Class C Mixtures as Alternates to Portland-cement-based Foundation Concrete

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INTRODUCTION

After completing mix development work for our Denver-client Flashfill Services, LLC utilizing foamed flashfill to mitigate frost-heave potential in street patches, we directed our attention towards fly ash products and markets for Flashfill Services and sister-company MK1 Construction Services, LLC in San Antonio, Texas.

We focused our attention towards an alternate to Portland cement based concrete mixtures that could be used on-site in “just-in-time” production via volumetric mixing trucks for drilled-shaft caissons and foundation walls. These applications require no hand-finishing, are typically not exposed to freeze-thaw durability issues that would require air-entrainment, and aesthetics are not an issue. Strength, sulfate-durability, and workability are the typical prime considerations.

Estimating and supplying the specific quantity of ready-mixed concrete needed for an on-going caisson drilling project can be a challenge. Add to the challenge the issues with the scheduling and coordination of trucks matching expected production rates and traffic issues (on the road and at the project). Often too much concrete is on-site, exceeding drilling production, therefore compromising concrete quality and acceptability. Conversely, concrete delayed in traffic puts site production at risk while crews wait for deliveries. The issues are compounded when groundwater is encountered. In the end, reliably matching concrete production and delivery to on-site production needs would vastly improve efficiency, quality and safety. The issue of concrete rejection due to time is eliminated as well.

Imagine the normal project site congested by equipment, materials and personnel. Add to it the need to continually move concrete trucks in and out during drilled shaft and foundation wall construction. Now envision a single volumetric mixing truck parked near the concrete pump truck all day long. Water provided with a connection to a nearby fire-hydrant and Class C fly ash continuously supplied by pneumatic pump from one or more bulk powder trailers. Again, reliably matching concrete production and delivery to on-site production needs would vastly improve efficiency, quality and safety. The issue of concrete rejection due to time is eliminated as well.

Flashfill Services' trucks have a continuous production rate of 50 to 60 CY/hour. For a conventional volumetric mixing truck, a single-aggregate, concrete alternative has been developed; on-site production would be augmented with a small front-end loader and a stock-pile of material. In this configuration, a "portable aggregate stockpile" (a specially-sized, open-ended roll-off dumpster) would allow aggregate deliveries throughout the day, with no stockpile loss or aggregate contamination. A similar process for foundation walls could be implemented.

BACKGROUND

Recognition is given to Doug Cross, Jerry Stephens, and Mike Berry at the Western Transportation Institute at Montana State University for their 2009 article in "Ash at Work" (1). They described a demonstration project where recycled glass was used as the aggregate, and the Class C concrete was batched through a conventional batch plant and delivered with drum-mixing trucks, with all of the associated challenges. Their earlier work with Class C mixtures used traditional sand and gravel as the aggregates (2).

OBJECTIVES AND DESCRIPTIONS OF TWO CONCRETE MIXTURES

Generally, the objectives for on-site mixed concrete to be suitable for caisson and foundation construction would be a compressive strength readily meeting specified strengths of 4000psi, a workable slump of 6-10" and two hours or more time prior to flashing. ACI 318-08 Table 5.3.2.2 requires an over-design of 1200psi for 4000psi specified strength concrete when no field data of production is available. Our testing indicated the Class C mixtures readily met the ACI 5200psi strength requirement (4000 psi specified + 1200 psi over-design).

Mixture 1 incorporated 2950lb/cy of Class C fly ash, (from Xcel's Pawnee Power Station, located northeast of Denver, near Brush, Colorado), water and Borax (0.5% Borax by dry weight of the fly ash). The water-fly ash ratio was 0.21, culminating in a 9" slump. The addition of Borax at 0.5% retarded the flash so as to provide ample time to mix, test physical properties, fabricate specimens and have a "civilized clean-up". It should be noted that an earlier test batch lacked sufficient Borax to retard the flash-set resulting in time required to chip out the laboratory mixer. We developed this paste-only mixture to evaluate its engineering properties and determine if such a mix could be used in a structural application. On a side note, we found that the laboratory mixed mixture without aggregates required additional mixing effort utilizing a drill-powered mixing-paddle to homogenize and break down cementitious clumps. Homogenizing and breaking down cementitious clumps should be readily accomplished in volumetric mixing trucks with aggressive mixing augers.

FlashCrete with a 9" Slump

Mixture 2 included Pawnee's fly ash as discussed above and a by-product of local sand and gravel processing known locally as sgueegee. Squeegee is nominally sized as1/4" by 1/8" when processed, creating a #4 by #16-sized product. It is too fine for gravel and too coarse for concrete sand. It typically meets an ASTM C33 #9 grading. Similar aggregate by-products are available around the country known by different local names. Due to its abundance and low cost, it was intended as an economical means to reduce paste quantity without attempting aggregate-packing optimization. Dry-rodded unit-weight testing indicated that 2700lb/cy was the maximum theoretical amount that could be used. Previous test batches incorporated 2000lbs and 2500lbs of this aggregate. The 2000lb/cy mixture had more fluidity than needed, whereas the 2500lb/cy mixture was too harsh to place without vibration. Thus, the final mixture tested and reported below contained 2200lb/cy of squeegee, representing 50% of the volume of the Class C concrete. This mixture was batched at a 0.23 w/fa ratio and achieved a 9" slump.

FlashCrete with 2200lb of Squeegee, with a more traditional-looking 9" slump

LABORATORY MIXING & TESTING

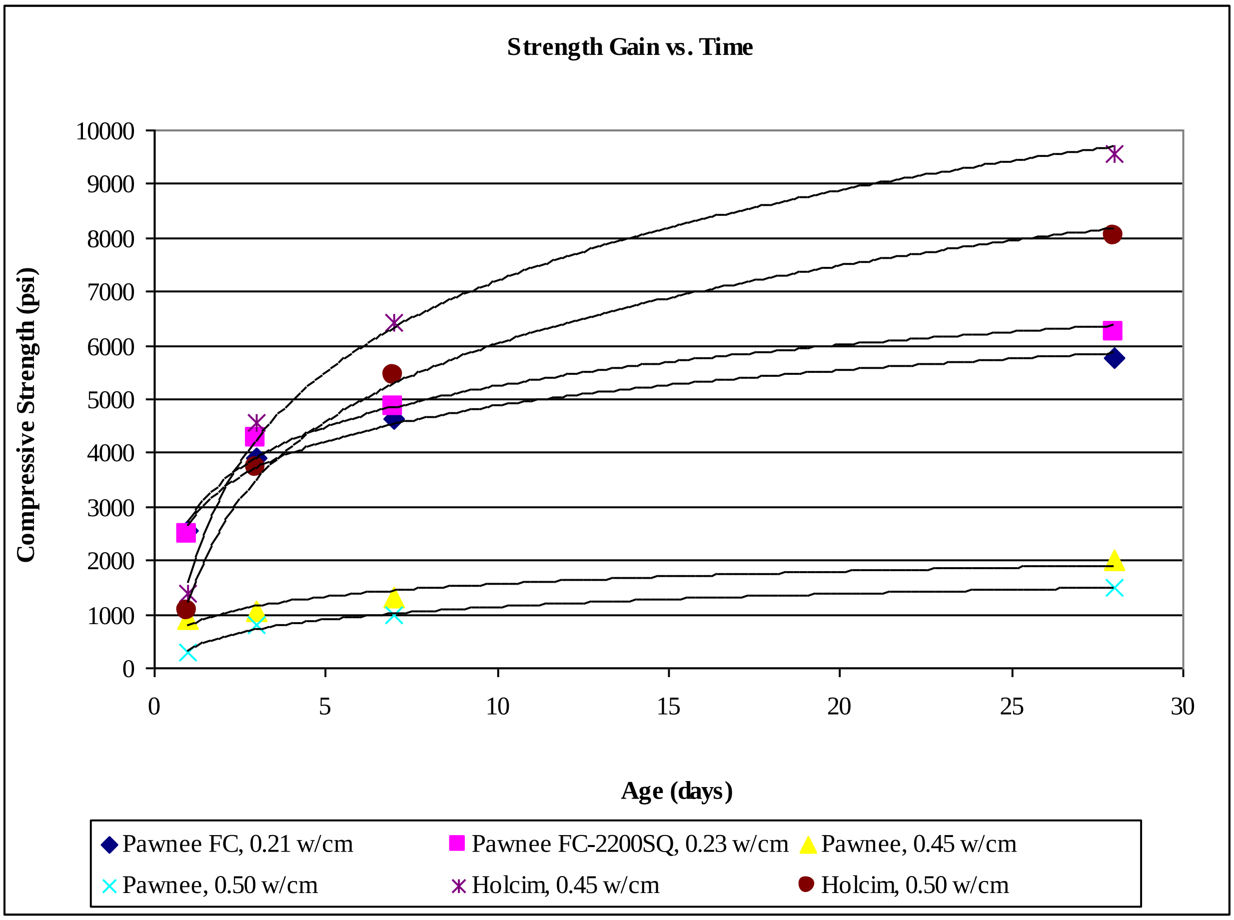
The two mixtures described above were batched on January 29, 2011. Fresh property testing was conducted and specimens for ASTM C39 (compressive strength), ASTM C496 (split-tensile strength), ASTM C1202 (rapid-chloride permeability) and ASTM C157 (drying-shrinkage) were fabricated. Testing was conducted in association with and by J.A. Cesare/CTS, an AASHTO-accredited laboratory. Additional compressive strength specimens incorporating a local cement product at 0.45 & 0.50 w/c ratios, and Pawnee at 0.45 and 0.50 w/fa ratios were also cast for comparison purposes. Specimens for sulfate resistance testing by ASTM C452 and C1012 were fabricated and tested at JAC/CTS's laboratory.

The fresh unit weights for the FlashCrete and FlashCrete with Squeegee were 124.4pcf and 142.7pcf, respectively. Air-contents measured 1.9% for the FlashCrete and 1.8% for the FlashCrete with Squeegee. Neither mixture was air-entrained, so the measured air contents are surmised to represent entrapped air due to mixing.

COMPRESSIVE STRENGTHS

The C39 compressive strengths for the mixtures discussed are summarized in the table below, and shown graphically for comparison.

Material	Pawnee Class C	Pawnee Class C & SQ	Pawnee Class C	Pawnee Class C	Holcim Cement	Holcim Cement
Mix ID	FC	FC-2200SQ	P-0.45	P-0.50	H-0.45	H-0.50
w/cm	0.21	0.23	0.45	0.50	0.45	0.50
1-day	2540	2490	900	300	1380	1050
3-day	3890	4270	1060	800	4560	3710
7-day	4620	4870	1330	990	6430	5440
28-day	5710	6190	2015	1480	9560	8040



Comment: The 1-day strengths with Class C concrete at about a 0.22 w/fa ratio are approximately 2500psi. Past results with Class C fly ashes with little or no Borax yielded approximately 3000psi in one day. The high early strength development could provide for an advantage in stripping and advancing forms when compared to normal cement-based concrete, unless accelerators are used. The three day strengths of the Class C concrete mixtures were comparable to the cement-paste strengths tested, whereas the cement had greater strengths at both 7 and 28 days. It should be noted that the Class C mixtures tested readily met the intended design strength of 4000psi for caisson and foundation concrete at 7-days and significantly exceeded those requirements at 28 days.

Fly ash is often used as a “cement replacement” in concrete mixtures subject to specified or practical limitations of the amounts of fly ash replacing the cement. The tested Class C fly ashes typically achieve approximately 6000psi at 28 days with a w/fa ratio of about 0.22. One Class C fly ash (not presented herewith) from Texas achieved over 7100psi at 28 days with a w/fa ratio of 0.25. The Class C fly ashes tested have adequate workability at 0.20 to 0.25 w/fa ratios and strengths sufficient for normal structural concrete of 4000psi. However, these same fly ashes perform poorly, when forced to operate at typical Portland-cement driven w/c ratios of 0.45 and 0.50. More discussion provided in our conclusions.

SULFATE RESISTANCE TESTING

The sulfate resistance of Class C fly ash concrete is being evaluated by two methods. First, ASTM C1012, the industry standard for cement & fly ash combinations for sulfate resistance testing is underway. While the results to date are similar to initial values of typical cements meeting the ACI-318 limits of Table 4.5.1, it is premature to make a conclusion based on our early age findings.

Second, ASTM C452 testing was employed. Mortar bars with fly ash alone and fly ash with silica classified #C109 ASTM #C778 graded sand (standard sand) were mixed with sufficient high-grade natural gypsum to achieve a 7.0% SO_3 as specified in C452. Bars fabricated without sand exhibited negligible expansions with measurements of 0.000% at 14 days; whereas, by comparison, the specimens with sand expanded 0.0010%. Both results meet the requirement in ASTM C150 for Type V cement tested by ASTM C452 of no greater than 0.040% expansion in 14 days. Hence, the tested Class C mixtures should be sufficiently sulfate resistant.

SPLIT TENSILE STRENGTHS

ASTM C496 split tensile testing was conducted on two 4” x 8” cylinder specimens each for the fly ash only concrete mixture.

Mixture ID	Average Splitting Tensile, psi
FlashCrete, FC	390

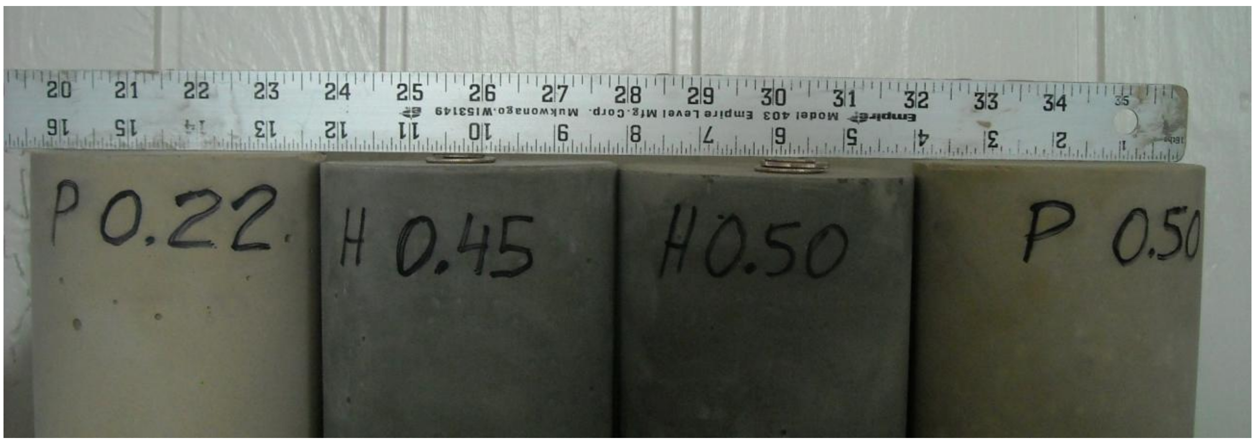
DRYING-SHRINKAGE TESTING

Drying shrinkage testing was performed on both Class C mixtures in general accordance with ASTM C157, rapid test method employing only 7 days of moist curing. 28 day shrinkage values were determined to be 0.002% for the FlashCrete with Class C fly ash alone and 0.001% for the FlashCrete with 2200lb of Squeegee, which should be expected with a reduction of the Class C paste volume. Normal-weight concrete has typical 28 day shrinkage values of 0.04% to 0.06%. Locally, limits of 0.04% for low-shrinkage concrete are typical. The FlashCrete mixtures tested demonstrate very low drying shrinkage compared to Portland-cement concretes, likely due to the low w/fa ratio.

CHEMICAL SHRINKAGE OF THE PASTE

Upon stripping compressive strength test cylinders from their molds and prior to curing and subsequent testing, observations were made that indicated significant subsidence (shrinkage) in the cement paste cylinders compared to the FlashCrete specimens.

Additional paste specimens were fabricated at a variety of w/cm ratios to measure the relative chemical shrinkage of both cementitious materials. The Class C mixtures were developed at the average of the two FlashCrete mixtures (0.022) as well as at 0.50. The picture listed below gives a visual presentation of the shrinkage observed. A dime and a quarter fit between the 0.45 w/cm ratio cement cylinder and the straight-edge, and a dime and two quarters fit between the 0.50 w/cm ratio cement paste cylinder.



Relative Chemical Shrinkage of Cement vs. Class C Pastes

The cylinder molds were carefully removed from the paste specimens at two days age from casting. Three length measurements were made on each cement past cylinder and mold; whereas four measurements were made on each Class C cylinder and mold. The averaged values in the table below indicate that Class C fly ash has minor chemical shrinkage, even when the setting time is delayed with Borax. The lower chemical and drying shrinkage exhibited in the Class C concrete mixtures would likely result in a positive reduction in volume changes in cast structures and/or lessened shrinkage cracking; both characteristics are important advantages in structural concrete applications.

Cylinder ID	Mold, in.	Cylinder, in	Difference, in	% Shrinkage
H-0.45	7.958	7.861	0.097	1.22%
H-0.50	7.964	7.803	0.161	2.02%
P-0.22	7.966	7.964	0.002	0.03%
P-0.50	7.964	7.960	0.004	0.05%

RAPID-PERMEABILITY TESTING

ASTM C1202 testing was performed on both Class C concrete mixtures to provide an indication of relative permeability. Testing was conducted on specimens cut from 4” x 8” cylinders after 28 days of moist curing. The FlashCrete mixture tested at 6493 coulombs passed in six hours and the FlashCrete with 2200lb of Squeegee tested at 1533 coulombs in six hours. C1202 Table 1 would characterize these two values as "high" and "low" Chloride Ion Penetrability respectively. We surmise that the mixture with squeegee had greater resistance due to having 50% of the volume being filled by inert aggregate. Additional testing on these mixtures is warranted before forming an absolute conclusion.

COEFFICIENT OF THERMAL EXPANSION

Upon completion of testing by ASTM C157, the Class C fly ash shrinkage bars were measured at various temperatures to determine their coefficient of thermal expansion. While not performed in accordance with AASHTO T336-10, the resulting values of 2.8 millionths per degree Fahrenheit (/dF) for FlashCrete and 2.5 millionths/dF for Flashcrete with Squeegee are approximately half of the average value for the coefficient of thermal expansion exhibited by cement based concrete. The PCA's Design and Control of Concrete Mixtures presents 5.5 millionths/dF (0.00055%/dF) for cement based concrete. Reinforcing steel has a coefficient of thermal expansion of 6.5 millionths/dF.

MODULUS OF ELASTICITY

6" by 12" ASTM C469 static modulus of elasticity specimens will be tested during the next phase of testing. We anticipate completion of testing by May, 2011.

INDUSTRY DEFINITIONS OF "CONCRETE"

The test results presented herewith for the Class C fly ash mixtures seem quite promising, if not advantageous. However, there's still the underlying question of will the design community accept Class C concrete mixtures for use in structural applications. A brief summary of existing definitions of concrete may prove enlightening:

- ASTM C125-09a Standard Terminology Relating to Concrete and Concrete Aggregates:
  Concrete: a composite material that consists essentially of a binding medium within which are embedded particles of fragments of aggregates; in hydraulic – cement concrete the binder is formed from a mixture of hydraulic-cement and water

- ACI 301-10 Specifications for Structural Concrete
  Normal weight concrete: structural concrete containing aggregate that conforms to ASTM C33 and that typically has a density between 135 and 160 pcf
  Structural concrete: concrete used in a member to resist loads and having a compressive strength of at least 2500psi

- ACI 318-08 Building Code Requirements for Structural Concrete and Commentary
  Concrete: Mixture of Portland-cement or any other hydraulic cement, fine aggregates, coarse aggregates, and water, with or without admixtures

Cementitious materials: Materials as specified in Chapter 3, which have cementing value when used in concrete either by themselves, such as portland-cements, blended hydraulic cements, and expansive cements, or other materials in combinations with fly ash, other raw or calcined natural pozzolans, silica fume, and/or ground granulated blast-furnace slag.
Structural concrete: all concrete used for structural purposes, including plain and reinforced concrete.
Chapter 3 requirements: Cements shall conform to C150, C595, C845 or C1157, fly ash used as an admixture shall conform to ASTM C618

- ASTM C94-09a Standard Specification for Ready-Mixed Concrete
  References C125 for Terminology and defines concrete as being central-mixed, truck-mixed, shrink-mixed, or ready-mixed (delivered to a purchaser in a fresh state).

- PCA's 15th Edition of "Design and Control of Concrete Mixtures", 2011
  Concrete: mixture of binding materials and coarse and fine aggregates. Portland cement and water are commonly used as the binding medium for normal concrete mixtures, but may also contain pozzolans, slag, and/or chemical admixtures.

COMMENTS, CONCLUSIONS, AND RECOMMENDATIONS

As discussed earlier, Class C fly ash concrete mixtures offer acceptable and superior structural properties at water to fly ash (w/fa) ratios where they perform best. Lately, the goals of higher utilization of fly ash in construction have focused on higher percentages of "cement replacement". Perhaps, to meet sustainability goals in the reduction of CO_2 gas emitted during production of Portland cement and utilize existing fly ash supplies, a solution is to emphasize the continued use of fly ash as a Portland cement replacement, subject to practical & durable limitations, and to allow for Class C fly ash only concrete mixtures. These mixtures should perform adequately in specific structural applications (non-finished applications), such as below grade piers, caissons and foundation elements.

While a review of the current industry definitions of concrete generally would allow the use of Class C fly ash as the primary cementitious binding agent, several definitions still allude to Portland-cement as the primarily intended material. Clearly the intent is to provide satisfactory performance at an economical cost, which fly ash can. So the task for ACI, the design and specifying community, and society is to re-evaluate the rules and definitions to allow for fly ash only concrete mixtures. In addition to continuing usage of fly ash as a cement replacement to achieve sustainability in construction, we should take into consideration taking the cement out of concrete in certain specific applications as mentioned above and maximize its use in association with recycled concrete aggregates in new below grade concrete construction.

CONCURRENT & FUTURE TESTING & DEVELOPMENTS

While these Class C fly ash mixtures are proposed for caisson and general foundation concrete, other mixture combinations are currently being tested to determine additional application. High-range water-reducers developed for use with Portland-cement concrete products have been found effective in applications with Class C fly ash. Compressive strengths of 3000 to 4500psi in 12 hours, 6000psi in 24-hours, and over 11,000psi at 28-days have been validated. These results indicate potential application in rapid permanent pavement repairs as well as high-strength and pre-cast applications. Efforts are underway to develop both a set-retarder in a liquid form, as well as water-reducers optimized for performance with Class C fly ash only concrete mixtures.

While FlashCrete with Class C fly ash only has demonstrated acceptable structural concrete properties and would qualify as a 100% recycled product, other combinations may provide even better economic viability and resource reduction. Mixtures incorporating aggregate-by-products and other recycled construction materials need to be developed and evaluated.

Recycled concrete is readily available nation wide. Previous testing suggests that only the coarse fraction be utilized in new concrete mixtures since the fine fraction has a high water-demand. We believe Class C fly ash, combined with optimized water-reducers, can produce a paste with 8,000 to 9,000psi; therefore, making it possible for the cost effective and efficient use of recycled concrete materials.

Several US patent applications have been filed on behalf of Flash Technologies, Inc. on the technologies and materials mentioned in this article. For more information contact Jack Karam, President of Flash Technologies, Inc. in San Antonio, TX or Stan Peters.

REFERENCES

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[2]. Cross, Doug, Stephens, Jerry, Jones, Warren, and Leach, Lynne, “Evaluation of the Durability of 100 Percent Fly Ash Concrete, DOE Project No. : 05-CBRS-W08, June 2008