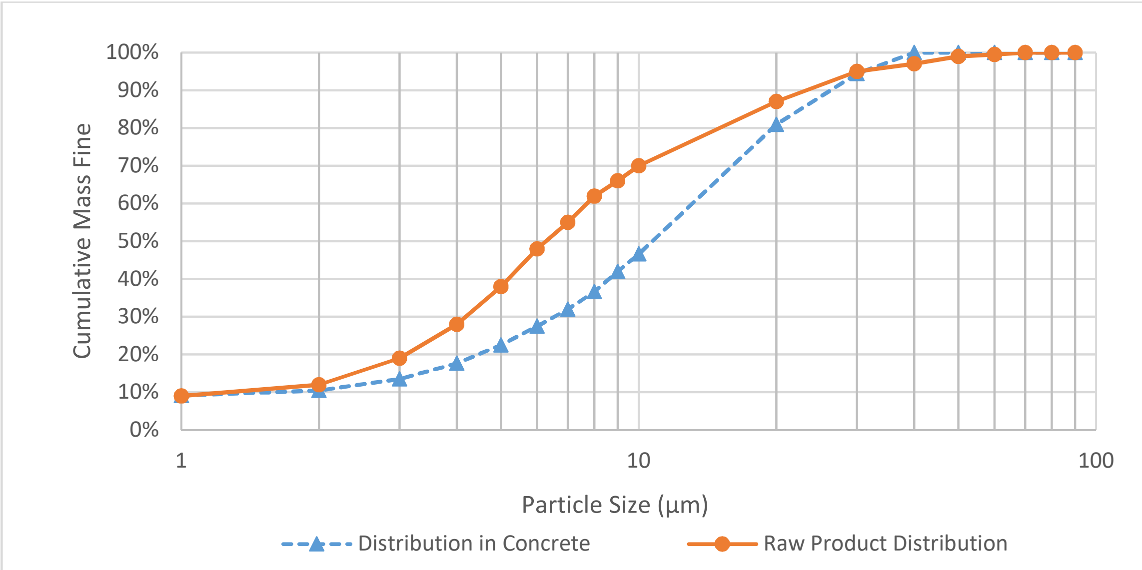

Figure 26. Limestone Powder Particle Distribution in Concrete (8 µm).

The distribution portrayed in Figure 26 of limestone particles by the cumulative mass is significantly larger than that of Figure 25. The distribution comparison between the limestone powder in concrete and as a raw product is still similar with a small increase in the cumulative mass by particle size. This increase can be an indication that a small percentage of limestone powder is clumping together. As the particle size increases the small sample size might also affect the results more.

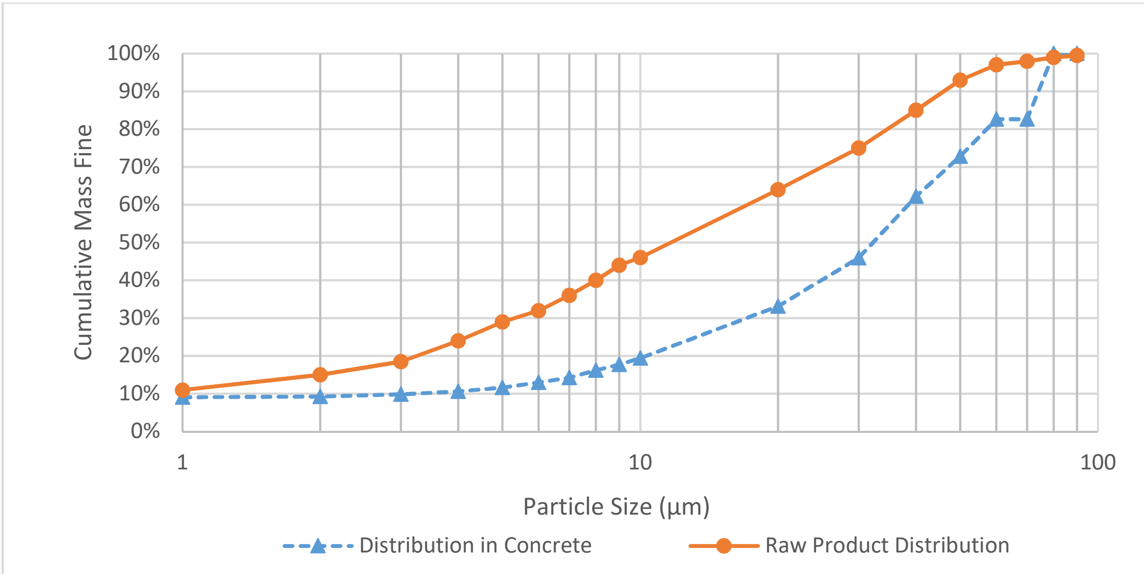

Figure 27. Limestone Powder Particle Distribution in Concrete (15 µm).

Figure 27 shows the larger particle distribution of the limestone powder in concrete following a similar trajectory of the raw limestone powder material. The larger particles might cause some additional clumping of limestone powder. Results may be affected by a small sample size and larger particles that overestimate the mass from larger particles. Based on Figure 24 the larger particles bigger than 10 µm represent less than 5% of particles though they significantly affect the distribution of mass. Table 11 shows little change in the area of occupation based on the particles size from two-dimensional images, and because there is minimal reaction between cement paste and limestone powder, it is assumed that the controlling factor is the volume of limestone powder occupation within the cement paste. The representative combination by mass of the particle size and count are negligible as long as the volume of occupation remains the same.

4.5 Efficiency of Limestone Powder in Concrete

The dilution effect of limestone powder results in a lower hydraulic reactivity, which in turn affects the compressive strength of the concrete. However, the dilution effect enhances homogeneity. This occurs by the dispersion of clinker particles which increases the bonds per unit of cement, which in turn, results in decreased porosity (KakaliL, Tsivilis, Aggeli, & Bati, 2010). To determine the efficiency of limestone powder as a cement replacement it must be compared to properties of cement. Even though limestone powder does not have cementitious properties, the effectiveness of the particles distribution can be evaluated by using a modified version of Féret’s equation. Using the test results of the compressive strength at 28 days and 90 days, the limestone powder factor of efficiency can be calculated in relation to cement.

$Modified\ Féret's\ Equation$:

$$f_c = K\left(\frac{c + (k_{ls} * ls)}{c + ls + w + a}\right)^2 \qquad \text{(Eq. 2)}$$

$Where$:
$f_c = Compressive\ stregth\ (PSI)$
$c = Cement\ (ft^3/yd^3)$
$w = Water\ (ft^3/yd^3)$
$a = Air\ (ft^3/yd^3)$
$K = Empirical\ Constant$
$ls = Limestone\ Powder\ (ft^3/yd^3)$
$k_{ls} = Efficiency\ of\ Limestone\ Powder$

Modification of Féret’s equation will encompass the same structure as the original equation, however, it modifies the integer numerator containing the volume of cement to include the limestone powder and the efficiency factor (k_{ls}). The denominator is also modified to adjust for the volume of the limestone powder due to a lower specific gravity. Using the compressive strength results of the control mix, the volumetric portions of cement, water, and air allows the ability to calculate K, an empirical constant using Féret’s equation. Because the aggregates and the mixing process remains unchanged in batches that contain limestone powder, the empirical constant K will remain constant and can be used in the modified equation with a value of 40544 for 28 days and 46223 for 90 days.

Table 12. Efficiency Factor of Limestone Powder in Concrete.

Mix Design	Control	Alpha-10	Beta-10	Gamma-10	Alpha-20	Beta-20	Gamma-20	Alpha-30	Beta-30	Gamma-30
Cement (ft^3/yd^3)	2.99	2.69	2.69	2.69	2.39	2.39	2.39	2.09	2.09	2.09
Limestone Powder (ft^3/yd^3)	-	0.35	0.35	0.35	0.70	0.70	0.70	1.05	1.05	1.05
Water (ft^3/yd^3)	3.77	3.77	3.77	3.77	3.76	3.76	3.76	3.77	3.77	3.77
Air Content (ft^3/yd^3):	0.65	0.59	0.62	0.59	0.57	0.61	0.59	0.61	0.57	0.54
28 Day CS (PSI)	6610	5684	5722	5816	5454	5378	5534	5218	5366	5197
90 Day CS (PSI)	7536	6427	6293	6524	5747	6011	6090	5576	5695	5703
28 Day Efficiency Factor	0	0.23	0.29	0.32	0.47	0.47	0.52	0.58	0.60	0.55
90 Day Efficiency Factor	0	0.20	0.15	0.26	0.32	0.43	0.45	0.49	0.51	0.50

The modified equation can be used on batches containing limestone powder to calculate k_{ls}, the efficiency factor based on volumetric portions of cement, water, air, and the compressive strength per Table 12. The efficiency factor gives a representation of cementitious properties of the limestone powder in relation to cement based on the volume occupied.

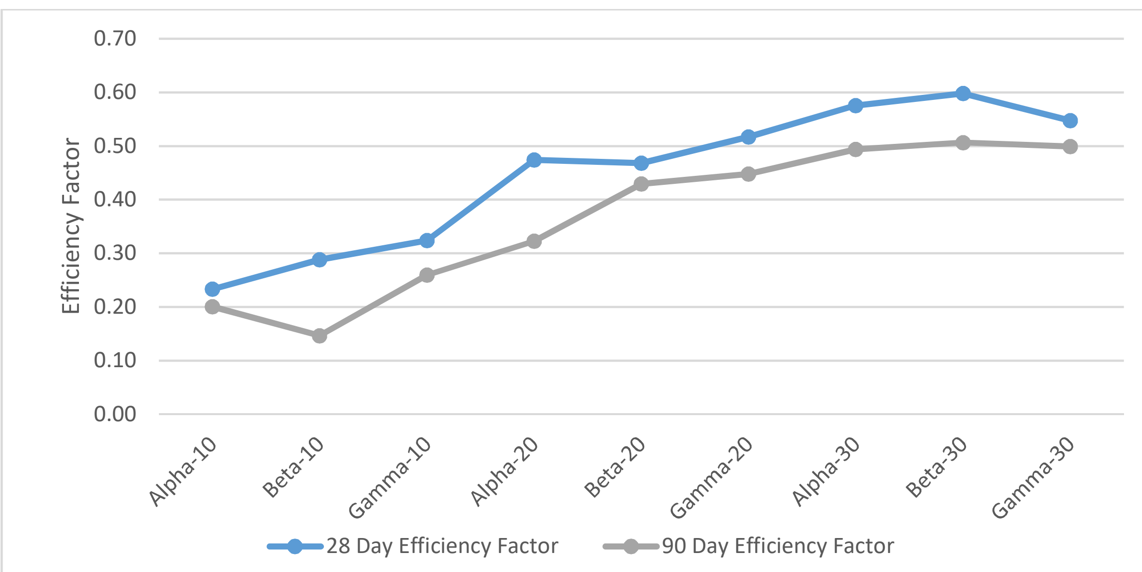

Figure 28. The Efficiency of Limestone Powder.

Figure 28 shows the calculated efficiency factor using the modified version of Féret’s equation and demonstrates how the efficiency factor increases when a greater amount of cement is replaced. The 28 day efficiency factor increases an average of 104% from 0.23 - 0.32 for a 10% replacement to 0.55 - 0.60 for a 30% replacement. With similar results for the 90 day efficiency factor that increases from 0.15 - 0.26 for a 10% replacement to 0.49 - 0.61 for a 30% replacement, there is an average of a 150% increase in efficiency. There is little variance in the efficiency factor based on the particle size, but it is not significant enough to make any conclusions other than the effects are negligible.

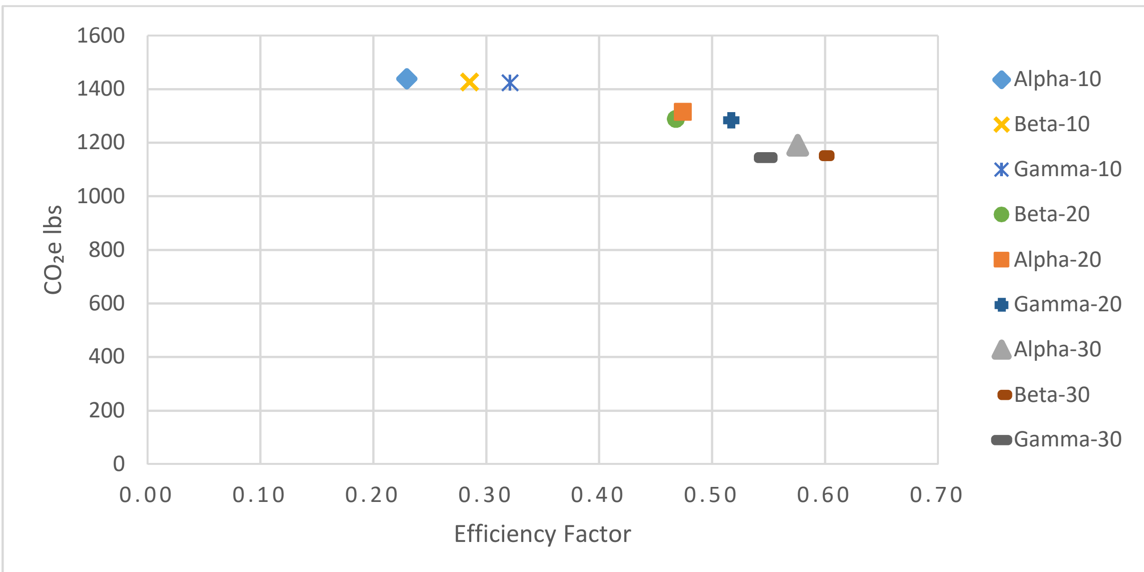

Figure 29. 28 Day Efficiency Factor and Emission Comparison.

The efficiency factor is a nominal representation of the limestone powder mechanical properties, but the environmental effects have to be considered in conjunction with each other to utilize limestone powder in concrete. Figure 29 illustrates that as the efficiency factor of limestone powder increases, it decreases the environmental impact of the concrete. Both the 20% and 30% limestone replacements efficiently utilize limestone powder in concrete with the 30% replacement most beneficial in any particle size.

4.5.1 Limestone Powder Predictive Model

Once the efficiency factor per replacement level and particles have been determined, Féret's modified equation can serve as a model to develop and predict the strength of mix designs containing limestone powder. The model is based on the same principles and element of Féret's equation that describe the relationships between mix compositions and compressive strength properties. Since the mix compositions of concrete differ based on the regions and material availability the model also utilizes a calculated empirical constant. This allows for the model to be applied to a mix design that has known mechanical properties. Using Féret's original equation and the volumetric portions of cement, water, and air the empirical constant can be calculated.

$Predictive\ Model\ of\ Féret's\ ModifiedEquation:$

$$f_c = K\left(\frac{c + (k_{ls} * ls)}{c + ls + w + a}\right)^2 \qquad \text{(Eq. 3)}$$

$Where:$
$f_c = Compressive\ stregth\ Prediction (PSI)$
$c = Cement\ (ft^3/yd^3)$
$w = Water\ (ft^3/yd^3)$
$a = Air\ (ft^3/yd^3)$
$K = Empirical\ Constant$
$ls = Limestone\ Powder\ (ft^3/yd^3)$
$k_{ls} = Efficiency\ factor\ of\ Limestone\ Powder\ (Replacement\ Level\ Averages)$

Since the size of limestone particles does not significantly effect on the mechanical properties, the average efficiency factor is used to simplify the model. The average efficiency factor for a 10% is 0.28, 0.49 for 20% replacement, and 0.57 for a 30% replacement at 28 days. The model also allows for the manipulations of water to cement ratios and air content.

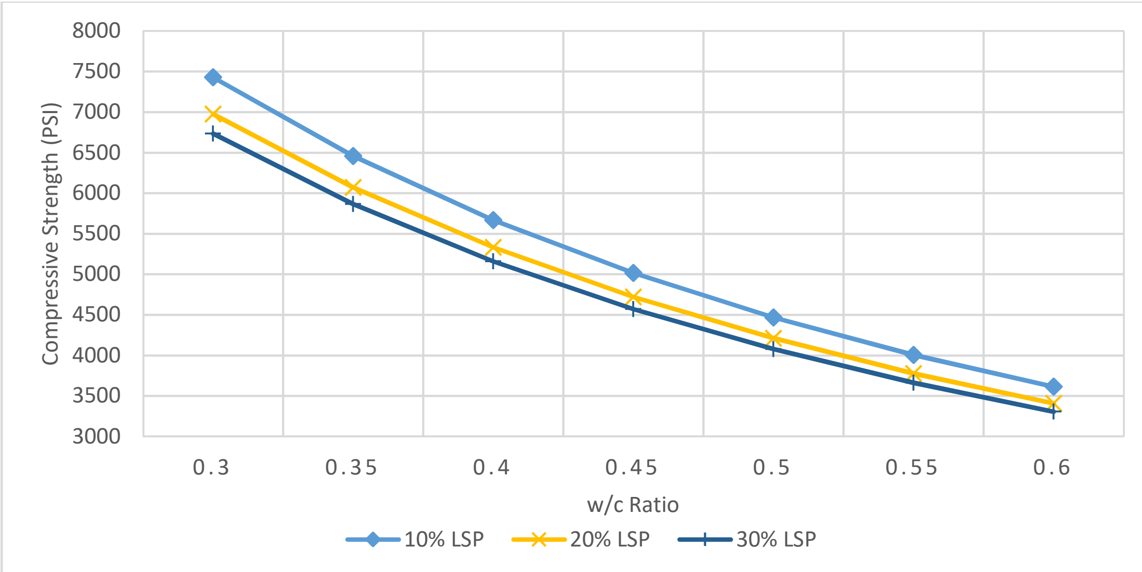

Figure 30. Limestone Powder Prediction Model with different w/c Ratios.

Figure 30 displays the 28 day compressive strength predictions based on the mechanical properties of the control mix design with different water to cement ratios. Strength prediction results range from 3306 psi to 3614 psi for a 0.6 w/c ratio and from 6733 psi to 7428 psi for a 0.3 w/c ratio. The 0.40 w/c ratio predicted results is almost identical to compressive strength test results with small variation. The prediction model can serve as a viable tool to plan for concrete mix designs containing limestone powder that meet specific specifications based on mix known mix designs.

4.6 Life Cycle Assessment of Limestone Powder in Concrete

Materials from the mix design and emission data in Table 13 are from the PCA report on the life cycle assessment of different mix designs (Nisbet, Marceau, & VanGeem, 2002). Data for the production of limestone powder emissions were attained from the manufacturer (HuberCrete, 2015). The environmental impact was assessed based on the carbon dioxide equivalents (CO_2e), found in the U.S. Environmental Protection Agency Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) to obtain the emission factors (Bare, Norri, Pennington, & McKone, 2012). There are several benefits of conducting a life cycle assessment, including the ability to evaluate the environmental affect materials and operations have in concrete production, identifying pollution shifts between operations, and providing benchmarks for improvement. This allows for comparison between limestone powder replacement levels and the different particle sizes and their associated environmental impacts. To accurately conduct an LCA, an inventory of all inputs and outputs are documented with a life cycle inventory.

Table 13. CO_2e Emission of a yd³ of Concrete.

CO_2e lb/yd³	Control	Alpha-10	Beta-10	Gamma-10	Alpha-20	Beta-20	Gamma-20	Alpha-30	Beta-30	Gamma-30
Cement	1425	1283	1283	1283	1140	1140	1140	998	998	998
Limestone	0.00	17.82	4.81	2.41	35.64	9.62	4.81	53.45	14.43	7.22
Water	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57
River Gravel	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13	13.13
River Sand	9.22	9.22	9.22	9.22	9.22	9.22	9.22	9.22	9.22	9.22
Transportation	49.94	49.94	49.94	49.94	49.94	49.94	49.94	49.94	49.94	49.94
Production	65.62	65.62	65.62	65.62	65.62	65.62	65.62	65.62	65.62	65.62
Total CO_2e lb/yd³	1564	1439	1426	1424	1314	1288	1284	1190	1151	1144
CO_2e Reductions	0.0%	8.0%	8.8%	9.0%	16.0%	17.6%	17.9%	23.9%	26.4%	26.9%

*Alpha - 4.5 μm *Beta - 8 μm *Gamma - 15 μm

Table 13 illustrates the carbon dioxide equivalents (CO_2e) of environmental impact for each material component, as well as for the transportation and production operations. The table clearly indicates the high degree of environmental impact from cement manufacturing in concrete production. Based on the control mix design, the manufacturing of cement accounts for 91% of the CO_2e emissions, although the concrete contains only 15.7% of cement. The main source of the emission is the operation of the kiln where CO_2 emissions are very high due to the calcination process while driving off CO_2 from $CaCO_3$.

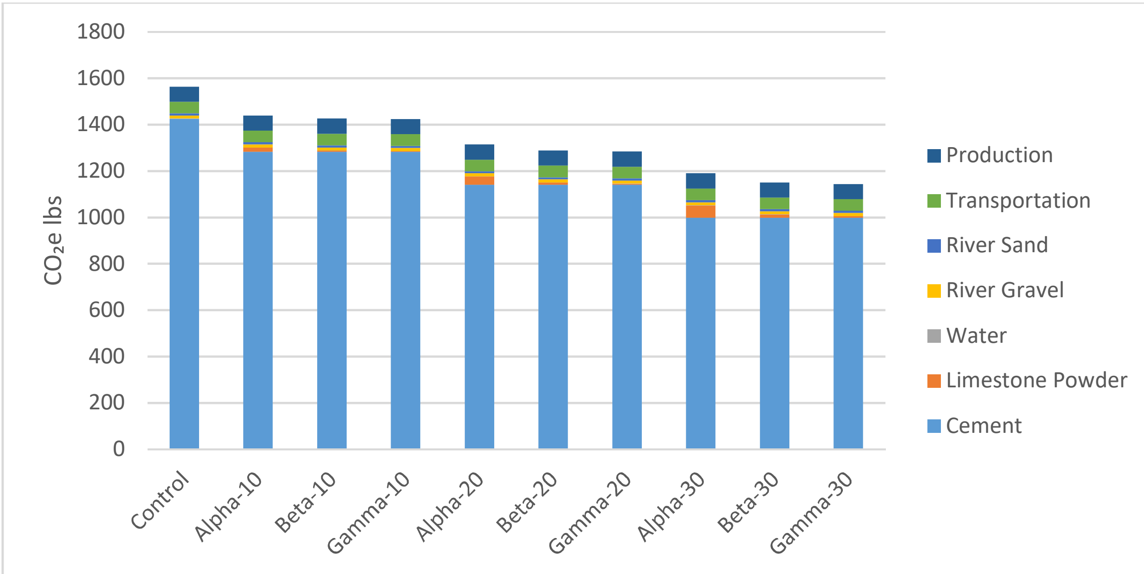

Figure 31. CO_2e Emission of Concrete Mix Designs.

Figure 31 shows the direct relation CO_2e emission has in the replacement of cement with limestone powder. As the levels of replacement increase and the particle size of the limestone powder increases, the CO_2e emissions of the mix designs decrease. Figure 31 indicates that for every 10% of cement that is replaced with limestone powder, the CO_2e emissions decreased by 8% to 9% depending on the particle size. The particle size of the limestone powder does not have a significant effect on CO_2e emissions. Reducing CO_2e emissions by 1% for every 10% replaced larger limestone powder particles.

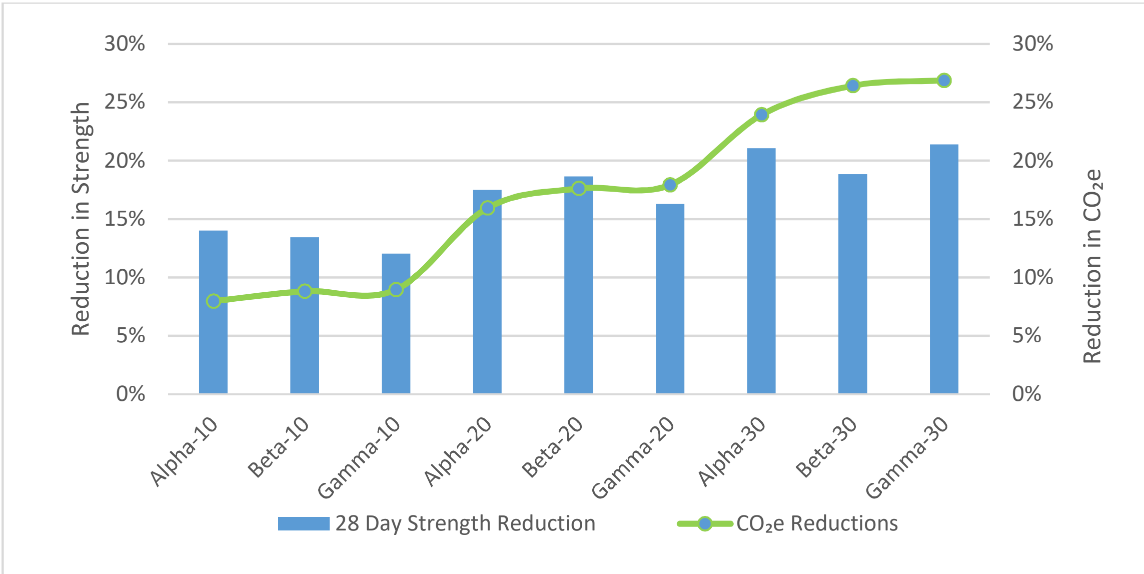

Figure 32. % CO_2e Reductions Compared to % Strength Reduction.

Higher levels of limestone powder replacement, however, adversely affect the compressive strength of concrete. Figure 32 compares the benefits of the reduction in CO_2e emissions and the adverse effects on the compressive strength. Figure 32 also indicates at what level of percentage replacement the benefits of CO_2e emissions are greater than the loss of strength. At a 10% replacement of cement, the compressive strength was reduced by an average of 13% at 28 days, and CO_2e emissions by 9.5%. With the loss of strength exceeding the emissions, this percentage of replacement is not very efficient. A 20% replacement of cement has an average of a 17% reduction in compressive strength at 28 days, while CO_2e emission is reduced by 17.2%. This indicates that at a 20% replacement level of cement, the benefits of the reduction of CO_2e emissions from using limestone powders in concrete starts to surpass the loss in strength. At a 30% replacement, the reduction of CO_2e emissions is greater than the loss of compressive strength, with an average 5.7%, making it the most effective level of cement replacement because the environmental benefits outweigh the reduction of the compressive strength.

4.7 Optimizing the Limestone Powder in Concrete

The use of limestone powder in concrete to replace portions of cement can help to meet demand and reduce the environmental impact of cement production. But with all supplementary materials, the proportional use must be optimized. Optimization of the use depends on multiple factors and can vary from region to region. Cost and availability are both important factors to consider for using limestone powder in concrete and will have to be assessed based on the local region. Due to the dilution effect, both the mechanical properties and environmental effects have to be considered with each other to utilize limestone powder in concrete. The optimal solution is based on the life cycle analysis results, the mechanical properties, and the efficiency.

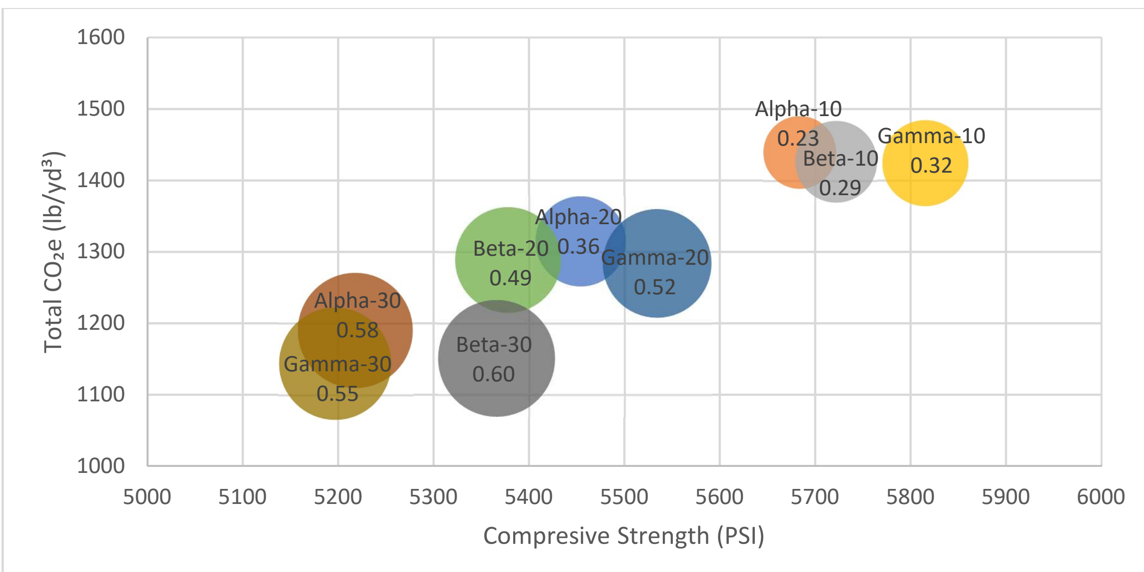

Figure 33. Optimizing the Limestone Powder in Concrete at 28 Days.

Figure 33 compares the life cycle analysis results, the mechanical properties and the efficiency factor of the limestone particles sizes and replacement levels. The graph reiterates that particles size is not a driving factor in the optimization and will be more dependent on the availability and cost of using limestone powder in concrete. The optimal use of limestone powder is in higher replacement concentrations. These concentrations reduce the environmental impact of producing concrete and are more efficient with Beta-30 having the highest efficiency at 0.60. The loss of strength does increase as the replacement levels increase, though the reduction in strength is less significant, but has to be accounted for when implementing limestone powder in concrete.

V. CONCLUSION

5.1 Summary

This study was conducted to evaluate the effects of high volume limestone powder with different particle sizes and levels of cement replacement have on the characteristics of concrete when blended during batching. Results from this experiment indicate that introducing limestone powder in high volumes has positive effects on concrete and the environment. Based on the established parameters, concentrations of limestone powders at higher levels are more effective when aspects of environmental effects and properties of strength are considered. However, the use of limestone powder as a cement replacement adversely affects the compressive strength. Based on the efficiency factor, the predictive model can be used to develop mix designs that meet specifications.

5.2 Conclusions

- The use of limestone powder as a cement replacement in concrete has little effect on the fresh properties. The density and air content of concrete in a fresh state are slightly lower with higher levels of replacement that likely has a more efficient particle distribution. The workability of the concrete does increase with the presence of limestone powder in the concrete, but not significantly.
- The level of cement replaced with limestone powder does affect the compressive strength negatively as levels increase. But at higher levels of limestone powder in concrete, the percentage of strength loss is less significant.
- The particle size of limestone used has little or no effect on the compressive strength of mortar and concrete at all levels of replacement that were conducted in this study.

- Mortar strength can be used to predict concrete strength due to the significant correlation between the compressive strength of the mortar and concrete, and that the rate of curing is the same as conventional concrete.
- The correlation between the splitting tensile strength and the modulus of rupture to that of the concrete compressive strength concludes that that particle size has little effect on flexural strength.
- The level of cement replaced with limestone powder does effect the shrinkage positively as levels increase by reducing shrinkage. But the particle size of limestone used has little or no effect on the shrinkage at all levels of replacement.
- The effectiveness of limestone powder in concrete is higher at higher levels of cement replacement. This is mostly likely due to the efficient particle packing and particle distribution of the limestone powder in the concrete.
- The replacement of cement with limestone powder significantly reduces emissions. This reduction in emissions is directly related to the level of replacement.
- The loss of compressive strength at low level replacement is greater than the benefits of emission reductions. But at higher replacement levels, the benefits of emission reductions outweigh the loss in compressive strength.
- The efficiency factor of limestone powder calculated from Féret’s modified equation increases the efficiency as replacement levels are increased.
- Féret’s modified equation can serve as a model to develop and predict the strength of mix designs containing limestone powder.

5.3 Recommendations

The following recommendations are based on the conclusions and results:

- To increase the strength of concrete, the batch design may have a lower water/cement ratio and to maintain the workability admixtures like plasticizers might be incorporated.
- To use Féret's modified equation as a predictive model to develop mix designs containing limestone powder to meet specifications from a mix design that the composition and mechanical properties are known.
- The use of concrete with limestone powder is recommended for horizontal applications like flatwork, such as pavements, foundations, driveways and sidewalks.

5.4 Future Research

Additional research is needed to support the use and application feasibility of concrete with high volumes of limestone powder. Future studies should investigate the following topics:

- Blending in pozzolanic materials can be used to reduce the negative effects on the compressive strength. By optimizing of the mixture design in concrete, positive effects on the life cycle can be maintained with minimal strength reductions.
- Proving the prediction model by modifying the water to cement ratio and comparing the results to the model for concrete with limestone powder.
- Evaluating the setting time and heat of hydration in concrete with limestone powder.
- Measuring thermal mass properties (emissivity and reflectivity) from the lighter colored limestone powder concrete.
- Conducting a cost benefit analysis and material availability assessment of limestone powder production for concrete applications.

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