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Use of Aggregates to Reduce Cement Content in Concrete

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ABSTRACT

There are two main reasons for increasing the amount of aggregates in concrete. The first is that cement is more expensive than aggregate and creates more CO_2 in its production, so using more aggregate reduces the cost of producing concrete and produces a cleaner carbon footprint. The second is that most of the durability problems of hardened concrete increase with increasing cement content. Two approaches to reduce the cement content were evaluated. First, aggregate shape and grading were improved to allow a reduction in paste volume. Second, the paste volume was held constant and dust-of-fracture aggregate were used as part of the paste volume. For each mixture, the high-range water-reducing admixture dose was adjusted to maintain constant slump. The effects on workability, compressive strength, drying shrinkage, and rapid chloride permeability were measured. The results quantify the extent to which the cementitious materials content provided for workability can be reduced through aggregate selection.

INTRODUCTION

Until well into the 20th century, natural sand was used nearly exclusively in portland cement concrete. It was readily available in nearly every construction market, inexpensive, well shaped for producing workable mixtures, and easy to obtain. ASTM C 33 Aggregates for Concrete was developed for natural sands; it was adopted by most public agencies in the United States. Since 1996, research at University of Texas at Austin has evaluated the effect of shape, texture, grading, mineral fillers (microfines), SCMs, and chemical admixtures on the performance of mortar and concrete. This research which was funded by the International Center for Aggregates Research (ICAR) has shown that good quality concrete can be produced using fine aggregate (FA) that does not meet ASTM C 33 standards [Quiroga 2005; Koehler 2007]. Compared to the same aggregate and grading without microfines, manufactured fine aggregates (MFA) with more than 17% microfines can be used to produce quality concrete that has the same or higher compressive and flexural strength, lower permeability, and higher resistance to abrasion.

Poorly shaped and poorly graded aggregates typically have a lower packing density than well shaped and well graded aggregates, resulting in more paste being required to fill the voids between aggregates. As the excess paste volume needed to fill the voids is reduced, the flowability of the paste must be increased to maintain a given workability level. Therefore, concrete mixtures with poorly shaped and poorly graded aggregates often have higher water and cementitious materials requirements than those with well shaped and well graded aggregates to maintain the same workability. The proper selection of aggregates can minimize the increased water and cementitious materials contents needed to ensure adequate workability while also reducing the overall cost of the mixture.

Although a certain amount of paste is needed to fill the voids between aggregates, this paste does not need to be comprised solely of water, cementitious materials, and air. Microfines can be used as part of the paste volume [Quiroga 2005; Koehler 2007]. Common concrete practice considers microfines as part of the aggregate, but research done by ICAR [Koehler 2007] has shown that since microfines are similar in size to cement it is more appropriate to consider them as part of the paste volume. Instead of considering the water-cementitious materials (w/cm) ratio as one factor related to workability, the water-powder ratio (w/p)—where powder is defined as all solid material finer than approximately 75 µm–is more appropriate. Furthermore, when sands with high contents of microfines are used in concrete without any adjustment to the water or cementitious materials contents, the w/p decreases (lower workability) and the paste volume increases (higher workability), resulting in a net reduction in workability. The main microfines characteristics affecting concrete workability have been found to be shape, grading, and cleanliness [Ho et al. 2003; Bosiljkov 2003; Koehler 2007]. The grading of microfines is important in the context of how the microfines affect the overall powder grading [Stewart 2006; Koehler 2007]. The shape characteristics of microfines can vary widely [Stewar 2006] and should be considered relative to the other powder materials the microfines may be replacing [Koehler 2007]. Clays sometimes present in microfines can increase water demand [Yool et al. 1998] and interact with polycarboxylate-based high-range water-reducing admixtures [Jeknavorian et al. 2003]. Other deleterious materials can also decrease concrete workability.

This paper describes the results of a research project to evaluate the effects of aggregates on the amount of cement required to ensure adequate workability and reduce production cost of concrete. The research was conducted in two phases. In Phase I, the effects of aggregate shape and grading were evaluated at various paste volumes by varying either the shape and grading. In Phase II, the use of microfines as part of the paste volume was evaluated.

TESTING PROGRAM

Materials

Aggregates from five sources were evaluated (Table 1), including three fine aggregates, two coarse aggregates, and three dust-of-fracture microfines. The fine aggregates included a natural sand (NAT-FA), a well-shaped limestone manufactured sand (LS-A-FA), and a poorly shaped limestone manufactured sand (LS-B-FA). The coarse aggregates (19-mm maximum size) included a cubical, well-rounded natural coarse aggregate (NAT-CA) and a cubical, angular crushed limestone coarse aggregate (LS-A-CA). The microfines included a limestone obtained as pond fines (LS-A-MF), a limestone obtained by sieving from screenings (LS-C-MF), and a granite obtained by sieving from screenings (GR-MF). All mixtures included a Type I/II cement. The dose of a polycarboxylate-based high-range water-reducing admixture was adjusted in each mixture to reach a target slump of 15 ± 2.5 cm.

Table 1. Aggregate Identification

Source	Coarse	Fine	Microfines
NAT	NAT-CA	NAT-FA	
LS-A	LS-A-CA	LS-A-FA	LS-A-MF
LS-B		LS-B-FA	
LS-C			LS-C-MF
GR			GR-MF

Mixture Proportions and Test Methods

For Phase I (effects of shape and grading), four combinations of fine and coarse aggregates were blended to achieve four different gradings: three gradings with sand-to-aggregate (S/A) ratios of 0.30, 0.40, and 0.50 and a fourth gap grading where all coarse aggregate finer than the 9.5-mm sieve were removed and the remaining material used as an S/A of 0.40. The aggregate combinations included NAT-CA with NAT-FA, NAT-CA with LS-A-FA, NAT-CA with LS-B-FA, and LS-A-CA with NAT-FA. Selected gradings for NAT-FA & NAT-CA and S/A=0.4 are shown in Fig. 1. As the S/A was changed, the aggregate shape remained approximately constant while grading varied, which allowed grading to be considered separately from shape. For each aggregate combination, the paste volume—which consisted of cement, water, and air—was varied and the w/c was held constant at 0.50. For each paste volume, the HRWRA demand for a 12.5-to 17.5-cm slump was determined. In addition, compressive strength (ASTM C 39), drying shrinkage (ASTM C 157), and rapid chloride permeability (ASTM C 1202) were measured.

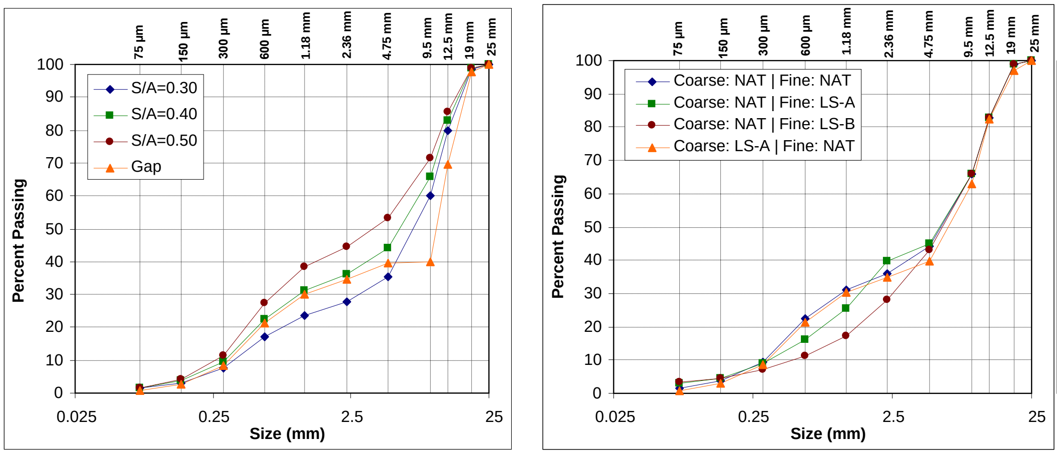

Fig. 1. Selected Combined Aggregate Gradings

For Phase II (use of microfines), the cement and water contents were reduced by 10, 20, and 30%, and the total paste volume was held constant at 28% by replacing the eliminated cement and water volume with microfines. As a result, the w/c was constant but the w/p was lower. In another mix, which was intended to represent the use of microfines as sand with no change in cement and water contents, the paste volume was increased to 34.5% and the w/p was reduced to 0.33. For each mixture, HRWRA demand for a slump of 12.5-to 17.5-cm, compressive strength, drying shrinkage, and rapid chloride permeability were measured.

TEST RESULTS AND DISCUSSION

Effects of Aggregate Shape and Grading. To best understand the effects of aggregate characteristics, shape and grading were evaluated separately. The effect of grading on HRWRA demand is depicted in Fig. 2 for each aggregate combination. In general, an increase in the fineness of the combined aggregate grading (higher S/A) resulted in higher HRWRA demand across a range of paste volumes. The gap-grading generally resulted in the lowest HRWRA demand in all but the NAT-CA with LS-A-FA combination. The improved workability associated with the gap grading may be due to the lack of interference between intermediate-sized particles. Improved workability and increased packing density associated with the gap grading has also been observed by de Larrard and by Koehler and Fowler.

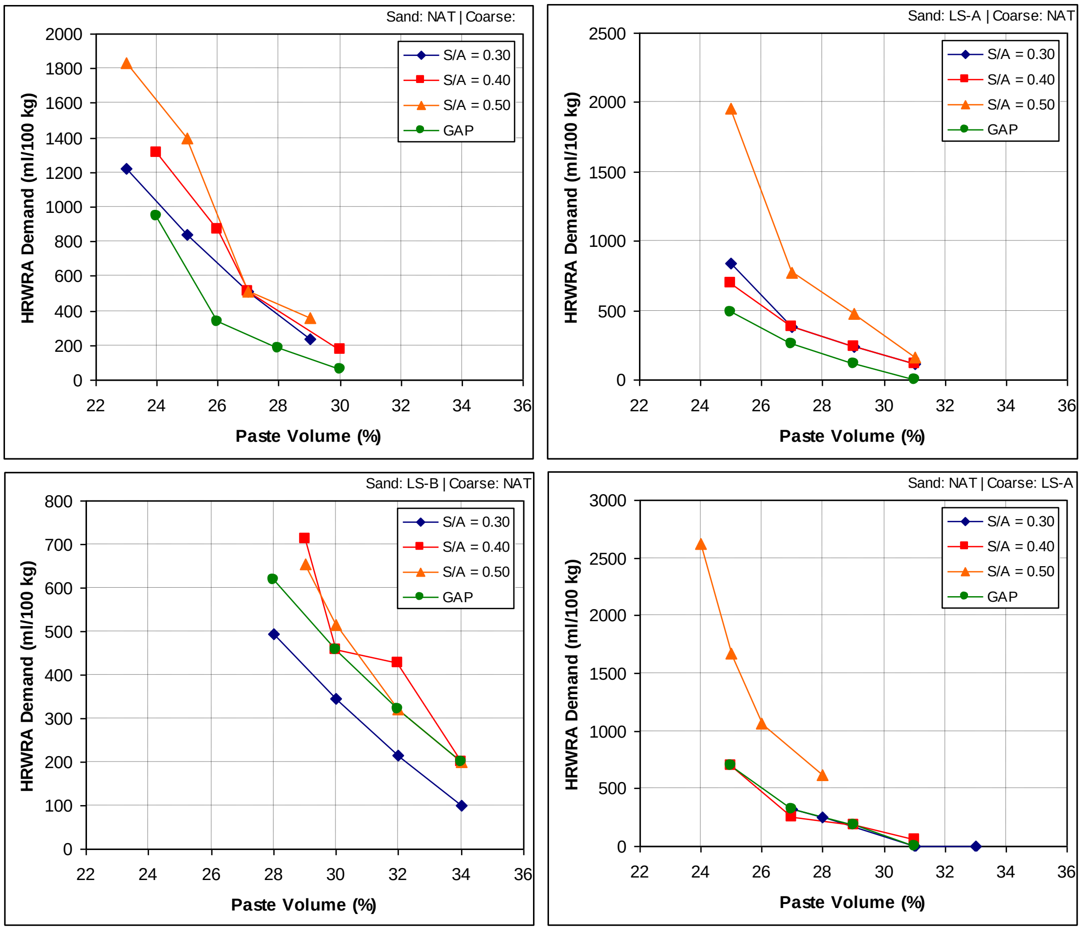

Fig. 2. Effect of Combined Aggregate Grading on HRWRA Demand

The effect of aggregate shape on workability was evaluated by comparing one aggregate combination to another. The aggregate combination with LS-B-FA and NAT-CA consistently had the highest HRWRA demand (Fig. 3). Of the two manufactured sands, LS-A-FA had better shape than LS-B-FA, although LS-A-FA was not as well shaped as NAT-FA. LS-A-FA had consistently lower HRWRA demand than LS-B-FA despite having a finer grading.

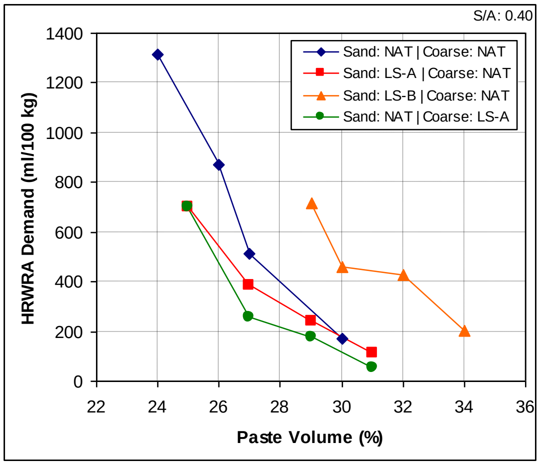

Fig. 3. Effect of Aggregate Source on HRWRA Demand for S/A=0.4

Compressive strength was similar for all concrete mixtures, regardless of paste volume, aggregate shape, or aggregate grading. Reductions in compressive strength were only observed when S/A=0.5 at low paste values (Fig. 4). The low strengths are believed to be due to mixtures having too much sand and too little binder (cement).

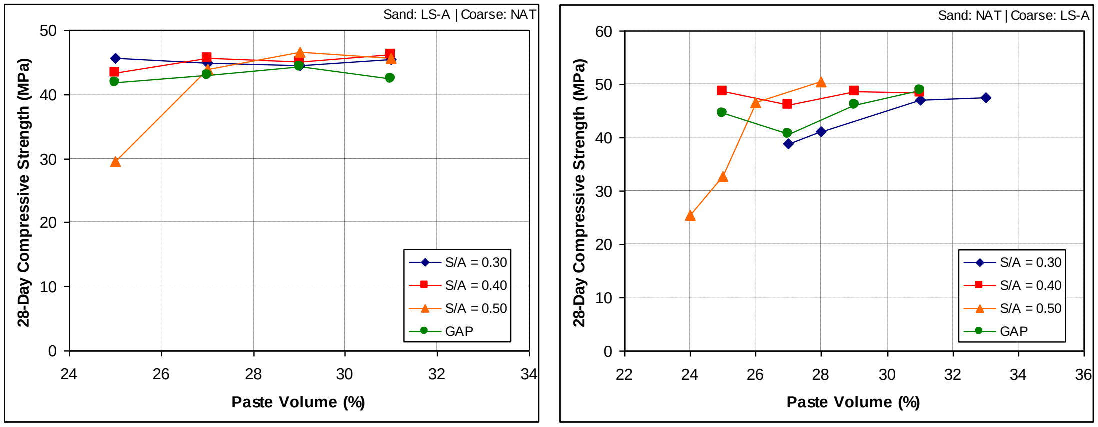

Fig. 4. Effect of Combined Aggregate Grading on Compressive Strength

As predicted, drying shrinkage increased with paste volume. Drying shrinkage was also affected by aggregate source (Fig. 5); Mixtures containing NAT-FA had higher shrinkage values after 112 days of testing. This may have been related to the stiffness of the fine aggregates in use. As for permeability (Fig. 5), reducing the paste volume reduced the permeability of the concrete regardless of the aggregate and grading.

To improve hardened properties, it is important to minimize paste volume by proper aggregate selection. The effects of aggregate shape and texture on hardened properties are mostly indirect. That is, poorly shaped or poorly graded aggregates can increase the paste volume, which in turn can be detrimental to hardened properties.

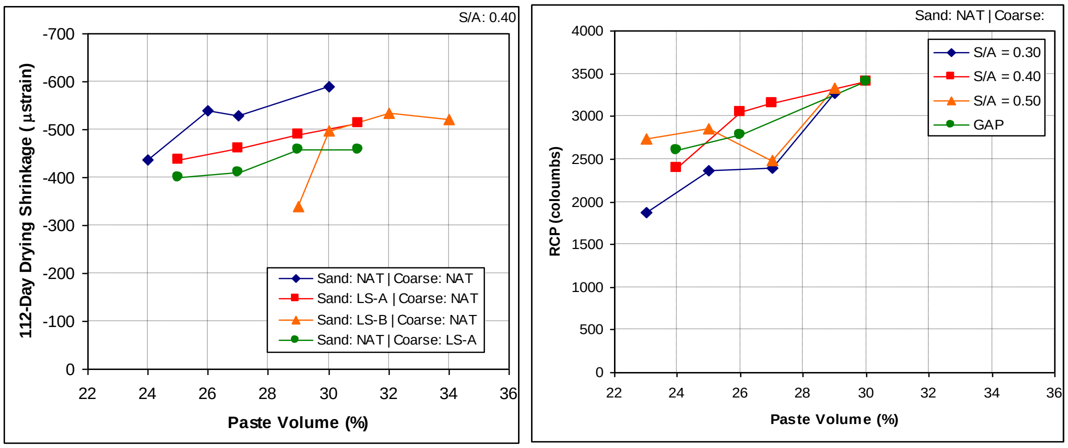

Fig. 5. Effect of Combined Aggregate Grading on Shrinkage and Permeability

In Phase I the goal was to reduce the paste content of the mixture by changing the aggregate gradation of the mixtures while maintaining a 15 ± 2.5 cm slump. Assuming the unit cost of a Type I/II is 100 dollars/ton and that the cost of the used HRWRA is 3 dollars/L, an estimate of the cost of the concrete mixtures made in phase I was computed (the cost of aggregates was not included). Fig. 6 shows that by optimizing aggregate gradation and reducing paste content, the cost of concrete can be reduced. The optimum gradation needed to achieve the highest cost reduction depends on the type of fine and coarse aggregate used. The results also show that the highest cost reductions were not necessarily associated with the lowest paste volumes. The cost of mixtures made with a manufactured sand (LS-A-NAT & LS-B-NAT) were higher than those made with a natural sand (NAT-FA), but the savings achieved when optimizing a mixture made with a manufactured sand was higher.

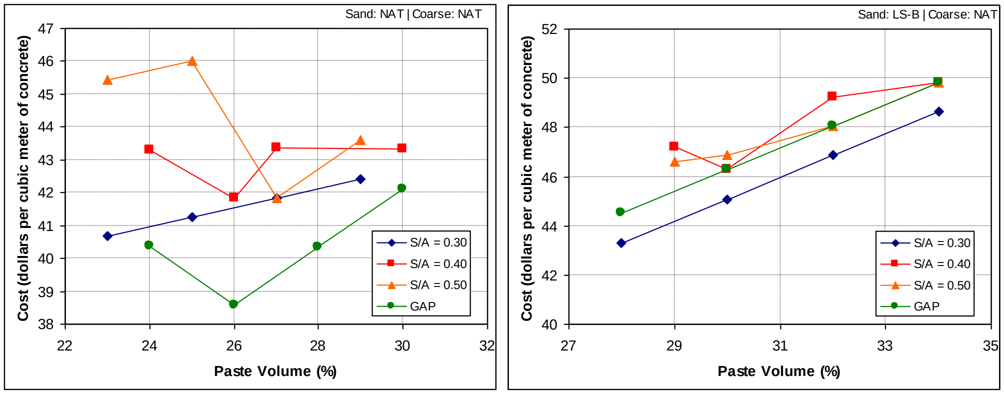

Fig. 6. Effect of Combined Aggregate Grading on Mixture Cost (Phase I)

Effects of Aggregate Microfines. Microfines were proportioned with constant paste volume but reduced water and cement contents, resulting in constant w/c and lower w/p. As a consequence of the reduced w/p, the HRWRA dose had to be increased to maintain constant slump as the cement and water content were reduced and the amount of microfines increased (Fig. 7). The LS-A and LS-C microfines resulted in consistently better workability than the GR-A microfines, which was likely attributable to their better shape or better grading relative to cement. All microfines were found to be free of clay or other deleterious materials. More data would be needed establish relationships between workability and the shape and grading of the microfines. It can be noted, however, that Koehler and Fowler [5] showed in a larger data set that the LS-A and LS-C microfines consistently performed better than GR-A microfines in self-consolidating concrete mixtures. The performance was attributed to the better shape of the LS-A and LS-C microfines and the better grading of the LS-A microfines.

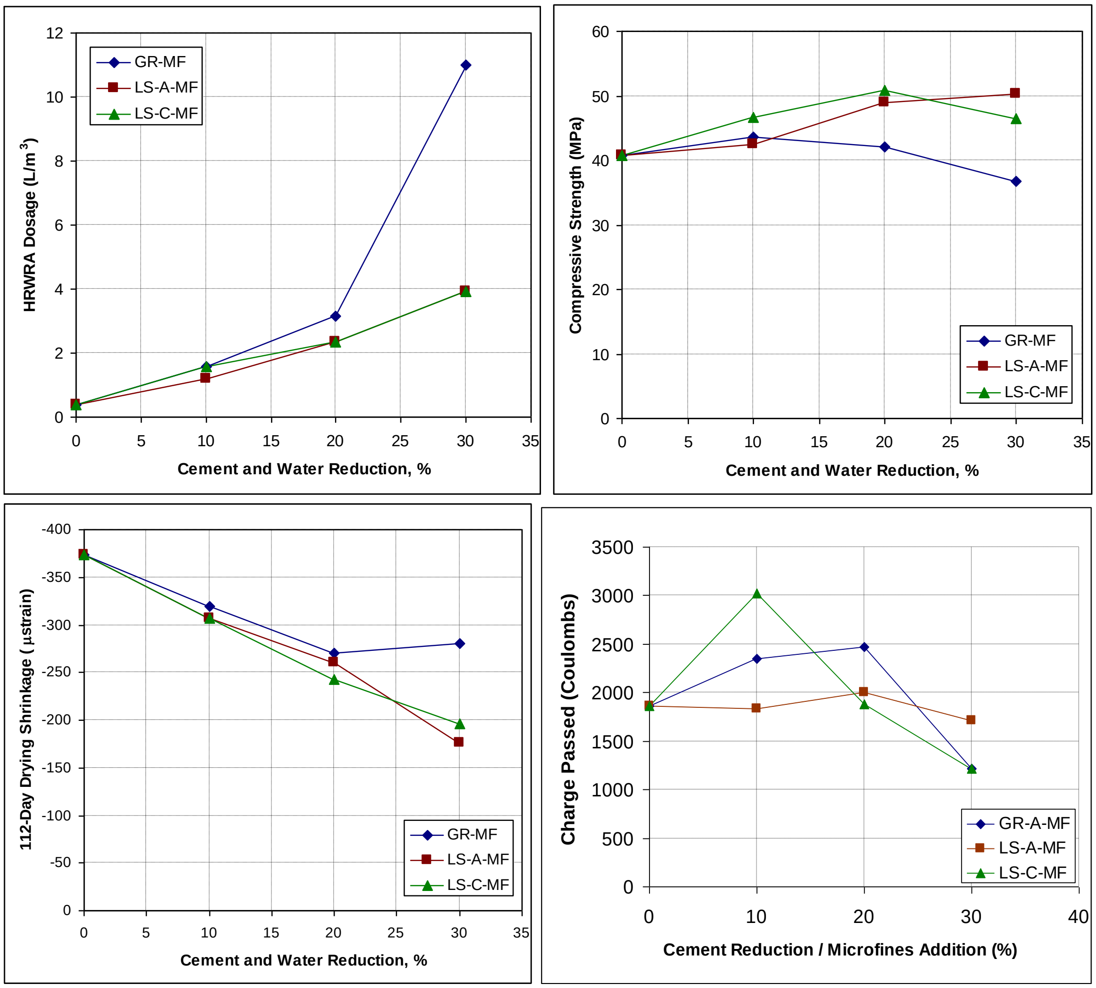

Fig. 7. Effect of Microfines Replacement Rate on Concrete Performance

Fig. 8 also shows that compressive strength increased as microfines were used to replace cement and water despite the reduced cement content. The increase in strength was likely attributable to the constant w/c, reduced water content per unit volume, improved powder packing due to the presence of the microfines, and use of HRWRA. The use of microfines resulted in a decrease in shrinkage, which was likely due to the reduced water and cement content even though the paste volume was held constant.

Fig. 8 compares the results in Fig. 7 to another scenario where the paste volume was increased and the w/p was reduced. Such a scenario would be associated with increasing the microfines content of the sand but keeping the cement and water contents constant. In this case, the increase in HRWRA demand was consistently less due to the higher paste volume. The HRWRA demand was still higher than the baseline case with no microfines due to the reduction in w/p from 0.50 to 0.33. The compressive strength was not significantly affected by the w/p or paste volume. The drying shrinkage was decreased when microfines were used, although to a smaller extent when the paste volume was increased to 34.5% than when it was held constant at 28.0%. There is little correlation between the permeability and the type of microfines. However, it is clear that as the amount of microfines increased, the permeability of the concrete was reduced. This is evident when the results from mixtures prepared with a 30% cement reduction are compared to those prepared with 10% cement reduction. The scatter is much smaller for the larger amount of microfines in the mixtures.

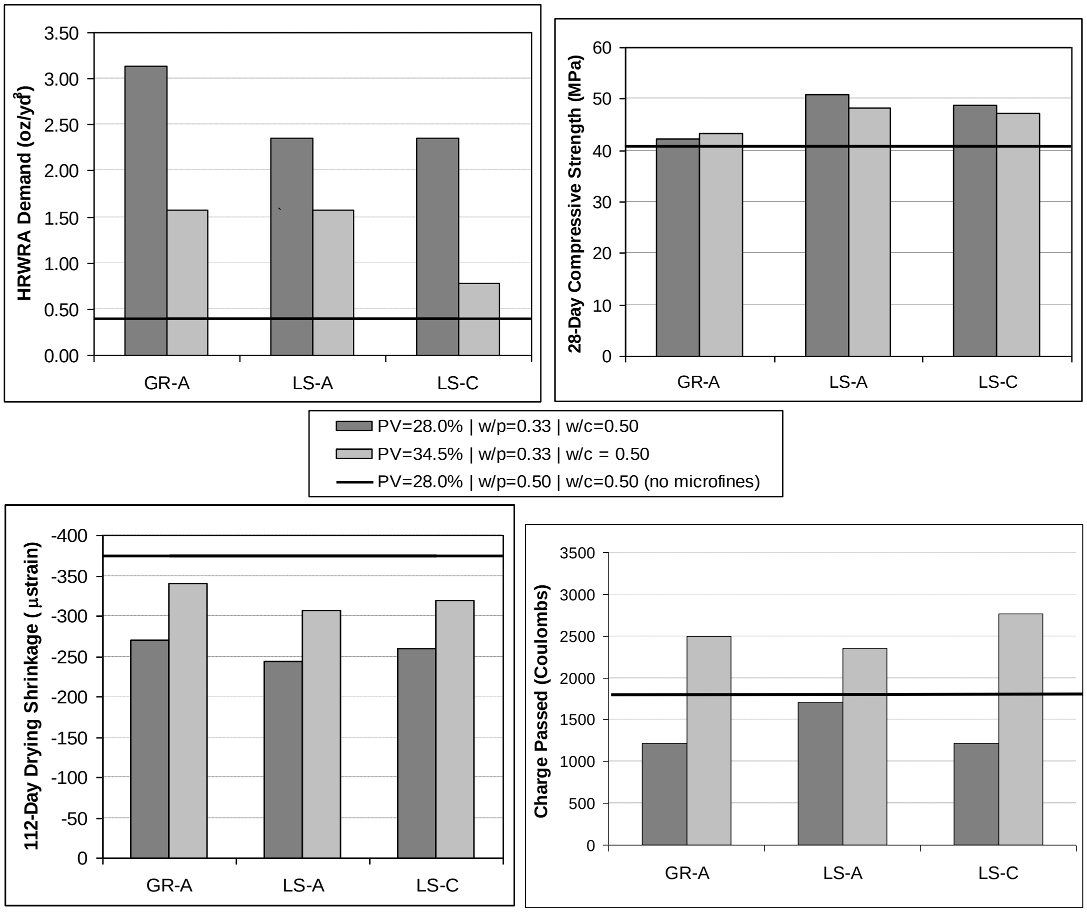

Fig. 8. Effects of Microfines Replacement on Concrete Performance

The two examples considered here—constant paste volume and reduced w/p or increased paste volume and reduced w/p—are just examples of two potential concrete mixture proportions with high microfines contents. These examples illustrate the importance of using paste volume and w/p to evaluate workability and using w/c or w/cm to evaluate hardened properties. The paste volume, w/p, and w/cm should be selected for each application based on the materials available and the performance requirements to achieve optimal mixtures. Due to the high HRWRA doses needed when the paste volume was held constant and the w/p was reduced, other mixture proportions may have been more practical.

Mixtures prepared considering the microfines to be part of the paste were found to have a lower permeability than the baseline mixture; at the same time, it was found that the permeabilities of the mixtures prepared considering the microfines as part of the fine aggregate are all higher than the permeability obtained from the baseline mixture. This is attributed to the higher water and cement content of the mixture and the lower amount of fine aggregate found in these mixtures. The higher cement content combined with the lower amount of fine aggregates made it possible for larger voids to be formed inside the concrete, therefore producing a higher permeability.

As for cost, Table 2 shows that the maximum cost benefit is not necessarily found for the mixture containing the maximum amount of cement substitution. In most cases, the mixture containing a 20% cement reduction was more cost effective than the other mixtures in the set. This was due to the large amount of water reducer admixture necessary to obtain the desired workability as the portion of substituted cement increased. The amount shown in grey in Table 2 represents a mixture that costs more than the baseline mixture. This cost is due to the high amount of water reducer needed to obtain the desired 15-cm slump for the GR-A mixture (30% cement reduction only). A substitution greater than 20% is not recommended when using microfines with properties similar to this granite for cost and durability reasons. However, it should be noted that, although the cost and strength of the GR-A mixture with a 30% cement reduction were not benefited, the drying shrinkage, abrasion and chloride penetration improved significantly compared to the baseline mixture. Mixtures prepared considering the microfines as part of the paste usually produced larger savings compared to mixtures in which the microfines were considered as part of the aggregate. Mixtures that considered the microfines as part of the aggregate required the same amount of cement as the baseline mixture. For this reason, the paste volume of the mixtures that considered the microfines as part of the aggregates was 34% as shown in Table 2.

Table 2. Cost Savings per Cubic Meter for Phase II (not including Aggregates)

Microfines	Mixture	Cement	Admixture	Microfines	Cost of Cement	Cost of Admixture	Combined Cost	Savings
		kg/m^3	L/m^3	kg/m^3				
None	Baseline	8587	1.767	---	$38.56	$5.36	$43.92	---
GR-A	10% reduction	7722	1.570	1890	$34.67	$4.77	$39.45	$4.47
	20% reduction	6873	3.141	3781	$30.86	$9.55	$40.41	$3.51
	30% reduction	6008	10.993	5671	$26.98	$33.39	$60.37	-$16.45
LS-A	10% reduction	7722	1.178	1826	$34.67	$3.58	$38.26	$5.66
	20% reduction	6873	2.356	3669	$30.86	$7.15	$38.02	$5.91
	30% reduction	6008	3.926	5495	$26.98	$11.93	$38.90	$5.02
LS-C	10% reduction	7722	1.570	1634	$34.67	$4.76	$39.43	$4.49
	20% reduction	6873	2.356	3268	$30.86	$7.15	$38.02	$5.91
	30% reduction	6008	3.926	4902	$26.98	$11.93	$38.90	$5.02

Note: Savings computed in reference to baseline mixture

Microfines	Mixture	Cement	Admixture	Microfines	Cost of Cement	Cost of Admixture	Combined Cost	Savings
		kg/m^3	L/m^3	kg/m^3				
None	Baseline	8587	1.767	---	$38.56	$5.36	$43.92	---
GR-A	As Fine Aggregate	8587	1.570	4694	$38.56	$4.77	$43.33	$0.59
	As Paste	6008	10.993	5671	$26.98	$33.39	$60.37	-$16.45
LS-A	As Fine Aggregate	8587	1.570	4550	$38.56	$4.77	$43.33	$0.59
	As Paste	6008	3.926	5495	$26.98	$11.93	$38.90	$5.02
LS-C	As Fine Aggregate	8587	0.785	4069	$38.56	$2.38	$40.94	$2.98
	As Paste	6008	3.926	4902	$26.98	$11.93	$38.90	$5.02

Note: Values computed here are for 30% cement reduction. Savings computed in reference to baseline mixture

Mixtures considering the microfines as part of the paste had a 28% paste volume (shown in Table 2). The amount of cement used in these mixtures was reduced by 30%, resulting in a savings of about $13.00 in cement per cubic meter. However, an increase in the amount of water reducer admixture to obtain the desired workability increased the price by approximately $6.50 per cubic meter.

CONCLUSIONS

The results of the research presented in this paper confirm that aggregates can play an important role in optimizing the cement content of concrete mixtures. Specifically, the following conclusions can be reached:

- Improving the aggregate shape and grading allowed a reduction in paste volume—and thus cement content—while maintaining workability and hardened properties.
  - Both shape and grading affected workability. Aggregates with angular shape resulted in increased paste volume and HRWRA demand. Aggregates with coarser grading generally required lower HRWRA demand but required higher paste volume to ensure adequate cohesiveness.
  - Higher packing densities were associated with lower minimum paste volume to ensure adequate cohesiveness; however, it was not clear the extent to which the lower minimum paste volume was due to a finer grading or a higher packing density. Packing density was not directly correlated with HRWRA demand.
  - Poorly shaped and poorly graded aggregates could be accommodated by increasing the paste volume, HRWRA dose, or both. A minimum paste volume was required to ensure adequate cohesiveness.
  - Compressive strength was similar for all concrete mixtures, it was only affected when mixtures having a low paste volume and a high fine aggregate ratio were used.
  - Decreasing the paste volume resulted in decreased shrinkage and permeability.
- The use of dust-of-fracture aggregate microfines allowed a reduction in cement content at a given paste volume while maintaining or improving hardened properties.
  - The reduction in w/p caused a decrease in slump, which could be offset by increasing the paste volume, HRWRA dose, or both. The use of increased HRWRA dose to maintain workability allowed the w/c to be maintained, resulting in equal or improved hardened properties.
  - Aggregate microfines are typically similar in size as cement; therefore, the paste volume and w/p should be considered when evaluating workability and the paste volume and either the w/c or w/cm when evaluating hardened properties.
- Both methods used to optimize mixtures led to a decrease in cost. Using less paste and/or more microfines reduced the cost of the concrete, but the lowest paste volume and/or the highest microfine content did not always correspond to the less costly mixture. Cost savings ranged from around $1.30 to $10.50 per cubic meter of concrete.

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