PARTICLE SIZE SELECTION

JOHN GUYNN, ROMAN CEMENT LLC, USA, INTRODUCES RESEARCH INTO USING PARTICLE SIZE OPTIMISATION TO INCREASE THE PERFORMANCE OF BLENDED CEMENTS.

Introduction

The cement and concrete industry continuously searches for new ways to substitute ordinary portland cement (OPC) with alternative materials that are both cost effective and have a low or zero carbon footprint. Limestone, flyash, and other mineral substitutes (supplementary cementitious materials, or SCMs) have been used as a component of blended cement and/or as a partial cement substitute in concrete. When used in blended cement, SCMs are typically interground with clinker to offset strength loss. Interground blended cements are sometimes ground more finely than OPC, which makes them more reactive, but is also known to have detrimental implications on water demand and concrete durability.

Limestone has been used by Turpin as an additive in mortars containing OPC and blends of OPC, flyash, and ground granulated blast furnace slag,[1] or by Zhang *et al.* in ternary blended cements as a partial cement substitute.[2, 3] Research conducted by Bentz *et al*.[4] and Cangiano *et al*.[5] used ultrafine limestone (sometimes called nano-limestone) to replace clinker, while maintaining similar strength at 28 days. Bentz *et al*.[6] also used fine and ultrafine limestone as a cement paste aggregate to reduce clinker content, while maintaining or increasing strength. The use of ultrafine limestone has been extended to ultra-high performance concrete.[7] Replacing clinker with ultrafine limestone is, however, economically unattractive in most markets.

A path to higher clinker reduction

Bentz et al.[8, 9] and Zhang et al.[2,3] demonstrated that mortar strength can be maintained or increased at reduced clinker content through careful particle size selection of cement and SCMs. Further reduction of clinker content, to an optimally low level, can be achieved with ternary blends containing an ultrafine SCM, a medium fineness cement, and a coarse SCM.[10] However, this approach has been hampered by lack of production capacity to process materials to the desired ranges of particle sizes.

The goal of the project described in this article was to use particle size selection techniques to identify and select inexpensive, readily available materials with complementary particle sizes. These materials can then be used to produce better optimised mortars and concrete, at low cost and high performance, thereby avoiding material processing costs for making blended cements. A source of inexpensive aggregate quarry fines was identified, which yielded mortars and concrete with reduced clinker content, high strength, and acceptable slump, when used in mortar and concrete containing OPC, and one or more SCMs, and utilising principles of particle size selection.

The quarry fines tested herein are a limestone aggregate byproduct with a particle size distribution ranging from about 50 – 150 µm. They contain calcite and a minor fraction of clay. The source selected for this project is located in Utah, US, and has not

Table 1. **Mix composition and strength of control mixes with 100% OPC, 20%, and 30% class F flyash, or 20% and 30% quarry fines vs. a concrete mix using a new design criteria**						
Components/compressive strength	**Mix ID**					
	1	**2**	**3**	**4**	**5**	**10**
Type I/II OPC (lb.)	564	451.2	394.8	451.2	394.8	366.6
Class F flyash (lb.)	0	112.8	169.2	0	0	84.6
Calcined shale (lb.)	0	0	0	0	0	84.6
Quarry fines (lb.)	0	0	0	112.8	169.2	141
Aggregate (lb.)	3122	3088	3070	3088	3070	2999
Water (lb.)	266.6	266.6	266.6	266.6	266.6	248.2
w/cm	0.47	0.47	0.47	0.47	0.47	0.44
w/c	0.47	0.59	0.675	0.59	0.675	0.677
3 day (MPa)	26.5	24.0	21.0	23.0	20.5	18.8
7 day (MPa)	31.6	28.2	26.7	25.3	23.2	30.0
28 day (MPa)	39.2	35.9	34.5	32.5	27.6	42.5
3 month (MPa)	43.0	42.3	40.7	35.9	33.9	49.4

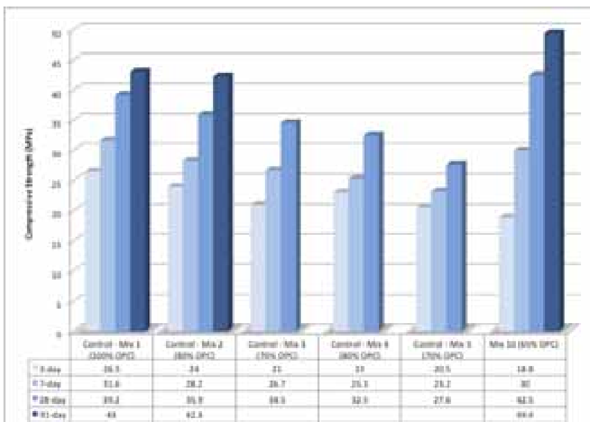

Figure 1. Compressive strength of 100% OPC mix and 20%/30% OPC reduction mixes using ordinary flyash and quarry fines vs. a concrete mix using a new design criteria.

previously been used in concrete. In the Utah market, quarry fines are approximately half the price of flyash and approximately a third of the cost of OPC. As OPC typically has no particles larger than 45 μm, and fine aggregates typically have few, if any, particles smaller than 150 μm, the quarry fines are larger than cement particles and smaller than fine aggregate particles. From a particle size selection standpoint, they occupy a region of empty space containing virtually no cement or fine aggregate particles. One might consider them to be an ultrafine aggregate because of the intermediate spatial region they occupy in the overall particle system. Based on this view, a new design criteria was then developed to simplify the use of quarry fines and make concrete with predictable strength and rheology at reduced clinker content. In many cases the quarry fines replaced a portion of both the cementitious binder and fine aggregates. At least a portion of the quarry fines was regarded as aggregate and not counted as cement when determining the water-to-cementitious binder ratio (w/cm), with predictable results.

Test protocol and results

Mortar mixes were tested in accordance with ASTM C109, while concretes mixes were based on a standard six-bag mix, with a 28 day design strength of 36 MPa as a starting point. The cementitious binders used in these mixes included OPC and one or more SCMs, such as flyash or calcined shale. Some mixes contained standard ASTM C618 class F flyash, or calcined shale, which costs about one third of flyash and one fifth of OPC in the Utah market. In other mixes, the class F ash was first processed using air classification into fine and coarse fractions, which provided greater particle size complementarity. Fine F ash was finer than OPC; coarse F ash was coarser than OPC. Lignosulfonate and/or polycarboxylate-based admixtures were used with commonly accepted doses to maintain a target water-to-cement (w/c) ratio and flow.

The composition of the mixes that were tested are shown in Tables 1 – 3. For concrete, quantities are normalised to 1 yd^3. Compressive strength results are shown in Tables 1 – 3 and Figures 1 – 4. Note that some testing for Control Mixes 3 – 5 is still ongoing, and data forthcoming.

In Figure 1, Mixes 1 – 5 were control mixes, with Mixes 1, 2 and 3 showing the relative effects of using OPC, vs. a binary blend of OPC and flyash, at 20% and 30% substitution. Mixes 4 and 5 included OPC and quarry fines at 20% and 30% substitution. As expected, the quarry fines, being non-reactive, performed worse than flyash when used as a cement substitute. However, when used in a concrete mix, following the design criteria outlined in this article, as

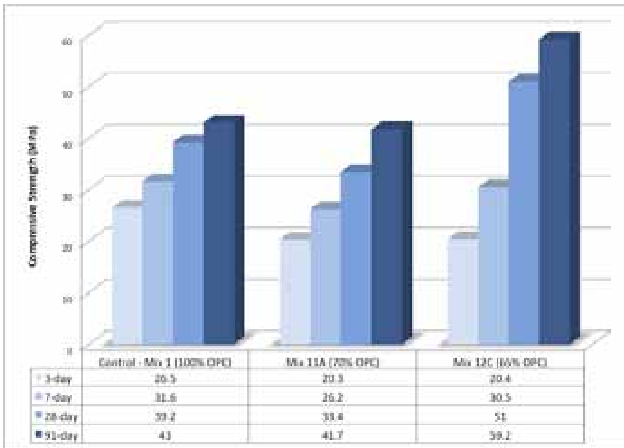

Figure 2. Compressive strength of 100% OPC mix vs. 30% flyash/quarry fines and 35% fine flyash/quarry fines.

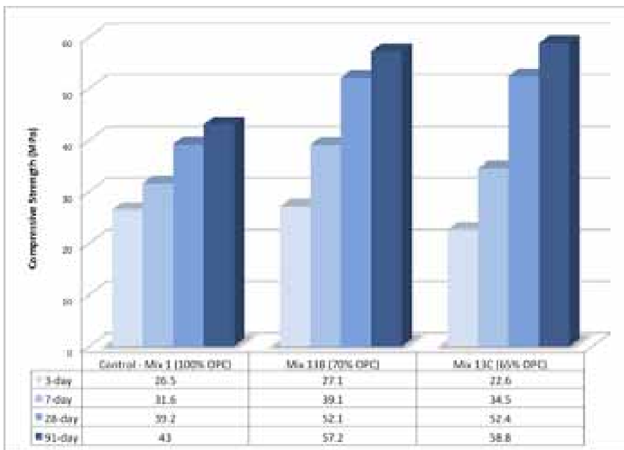

Figure 3. Compressive strength of 100% OPC mix vs. different 30% flyash/quarry fines/calcined shale blends in a concrete mix using the new design criteria.

in Mix 10, quarry fines enhanced overall strength, even though Mix 10 had the lowest clinker content at 65%, and highest absolute w/c ratio.

As in Mix 10 (Table 1 and Figure 1), quarry fines were effective in increasing the strength of a variety of concrete mixes at different clinker reduction rates. All mixes in Table 2 had comparable or superior strength than Control Mixes 1 – 5.

In the concrete mixes that were tested in this project, fine class F flyash obtained by air classification enhanced performance when compared to similar mixes containing ordinary class F flyash. As shown in Figure 2, strength performance in Mix 12C, a concrete mix where 35% of OPC was reduced using fine flyash and quarry fines, exceeded that of both pure OPC (Mix 1) and of a similar mix where 30% of OPC was reduced using ordinary flyash and quarry fines (Mix 11A). Using a combination of shale dust and fine flyash, in lieu of ordinary flyash, further enhances early strength performance at 3 and 7 days. Figure 3 shows that Mix 13B, where 30% of OPC was reduced by using quarry fines, calcined shale and fine flyash, far outperforms the 100% OPC control mix.

Higher performance can also be expected when a fraction of the fine aggregate is substituted by alternate materials, such as quarry fines and coarse flyash, as shown in Figure 4 (Mixes 14A and 14B). Here, 45% of OPC has been substituted by a blend of regular ash and fine flyash, and additional coarse flyash has been added in substitution of a fraction of the aggregate fines. After 7 days, Mix 14A (45% OPC substitution) has already reached the 28-day strength of the 100% OPC mix (Mix 1).

The coarse flyash used as one of the ternary blend components in Mixes 14A and 14B clearly leads to an overall better performance, but the difference in performance between 14B and 14A also shows that

Table 2. Mix composition and strength of concrete mixes. All mixes were made using the design criteria outlined in this article

Components/compressive strength	**Mix ID**				
	11A	**11B**	**12C**	**13B**	**13C**
Type I/II OPC (lb.)	394.8	394.8	366.6	394.8	366.6
Class F flyash (lb.)	84.6	0	0	0	0
Calcined shale (lb.)	0	84.6	0	84.6	50.8
Fine F ash (lb.)	0	0	141	84.6	141
Quarry fines (lb.)	112.8	112.8	112.8	56.4	62
Aggregate (lb.)	2952	2952	3009	2985	2987
Water (lb.)	248.2	248.2	242.5	248.2	248.2
w/cm	0.44	0.44	0.43	0.44	0.44
w/c	0.63	0.63	0.66	0.63	0.677
3 day (MPa)	20.3	22.4	20.4	27.1	22.6
7 day (MPa)	26.2	27.3	30.5	39.1	34.5
28 day (MPa)	33.4	38.1	51.0	52.1	52.4
3 month (MPa)	41.7	45.6	59.2	57.2	58.8

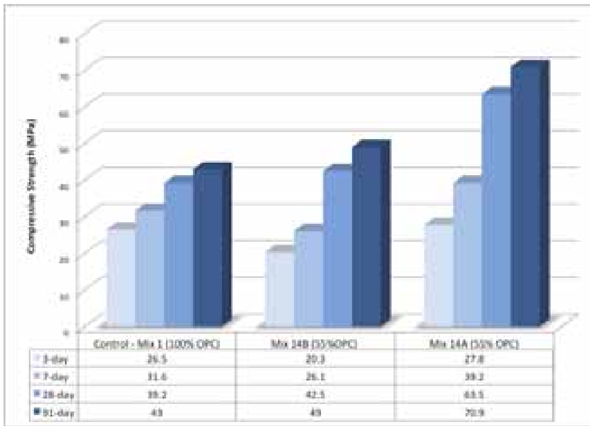

Figure 4. Compressive strength of 100% OPC mix vs. blends with 45% OPC reduction and added substitution of aggregates with coarse flyash.

***Table 3.* Mix composition and strength of concrete mixes containing coarse class F flyash. All mixes were made using the design criteria outlined in this article.**		
Components/compressive strength	**Mix ID**	
	14B	**14A**
Type I/II OPC (lb.)	317.3	317.3
Class F flyash (lb.)	105.8	105.8
Fine F ash (lb.)	105.8	105.8
Coarse F ash (lb.)	282.1	162.2
Quarry Fines (lb.)	0	119.9
Aggregate (lb.)	2863	2863
Water (lb.)	211.5	211.5
w/cm	0.30	0.30
w/c	0.67	0.67
3 day (MPa)	20.3	27.8
7 day (MPa)	26.1	39.2
28 day (MPa)	42.5	63.5
3 month (MPa)	49.0	70.9

using coarse quarry fines in lieu of a portion of coarse flyash, in a concrete mix with low w/c ratio substantially increases strength when all other variables are kept constant.

Conclusion

Commonly used SCMs, such as flyash, often induce a dilutive effect on OPC in concrete mixes, resulting in early age strength loss, thereby making it difficult to reach higher cement substitution rates. Such cement replacement materials are generally unreactive at early ages. In addition, since their particle size distribution closely resembles that of OPC itself, the overlap of similarly sized particles leads to a higher ratio of porosity to reactivity and a higher w/c ratio. By adding materials of different particle sizes, such as quarry fines, shale dust, and/or fine and coarse fractions of classified flyash, one creates a blend with particle sizes that are finer and/or coarser than OPC, which translates into concrete and mortars with a more optimised particle size distribution, considering all the particles as an interrelated particle system, and lesser porosity and water demand. Quarry fines containing coarser limestone particles are an attractive alternative to fine and ultrafine limestone, as they provide a low-cost limestone source to further fill interparticle porosity with nucleation sites, leading to more rapid strength gain than conventional pozzolanic materials used alone. This, in turn, creates an opportunity for the concrete producer and specifier to reduce clinker content and increase SCM content, while maintaining similar or better performance. This is seen, for example, in Mix 14B (45% substitution), which performs better than Control Mix 2 (20% substitution) and better than a 100% OPC binder (Control Mix 1).

The use of an integrated particle size selection model that considers the interrelationship between the particle sizes of all components, including the cement and aggregate particles as an integrated system, offers a practical alternative to simply using blended cements to reduce clinker content. This creates not only environmental benefits, but it is also a potential source of cost reduction, as this method can be applied with different materials that are either waste streams from other industrial processes or otherwise abundantly available at low cost. This includes the use of quarry fines or shale dust, as shown in this article, or, for example, natural pozzolans.

References

1. U.S. Pat. No. 6,451,105 (Raymond C. Turpin, Jr.).
2. TONGSHENG, Z., *et al*., 'Influence of preparation method on the performance of ternary blended cements', *Cement & Concrete Composites* 52 (2014), pp.18 – 26.
3. TONGSHENG, Z., *et al*., 'A new gap-graded particle size distribution and resulting consequences on properties of blended cement', *Cement & Concrete Composites* 33 (2011), pp. 543 – 550.
4. BENTZ, D., *et al*., 'Design and Performance of Ternary Blend High-Volume Flyash Concretes of Moderate Slump', *Construction and Building Materials* 84 (2015), pp. 409 – 415.
5. U.S. Pat. No. 5,908,502 (Stefano Cangiano, *et al*.).
6. BENTZ, D., *et al*., 'Minimizing Paste Content in Concrete Using Limestone Powders – Demonstration Mixtures', NIST Technical Report (January 2016), DOI 10.6028/NIST.TN.1906 .
7. U.S. Pat. Pub. No. 2012/0037045 (Phillipe Fonollosa, *et al*.).
8. BENTZ, D., *et al*., 'Optimization of cement and flyash particle sizes to produce sustainable concretes', *Cement & Concrete Composites* 33 (2011), pp. 824 – 831.
9. BENTZ, D., *et al*., 'Optimization of Particle Sizes in High Volume Flyash Blended Cements', NISTIR 7763 (2011).
10. U.S. Pat. No. 8,377,201 (Guynn, *et al*.).