

Reducing Thermal and Autogenous Shrinkage Contributions to Early-Age Cracking

by Dale P. Bentz and Max A. Peltz

Early-age cracking continues to be a significant problem for new concrete construction. Two of the major contributors to such cracking are the heat released by cement hydration during the first few days of curing and the autogenous shrinkage that often occurs during the same time frame. In this paper, three potential alternatives for reducing these contributions by modifying the concrete mixture proportions are investigated, namely increasing the water-cement ratio (w/c), using a coarser cement, or replacing a portion of the portland cement with a coarse limestone powder. Each alternative reduces the heat generated per unit volume by either reducing the volumetric cement content or its early-age reactivity, and reduces autogenous shrinkage by increasing the interparticle spacing between grains in the three-dimensional microstructure. These reductions are quantified for paste and mortar systems by measuring their semi-adiabatic temperature rise and autogenous deformation along with measurements of compressive strength to indicate the strength trade-off that will be experienced in reducing the risk of early-age cracking. These mixtures each have the additional advantage that they should result in a cost savings in comparison with an initial (control) mixture.

Keywords: cracking; early ages; shrinkage.

INTRODUCTION

Despite efforts to avoid it, many concrete structures crack, often at early ages.¹ In fact, for a variety of reasons, high-performance concretes are often more susceptible to early-age cracking than the concretes that were placed 50 years ago.^{2,3} These reasons include their typically higher cement contents, the use of finer (and finer) cements with higher tricalcium silicate and alkali contents, the formation of a denser paste matrix via the reduction of water-cementitious material ratio (w/cm), and the addition of fine pozzolans such as silica fume.^{4,5} One indication of the magnitude of the early-age cracking problem is that there are now viable mitigation strategies that are being actively marketed by chemical admixture, lightweight aggregate, and specialty cement suppliers. Such strategies include the use of a shrinkage-reducing admixture (SRA) to reduce autogenous shrinkage,^{6,7} the incorporation of internal curing via prewetted lightweight aggregates,⁸ and the use of expansive cements.⁹ Each of these strategies reduces autogenous shrinkage and may even result in an autogenous expansion at early ages, but none of them directly addresses the heat released by hydration that will lead to a temperature rise and fall that may exacerbate early-age cracking. For example, internal curing may actually increase early-age hydration rates, thus increasing this heat release, but fortunately, the additional thermal (heat) capacity of the internal curing water may reduce the temperature rise produced by a given amount of heat release. Additionally, each of these three technically viable solutions will generally increase the cost of the concrete mixture.

Two key physical parameters influencing the heat generation and autogenous deformation of cement pastes are surface area and interparticle spacing. Early-age reactivity and heat release will generally be proportional to the former, whereas the latter will control the size of the pores emptied (and thus the stresses generated) during the early-age self-desiccation that may occur due to the chemical shrinkage that accompanies the cement hydration reactions.¹⁰ While SRAs reduce autogenous shrinkage by lowering the surface tension of the pore solution and internal curing provides mitigation by avoiding self-desiccation of the hydrating cement paste as the larger pores in the lightweight aggregate reservoirs empty instead, a third approach to decreasing early-age cracking susceptibility would be to modify the physical geometry of the initial cement paste microstructure. In this paper, three distinct methods for coarsening the initial spatial distribution of cement particles will be investigated, namely, the use of a coarser ground cement, an increase in the water-cement ratio (w/c), and the replacement of a fraction of the cement by a (coarse) limestone powder. To conserve cement and energy, ASTM C150¹¹ currently permits a 5% limestone addition to portland cement, and the Canadian Standards Association is considering raising this value to 10 or 15%. It will be shown that each of these three methods can reduce both the thermal and autogenous deformation contributions to early-age cracking. In addition, each of these should potentially offer a cost advantage over the control mixture that is being modified. It is recognized that there are other viable approaches to achieve the goals of cost reduction concurrent with reduced early-age cracking, such as the development of high-volume fly ash concretes for sustainable development.¹²

RESEARCH SIGNIFICANCE

Whereas concretes are designed to meet strength requirements and to promote long-term durability of concrete structures, both of these can be compromised if the concrete cracks at early ages. Early-age cracking is a complex process that depends on materials, construction practices, structural loads, and environmental conditions.¹³ The potential of a given concrete mixture for such cracking can be analyzed by measurement of a variety of early-age properties such as (semi)adiabatic temperature rise and autogenous deformation.^{13,14} When a mixture exhibits a high potential for such cracking, modifications to its mixture proportions may be required to reduce this potential. In this paper, three such modifications that focus on modifying the surface area and interparticle spacing of the particles

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comprising the cementitious matrix component of the concrete are quantitatively examined. Each modification also has the potential to reduce the materials cost of the concrete. The results will provide guidance to designers in making the necessary modifications to reduce the probability of early-age cracking of a given concrete mixture.

EXPERIMENTAL

Two Type I/II cements of widely different fineness and two limestone powders (94% CaCO₃) were obtained for this study. The chemical and physical characteristics of the cements are summarized in Table 1. They are quite similar in chemical composition except for the coarser cement having

Table 1—Cement oxide compositions, Bogue potential phase mass fractions,¹¹ and fineness

Oxide or property	Fine cement mass fractions	Coarse cement mass fractions
CaO	0.633	0.648
SiO ₂	0.203	0.209
Al ₂ O ₃	0.045	0.045
Fe ₂ O ₃	0.0339	0.041
SO ₃	0.0268	0.022
Na ₂ O	0.00077	0.003 (equivalent)
K ₂ O	0.00622	Not reported
MgO	0.0373	0.012
P ₂ O ₅	0.00127	Not reported
TiO ₂	0.00309	Not reported
Bogue - C ₄ AF	0.103	0.125
Bogue - C ₃ A	0.062	0.050
Bogue - C ₃ S	0.625	0.625
Bogue - C ₂ S	0.109	0.127
Specific gravity	3.22	3.21
Blaine fineness	380 m ² /kg	311 m ² /kg

Table 2—Mortar mixture proportions used in study

Material	w/c = 0.35 (fine and coarse cement), g (lb)	w/c = 0.4 (fine cement), g (lb)	w/cm = 0.357 (fine cement with limestone), g (lb)
Type I/II cement	1860.5 (4.10)	1757.3 (3.87)	1544.2 (3.40)
Limestone	0.0 (0.0)	0.0 (0.0)	175.5 (0.39)
Water	651.2 (1.43)	702.9 (1.55)	614.2 (1.35)
F95 fine sand*	972.1 (2.14)	985.0 (2.17)	916.5 (2.02)
Graded sand ¹⁶	738.8 (1.63)	748.6 (1.65)	696.6 (1.53)
20-30 sand ¹⁶	738.8 (1.63)	748.6 (1.65)	696.6 (1.53)
GS16 coarse sand*	1438.7 (3.17)	1457.7 (3.21)	1356.5 (2.99)

*F95 and GS16 correspond to sand supplier designations.

a lower total alkali content. The measured particle size distributions of all four powders are provided in Fig. 1. A specific gravity of 2.71, as supplied by the manufacturer, was used for the limestone in proportioning the mortar mixtures.

For this study, specimens prepared using the finer cement with a w/c of 0.35 were selected as the control system. Several possible variations from this control were investigated to quantify their effects on strength development, semi-adiabatic temperature rise, and autogenous deformation. These included the substitution of the coarser cement for the finer one, an increase in w/c to 0.4 for the fine cement, and replacing a portion of the fine cement with either a fine or a coarse limestone. Due to the differences in specific gravity between limestone and cement, the limestone replacement was conducted to maintain the same volumetric ratio of water-to-solid powders in the various mixtures. Thus, a 10.2% replacement by mass (approximately 12% by volume) of limestone for cement and a w/cm of 0.357 were employed for the two systems with either fine or coarse limestone replacement for cement, giving an effective w/c (not considering the limestone) of approximately 0.4 for these mixtures.

Semi-adiabatic calorimetry studies were conducted on cement paste specimens during the course of 3 days of hydration, using a custom-built experimental setup.¹⁵ The pastes were prepared using a high-speed blender and immediately cast into a cylindrical plastic mold with an inner diameter of 47 mm (1.85 in.) and a height of 97 mm (3.8 in.). A typical sample mass was approximately 330 g (0.73 lb). The filled mold was immediately placed in an insulative holder (constructed of microporous insulation) and a single Type J thermocouple inserted into the center of the paste volume. This temperature, along with the room temperature, was then monitored during the course of several days of semi-adiabatic hydration. Replicate specimens had indicated a standard deviation of 1.4 °C (2.5 °F) in the maximum specimen temperature achieved during this period.

For the evaluation of compressive strength and autogenous deformation, mortar mixtures were prepared following the proportions provided in Table 2. For the various mortars, the same volume fraction of sand (54.8%) was maintained in each mortar mixture. Thus, for this study, the limestone is being considered as part of the cement paste and not as part of the aggregates in the mortar for the purposes of mixture proportioning. A blend of four normalweight sands (specific gravity of 2.61) that has been shown to provide improved particle packing for high-performance mortars was employed

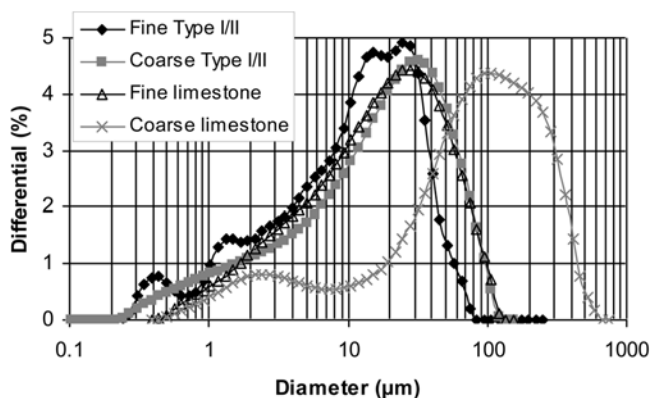


Fig. 1—Measured differential particle size distributions for various materials used in study. (Note: 1 μm = 3.9 × 10⁻⁵ in.)

in all mortar mixtures.¹⁴ Mixing of the mortars was conducted according to ASTM C305.¹⁷

Autogenous deformation was assessed using the sealed corrugated tubes as developed by Jensen and Hansen.¹⁸ In most cases, three replicate specimens were evaluated concurrently. For each mortar mixture, the autogenous deformation measurements were zeroed at the following times, based on the measurement of the final (Vicat) setting times of cement paste specimens of the same w/c ¹⁴: 4 hours for a w/c of 0.35 coarse cement mortar, 5 hours for a w/c of 0.35 fine cement mortar, and 6 hours for a w/c of 0.4 fine cement mortar and both mortars with limestone replacements (effective w/c of 0.4). By definition, autogenous deformation should be measured under isothermal conditions and such conditions are being assumed for the corrugated tubes employed in this study. For mortar specimens, measure-

ments have indicated a maximum temperature increase in the center of the test specimen of 2 °C or less.

Compressive strength testing was conducted on 50 mm (2 in.) mortar cubes at the ages of 1, 3, 7, and 28 days. The cubes in their molds were stored in double-sealed plastic bags during the first 24 hours of curing, demolded, and placed in saturated limewater until the time of testing. The mass of each cube was measured upon demolding and just prior to compressive strength testing. Curing and measurements of autogenous deformation were conducted at a temperature of 25 ± 1 °C (77 ± 2 °F), as maintained in a walk-in environmental chamber.

RESULTS AND DISCUSSION

Initial paste microstructures

To provide a specific image of how surface area and interparticle spacing vary among the mixtures examined in this study, three-dimensional simulations of the starting microstructures of four of the paste mixtures were conducted using digitized spherical particles and a simulation volume of $100 \times 100 \times 100 \mu\text{m}$ ($0.0039 \times 0.0039 \times 0.0039$ in.).^{14,19} Sample two-dimensional slices from the four systems are provided in Fig. 2. The coarse $w/c = 0.35$ cement system (Fig. 2(b)) is seen to have the largest interparticle spacing, followed by the fine $w/c = 0.4$ cement system (Fig. 2(c)), the $w/cm = 0.357$ system with fine limestone (Fig. 2(d)), and finally by the fine $w/c = 0.35$ cement paste (Fig. 2(a)). Because the effective w/c in the systems with limestone replacement is approximately 0.4, the spacing in the system with the coarser limestone filler (not shown in Fig. 2) would be expected to be similar to that of Fig. 2(c), assuming that the cement paste occupies space between the relatively larger limestone particles and neglecting any interfacial transition zones that may form around the larger limestone particles.

Compressive strengths

The compressive strength testing results are summarized in Table 3 and a relative comparison to the control system is provided in Fig. 3. In every case, the mixture modifications performed to coarsen the pore structure resulted in substantial decreases in the 1-day strength values. Depending on the modification, the observed decrease in strength at early ages could be due to one or more of the following reasons: an increase in porosity (for instance, $w/c = 0.4$ versus $w/c = 0.35$), a decrease in hydration product formation either due to a decreased cement content (systems with limestone replacement)

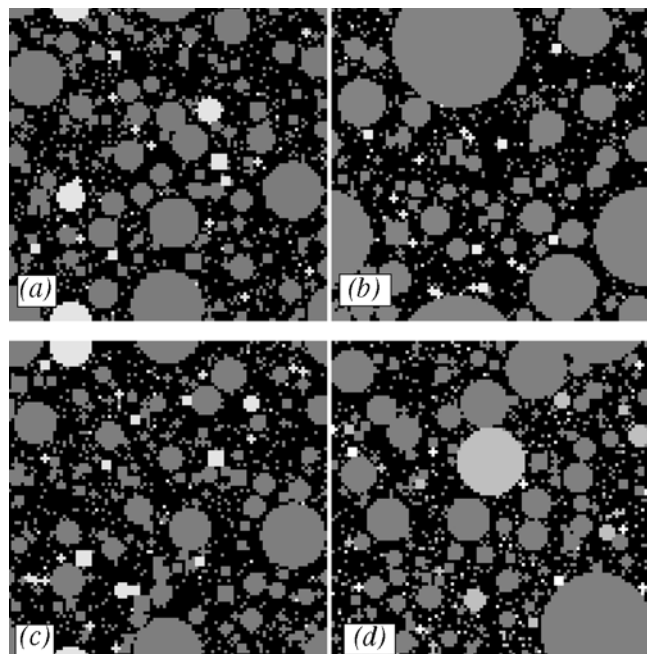


Fig. 2—Two-dimensional slices ($100 \times 100 \mu\text{m}$ [0.0039×0.0039 in.]) from simulated three-dimensional starting paste microstructure for various mixtures. Bright particles are gypsum, dark gray particles are cement, and in Fig. 2(d), light gray particles are limestone. Water-filled porosity is black. Microstructures are for: (a) $w/c = 0.35$ fine cement; (b) $w/c = 0.35$ coarse cement; (c) $w/c = 0.4$ fine cement; and (d) $w/cm = 0.357$ fine cement with fine limestone replacement.

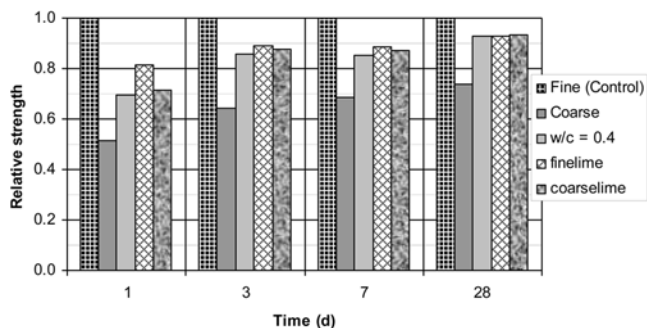


Fig. 3—Relative strength values for various mortar mixtures.

Table 3—Compressive strength results for mortar cubes

Mixture	1-day strength, MPa/psi	3-day strength, MPa/psi	7-day strength, MPa/psi	28-day strength, MPa/psi
$w/c = 0.35$ fine cement	36.2 (1.4)*/5250	55.6 (2.4)/8070	64.8 (1.0)/9390	78.5 (2.2)/11,380
$w/c = 0.35$ coarse cement	18.5 (1.2)/2690	35.8 (3.1)/5190	44.4 (2.4)/6450	58.0 (3.5)/8410
$w/c = 0.4$ fine cement	25.2 (0.4)/3650	47.6 (1.5)/6910	55.1 (1.6)/8000	72.8 (1.4)/10,560
$w/cm = 0.357$ fine cement/ fine limestone	29.5 (1.0)/4280	49.4 (2.7)/7170	57.4 (0.2)/8320	72.9 (3.9)/10,580
$w/cm = 0.357$ fine cement/ coarse limestone	25.8 (1.0)/3750	48.8 (1.1)/7080	56.4 (3.0)/8180	73.3 (3.4)/10,630

*Numbers in parentheses indicate one standard deviation in MPa as determined for three replicate specimens tested at each age.

or a decreased cement surface area (coarser cement), or an increase in average pore size (all modified systems).

Of course, it is well known that compressive strength will decrease with an increase in w/c . Still, it is interesting to note that whereas the 1-day strength of the $w/c = 0.4$ mortar is only 70% of that of the $w/c = 0.35$ mortar, by 28 days, a strength that is 93% of the control mortar is achieved. One may be willing to trade off such a loss in 28-day compressive strength if the semi-adiabatic temperature rise and autogenous shrinkage are substantially reduced in the higher w/c concrete.

The use of coarser cements in high-performance concretes has been suggested previously due to the fact that, in these generally low w/cm concretes, only a fraction of the cement has space to hydrate.²⁰ Thus, the same long-term degrees of hydration (and strengths) may be achieved by a coarse cement as by a finer one. Previously, simulations had indicated the same long-term (160-day) degree of hydration for coarse and fine cements for $w/c = 0.246$ and similar values for $w/c = 0.3$.²⁰ The experimental results in this study, however, indicate that for $w/c = 0.35$, while the coarser cement improves from having 51% of the 1-day strength of the control (fine cement) system to having 74% of its 28-day strength, the coarser cement will likely not achieve a totally equivalent strength, even at longer ages. Coarser cements, however, may offer other benefits such as the increased durability of concretes produced with coarser cements as pointed out by Brewer and Burrows² over 50 years ago and a reduced autogenous deformation, as to be subsequently presented.

In low w/cm concretes, an even greater potential exists to conserve cement and energy by replacing the coarsest cement particles with limestone powder.²¹⁻²³ In this study, the influence of the fineness of the limestone was examined by replacing approximately 10% of the cement by mass with either a fine or a coarse limestone (Fig. 1). Considering strength, the replacement by the fine limestone particles offers a superior performance at 1 day, perhaps due to its smaller initial interparticle spacing (Fig. 2(d) versus 2(c)). Whereas the initial acceleration of the cement hydration reactions by limestone can be dependent on the limestone powder's surface area,^{24,25} isothermal calorimetry¹⁴ results indicated basically identical heat flow versus time curves for the first 24 hours of hydration for both $w/cm = 0.357$ pastes with fine or coarse limestone replacements for cement. Thus, it appears that the greater strength produced at 1 day by the mortar with the fine limestone replacement is not due to acceleration of the cement hydration reactions in this case, but rather due to smaller pores between the initial cement and limestone particles. Beyond 1 day, the coarser limestone system produces nearly equivalent strengths by 3 days, and by 28 days, the measured strengths are essentially equal within experimental uncertainty. Due to its initially coarser pore structure, the mortar cubes with the coarser limestone are able to imbibe more external curing water to promote long-term strength gain. For example, at 3 days, the cubes containing the finer limestone had imbibed 0.017 kg of water per kg of cement (0.017 lb of water per lb of cement), whereas those containing the coarser limestone had imbibed 0.027 kg of water per kg of cement (0.027 lb of water per lb of cement), an approximately 60% increase. As shown in Table 3, with their effective w/c of 0.4, the two systems with limestone replacement for cement exhibit 28-day strengths that are basically equivalent to that of the pure portland cement $w/c = 0.4$ mortar. Whereas the two mortars with limestone replacements exhibit similar 28-day strengths,

however, (as will be shown in the results to follow) limestone fineness also has an influence on the semi-adiabatic temperature rise and particularly on the measured autogenous deformation of mortars.

Semi-adiabatic temperature rise

The semi-adiabatic temperature rise curves are provided in Fig. 4 and the maximum temperatures recorded for each mixture are included in Table 4. Each of the modified mixtures is observed to significantly reduce the maximum temperature achieved during the early-age hydration. Because the $w/c = 0.4$ cement paste had an increased heat capacity relative to the other mixtures and could maintain a higher rate of hydration at later ages, both of these being due to its higher volume fraction of water, it shifted the temperature maximum to a later time by approximately 2 hours. The maximum temperature was also shifted somewhat for the coarser cement, but in this case, it was caused by this cement's lower early-age reactivity due to the coarser particles and a reduction in (reactive) surface area. Conversely, the systems with limestone exhibited their temperature maximums only slightly later than the control system. Whereas these systems had the same volume fraction of water as the control system, and thus a similar heat capacity, they did have less cement per unit volume generating heat and relatively more space for the precipitation of hydration products in comparison with the control system.

The results in Table 4 indicate that the mixture based on the coarser cement had over double the maximum temperature reduction (relative to ambient) as the mixtures based on a higher w/c or limestone replacements. Of course, this reduction comes at the expense of early-age strength and it is interesting to note that for the five mixtures examined in this study, there was a reasonably linear relationship (correlation coefficient, $r^2 = 0.9$) between the maximum temperature

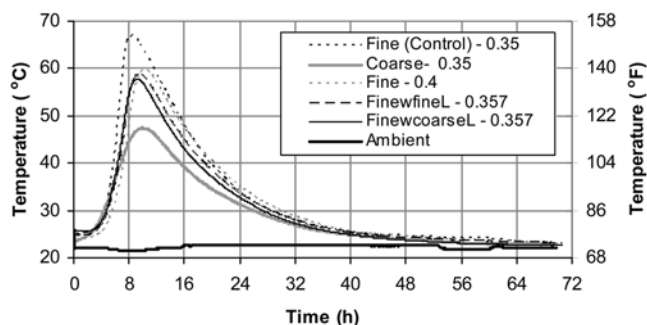


Fig. 4—Semi-adiabatic temperature rise versus time for various cement pastes.

Table 4—Maximum temperature achieved in semi-adiabatic testing and ($\epsilon_{min}-\epsilon_{max}$) at 7 days for cement pastes and mortars, respectively

Cement paste or mortar	Maximum temperature and (% reduction versus control)	($\epsilon_{min}-\epsilon_{max}$) at 7 days and (% reduction versus control)
$w/c = 0.35$ fine cement	66.9 °C (153 °F) (—)	–127 microstrains (—)
$w/c = 0.35$ coarse cement	47.4 °C (117 °F) (43)	–49 microstrains (61)
$w/c = 0.4$ fine cement	59.8 °C (140 °F) (16)	–100 microstrains (21)
$w/cm = 0.357$ fine cement/fine limestone	58.8 °C (138 °F) (18)	–163 microstrains (–28)
$w/cm = 0.357$ fine cement/coarse limestone	57.8 °C (136 °F) (20)	–88 microstrains (31)

observed in the semi-adiabatic testing and the 1-day compressive strengths provided in Table 3. Whereas this relationship would likely not be maintained across other mixtures, certainly, in general, more energy released by cement hydration will imply a greater degree of hydration (and thus strength) and an increased semi-adiabatic temperature rise. It is recognized that these studies have only considered semi-adiabatic temperature rise and have not addressed the thermal gradients that may exist between the interior of the concrete and its exterior surface, which may be of paramount importance with regards to early-age cracking.¹³ It is conjectured, however, that mixtures with a larger semi-adiabatic temperature rise will likely experience larger (and more damaging) temperature gradients.

Autogenous deformation

The plots of autogenous deformation in Fig. 5 and 6 show the results out to 7 and 28 days, respectively. Whereas reductions in the autogenous shrinkage as compared with the control $w/c = 0.35$ mortar (which is based on the fine cement) are exhibited by all of the modified systems except for the one incorporating the fine limestone replacement for cement, a wide variation is observed in their specific performances. The mortar with an increased w/c exhibits an early-age autogenous expansion with an overall deformation of -80 microstrains at 26 days. Autogenous deformation is always a competition between autogenous shrinkage due to self-desiccation and autogenous expansion due to some aspects of the cement hydration reactions that produce swelling at early ages (perhaps ettringite formation, the growth of calcium hydroxide crystals, and/or imbibition of water by the gel hydration products).^{10,26} For a given cement

fineness and mortar proportions, there will be a threshold w/c below which autogenous shrinkage will dominate and above which an overall expansion (for instance, at 28 days) will be measured.²⁶ For the finer cement used in this study, this threshold is seen to be above 0.4, whereas for the coarser cement, based on the results in Fig. 5 and 6, it is somewhat less than 0.35, as the $w/c = 0.35$ coarser cement mortar still exhibited an overall deformation of 50 microstrains (expansion) after 28 days of sealed curing.

The autogenous deformation results for the two systems with limestone replacements for cement are particularly interesting. As shown in Fig. 2, the system with the fine limestone powder produces a microstructure with similar initial pore sizes to that of the control mortar. In this case, no improvement in autogenous deformation is observed. The results in Fig. 5 and 6 indicate that following a slight difference in their initial expansions, the system with the fine limestone replacement produces an autogenous deformation curve that is basically parallel to that of the control $w/c = 0.35$ mortar. Any differences between these two curves could be well within the measurement variability and/or partially due to the fact that their autogenous deformations were zeroed at slightly different times—5 hours for the control mortar and 6 hours for the mortar with fine limestone replacement. Conversely, the results for the coarse limestone powder replacement are seen to be quite different from those with fine limestone, exhibiting a significant expansion to an age of 1 day and then an autogenous shrinkage, with an overall deformation of approximately -15 microstrains after 28 days. It was mentioned previously that the spacing between cement particles in this system might be similar to that in the $w/c = 0.4$ fine cement system, and indeed, after their initial expansions reached some (different) maximum values, these two systems exhibited basically parallel curves for the (relative) shrinkage portions of their autogenous deformation.

It is unknown at this time why the initial autogenous expansion of the mortar with the coarse limestone replacement is so much larger than that observed in the other mortars using the fine cement. Possibilities could include the formation of large expansive crystals of calcium hydroxide²⁶ and/or ettringite and carboaluminate hydration products (as recently observed by Sato and Beaudoin²⁵ in systems with nano-limestone additions) leading to an enhanced expansion, or perhaps a more uniform distribution of gel hydration products on both the cement and limestone grains leading to a greater expansion of the paste during water imbibition by this gel. The system with the finer limestone replacement, with its smaller initial pore sizes, might not provide sufficient space for the formation of such large crystals, and any enhanced expansion of the gel hydration products could be offset by the large shrinkage strains generated, as these much smaller pores empty during self-desiccation in this system (Fig. 2(d)). Clearly, further research is needed in this area.

Recently, Cusson²⁷ has advocated the use of the (net) difference between the maximum (peak) and minimum (post-peak) deformations achieved during the first 7 days of curing as an effective measure of the risk of cracking in a concrete structure, as a concrete typically reaches a zero-stress state sometime after the peak (expansion) is achieved, but prior to the autogenous deformation returning to zero (or achieving its minimum value). Beyond this zero-stress time, tensile stresses develop and build and may ultimately lead to early-age cracking if the tensile strength of the concrete is exceeded at any time.^{13,27} For the five mixtures examined

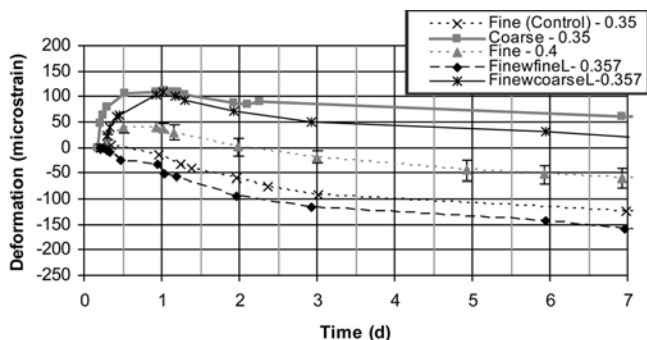


Fig. 5—Autogenous deformation versus time for first 7 days for mortar mixtures. Error bars shown on fine 0.4 curve indicate typical standard deviation for replicate specimens.

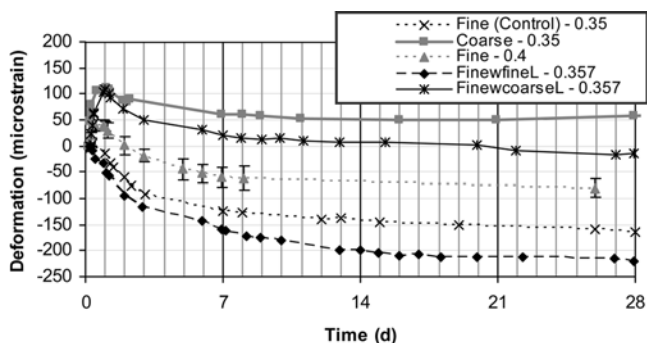


Fig. 6—Autogenous deformation versus time for 28 days for mortar mixtures.

in this study, these values of net autogenous shrinkage ($\varepsilon_{min}-\varepsilon_{max}$) are provided in Table 4. In terms of this performance parameter, the ranking of the mixtures would be: 1) the coarser cement with $w/c = 0.35$; 2) the fine cement with the coarse limestone replacement; 3) the fine cement with $w/c = 0.4$; 4) the fine cement with $w/c = 0.35$; and 5) the fine cement with the fine limestone replacement. If these performance criteria were considered to be the critical measure for autogenous deformation contributions to early-age cracking, as indicated in Table 4, the coarser cement would provide the best performance for reducing both the thermal and autogenous deformation contributions to early-age cracking.

It is important to note that the results with the coarse limestone replacement presented in this paper have been obtained by blending a coarser limestone powder with a finer cement. Such a distribution of these two materials, for instance, would be unlikely to be obtained by intergrinding a softer limestone with a harder cement clinker—a procedure that is often currently employed within the cement industry. The coarser limestone contributes to an increase in the initial interparticle spacing of the blended cement that reduces the autogenous deformation at early ages, while not dramatically impacting the 28-day strength.

Potential costs and durability

It is always important to consider the cost implications of any modifications to mixture proportions because unit costs are the bottom line that drives much of construction today. Fortunately, in this case, it is projected that each of these three different mixture modifications will result in a materials cost reduction. For example, by increasing the w/c from 0.35 to 0.4 at a fixed paste volume fraction, the volume of cement used will be reduced by 7%. As cement is generally the most expensive component of the concrete mixture (neglecting admixture costs), the overall concrete cost should be reduced by at least several percent. Whereas the use of a coarser cement does not in itself reduce cement consumption, it should reduce the energy costs involved in grinding the cement to the needed fineness. As indicated previously, the mixtures with limestone replacement will result in a 12% reduction in the volume of cement per unit volume of concrete, and may potentially offer the largest cost savings, depending on the cost of the limestone powder. And, of course, if these mixture modifications reduce early-age cracking, leading to an increase in concrete durability, the life-cycle costs of any concrete structures produced with these mixtures could be dramatically reduced.

Still, it is natural to question what will be the long-term durability implications of these mixture modifications. Whereas there is no question that each of the modifications is coarsening the early-age pore structure and that a coarser pore structure often implies lower durability due to higher transport rates, the ultimate pore structures of these mixtures achieved at and beyond 28 days of hydration could be quite similar, as exemplified by the convergence of their 28-day compressive strengths. Whereas some frown on using strength as a durability measure, most durability properties do exhibit a very good correlation to strength for mixtures that do not vary too widely.²⁸ Thus, if equivalent or nearly equivalent strengths are achieved at 28 days for these mixtures with relatively minor modifications from the control systems, equivalent durability might be expected. Of course, one must keep in mind chemical issues specific to the materials being

employed, such as the thaumasite form of sulfate attack^{29,30} in the systems containing limestone replacements for cement.

There has always been and will continue to be a delicate balance between early-age strength development and the likelihood of early-age cracking.³¹ Currently, the pendulum has perhaps swung too far in the direction of high early-age strengths. The mixture modifications examined in this study can hopefully assist in moving it back toward center with equal emphasis on strength and early-age cracking.

CONCLUSIONS

High early-age strength often correlates with a high semi-adiabatic temperature rise and an increased autogenous shrinkage. By modifying the initial geometry of the cement particles, specifically their surface area and interparticle spacing, both of these contributions to early-age cracking can be reduced. Three possible modifications are an increase in w/c , the use of a coarser cement, or the replacement of part of the cement by a coarse limestone powder. Whereas these modifications do reduce early-age strength significantly, in several cases, the reduction in 28-day strength is below 10%. The coarser cement offers the largest benefit in terms of reducing semi-adiabatic temperature rise and effective autogenous shrinkage at 7 days, but also produces the lowest strength mortars at all ages tested. The replacement of approximately 10% by mass of the cement by a coarse limestone produced a mortar with an overall autogenous deformation near zero at 28 days and a net autogenous shrinkage of -88 microstrains at 7 days, and may be the most economical and sustainable of the three modifications. An increase in w/c reduced both autogenous shrinkage and semi-adiabatic temperature rise and can be easily achieved without obtaining any additional materials.

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