COMPARISON OF HIGH FLOW CONCRETE MADE WITH TYPE III CEMENT WITH VARYING LIMESTONE POWDER FINENESS

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ABSTRACT

This research compares the behavior of high flow concrete made from Type III cement with varying fineness of supplementary limestone powder. In the precast industry, where limestone powder is added to concrete mixes with Type III cements, benefits have been recognized, including increased cohesion and improved surface finish. Being able to predict hydration, strength and workability trends based on both the size of the limestone particle and the limestone content, would assist concrete suppliers in tailoring precast concrete mixes. Guidelines such as the ACI 211.7R: Guide for Proportioning Concrete Mixtures with Ground Limestone and Other Mineral Fillers provide very general trends for how limestone affects concrete properties, but specific guidelines based on limestone median particle size are not available. The results show how varying median particle size of limestone powder of 3, 25 and 40 μm influence heat of hydration, time of set, compressive strength, workability, surface finish and drying shrinkage of high flowing concretes. This investigation lays the groundwork for developing specific guidelines for concrete mix designs which include limestone cement blends.

Keywords: Limestone blended cements, high flow concrete

INTRODUCTION

Precast plants use self-consolidating concrete (SCC) mixes to increase production, reduce or eliminate the need to vibrate formwork and to achieve concretes with improved surface finish, leading to reduced post-production time[1]. To reduce bleeding, SCC mixes must either have a high fine particle content or use a viscosity modifying agent (VMA)[2]. Replacing a portion of the cement with an inexpensive filler, such as limestone powder is a cost-effective method to maintain workability at a reduced cost, since limestone filler costs about half of cement. According to some studies, limestone cement blends can be beneficial to both cost and flowability by lowering the cement fraction, but may cause additional shrinkage and creep[3].

Adding limestone to mixes affects the hydration of cement in several ways. Due to the replacement of reactive cement with slightly reactive limestone, a dilution effect is anticipated[4,5,6]. Secondly, depending on the particle size of the limestone powder, additional nucleation sites for cement hydration products may be introduced[7,8,9]. Thirdly, depending on the median particle size of the limestone powder, it may promote efficient particle packing, and hence lower porosity[10,11].

Limestone powders ground finer than the base cement should increase nucleation, accelerate hydration and lead to increased early compressive strengths[8]. Cements and limestone powders having finer particle size distributions react more quickly than coarser ground powders due to their increased surface area, smaller interparticle spacing and increased number of sites for calcium-silicate-hydrate (CSH) nucleation[6]. Increased fineness leads to increased paste cohesion and stability but may in turn reduce workability. On the other hand, when coarser ground limestone is blended with cement, the increased particle dispersion may improve workability. Coarser ground limestone powders can lower packing density and through dilution, lower heat of hydration[9,12,13].

Heat of hydration, time of set, workability and hardened concrete mechanical properties are affected by the relative particle size distribution between the base cement and the limestone powder being used as partial cement replacement by mass[9,14,15,16]. Understanding these influences can be used to better tailor concrete mixtures used for concrete applications and to adjust water reducing admixtures based on workability. Being able to predict hydration rate, workability, and mechanical property trends based on both the size of the limestone particle cement substitutions and the limestone content would assist concrete suppliers in tailoring concrete mixes. Guidelines such as the ACI 211.7R provide very general trends for how limestone affects concrete properties, but specific guidelines based on limestone median particle size are not available[17]. How these constituents influence concrete mixes made with Type III cement is of particular interest to the precast industry, which almost exclusively uses high early strength cement. This investigation aims to lay the groundwork for developing guidelines for concrete mixtures made with limestone blended Type III cements.

MATERIALS

A Type III cement and three limestone powders were used throughout this research. The Type III cement conformed to ASTM C150 and had a specific gravity of 3.10[18]. The three limestone powders came from the same quarry, but were ground to varying fineness. They are classified by the supplier according to their median particle size of 3, 25, and 40 µm and have specific gravities of 2.7.

Laser diffraction was used to determine the physical particle size distribution (PSD) of the materials and compare it with that of the Type III cement. As seen in the results of the PSD in Figure 1, the 3 µm limestone can be classified as finer than the Type III cement, the 25 µm limestone powder is the most similar to the cement, and 40 µm limestone can be classified as coarser than the cement.

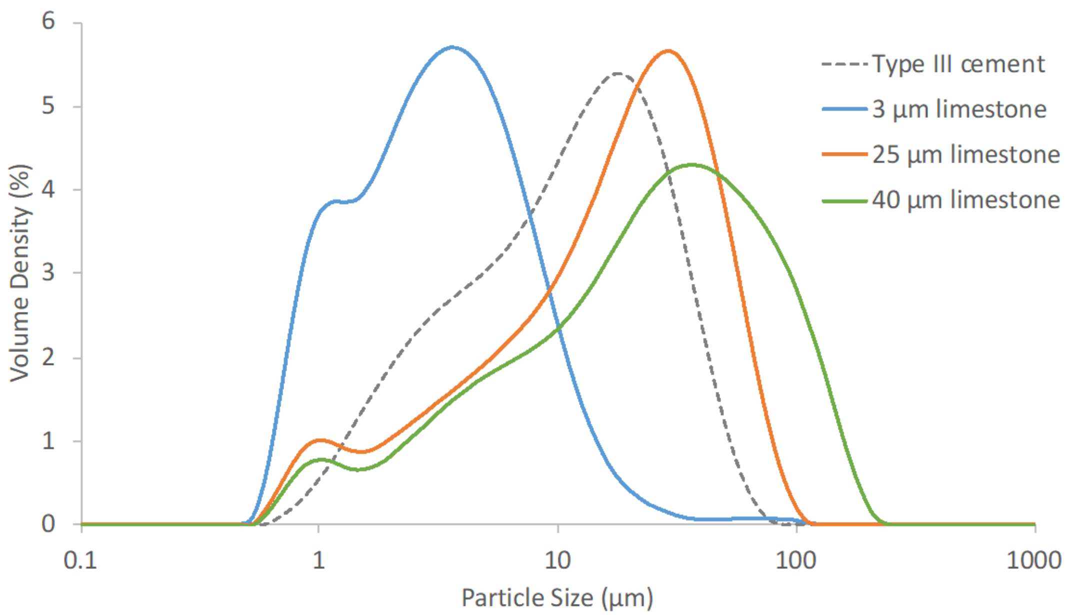


Fig. 1: Particle Size Distribution of Type III Cement and Limestone Powder

In addition to cement and limestone powder, concrete mixes were made with coarse aggregate, fine aggregate and a high range water reducing admixture. The coarse aggregate is a granitic gneiss meeting the requirements for AASHTO #67 stone with a maximum aggregate size of 3/4 inch (19 mm), a specific gravity of 2.61 and an absorption capacity of 0.58%. The fine aggregate was a natural, alluvial sand with a specific gravity of 2.63, a fineness modulus of 2.4, and an absorption capacity of 0.4%. For producing SCC mixes, a high range water reducing admixture (HRWRA) was used. The polycarboxylate HRWRA met the classification of ASTM C494 Type A and F[19].

In this study, cement pastes and concrete mixes are classified by (1) the size of the limestone powder: L3, L25, and L40 for limestone powders with median particles sizes of 3, 25, and 40 µm, respectively, and (2) the percent cement substitution denoted in parenthesis (X). Thus, T3L25(15) is a mix blending Type III cement with 25 μm limestone powder at a 15% cement replacement.

EXPERIMENTAL PROGRAM

ISOTHERMAL CALORIMETRY

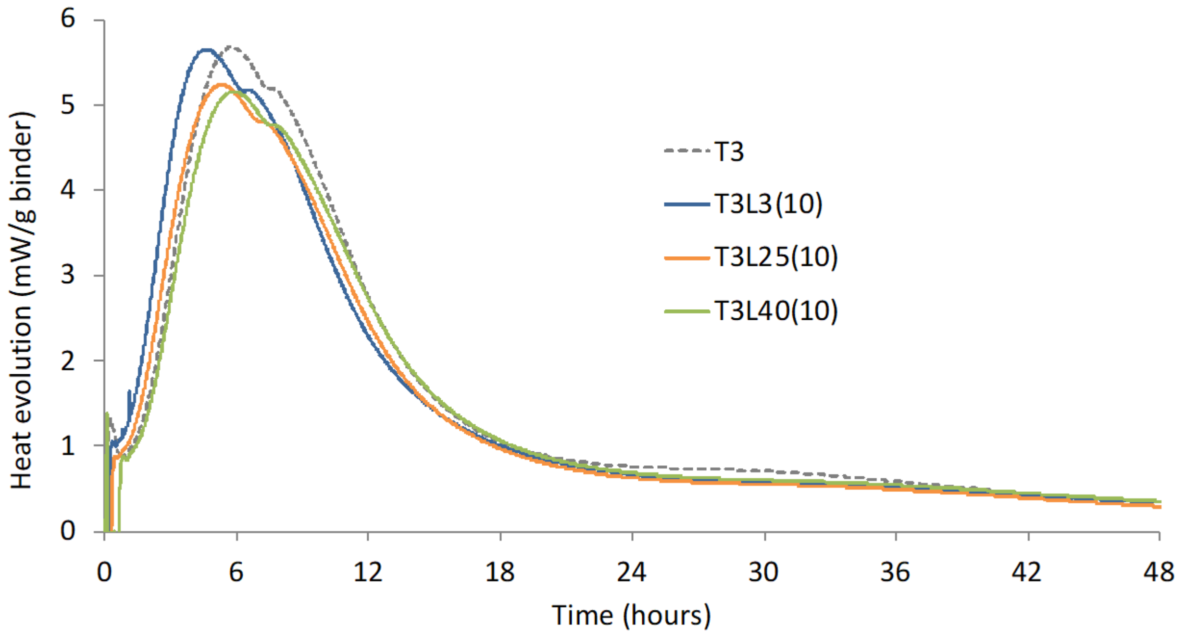
To understand the hydration kinetics of hydrating blended limestone cements, isothermal calorimetry was used to measure the heat produced by the hydrating cement pastes and to determine the cumulative heat (the integral of the hydration curve) over 48 hours, per ASTM C1679[20]. Cement and limestone powder blends were mixed with deionized water keeping a constant water-to-powder (w/p) ratio of 0.38. The cement paste mix proportions are shown in Table 1.

Table 1: Cement paste mix for isothermal calorimetry

Mix ID	T3	T3L3(10)	T3L25(10)	T3L40(10)
Cement (g)	50	45	45	45
Limestone (g)	-	5	5	5
Water (g)	19	19	19	19

Figure 2 shows that a 10% substitution of the fine 3 μm limestone powder accelerates the rate of hydration demonstrated by a shift to the left of the hydration curve. This leftward shift is most likely due to increased nucleation sites of the finer powder. Compared to the pure cement paste, the peak hydration of the blended 3 μm paste is almost identical, but the 3 μm paste reaches its peak hydration about 20% earlier than the mix with no limestone. The blended 25 μm limestone powder paste shows a slight hydration acceleration also of around 8% compared with the pure cement paste. It reaches its peak hydration about 8% earlier than the pure cement paste, but the peak hydration is reduced mainly due to dilution by around 8%. The blended 40 μm limestone paste shows almost straight dilution, with no shift of the hydration curve to the left and a reduced peak hydration of 10% less than the pure cement paste.

The cumulative heat curve shows that after 48 hours of hydration, the blended 25 μm and 40 μm limestone pastes have the least amount of cumulative heat gain compared with the pure cement paste. Both blends have an 8% reduction in overall heat. The cumulative heat gain of the blended 3 μm limestone paste is actually greater than the pure cement paste for the first 10 hours of hydration, but then reduces to about 5% of the pure cement paste total heat gain by 48 hours.



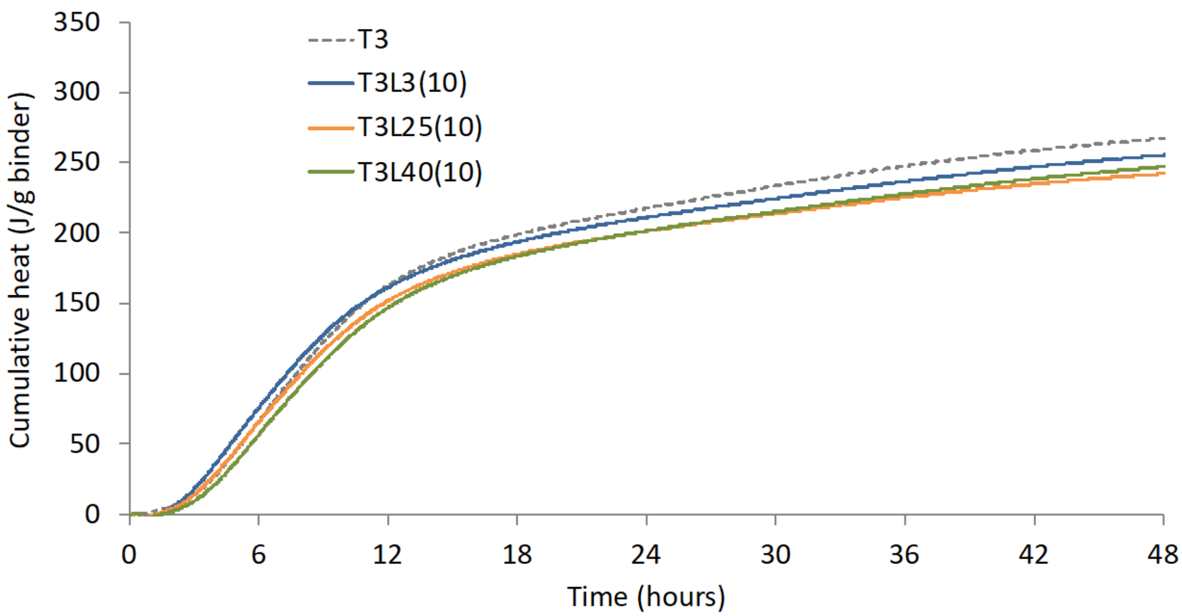


Fig. 2: Heat of hydration curve (above) and cumulative heat (below) of Type III cement and limestone blended cements

VICAT TIME OF SET

The Vicat time of set provides an indication as to how quickly the cement will harden. The procedures outlined in ASTM C191 were followed to determine the time that cement pastes reached initial set, indicated by a needle penetrating the paste 25 mm, and the time at which the paste reached final set, indicated by a needle making no penetration into the cement paste[21]. The experiments were performed on pure Type III cement paste and on Type III cements blended with 3, 25, and 40 µm limestone powder at a 10% cement replacement. The ASTM standard calls for using a water-to-binder ratio that produces a paste with normal consistency defined by ASTM C187 as a 10 mm diameter needle penetrating the cement paste no deeper than 10 ± 1 mm[22]. Normal consistency of the Type III cement paste was reached at a water-to-binder ratio of 0.272. Following the procedure of ASTM C305, cement pastes were made by mixing 650 g of cement or cement plus limestone powder with deionized water[23]. Table 2 shows the cement paste proportions used to evaluate time of set.

Table 2: Cement paste mix used for Vicat time of set

Mix ID	T3	T3L3(10)	T3L25(10)	T3L40(10)
Cement (g)	650	585	585	585
Limestone (g)	-	65	65	65
Water (g)	177	177	177	177

Three specimens were made from each batch and the results were averaged. The results are shown in Figure 3.

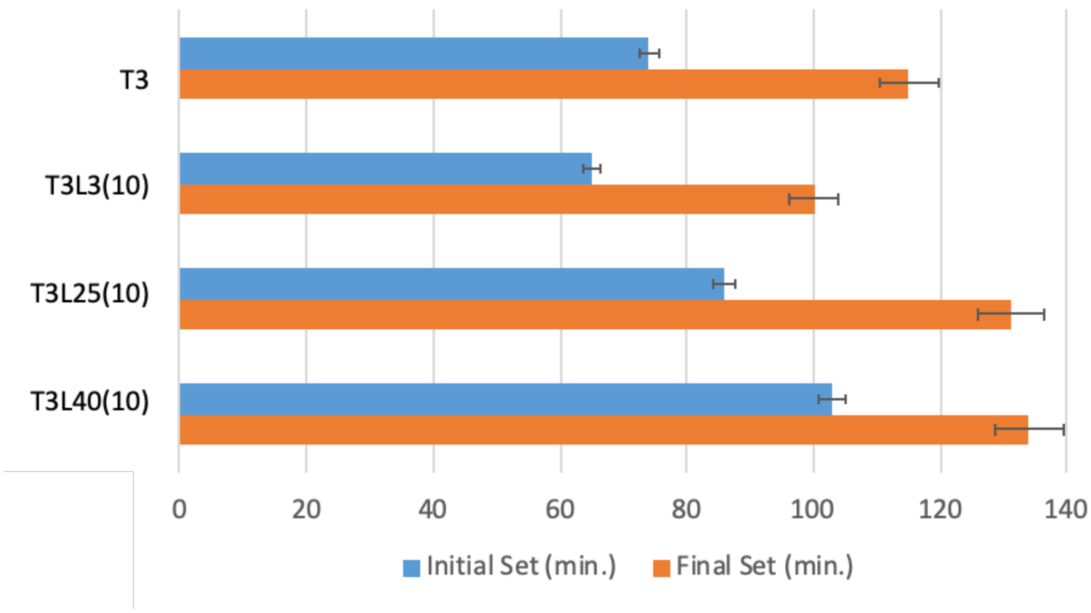


Fig. 3: Vicat time of set for Type III cement and limestone blended cements

The initial and final set times for the blended cement pastes made with 3 µm limestone powder were 12% faster than the pure cement paste. This result follows a similar increased hydration rate shown in the calorimetry experiment. The initial and final set times for the blended cement pastes made with 25 and 40 µm limestone pastes were 15% and 20% slower, respectively, than the pure cement pastes. This is most likely due to the dilution effect from the limestone powder ground coarser than the cement.

CONCRETE MIXES

Self-consolidating concrete mixes were developed to study the fresh and hardened concrete properties of mixes with limestone powders. The basis for the concrete mixes investigated was on a mix from a local precast manufacturer which used a Type III cement blended with a limestone powder having a median particle size of 25 µm, which achieved a slump flow of 20 inches and reached a compressive strength of 4,000 psi in 24 hours and 5,000 psi in 3 days, without accelerated curing. In the experimental mixes, the water content of the base mix was modified slightly to account for the moisture content of the aggregates used and the HRWRA dosage to achieve a 20-inch slump flow just after mixing.

Mixes were made of unblended Type III cement, along with blends of Type III cement and 15% cement substitutions of 3 µm, 25 µm, and 40 µm limestone powder, see Table 3. A 15% cement substitution was used to better match the proportions of the mix design from the local precast manufacturer. The high cement content was deemed adequate to achieve high early strength, to ensure that the effects of limestone substitution would be advantageous, to reduce bleeding and to achieve an appropriate level of workability. Additionally, to better isolate the influence of the limestone powder, a constant water-to-powder ratio, and coarse and fine aggregate content was maintained. The HRWRA was modified slightly on the unblended Type III mix (T3) and the blended Type III plus 3 µm limestone (T3L3(15)) to achieve a 20-inch slump flow.

Table 3: Concrete mix proportions per cubic yard

Mix ID	T3	T3L3(15)	T3L25(15)	T3L40(15)
Cement (lb)	850	725	725	725
Limestone (lb)	-	125	125	125
Water (lb)	340	340	340	340
#67 stone (lb)	1724	1724	1724	1724
Natural sand (lb)	1200	1200	1200	1200
HRWR (ounces)	2	2.22	1.78	1.78

Approximately 2 ft^3 of the concrete mixes were prepared in a 5-ft^3 revolving drum mixer per ASTM C192[24]. Coarse and fine aggregate were added to the mixer and mixed until thoroughly blended. The cement and limestone powder, if used, were added next and mixed for a few minutes until the aggregate was fully coated by the cement blend. Next, the mixing water was added to the mixer and the timer started. The mixer would run for one minute followed by a brief pause when the HRWRA was added to the mix. Finally, the mixer was allowed to run for two additional minutes, followed by a 3-minute rest period and a 2-minute final mix.

Concrete workability

In field applications, concrete suppliers use four main methods for determining workability, relative viscosity, self-healing and stability of self-consolidating concrete mixes – slump flow, flow rate, S-groove test, and the visual stability index, VSI. Slump flow was determined according to ASTM C1611, where the SCC mixes were placed in a dampened inverted Abram's cone in one lift without vibrating or tamping resting on a dampened base plate[25]. After raising the cone and allowing the concrete to spread freely, slump flow was determined as the average spread measured in two orthogonal directions. A common acceptable slump flow for precast applications is 20 in. (500 mm). The slump flow results of the four concrete mixes are listed in Table 4.

Flow rate, T_{20}, is the time it takes for the slump flow to reach a spread of 20 in. (500 mm) from the time of initial lifting of the cone. It is generally considered to be a measure of relative viscosity among the concrete mixes. The flow rate results of the four concrete mixes are listed below in Table 4.

The S-groove test was used to determine the self-healing ability of SCC mixes. During the test, an "S" was drawn into the concrete after measuring slump flow and flow rate, and a disappearing "S" indicates a self-healing mix. The results from the S-groove test are shown below in Table 4.

Finally, the stability of the concrete mixes was determined using the VSI criteria of ASTM C1611 where the distribution of aggregate within the concrete mass, and mortar fraction and bleeding along the perimeter of the slump flow are visually noted as 0, 1, 2 or 3[25]. Per the ASTM, a VSI equal to 0 indicates a highly stable mix with no indication of bleeding or segregation; a VSI equal to 1 is a stable mix with no segregation, but slight bleeding; a VSI equal to 2 is unstable with a slight mortar halo and/or aggregate pile; and a VSI equal to 3 is highly unstable with clear segregation, a large mortar halo and/or large aggregate pile. The VSI results are shown in Table 4.

Table 4: Workability and VSI of concrete mixes

Mix ID	Slump Flow (in)	T20 (s)	S-groove	VSI	HRWRA (oz/ft^3)
T3	24	4	YES	0	54
T3L3(15)	25	3	YES	0	60
T3L25(15)	23	3	YES	0	48
T3L40(15)	21	3	YES	0	48

All four mixes achieved a slump flow greater than 20 inches, passed the S-groove test and had VSI of zero. The concrete mix with unblended Type III cement (T3) and the blended Type III plus 3 μm limestone (T3L3(15)) required 12% and 25%, respectively, more HRWRA to achieve the 20-inch slump flow than the concrete mixes made with either 25 or 40 μm limestone powder.

Surface finish

The finished surface of precast elements is of great importance to precast suppliers. Post-production work such as patching bug holes and honeycombing costs valuable time and money. Therefore, self-consolidating concrete mixes that produce smooth surface finishes is beneficial to precast production rates. To quantify and compare the surface finish produced by the concrete mixes, the number and size of bug holes and imperfections were manually counted and compared between the different concrete mixes on six 3 in. x 3in. x 11 in. (76 mm x 76 mm x 280 mm) concrete prisms per concrete mix. See Figure 4.

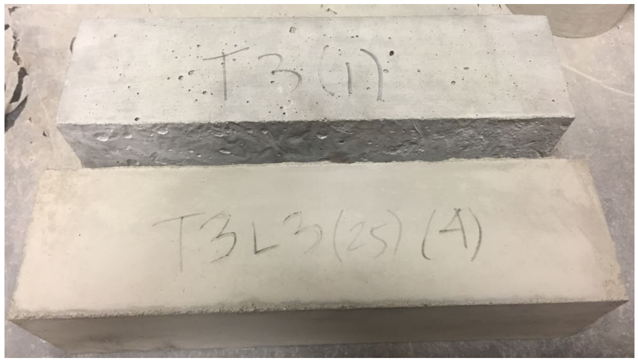


Fig. 4: Surface finish of concrete without (top) and with limestone powder (bottom)

Surface imperfections were classified as either small (under 0.1 in., the size of a pinhead) or large (greater than 0.1 in.). The total number of bug holes on six specimens were tallied and the average was reported, see Figure 5.

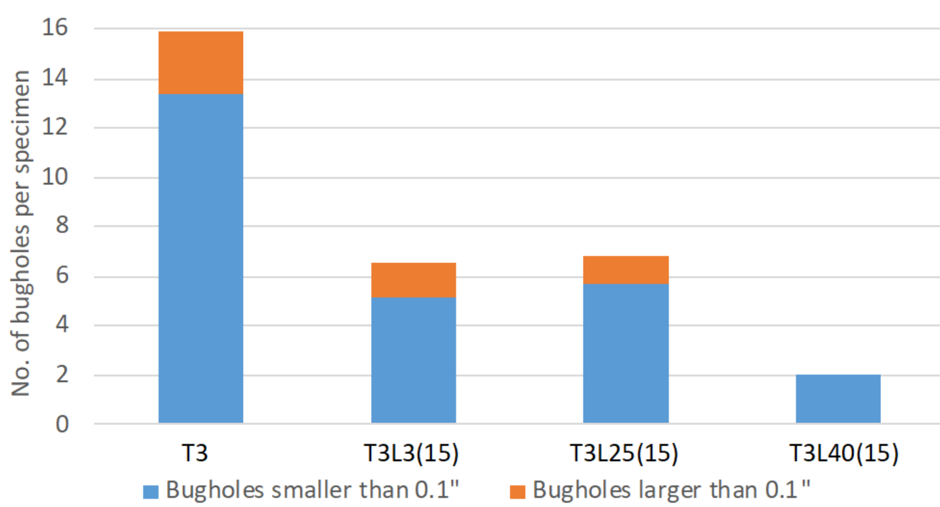


Fig. 5: Surface finish of concrete mixes with varying limestone blended cements

Concrete mixes produced with blended limestone cements showed far fewer large and small bugholes compared with the pure cement mixes without limestone. The concrete mixes produced with the blended 3 and 25 µm limestone had almost equal quantities of large and small bugholes, while the blended 40 µm had no large bugholes and approximately one-third fewer small bugholes compared with the other limestone blends.

Compressive Strength

Using ASTM C39, compressive strength was measured on 4 in. diameter x 8 in. tall concrete cylinders cast from the concrete mixes[26]. The cylinders were demolded 24 hours after casting and stored in a fog room at 100% relative humidity at 73.5 ± 3.5 ^{0}F until ready for testing. Three cylinders from each batch were tested at 1, 3, 7, 28, and 90 days, using a load rate of 26.4 kip/min. The results presented in Figure 6 is the average of the three tests.

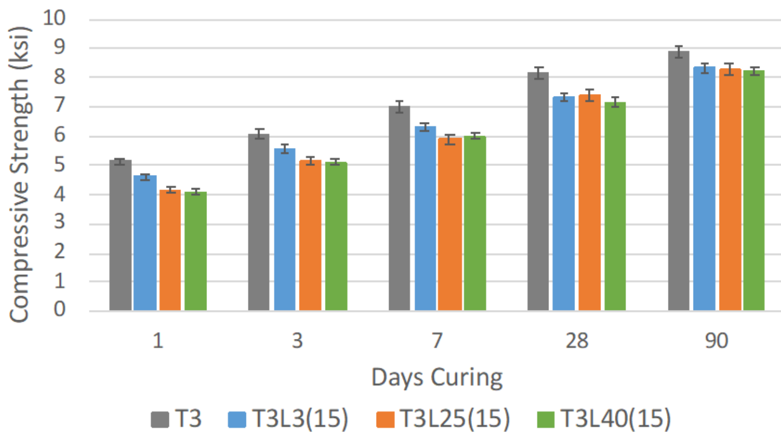


Fig. 6: Compressive strength of Type III cement and limestone blended cements

The compressive strength at 24 hours for the mix made with the 3 µm limestone powder is 10% less than the unblended cement mix, while the strength of the 25 and 40 µm limestone powder mixes are approximately 20% less. The strength of 25 and 40 µm limestone blends slowing begins to increase and by 3 days is only 15% less than the pure Type III concrete mix. By 28 days, the three mixes regardless of the limestone powder median particle size used is approximately 10% less than the unblended cement mix.

Drying Shrinkage

Drying shrinkage was determined following the procedures of ASTM C157 on 3 in. (76 mm) x 3 in. (76 mm) x 11 in. (286 mm) concrete prisms, but with a slight modification to the curing regime[27]. The standard requires that concrete samples be stored in limewater for 28 days before testing. Since precast members are generally demolded after 24 hours and tensioned shortly after, it did not seem representative of construction practices to cure the drying shrinkage specimens in limewater for 28 days. Additionally, the drying shrinkage behavior of small specimens is not entirely representative of large precast specimens. Nonetheless, since the main objective is to compare how drying shrinkage is affected with limestone substitution and fineness, the curing regime was varied to best represent the worst-case scenario that may occur at precast plants.

Three molds were cast for each concrete mix. The specimens were covered and cured in their molds in a fog room at 100% relative humidity at 73.5 ± 3.5 ^{0}F and demolded after 24 hours. After demolding, the specimens were placed in a limewater bath for 7 days, then allowed to air dry at 50 ± 4% relative humidity at 73 ± 3^{0}F. Change in length measurements were taken at 4, 7, 14, 28, 56, 112 and 224 days after initial curing. The results are shown in Figure 7.

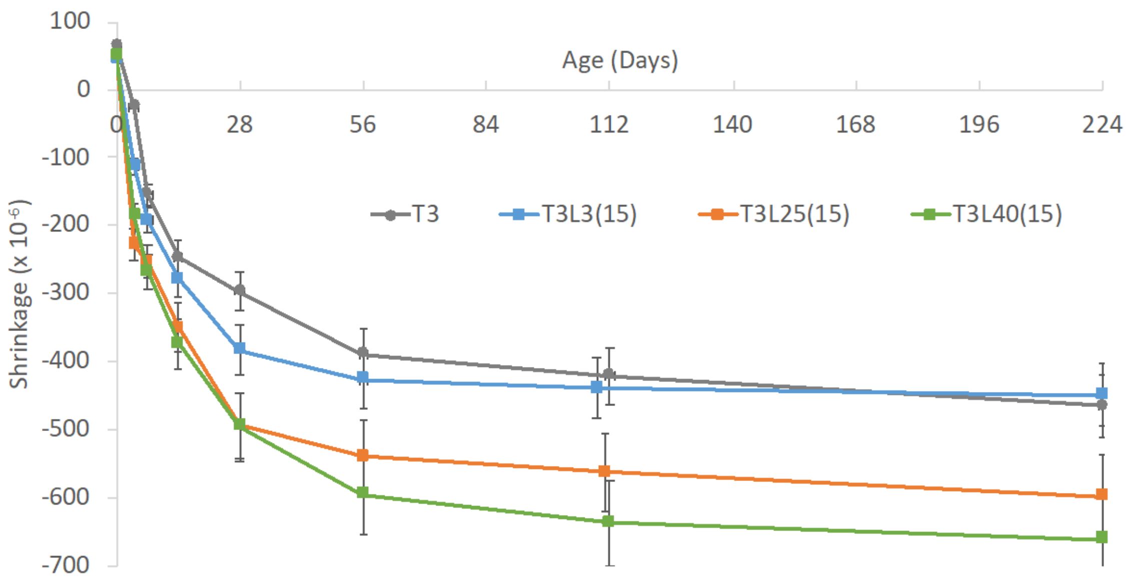


Fig. 7: Drying shrinkage of concrete prisms cured for 24 hours and allowed to air dry

At 15% cement replacement the drying shrinkage profile for the T3L3(15) mix is similar to that of the Type III mix with no limestone replacement. The two mixes made by replacing 15% of the cement with either 25 or 40 µm mixes showed a similar profile to each other at early ages and then differing by around 13% at later ages. These two mixes experienced approximately 30% and 45%, respectively, more shrinkage than the unblended cement and 3 µm mix at later ages, starting at around 63 days of air drying.

CONCLUSION

Self-consolidating concrete mixes made with Type III cement blended with limestone powder are affected by the median particle size of the limestone powder.

<u>Effect of 3 µm limestone powder on cement pastes and concrete mixes</u>

- Due to the increased number of nucleation sites for hydration, cement pastes made with a 10% cement replacement of the 3 µm limestone powder, experienced an accelerated hydration rate and 12% faster initial and final set times compared with a neat Type III cement paste.
- SCC mixes made with 15% cement replacement of the 3 µm limestone powder required 25% more HRWR to achieve the same workability as the 25 and 40 µm limestone powders.
- SCC mixes made with 15% cement replacement of the 3 µm limestone powder obtain 10% less compressive strength at 24 hours and have comparable drying shrinkage rates as the unblended Type III SCC mixes.

Effect of 25 µm limestone powder on cement pastes and concrete mixes

- Due to the dilution effect, cement pastes made with a 10% cement replacement of the 25 µm limestone powder, experienced an 8% reduction in peak hydration and cumulative heat gain at 48 hours as well as a 15% slower initial and final set times compared with a neat Type III cement paste.
- SCC mixes made with 15% cement replacement of the 25 µm limestone powder have good workability.
- SCC mixes made with 15% cement replacement of the 25 µm limestone powder obtain 20% less compressive strength at 24 hours, but only 10% less compressive strength at 28 days compared with the unblended Type III SCC mixes.
- SCC mixes made with 15% cement replacement of the 25 µm limestone powder have approximately 30% more shrinkage than unblended Type III SCC mixes.

Effect of 40 µm limestone powder on cement pastes and concrete mixes

- Due to the dilution effect, cement pastes made with a 10% cement replacement of the 40 µm limestone powder, experienced a10% reduction in peak hydration and an 8% reduction in cumulative heat gain at 48 hours as well as 20% slower initial and final set times compared with a neat Type III cement paste.
- SCC mixes made with 15% cement replacement of the 40 µm limestone powder have good workability.
- SCC mixes made with 15% cement replacement of the 40 µm limestone powder obtain 20% less compressive strength at 24 hours, but only 10% less compressive strength at 28 days compared with the unblended Type III SCC mixes.
- SCC mixes made with 15% cement replacement of the 40 µm limestone powder have approximately 45% more shrinkage than unblended Type III SCC mixes.

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