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Mortar properties obtained by dry premixing of cementitious materials and sand in a spout-fluid bed mixer

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Abstract

This study examines the efficacy of a pneumatic, dry premixing process for producing commercially acceptable, ternary-blend mortars, using less cementitious material. Data are presented comparing flowability, compressive and flexural strengths, drying shrinkage, and pore size distribution in the mortars using dry, premixed material with that prepared conventionally in a small-scale, high-shear, rotary mixer. A second generation, spout-fluid bed mixer was developed for dry premixing of sand and cementitious materials which is capable of being scaled to industrial size. This advance provides uniform particle distribution, improves the particle packing density leading to more reproducible mixes, and produces mortars equivalent to those produced with high shear, rotary mixers.

Dry premixing allowed the production of commercially acceptable ternary-blend mortars using less cementitious material. At a sand-to-binder ratio of 3.2:1, the compressive strength of the dry premixed mortars was about 10% higher than that of the small-scale, high shear, rotary mixed mortars of the same composition. Other properties of the mortar were also positively affected, including a decrease in the shrinkage, and an increase in the workability.

Keywords: Mixing methods; Dispersion; Workability; Compressive strength; Drying shrinkage; Porosity

1. Introduction

The need to produce roads and bridges with structures and surfaces that are stronger, more durable, and less costly to maintain is imperative. To improve the performance of concretes in these structures, recent compositions have included fly ash and condensed silica fume. These materials increase the strength of concrete, reduce its permeability, and have the potential to decrease cracking through improvements in the paste–aggregate bond.

However, most of these fine particles, particularly the silica fume, exist in the form of fine spheres linked together into clusters, rather than as isolated spheres [1]. The performance gains from using materials like silica fume are primarily related to the chemical reaction between calcium hydroxide and the fine material, and secondarily due to the improved particle packing density resulting from the uniform incorporation of finer and finer particles into the mix [2,3]. Diamond and Sahu [4] point out that most silica fume used in concrete is in the dry, densified form and consists of agglomerates of sizes between 10 μm and several millimeters. Lagerblad and Utkin [5] have reported that granulated condensed silica fume is not easily dispersed. In conventionally mixed concrete, the breakdown of densified silica fume agglomerates is incomplete and a portion of the agglomerates remains at least partly intact. Undispersed agglomerates in mortars and concretes result in poor performance gains due to the inability of the finest size fraction of the particles to effectively enter the interfacial transition zone.

Dispersing fine particles is normally achieved in the liquid phase using surfactants known as superplasticizers [6]. These admixtures have long been used to help disperse the cementitious powder but the dispersive action occurs only after water is added and the 'polymerization' (hydration and micro-crystalline interlocking) reactions begin [7,8]. Scrivener [9] reported that despite the use of superplasticizer, some clumps of silica fume are still present and so the material is not used as efficiently as it could be.

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Another approach to providing better dispersion of the agglomerates is to take advantage of the recent advances in dry-phase processing techniques [10]. These techniques provide the means to transform the mechanical properties of the cement by dispersing the powder uniformly in very small clumps prior to hydration. The addition of fine particles in coarser ones improves the fluidization characteristics of the coarser material [11] by dispersing fines into the voids between the larger particles and reduce the channeling and bubbling of the fluidizing gas [12]. The mixture prevents a cohesive powder such as cement from behaving as a 'weak' solid, held together by chemical and electrostatic forces. Without the addition of the large particles, the powder would crack causing channeling of the gas to take place, rather than aeroation and mixing of the particles [13].

A dry mechanical dispersion of powders should lead to a more uniform mixture and would serve as a precursor to chemical dispersants such as superplasticizers allowing them to work more effectively since the diffusion length required to get to the center of a particle clump will be reduced. Unfortunately, conventional concrete or mortar mixing equipment cannot provide the intensity of agitation necessary to effectively mix and disperse the finest particles [14]. Thus, obtaining a uniform mixture of these components is generally difficult, inhibiting performance gains and increasing the cost of the materials. The dry premixing process, if executed correctly, should be able to produce mortars with properties comparable to the best, high-shear rotary mixers, but at much higher throughputs than are possible with rotary mixers alone.

Plawsky et al. [15] reported that the dry premixing of sand and cement using a first-generation, spout-fluid bed mixer was more effective as the cement content was reduced and that it might be possible to produce commercially acceptable mortar with lower cement content. However, a considerable amount of cement fines passed through the cyclone separator and ended up, unincorporated, in a baghouse filter unit. Due to this loss, the early strength gain of the initial mixtures was slower than the control samples even though the long-term strengths of the dry, premixed and control samples were comparable. The loss of fine particles may significantly affect mortar performance particularly when ultrafine fly ash and silica fume powders are added to the mixture. To insure complete incorporation of all materials, a second generation spout-fluid bed mixer was designed. That mixer, seen in Fig. 1, is more reliable and easier to operate than the first generation mixer.

Key elements of this work reported in this paper include: investigating reducing the amount of cement in mortars while still producing commercially acceptable compressive strengths, determining if the premixing process results in less shrinkage, and incorporating other cementitious materials such as fly ash and silica fume to produce a high performance mortar blend.

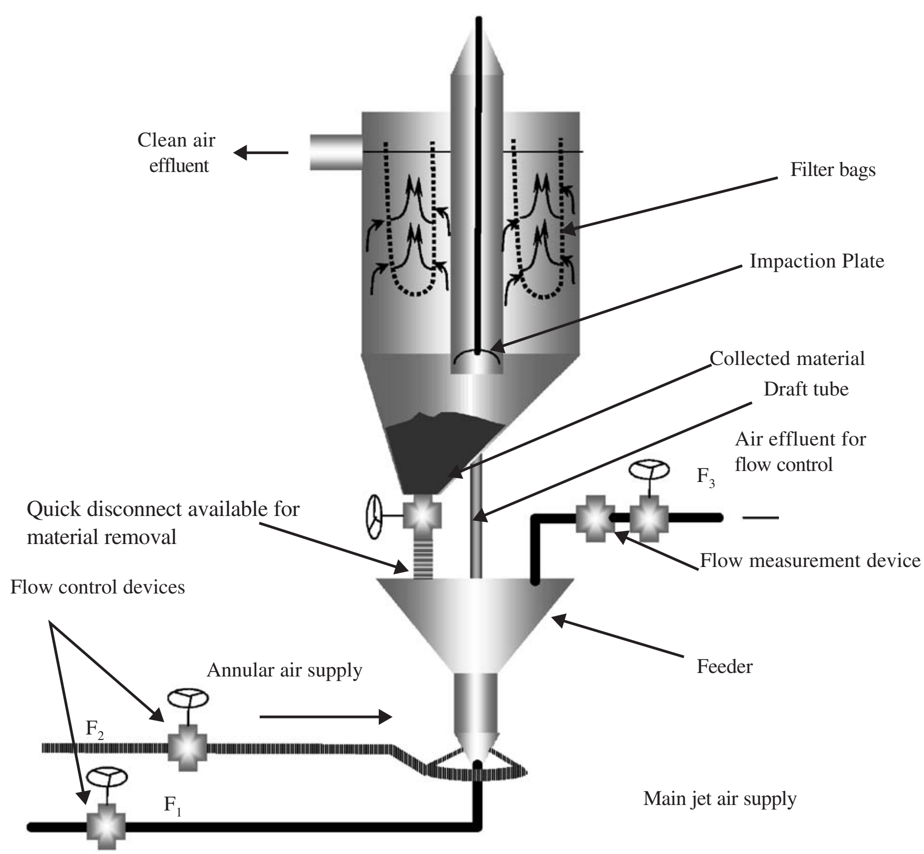


Fig. 1. Schematic diagram of second generation spout-fluid bed mixer.

2. Materials, apparatus, and operation

2.1. Materials and mixture compositions

The materials used in this study were Type I Portland cement, Class F fly ash, and silica fume. The chemical compositions of the cementitious materials are given in Table 1. A natural sand from Wynantskill, NY was used in this study. The sand was dried prior to use. The mortar specimens were prepared with a constant water-to-binder ratio of 0.45:1 and sand-to-binder ratios of 2.05, 2.7, and 3.2:1. The mortar batches were prepared with combinations of 74 wt.% Type I Portland cement, 20 wt.% Class F fly ash, and 6 wt.% silica fume according to NYSDOT (New York State Dept. of Transportation) standard specifications [16].

2.2. Apparatus

Fig. 1 is a schematic representation of our second generation mixer. It will intimately blend a dry, cohesive powder (cement) with a non-cohesive powder (sand) to produce a dry mortar mix. The batch size for the lab-scale mixer was 50 kg.

The draft tube, spout-fluid bed mixer (DTSFBM) is versatile, flexible, and scalable to industrial size.[1] Batch mixing times were less than 30 s and energy usage was less than that of a high shear mixer. The mixes were uniform from batch to batch and the mixed powder included flyash and microsilica when necessary.

The particles to be mixed were charged to the feeder and lifted through the draft tube by the pressure drop across the tube. Clumps of cohesive particles entering the draft tube were reduced in size due to turbulence in the draft tube and by collision with the impaction plate located at the exit of the draft tube. The entrainment air was separated from the particles by filter bags and the dry, mixed powder fell to the bottom of the separator where it was either recycled or removed as a mixed powder blend.

The first generation mixer is described in Plawsky et al. [15] differs from the second generation mixer in the design of the air–particle separator. In the first generation mixer, a cyclone incompletely separated the air from the particles and created additional fines by attrition. Fines exiting the cyclone were caught in a bag filter and manually returned to the main mix. The returned material was only a small fraction of the total mix.

The mixing of sand with cement improves the flowability of the cement powder and retains approximately the bulk density of the sand. When 6% by weight of the cement was replaced by cohesive microsilica, pourability of the dry mix improved over that for a sand–cement mixture. The bulk density of the mix containing microsilica increases slightly probably as a result of changes in the static charge between particles. Measurement of the angle of repose and bulk density were not particularly useful indices of how the material handled but observations indicated that the powders were well mixed.

[1] Scaling the DTSFBM is a straightforward procedure. By contrast, scaling of rotary mixers to large size is more art than science and often unpredictable (see A Guide to Fluid Mixing by J.Y. Oldshue and N.R. Nernst, Mixing Equipment Co, Rochester, NY, 1990).

Table 1
Chemical composition of cementitious components

	OPC Type I	Fly ash	Silica fume
Specific gravity, g/cm^3	3.16	2.27	2.2
Blaine fineness, cm^2/g	3670	3890	200,000
Loss of ignition, wt.%	1.3	3.95	
SiO_2, wt.%	20.5	47.89	92–98
Al_2O_3, wt.%	4.9	23.34	0.5
CaO, wt.%	63.0	3.41	0.8
MgO, wt.%	3.5		0.3
SO_3, wt.%	2.9	0.58	0.2
Na_2O equiv, wt.%	0.57	–	0.1
Fe_2O_3, wt.%		18.51	2.1
Clinker phase content			
C_3S, %	61		
C_2S, %	19		
C_3A, %	10		
C_4AF, %	10		

The operation of the mixer involved first setting the draft tube spacing and then the mass value of the air flow rates F_1 and F_2 in Fig. 1 needed to cause the transport of particles through the draft tube in a dense phase turbulent flow. The annulus air flow (F_2) was adjusted to set the desired solids fraction in the draft tube and the jet flow (F_1) to determine the particle velocity. Solids mass flow rates up to 0.76 kg/s flowed through the 28.45 mm draft tube (299 kg/m^2 s). The solids mass flow rate can be varied by changing the draft tube spacing, the aeration of the annulus, or the jet flow rate. Table 2 presents typical operating parameters for the second generation mixer.

2.3. Mixing and testing

After dry premixing of the powders, water was added and the mortar was mixed for a total of 4 min in a 30 qt. Hobart Mixer. From each mortar, the flow was measured using a flow table in accordance with ASTM C 1437. The mortar was cast in 2 in. cubic molds for compressive strength (ASTM C 109) testing, $40 \times 40 \times 160$ mm prism molds for flexural strength (ASTM C 348) testing, and $1 \times 1 \times 11.25$ in. prism molds for drying shrinkage (ASTM C 490) measurements. The mixed mortars were also tested for pore structure using a mercury intrusion porosimetry (MIP). Mortars were prepared from ternary blend cements, with and without the dry premixing of the sand and cementitious materials before adding the water. The ternary mortar testing results were compared to the ordinary Portland cement mortar.

3. Testing results

Fig. 2 shows SEM images of cement distributions on a sand surface after dry-premixing the powders in the spout-fluid bed mixer (Fig. 2a) and by dry mixing of the components in a conventional, high-shear, rotary mixer (Fig. 2b). Although dry premixing in the spout-fluid bed mixer breaks down the cement powder agglomerates, it also increases the triboelectric

Table 2
Typical operating variables of the second generation mixer

F_1, slpm	F_2, slpm	Ws, kg/s	No. of cycles	Additional comments
~600	~100	Up to 0.76	1	Dense phase pneumatic transport

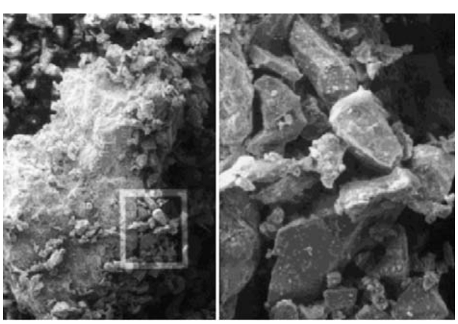
F_1—jet air mass flow; F_2—annulus mass flow rate; Ws—particle mass flow rate in draft tube.

charging of the particles causing the sand particles to be more densely coated with cement. The breakdown of cement agglomerates should also lead to an increase of packing density and to better flowability of the mixed powder. This was observed in the experiments as the dry mixed material behaved much more like sand than cement.

The flow behavior of Portland cement paste depends primarily on the concentration of particles and on the cement's tendency toward flocculation [17]. Krieger and Dougherty's equation [18] shows that the viscosity of a dispersed suspension rises with an increasing concentration of solids. The mathematical form of that equation is:

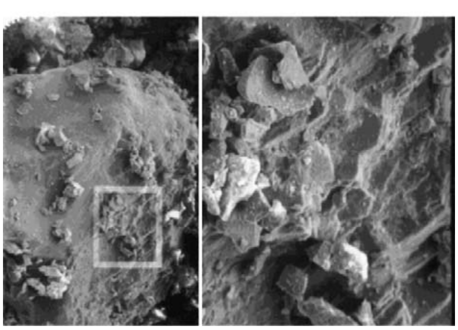
$$\frac{\eta}{\eta_c} = \left(1 - \frac{\phi}{\phi_M}\right)^{-[\eta]\phi_M} \tag{1}$$

where η is the apparent viscosity of the suspension, η_c is the apparent viscosity of the continuous phase, ϕ is the concentration of solids (by volume), $[\eta]$ is the intrinsic viscosity of the suspension (defined as $\lim_{\phi\to 0}\left[\frac{(\eta/\eta_c)-1}{\phi}\right]$), and ϕ_M is the maximum solids concentration (by volume).



x 200; x 1,000

a) Powder mixed in the spout-fluid bed.



x 200; x 1,000

b) Powder mixed conventionally in a high-shear, Hobart mixer

Fig. 2. Effect of dry premixing on cement distribution. Both sets of powders were dry-mixed for the same length of time. The powder mixed in the spout-fluid bed is equivalent to that from the high shear conventional mixer.

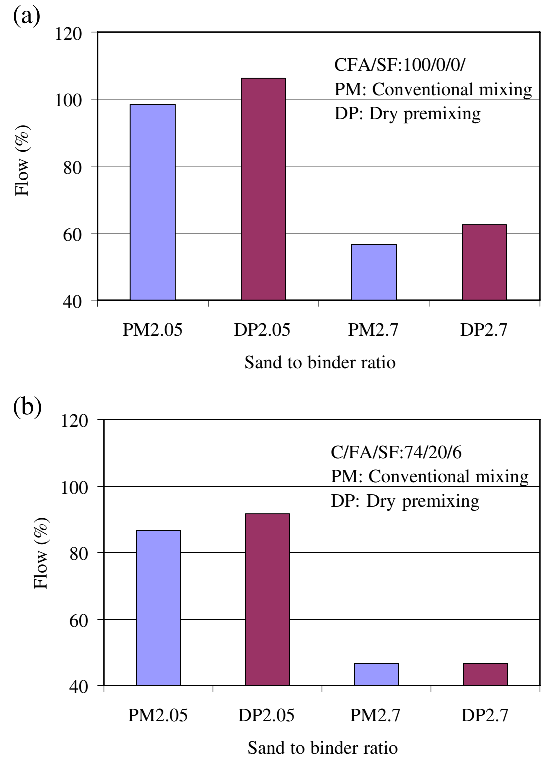


Fig. 3. Flow as a function of sand to binder ratio comparing mortars made with dry, premixed powder versus mortars made by conventional mixing. (a) Binary sand/cement mixture; (b) ternary blend containing cement, flyash and silica fume. A flow of 100% indicates that the initial diameter of the mortar had grown by a factor of two following the ASTM flow table testing procedure.

The viscosity of a suspension also increases with the degree of flocculation. Fig. 3 shows the results of flow tests using mortar made from the dry, premixed powder and mortar made by conventional mixing. The flow of mortar made by dry, premixing was slightly higher than that of conventionally mixed mortar indicating that the breakup of the cement agglomerates is similar in both mixers. Similar behavior was to be expected since the spout-fluid bed is designed to produce material equivalent to a high-shear rotary mixer.

The flow behavior will also be changed by the sand content. Krell [19] calculated the layer thicknesses of the paste around aggregate. He reported that the flow spread was larger for increasing paste layer thicknesses since the paste acts as a lubricant for the aggregate particles. The paste layer thickness decreases with an increase in the number density, surface area, and diameter of the aggregate. A higher sand content in the mixture decreases the bulk density of the powder mix causing a decrease in the packing density. This decrease in packing density translates into an increase in the voidage, that is, the ratio of the volume of voids between the aggregate particles to the volume occupied by the aggregate [20]. Thus, for a higher sand content, the voidage will increase and the cement paste may not sufficiently fill the voids to lubricate the aggregate particles. Kaplan [21] reported that for a given mix proportion, the workability of the concrete decreases with an increase in the voidage. Fig. 3 shows that the flow of mortar significantly decreased with increasing sand content.

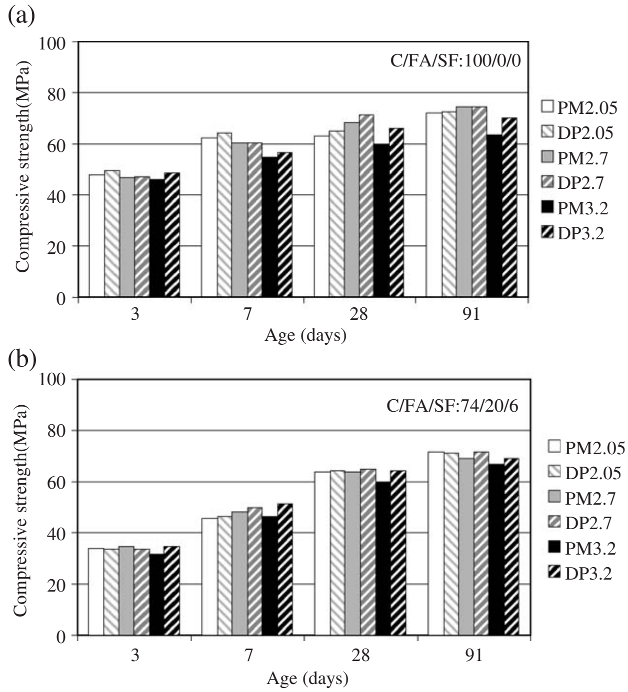


Fig. 4. Compressive strength as a function of age. (a) Mortars made using only sand and cement (control); (b) mortars made using ternary blend cement.

The flow testing results also show the effect of mineral admixtures containing fly ash and silica fume (Fig. 3b). The flow of mortar with ternary blend cements was lower than that of plain Portland cement mortar (Fig. 3a) even though the water-to-binder ratio was held constant at 0.45:1 for all mixtures. It is well known that, if the volume concentration of solids is held constant, the addition of mineral admixtures improves mortar performance but reduces workability. This results because the addition of mineral admixtures increases the number of fine particles in the mix and this increases the density of the matrix and the overall solids surface area. The increase in surface area results in an increase in water demand since more water is required to saturate the surface of the particles. It also increases the plastic viscosity of the paste–aggregate pseudo-fluid.

Fig. 4a shows the results of the compressive strength testing of mortars. The compressive strength of the dry, premixed mortars was higher than that of the control mixtures at all ages. The improved second generation design retains the fine particles and hence does not affect the early age strength development. This design also replicates the action of a high shear rotary mixer on a much larger scale. The effects of dry, premixing of sand and cementitious materials on the strength development are most significant in mortars with higher sand-to-binder ratios. In these mortars it is more important to effectively distribute the cement and binder materials so that the paste contacts all the sand particles. At a sand-to-binder ratio of 3.2:1 the compressive strength of the dry, premixed mortars was about 10% higher than that of the rotary mixed mortar.

Strength development depends upon two factors: the binding of all components together and the efficient packing of the materials. Mixing after the addition of water is also 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 affects the density and uniformity of the specimens, which can lower strength and increase variability in the test results. The ability to more efficiently disperse the powder components leads to a more uniform paste material, more uniform dispersion of the aggregate and hence better strength properties of the mixture. Water is also more effectively used in this situation since by dispersing the cement more efficiently the rate of hydration of the cement is increased.

Fig. 4a also shows the effect of sand content on the strength development. We usually expect that a high sand-to-cement ratio [22] leads to a reduction in the strength because strength development comes from the hydration of cement. However, in this experiment with a water-to-cement ratio of 0.45:1, the amount of sand does not significantly affect the strength development. We attribute this to more effective mixing of the water and solid materials so that the final mortar and cement hydration is more uniform.

The combination of fly ash and silica fume in a ternary cement system should result in a number of synergistic effects contributing to strength development. We know that incorporating fly ash leads to a delay in strength development and that silica fume compensates for the low, early strength of mortar incorporating fly ash. Thomas et al. [23] reported that the combination of silica fume and low CaO fly ash, at water-to-cementitious material ratios ranging from 0.26 to 0.35:1, results in concrete with improved early age and long-term strength.

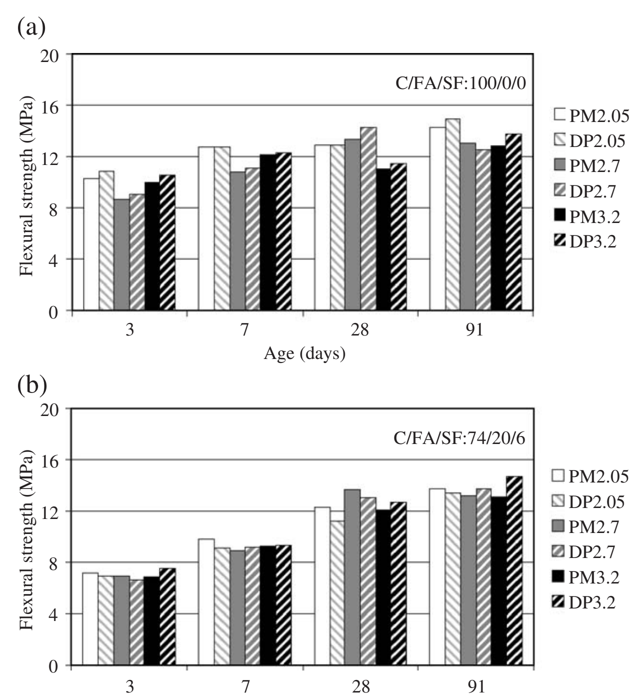


Fig. 5. Flexural strength as a function of age. (a) Mortars prepared using sand and cement only; (b) mortars prepared using a ternary blend cement.

However, Khan et al. [24] pointed out that the strength development will change with each different combination of cement replacement and that the strength is reduced in ternary blended systems. In Fig. 4b, for ternary blended mortar with fly ash and silica fume (20% and 6%, respectively), the compressive strength is significantly lower than the control mortar (cement and sand only) of Fig. 4a prior to 28 days and then the strength of the ternary mixture is almost same as the strength of the control mortar at 91 days.

Similar results are shown for the flexural strength in Fig. 5a and b. The flexural strength is a function of the surface energy and interparticle bonding upon drying [25]. The flexural strength increases as the moisture content decreases [26]. Based on this hypothesis, the flexural strength of mortar made with high sand-to-binder ratios should decrease due to the poor interparticle bonding. However, the dry, premixing method improves the flexural strength development as a result of an increase in surface energy and interparticle bonding force. Dry premixing is most effective for high sand-to-binder ratios where dispersion of the fine materials matters most. More experiments are needed to determine the effects of sand-to-binder ratio on the strength development of mortar with different water-to-solids ratios, however we believe that mixing has a pronounced effect and that proper mixing allows the use of higher sand-to-binder ratios.

One interesting observation is that the spout-fluid bed mixer system worked better when fly ash and microsilica were added. This was judged by the closure of the mass balance for each run. Using cement and sand, the mass balances were closed to within 5%. However, when mineral admixtures were added these balances closed to less than 1% indicating that not as much fine material was being lost due to its adherence to the solid surfaces of the equipment. One reason for this enhanced recovery may be due to changes in triboelectric charging causing the cement and mineral admixtures to bind more tightly to one another and to the sand. Thus it appears better coating of sand with binder is achieved when the mineral admixture is added.

Table 3 shows the results of drying shrinkage measurements for the mortar we studied. In our work, all specimens were kept in a curing box prior to measurement at a relative humidity (RH) of 45%, controlled using a potassium carbonate sesquihydrate solution. The drying shrinkage of mortars made from dry, premixed powders was slightly smaller than that of mortars made using conventional mixing, especially at long-term ages. As expected, the drying shrinkage of mortar with high sand-to-binder ratios decreased. One role of sand in mortar is to restrain the shrinkage of cement paste. Consequently, the drying shrinkage of mortar is about 1/4 of that of cement paste [27]. The relationship between the aggregate content and the drying shrinkage is described by Pickett's equation [28]:

$$\varepsilon = \varepsilon_p (1 - V_s)^{\alpha} \tag{2}$$

where ε is the fractional shrinkage of mortar, ε_p is the fractional shrinkage of cement paste, V_s is the volume ratio of sand to cement, and α is an exponent specific to each mortar blend. Eq. (2) shows that the shrinkage of mortar decreases with an increase in the sand content similar to what is observed in the table. Table 3 also shows the effects of mineral admixtures on the drying shrinkage of mortar. The ternary blend cement mortar reduced the shrinkage compared to cement along as a result of better packing of the materials. As the sand-to-binder ratio was increased, the shrinkage was reduced so that a 50% increase in sand-to-binder ratio yielded about a 30% decrease in the shrinkage.

4. Conclusions

A second generation spout-fluid bed mixer was developed to achieve what is normally obtained with high shear rotary mixing and can provide excellent dispersion of the dry components on an industrial scale. It is advantageous to separate dry material mixing from water addition if the fine powders are to be dispersed uniformly and the cement paste is to have a more uniform composition. With proper mixing and dispersion of water and particles, mortars of acceptable compressive strength can be produced at sand/binder ratios up to 3.2. The dry premixing process also provides high flexural strength, slightly improved drying shrinkage, and better flow compared with cement-only mortars. The strength and shrinkage results improve when ternary blend cements are

Table 3
Dry shrinkage results

Series	Mixing methods	Sand to binder ratio	Dry shrinkage ($\times 10^{-3}$ mm/m)				
			1 day	1 week	2 weeks	3 weeks	4 weeks
Ref.	PM	2.05	244.0	954.0	1182.0	1178.0	1218.0
	DP		202.0	930.0	1184.0	1132.0	1202.0
	PM	2.7	150.0	760.0	896.0	874.0	1004.0
	DP		156.0	756.0	896.0	868.0	1000.0
	PM	3.2	122.7	736.7	840.0	814.0	920.0
	DP		128.0	706.0	813.3	781.3	880.0
Ternary	PM	2.05	168.0	892.0	973.3	1010.0	1092.0
	DP		182.0	872.0	966.0	1008.0	1084.0
	PM	2.7	186.7	813.3	845.3	888.0	964.0
	DP		200.0	766.0	824.0	858.0	922.0
	PM	3.2	170.7	776.0	776.0	786.0	810.0
	DP		166.0	728.0	728.3	732.0	722.0

used and the dry, premixing process is more effective as the sand-to-binder ratio increases.

Acknowledgements

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