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Exploring the effect of dry premixing of sand and cement on the mechanical properties of mortar

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Abstract

A spout-fluid bed device was developed for dry premixing sand and cement to produce mortar. The goal of the work was to explore the efficacy of a new method for dispersing cement in sand to produce a mortar with better mechanical and physical properties. This strategy was found to work best at high sand/cement ratios, indicating that the dry premixing is more effective as the cement content is reduced and that it may be possible to produce commercially acceptable mortars with a lower cement content. Other properties of the mortar are also positively affected, including a decrease in the shrinkage and an increase in the workability.

Keywords: Dispersion; Mixture proportioning; Mechanical properties; Physical properties; Mortar

1. Introduction

The need to produce road and bridge structures with surfaces and foundations that are stronger, more durable, and economically viable is imperative. Of equal importance appears to be the need to use less energy in the overall construction process and to produce less greenhouse gases, too. New, stronger, and more durable concretes that make more efficient use of expensive, energy-intensive cementitious materials will be the key to meeting these goals. In an effort to increase the performance of concrete, compositions have included fly ash and microsilica. These materials increase the strength of the concrete, reduce its permeability, and decrease cracking, but can be more expensive. The performance gains are primarily related to the pozzolanic reaction between silica and calcium hydroxide, and secondarily to improved particle packing efficiency due to the incorporation of finer and finer particles [1–3].

Dispersing these finer and finer particles is normally achieved via the inclusion of surfactants known as water-reducing admixtures, but may also require increasing the amount of mechanical energy imparted into the mix. This insures that momentum is transferred from the turbulent fluid phase to the cohesive cement particles at a scale that will be able to affect and modify the dispersion of that phase. Unfortunately, some report that conventional concrete or mortar mixing equipment cannot provide the intensity of agitation necessary to effectively mix and disperse the finest particles [4]. Thus, obtaining a uniform mixture of these components is extremely difficult and this inhibits performance gains and increases the cost of the materials. The reason behind the performance limitations of most conventional equipment lies in the way the mixing occurs. Normally, material is batched into the mixer and water and appropriate admixtures are added. Mixing then commences, with the fluid phase being water. Water is the dispersing agent and a reactant. Its effectiveness as a dispersing agent is limited since there is a limited amount of water that can be added to the mixture before the properties of the mortar or concrete are compromised. This is why most commercial concrete produced today includes one or more chemical dispersants at the normal, mid-, or high-range level of effectiveness. Since cement reactions are initiated at the moment water is added, mixing and reaction occur simultaneously at least until the dormant period slows hydration. It can, therefore, be difficult to fully disperse the reactive components and so it is of

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interest to find ways to improve the dispersion of fine particles in mortar and concrete.

This paper will report on *exploratory* experiments and findings using a new spout-fluid bed feeder to a transport pipe that dry mixes cement and sand pneumatically to produce a dispersion of cement in sand prior to water addition. The device divorces solids mixing from reaction and since air is 1000 times less dense than water, we can generate much higher levels of turbulence and thereby impart more energy at the smaller length scales necessary to disperse the finest components of the mortar. We will discuss the equipment design and operation, the mixing process, and exploratory experiments indicating the effects of the dry mixing process on the mechanical and chemical properties of the mortar. Preliminary, nonrigorous observations of the microstructure of the mortar are also reported.

2. Materials, apparatus, and operation

Typical materials meeting New York State Department of Transportation construction guidelines [5] were used in the project. The Bogue calculation phase composition of the cement and the size distribution of sand are shown in Tables 1 and 2. The sand was dried prior to use. The Blaine surface area of the cement is 356 m^2/kg.

2.1. Apparatus

Fig. 1 is a schematic representation of the apparatus based on an earlier design [6] for coating particles. The main components of the equipment are as follows.

2.1.1. Conical spout-fluid bed feeder

This portion of the device holds the sand and cement and feeds it into the transport line. The feeder controls the solids circulation rate through the transport line and the regime of operation (dense- versus dilute-phase flow). The circulation rate is adjusted by changing the draft tube spacing (the distance between the top of the inlet jet tube and the inlet to the transport line) and the air flow entering the annulus surrounding the transport line.

2.1.2. Vertical pneumatic transport line

This section transports the air/solids mixture in turbulent flow at high velocities, promoting mixing and dispersion at the finest particle size scale.

Table 1
Bogue calculation phase composition of LaFarge cement

Component	Percentage by weight
C_3S—tricalcium silicate	60.4
C_3A—tricalcium aluminate	6.4
C_2S—dicalcium silicate	14.2
C_4AF—tetracalcium aluminoferrite	9.4

Table 2
Size distribution of sand

Sieve opening (μm)	Fraction by weight
2360	0.7
1601	17.6
571	68.7
225	11.1
112	0.2
55.50	1.7

2.1.3. Cyclone with auxiliary air flow

This section allows us to disengage most of the solids from the air stream. Particles smaller than about 5 μm are separated and returned either to a holding tank or to the spout-fluid bed feeder. The auxiliary air flow feature allows us to maintain the optimum flowrate through the cyclone to insure the best particle separation efficiency.

2.1.4. Collection tank

The collection tank provides for temporary storage of the solid mixture either for collection at the end of a mixing run or for intermediate collection to determine the solids circulation rate.

2.1.5. Baghouse filter

This section of the apparatus is a final filtration that removes all particles less than about 5 μm from the air stream. These particles can then be collected and removed from the system or periodically returned to the mortar mixture.

2.1.6. Data acquisition and control system

A custom Labview-based data acquisition and control system was designed to automatically control and maintain the solids circulation rate in the device.

2.2. Operation—running mixing experiments

Typical operation of the mixing system involved first setting an initial value of the air flow velocity [10–15 m/s, 400–700 standard liters per minute (slpm)] through the draft tube to transport the particles and provide the desired level of turbulence. Then, the desired utility air flow rate for the cyclone was set. The draft tube spacing, L_t, and annulus air flow were adjusted to the desired solids circulation rate (in a range from 2 to 20 kg/min) and the operating regime. L_t was generally varied between 3 and 7 cm. Control valve 2 was used to control the air feed into the annulus section of the feeder. Typically, the valve was adjusted to provide a flow rate of 25–75 slpm.

The apparatus can be operated in two flow regimes. In *dilute-phase pneumatic transport*, the solids fraction is relatively low (on the order of a few percent of solids). Solids circulation rates less than 10 kg/min were achieved by decreasing the draft tube spacing, decreasing the aeration of the annulus, and increasing the jet flow rate. In *dense-phase*

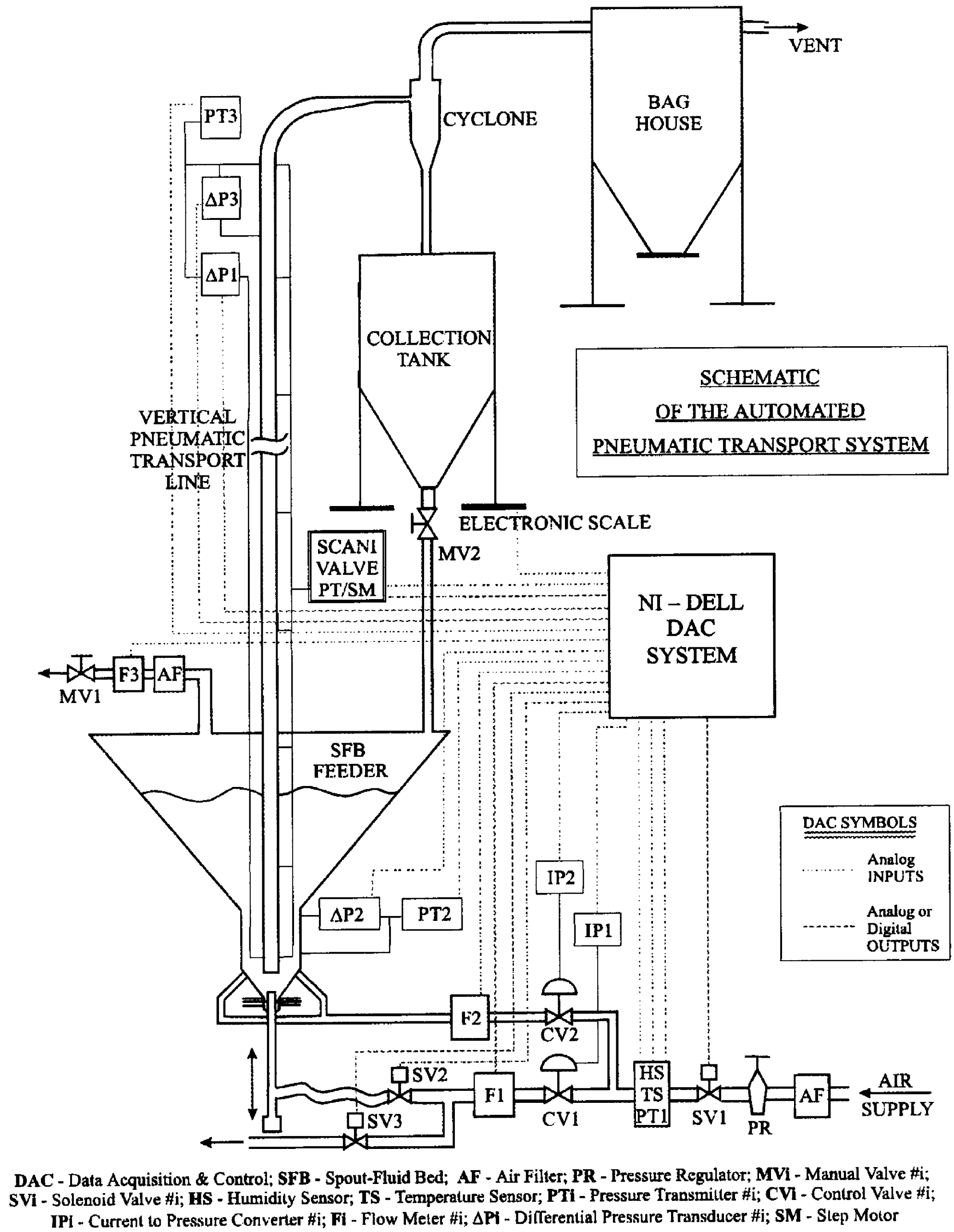

Fig. 1. Schematic of the equipment.

pneumatic transport, the solids fraction is higher and the solids circulation rates are greater than 15 kg/min. This flow regime was obtained by increasing the draft tube spacing, increasing the aeration of the annulus, and decreasing the jet flow rate while still maintaining it above the choking velocity of the feeder.

Approximately 50 kg of mortar was made at any one time. The raw material was loaded into the feeder sequentially and the process started. After a few minutes to reach steady-state operation, the solids circulation rate was measured to fix the cycle time or time required to transport the 50 kg of mortar mix. Next, the mixing time or number of cycles was set for the run. In some runs, material filtered out by the baghouse filter was removed from the system; in other runs, that material was periodically recycled back into the mortar mix. Table 3 outlines the mixtures produced and the operating parameters for each run.

3. Results

In this section, we present preliminary results from the first exploratory experiments. We performed nine plus two

Table 3
Summary of runs performed

Mix	Run purpose	SCR[a]	Primary air flow, F_1^a (slpm)	Feeder air flow, F_2^a (slpm)	Circulation rate, W_s^a (lb/min)	Number of cycles	Comments
1a	Sand attrition		660	0	13–14	8	
1b	Sand attrition		660	40	15–16	20	
R1	Mixing	2	440	0	3–5	10	Raw sand
							U = 10 m/s
			660	40	4–6		U = 15 m/s
			660	50	12–14		U = 15 m/s
R2	Mixing	2	440	25	8–10	10	Narrowly sieved sand ($300 < d_p < 600$)
R3	Mixing	2	440	0	3.5	10	Presieved sand
			440	25	12–15		($d_p < 1200$ m)
R4	Mixing	3.2	440	25	10–12	20	Low cement content
			440	75	40		
R5	Standard mixing	2.3	530	50	15	25	Semidense-phase PT
R6	Standard mixing	2.4	660	25	5	20	Dilute-phase PT (L_t = 1")
R7	Standard mixing	2.2	480	75	25	23	Dense-phase PT
R8	Mixing with SACF[b]	2.35	660	25	5	5 + 17 = 23	Dilute-phase PT followed
			480	75	25		by dense-phase PT
R9	Mixing with BHCRF[c] and SACF[b]	2.05	660	25	5	5 + 20 = 25	Dilute-phase PT followed
			480	75	25		by dense-phase PT
R10	Mixing with BHCRF[c] and SACF[b]	~2.4	660	25	5	5 + 15 = 20	Dilute-phase PT followed
			480	75	25		by dense-phase PT (ruptured SS tube caused some loss of s/c)
R4-F	Mixing with BHCRF[c] and SACF[b]	3.1	660	25	5	No data	Dilute-phase PT followed
			480	75	25		by dense-phase PT
R9-F	Mixing with BHCRF[c] and SACF[b]	2.0	660	25	5	No data	Dilute-phase PT followed
			480	75	25		by dense-phase PT

Water/cement ratio was nominally 0.45 for all runs.
[a] SCR—s/c mass ratio; L_t—draft tube spacing; F_1—jet mass flow rate; F_2—annulus mass flow rate; W_s—solids circulation rate; U—superficial gas velocity through the transport line; PT—pneumatic transport.
[b] SACF—sequential addition of cement to the feeder.
[c] BHCR—baghouse cement being returned to the feeder.

repeat experiments on sand/cement (s/c) mortar mixtures using the spout-fluid bed feeder apparatus. Though only a limited number of runs were performed, we learned quite a bit about the dry mixing process and how the mixing affects mortar properties.

For several runs of the spout-fluid bed unit, a comparable mortar was prepared using conventional mixing techniques (ASTM C305/99). Water was added to both mixtures so that the water/cement ratios were approximately 0.45 in all cases. Then the mortars were cured according to ASTM standards prior to mechanical testing (ASTM C511). For the spout-fluid bed mixtures, the input proportions of the ingredients were known precisely, but due to small system losses and attrition, the output proportions were known only approximately. Since the cement contents in the spout-fluid bed mixtures were uncertain to some degree, the water/cement ratio for these same mixes was uncertain as well. However, our ability to discern the output proportions of the spout-fluid bed mixtures improved over the duration of the project such that the conventionally mixed, control mixtures were continually closer to the actual composition of the spout-fluid bed mixtures as the work progressed.

3.1. Mechanical properties

Ten mixes were evaluated as well as a large-scale modification rerun of an earlier experiment (modification and large-batch processing of Trial 9), plus an abbreviated rerun of a low-cement mortar (trial 4). These are all listed in Table 3. The compressive strength of 2-in. mortar cubes (ASTM C-109), the flexural strength of 1-in. mortar bars (ASTM C-348/97), and the compressive/flexural strength ratios are shown as bar charts in Figs. 2–4. Solid bars indicate spout-fluid bed mixes; corresponding control mixes are of the same shade, but with diagonal stripes. Compressive strength, flexural strength, and the ratio of flexural to compressive strength are included.

Each reported value here represents an average of three separate measurements on three separate specimens. These specimens were cast from the same large batch of mortar, mixed and cured according to ASTM guidelines. Standard deviations within a batch were generally low, ± 100 psi (compression tests) ± 40 psi (flexural tests). Variations from batch to batch may be higher, though we were not able in this exploratory phase of the work to perform enough repeat experiments to characterize batch-to-batch repeatability quantitatively. Thus, we will concentrate primarily on trends we observed in our experiments rather than on specific values of compressive strength or flexural strength, etc.

Considering the compressive strength results, the first, dry premixed mortars appeared to have two problems: the early strength gain was much slower than the control samples, and there appeared to be some inconsistencies in the sample properties and mechanical performance. It is important to understand that only cement and sand were used in the mixtures so that the cement is being used for two purposes:

1. as a binding agent; and
2. as a filler for packing purposes.

Strength development depends upon two factors: the binding of all components and the efficient packing of the materials. With this in mind, we have developed several working hypotheses to guide us in explaining the data in the figures.

(a) In the dry state, cement particles are cohesive and cement behaves like a weak solid because of the presence of interparticle forces [7]. Rather than dispersing into the sand, cement breaks into multiparticle clumps as it is sucked into the transport line. These clumps break down further due to the turbulence of the air in the transport line, producing smaller clumps and some individual particles. A second effect of the transport line is to disperse the clumps and individual particles as uniformly as possible among the sand particles. The objective of the dry mixing process then is to produce multiparticle clumps of cement of the smallest possible size, uniformly dispersed in the sand.

The air velocity required to suspend a particle or clump is a function of its size and its density. Since sand is the largest particle in the mix, the lowest transport velocity is determined by the sand used. There are cement and sand fines in the mortar mix and the size difference between these materials and the sand is large. Very fine particles, such as cement and attritted sand (generated in the cyclone), are easily transported through the system. The finest of these particles (less than about 5 μm) are entrained through the cyclone separator and ultimately collected in the baghouse filtration unit. This has a number of effects on the final mortar mix. The finest cement particles react with water first and dominate the early strength gain of the mortar. A loss of those particles will reduce the rate of strength gain at early ages, but strength should approach the normal control samples at later times as long as the total cement content is not significantly reduced [3]. The finest particles also contribute to efficient particle packing and water demand with attendant effects on workability, strength, porosity, shrinkage, and permeability.

(b) The mixing process is affected by the overall mix composition, i.e., the s/c ratio. If a great excess of cement is added to the system, then cement is present everywhere and the degree of mixing makes little difference to its strength. Thus, low s/c ratio mixes (high cement content mixes) should all lead to essentially the same mechanical behavior regardless of how well the material is mixed and dispersed. The operating parameters of the feeder then should have little effect on the final mechanical properties except for the loss of the finest material, which would lead to lower rate of strength gain.

(c) Mixing after the addition of water is critical to the mechanical performance of the mortar. Insufficient dispersion of the cement and water affects the degree and uniformity of hydration of the cement. Further, insufficient consolidation of the mortar (removal of large air voids) affects the density and uniformity of the specimens, which can lower strength and increase variability in the test results.

We believe the results of our exploratory experiments provide evidence relating to these theories. Our first experiments showed that we lose a considerable amount of cement fines that eventually end up in the baghouse filter unit. Due to this loss, the early strength gain of these initial mixtures is slower than the control samples even though the long-term strengths for dry premixed and control samples became comparable. To test Hypothesis A, we began to change our operation by feeding the cement into the unit sequentially so that the cement was always mixed into a preexisting large amount of sand, and by returning the fines from the baghouse filter to the mix. When these modifications were implemented (not optimally due to the initial equipment design and proscribed manual feeding operation), we were able to create mortars that were comparable—and, in a few cases, better—than the conventionally mixed control samples in all mechanical property measures (see Figs. 2–4).

Even though we achieved high-performing mortars at low s/c ratios, there was still only a single instance in which the dry premixed mortar outperformed the control sample, and that was Mixture 4. Table 4 shows the compressive strength results for this mixture whose s/c ratio was around 3 as compared with Mixture 3 where the s/c ratio was nominally 2. At this exploratory stage of the project, it was not possible to take data for all the samples over the entire 90-day time period. Thus, data in certain cells of the table may be missing.

Notice that the dry premixed mortar at low s/c ratio (R3) begins very much below the strength of the conventionally mixed mortar (C3) but, as time progresses, asymptotically approaches the strength of the control. By contrast, when the cement content is reduced, the discrepancy between the

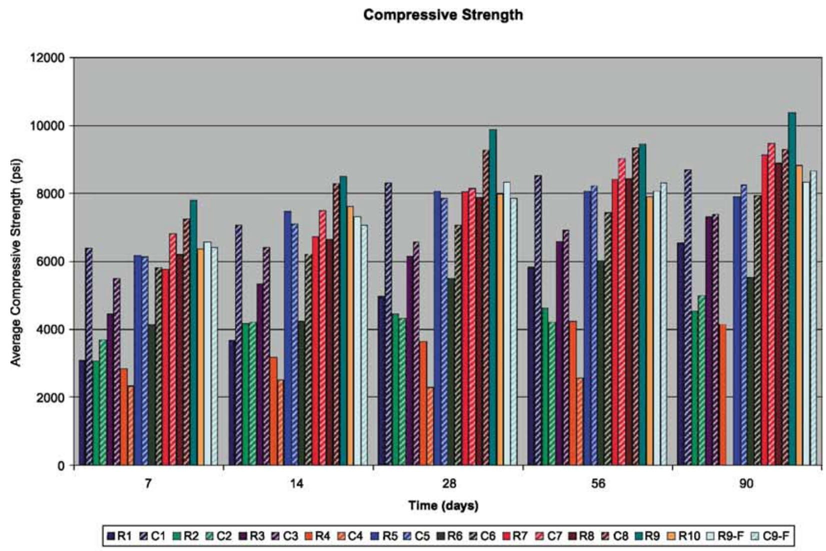

Fig. 2.

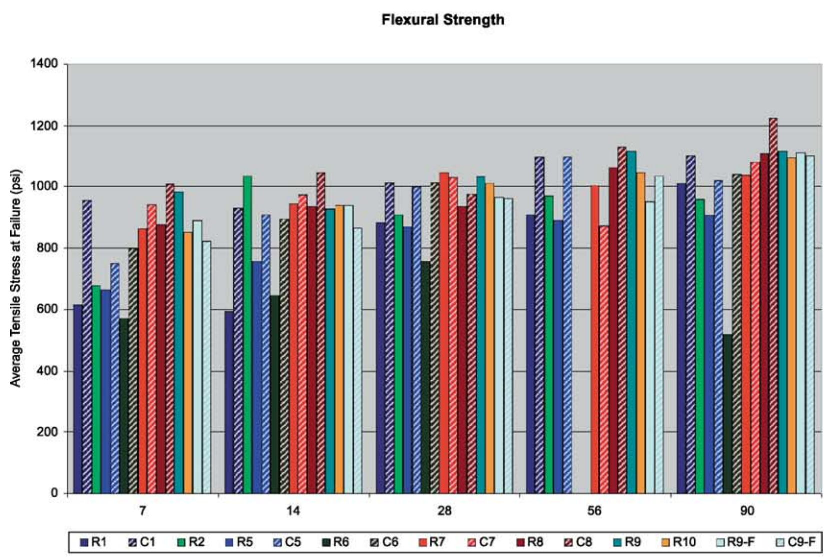

Fig. 3.

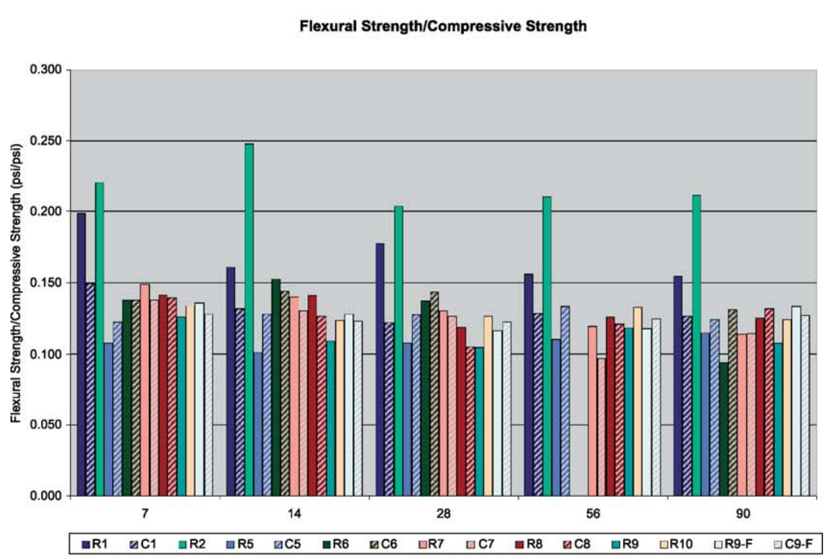

Fig. 4.

Table 4
Average compressive strength (psi)

Mixture	7 days	14 days	28 days	56 days	90 days
R3	4440	5340	6150	6580	7320
C3	5510	6410	6560	6910	7380
R3 − C3	*− 1070*	*− 1070*	*− 410*	*− 330*	*− 60*
R4	2820	3170	3640	4240	4140
C4	2340	2500	2290	2580	–
R4a	3420				
R4 − C4	*480*	*670*	*1350*	*1660*	–

mechanical performance of the dry premixed (R4) and control mortar (C4) is still increasing after 90 days. Though the control sample (C4) shows virtually no strength gain from the 7th to the 90th day, the dry mix has almost doubled in strength. This experiment was one in which the cement content was reduced to a s/c ratio of 3.2 (later analysis showed the s/c ratio to be closer to 3.4). The performance of this mixture led us to develop Hypothesis B because it appears that in this lean mixture, the effect of mixing is more pronounced and dispersion of the cement much more important. When coupled with the fact that this early mix did not have sequential cement addition nor baghouse fines return, it seemed that the performance of this lean mixture could be greatly improved. Indeed, a repeat of Trial 4 with manual addition of cement and periodic return of some of the fines yielded a 600-psi (21%) improvement in strength at the 7-day mark. The success of this lean mixture shows that it may be possible to reduce cement content and produce mortars with acceptable levels of strength by the dry mixing process.

One of the goals of these exploratory experiments was to determine exactly which type of particle transport would lead to the best mortar mix: dilute-phase transport with low solids circulation rates but intense gas-phase turbulence, or dense-phase transport with higher solids circulation rates and increased particle or clump interaction. The results of the last four mixes shown in Table 3 (high s/c ratios) and Figs. 2–4 suggest that dense-phase transport, with its enhanced particle or clump collision rate, produces the highest strength mixtures. We believe that momentum transfer from the turbulent gas phase to the particles and clumps is more efficient in dense-phase transport, resulting in better dispersion of material and better overall solids mixing.

An interesting result occurred when we ran the mixer with a sand that had been prescreened to yield a relatively narrow size range (Trial 2). As shown in Fig. 4, the flexural/compressive strength ratio of this mixture was much higher than any other mixture tested. There is

Table 5
Preliminary chemical analyses of raw cement and baghouse filter residue

Component	LaFarge cement (%)	Baghouse filter residue (%)
Silicon dioxide	20.8	22.8
Aluminum oxide	4.4	5.6
Ferric oxide	3.1	3.8
Magnesium oxide	2.1	2.2
Sodium oxide	0.2	0.3
Potassium oxide	0.7	1.7
Titanium dioxide	0.2	0.3
Phosporous pentoxide	0.1	0.1
CaO (free lime)	1	
CaO		54.8
Na_2O Eq.	0.7	1.4
Sulphur trioxide	2.8	4.5

evidence in the literature that narrowing the size range does improve this ratio in concretes [8–10], but it seems clear that the mixing process also greatly affects this ratio. Data on the modulus of rupture in concrete tend to scatter, making it difficult to predict for design purposes [11]. This may be attributable to variability in the way the concrete was mixed, but is generally assumed to be related to the overall sample preparation and testing procedure. The good dispersion and excellent mixing afforded by the pneumatic premixing method are worth investigating further if it is desirable to maximize the flexural/compressive strength ratio in mortars.

3.2. Chemical properties

The loss of fines may influence the chemistry of the cement, too. We present some preliminary chemical analysis data in Table 5. Unfortunately, the CaO in the LaFarge cement was not determined and cannot, therefore, be compared with that in the baghouse. We believe that the dry premixing process can alter the cement chemistry with attendant impact on rate of hydration and strength gain, and perhaps shrinkage as well since there is a high degree of solids–gas turbulence interactions, solids–solid interaction, and solids attrition in the cyclone as the material recirculates. The extent and rate of attrition are related to the particles' hardness and density. Thus, softer and less dense materials are reduced overall in their size range and end up disproportionately in the baghouse filter. If the baghouse material is not recycled back into the mix, there may be, effectively, a chemical separation of the components of the cement. The weight of sand fines is very small so little sand ends up in the baghouse filter. This entire matter needs further investigation and more detailed chemical analysis.

Fig. 2. Comprehensive compressive strength results.

Fig. 3. Comprehensive flexural strength results.

Fig. 4. Comprehensive flexural/compressive strength ratioss.

These chemical changes may be one reason for the slower early strength gain that is corrected by returning the baghouse material to the blend. It may also show up in reduced chemical shrinkage as discussed below. The Justnes Norwegian method [12] has been used at Cornell to estimate the nondrying bulk shrinkage of mortars as well as to perform conventional shrinkage tests on mortar bars (ASTM C596). To determine the nondrying bulk shrinkage, about 300 g of freshly mixed mortar is placed in a latex membrane and its weight is measured in air and in water. Using Archimedes' principle with a number of corrections to account for mass and volume changes in the membrane itself, the volume of the mortar sample is tracked over a period of 7 days. Final results (expressed as a percent of the original volume) give an estimate of the shrinkage resulting from hydration and capillary tension in the absence of external drying. The results of these experiments are shown in Fig. 5. The dry premixed mixtures generally gave lower shrinkage in this test and in the conventional bar tests, indicating an effect on the mixing and distribution of chemical components in the mix. Note that of all mixes tested, R9-F yielded the lowest shrinkage at 7 days, a curious result since this mixture also had fines return. Much more work is necessary to determine how much shrinkage reduction is due to mixing and dispersion, and how much chemical alteration is due to loss of cement fines.

3.3. Flow test results

The results of the flow tests are shown in Figs. 6 and 7. This is a standard ASTM dynamic flow test (ASTM C1437). These bar charts show the flow of each mix at each stage of the mixing process and in the final stage before casting, respectively. Mixes that do not appear at any or all of the stages were not workable enough to obtain reliable flow data at such stages. Such mixes crumbled on the flow table, so any measurements of the final base diameter of the cone were not meaningful. One exception is mix R7, for which the flow data are unavailable. It was observed, however, that R7 was slightly more workable than its control mix, C7. Mixes C5, C6, and C7 were also used as the control mixes for R9 and R10 due to similarity in s/c ratio. However, in the final large batch casting, the R9 mix (modified with the return of fine materials—denoted as R9-F) was paired with control batch (C9-F), which matched the s/c and water/cement ratios of R9-F to a degree that exceeded all other tests performed. It is noted that while the dynamic nature of the flow test makes this a significant improvement over the slump test, a more informative test of rheological properties would be useful [13]. In many instances, the workability of the dry premixed mortars was better than that of the control mixtures. Part of that increase may be due to the loss of the finest fraction of cement in the baghouse filter; however, dry premixed mortars were more workable even when the fines were returned to the mix.

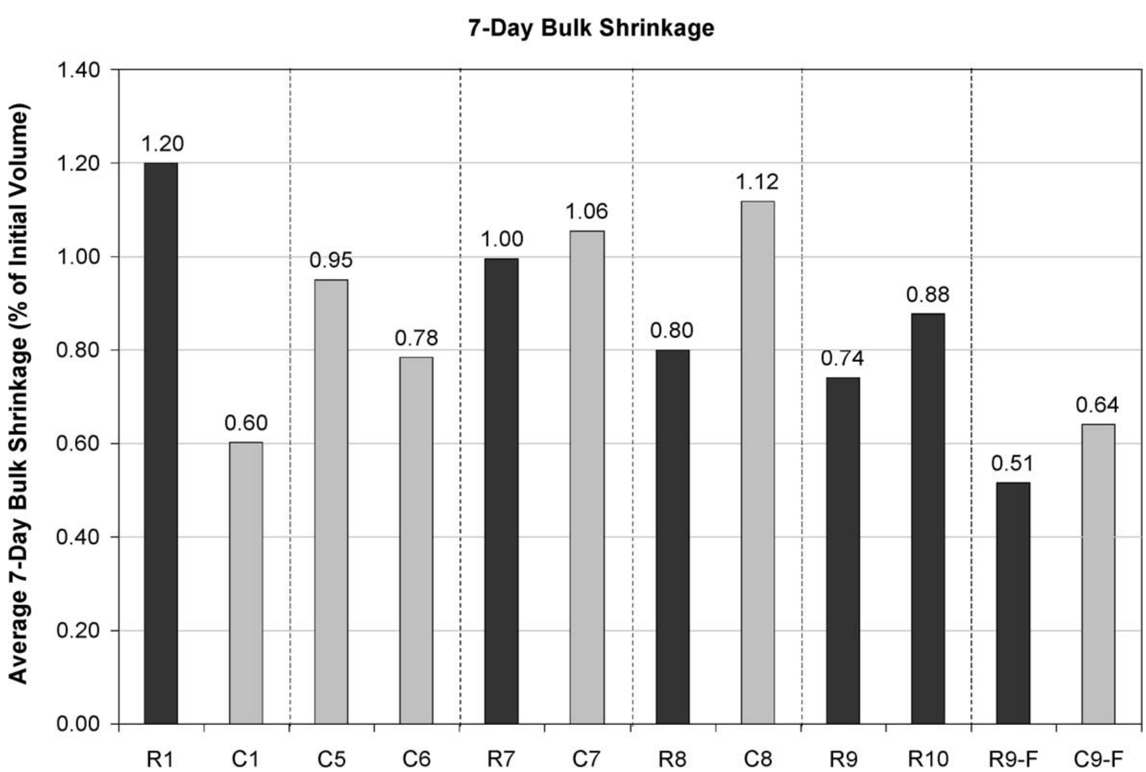

Fig. 5. Comprehensive 7-day bulk shrinkage results.

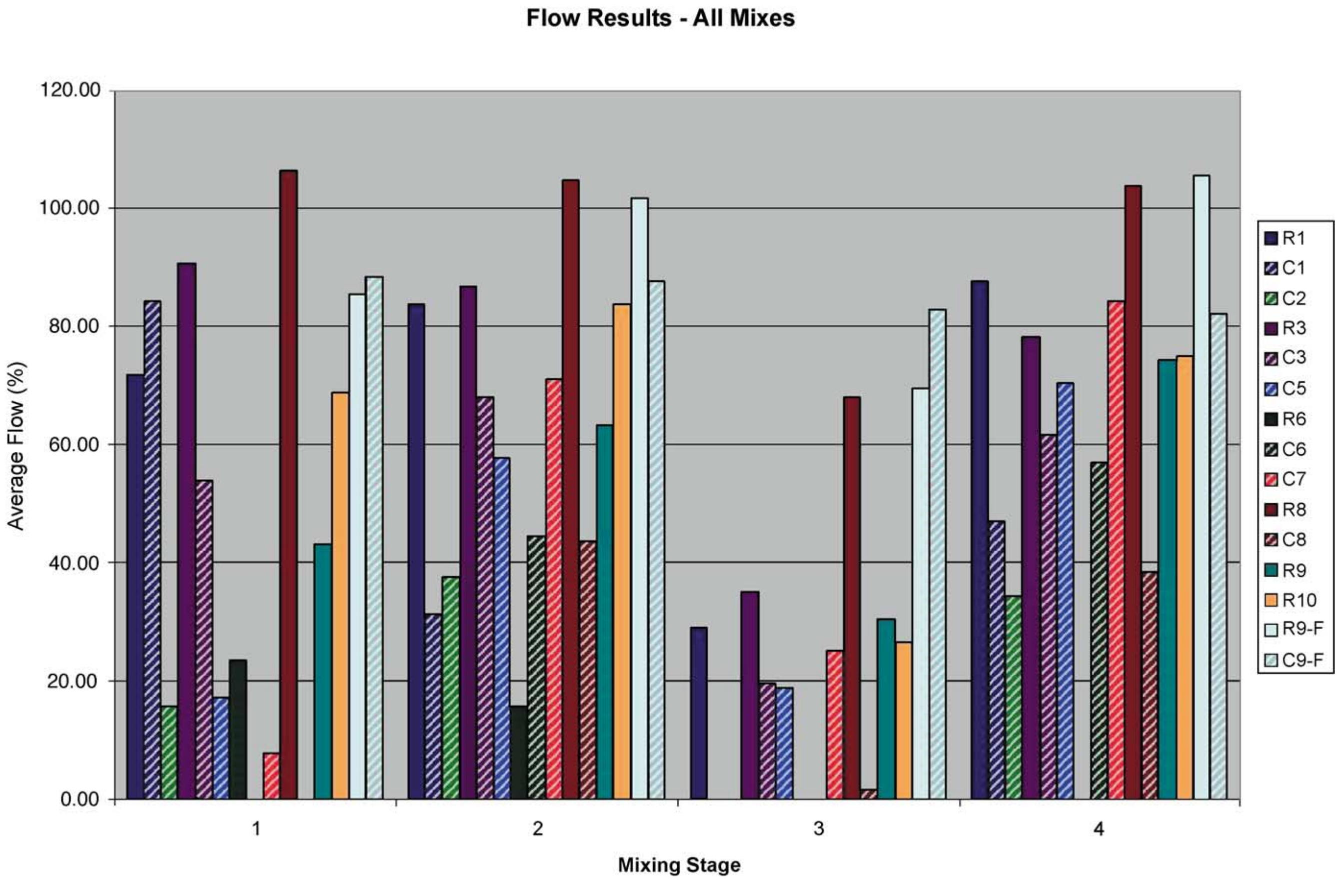

Fig. 6. Flow data at individual stages of mixing.

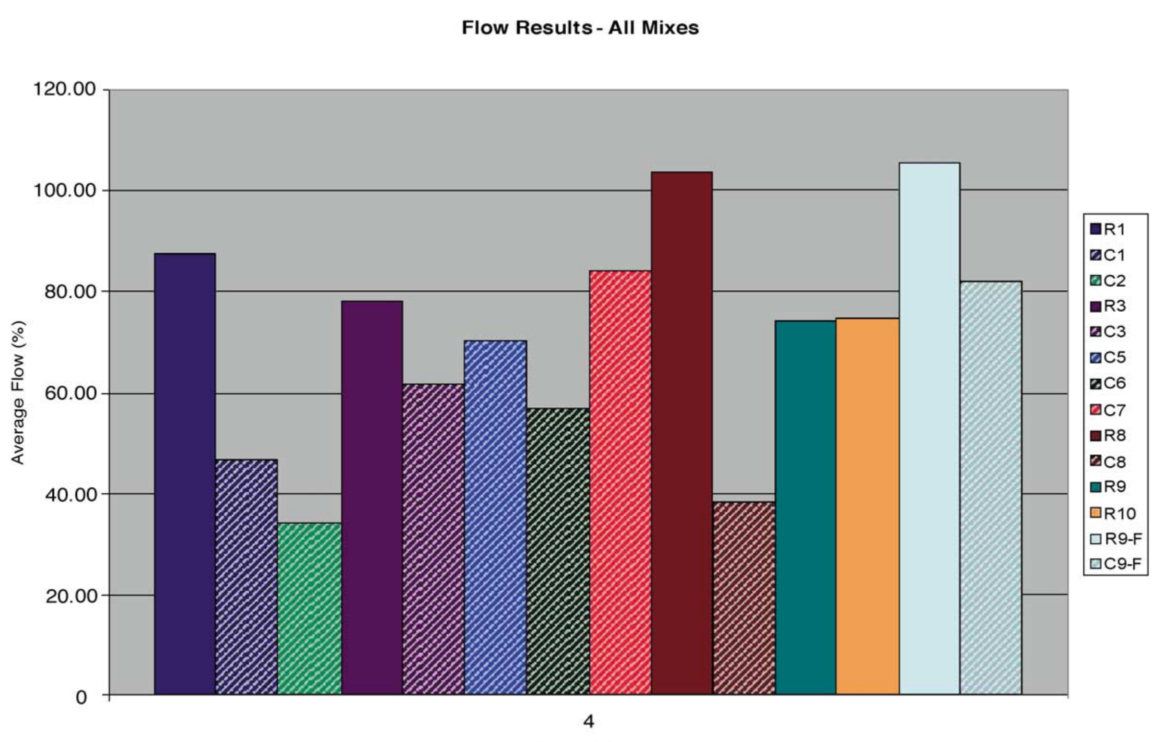

Fig. 7. Flow results at final mixing stage.

4. Conclusions

The dry premixing of sand and cement shows promise of improving the properties of mortar and concrete. Our final runs confirmed several of our theories about how the mixing equipment operates and that it may be possible to reduce cement content and produce mortars of acceptable strength using the dry, premixing process. To summarize the preliminary findings from this exploratory work:

- The dry premixing process produced mortar that is equivalent—and, in some cases, even better—in mechanical properties than those obtained by conventional methods. Mortar with a nominal w/c of 0.45 had 28-day compressive strengths as high as 9890 psi. Concrete made from the dry premixed material has a 28-day compressive strength of 5830 psi.
- When fines are not returned to the blended material, the dry premixing process affects the chemical composition of the cement, and the cement fineness. These changes appear to have an effect on both the fresh and hardened mortar, as well as on the rate of setting, the workability, and the strength gain.
- There are two fundamental mixing problems in preparing mortars: nonuniformity of dispersion and blending of the cement component in blended dry solids, and the dispersion of water in the mixed solids. Limited dispersion and blending can be accomplished once water is added to the mixture because the cement hydration reactions inhibit the dispersion of the cement itself.
- In the dry state, cement particles are cohesive and cement behaves like a weak solid due to interparticle forces. The dry mixing apparatus breaks the cement into small, multiparticle clumps and mixes them as uniformly in the sand as possible.
- Understanding of the mixing process has developed to the point where we know how to design a second-generation apparatus to produce substantially improved mortar mixes. Such an apparatus needs to provide dense-phase circulation of material and breaks the cement up into clumps of smaller size. It should minimize particle attrition, return fines to the mixture, and automatically feed cementitious components into a preexisting sand bed.

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