# Structural Applications of 100 Percent Fly Ash Concrete

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## INTRODUCTION

Over the past four years, significant research has been done at Montana State University (MSU) on fly ash concrete for structural applications. The material being investigated is a conventional concrete mixture in which the Portland cement has been replaced by Class C fly ash for the binder. Work on this material was originally pursued at MSU based on an interest in minimizing the myriad of environmental impacts associated with traditional concrete by using a locally available recycled by-product for the binder (Class C fly ash from the Corette power plant in Billings, MT) rather than Portland cement. In working with this new material, it was quickly discovered that it offered exceptional performance with respect to short term strength gain, long term ultimate strength, and workability relative to traditional Portland cement concrete. Mixtures similar to conventional concrete mixes in which the binder was fly ash have routinely produced 2 day strengths in excess of 20 MPa (2900 psi) and 28 day strengths in excess of 33 MPa (4800 psi) (without extraordinary curing measures). Subsequent long term strengths have reached as high as 55 MPa (8000 psi) at one year of age. These results have been achieved with very workable mixtures (slump of 152 mm (6 in)) without the use of sophisticated admixtures common in the concrete industry.

While these results were encouraging, additional research on the performance of this material was found to be necessary for it to be used without reservation in commercial applications. Remaining tasks in this regard included:

a) determining its engineering properties, as required for structural design,
b) confirming that its behavior and performance, as observed in the laboratory, was reproducible at a large scale using conventional concrete equipment, and
c) investigating its durability when exposed to a variety of environmental conditions.

The work described in this paper addresses the first two issues listed above. Relative to determining the properties of fly ash concrete for engineering design, tests were run to ascertain the Young's modulus, tensile splitting strength, tensile rupture strength, shrinkage, and reinforcing bar anchorage characteristics of this material. Additionally, the results of these tests were used to determine whether or not the equations developed for Portland cement concrete to predict these properties from the unconfined compressive strength of the concrete were also valid for fly ash based concrete.

Once the basic properties of this new concrete were determined, they were used in Portland cement based concrete design equations to predict the capacity of common structural elements (beams and columns). Such elements were subsequently constructed and tested to failure to determine if these design equations reasonably predicted their capacity, as well as to identify the nature of their failure and to assess their ductility.

Relative to moving this work out of the laboratory and into the work place, two full scale field trials have been conducted. In the first trial, 2.3 $m^3$ (3 $yd^3$) of fly ash concrete were mixed in a ready-mix truck in Billings, MT and used to cast landscape blocks and other items. In perhaps a more ambitious project, two vault toilets were cast at a precast yard. In both cases, casting proceeded with nominal adjustments to the conventional batching, mixing, and placing process. The final products were a success relative to their compressive strength and aesthetics.

The one major obstacle to the widespread introduction and use of this material in construction is the absence of information on its durability. Hopefully such information will be collected in future investigations.

## ENGINEERING PROPERTIES OF FLY ASH CONCRETE

The engineering properties of concrete made with the fly ash from the Corette Power Plant as the binding material were evaluated through experimental testing. Considerable uncertainties exist in analytically predicting the behavior of concrete materials. Therefore their performance is still best evaluated through testing. Tests were done to determine Young's modulus (E), splitting tensile strength ($f_{ct}$), tensile flexural strength ($f_r$), shrinkage properties, and reinforcing bar bond behavior. Empirically derived equations are available to estimate some of these properties for conventional Portland cement concretes based on the unconfined compressive strength of the material (which is perhaps the simplest property to obtain and single most informative property for conventional Portland cement concrete). The appropriateness of these equations for estimating the same properties of fly ash concrete based on their compressive strength was evaluated.

The various sampling and testing done in this program was conducted as possible and appropriate in accordance with accepted procedures (e.g., American Society for Testing and Materials (ASTM) Standards[1]). While considerable information is available on tests for evaluating the properties of Portland cement based concrete, little is available on evaluating the properties of fly ash based concrete.

Materials - The concrete used in this part of the research effort was made with conventional aggregates, fly ash, lime, water, and a chemical admixture to retard the set. The aggregates used in the mixtures met the requirements of ASTM C33 (the standard for conventional concrete aggregate) and comprised approximately 60 percent of the total mix volume. The aggregate was further divided into fine and coarse fractions (at 40 and 60 percent of the aggregate volume, respectively), with a maximum course aggregate size of 19.1 mm (0.75 in). The fly ash used in this project was from the Corette Power Plant in Billings, Montana. This ash, provided by the Billings office of Headwaters Resources, Inc., is a Class C fly ash. Table 1 lists the chemical composition and some of the physical properties of this ash. One of the more notable features of this fly ash is its high calcium content (approximately 28 percent). The water-to-fly ash ratio of the mixtures used in this investigation was 0.23.

Table 1. Chemical and Physical Properties of Corette Power Plant Fly Ash

| Chemical Compound | Percent of Composition |
|---|---|
| Silicon Dioxide | 32.2 |
| Aluminum Oxide | 17.6 |
| Iron Oxide | 5.4 |
| Sulfur Trioxide | 2.1 |
| Calcium Oxide | 28.5 |
| Moisture Content | 0.0 |
| Loss on ignition | 0.2 |

| Physical Test | |
|---|---|
| Fineness, Retained on #325 Sieve (%) | 14.4 |
| Soundness, Autoclave Expansion (%) | 0.10 |
| Drying Shrinkage, Increase@28 Days (%) | 0.01 |
| Density | 2.72 |

The average slump of the nine concrete mixtures made for this project using the proportions outlined above was 102 to 152 mm (4 to 6 in), and the average set time was 2 to 3 hours. Relative to set time, the concrete in early mixes flash set just a few minutes after it was mixed. Borax was found to be effective in retarding the set. The amount of borax in these mixtures was 1.25 percent of the weight of fly ash used. A small amount of lime (0.3 percent by weight of fly ash) was also used in the mixtures. At this dosage rate, the lime had nominal influence on the compressive strength of the concrete, but it did improve its finishability. The average 28 day unconfined compressive strength of the mixtures was 32 MPa (4700 psi).

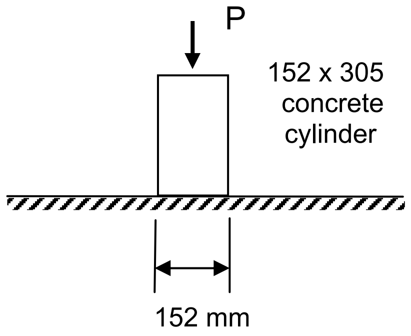
The mix described above was believed to be an “all-purpose” concrete, in that it offered sufficient workability, set time, and strength to be used in a variety of construction applications. Due to resource constraints, subsequent work on the engineering properties of fly ash concrete was done for this one mix design. Note that more information on fly ash concrete mix design and performance (workability, set time, and strength) as a function of water-to-cementitious materials ratio and retarder dosage rate is available in 1) Stephens, Cross, Frerking, and Anderson[2] and 2) Cross and Stephens[3].

Methods - Young's modulus was determined from load-deformation measurements made on 152-by-305 mm (6-by-12 in) cylinders tested in uniaxial compression (ASTM C469), as shown in Figure 1(a). Splitting tensile strength was also calculated from tests on 152-by-305 mm (6-by-12 in) concrete specimens (ASTM C496). In these tests, the cylinders were loaded laterally to failure (Figure 1b). Tensile flexural strength, referred to as the modulus of rupture, was determined from bending tests done on 152-by-152-by-508 mm (6-by-6-by-20 in) beams (Figure 1c) cast from each material (ASTM C78). While an ASTM test is available to measure shrinkage in concrete (ASTM C490), a simpler test that is sometimes used with traditional cementitious building materials was used in this investigation. Following this test, the change in length of a beam 76 mm (3 in) square in cross-section that is initially 914 mm (36 in) long is monitored after the beam is cast (Figure 1d). Shrinkage in cementitious materials is generally associated with moisture loss, which typically occurs over time. Thus, the humidity conditions under which these tests are conducted can be important. In this case, the fly ash concrete specimens were simply placed on the bench top and allowed to age under ambient temperature (approximately 21 degrees C (70 degrees Fahrenheit)) and humidity (relative humidity of 20 to 40 percent) conditions. Length measurements were made periodically over a one month period.

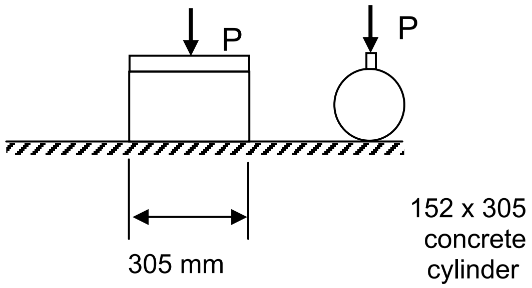
The ability of fly ash concrete to bond with, and develop resistance to reinforcing bar pull-out, was investigated through a sequence of simple pullout tests of deformed bars embedded in 152-by-312 mm (6-by-12 in) test specimens (ASTM C234). Note that while this test method is simple to perform and may yield useful information on bar performance, it has been retired by ASTM, and no specific standard has been developed as a replacement for evaluating concrete bond performance. ASTM A944 does address bond behavior of reinforcing steel embedded in concrete, but it is intended to determine relative bond performance based on surface characteristics of the bar rather than the properties of the concrete. The decision was made to proceed in this investigation following the provisions of the suspended standard ASTM C234. No information was discovered on the performance of conventional Portland cement concretes in this type of test, so the decision was made to construct some Portland cement concrete specimens in addition to the fly ash concrete specimens.

The specimen configurations used in the pullout tests are given in Figure 2. During these tests, a record was made of the maximum tensile force carried by the specimen as the pullout force was applied to the bar. The failure mechanism of the specimen was also noted (i.e., bar failed, bar pulled out, concrete split).

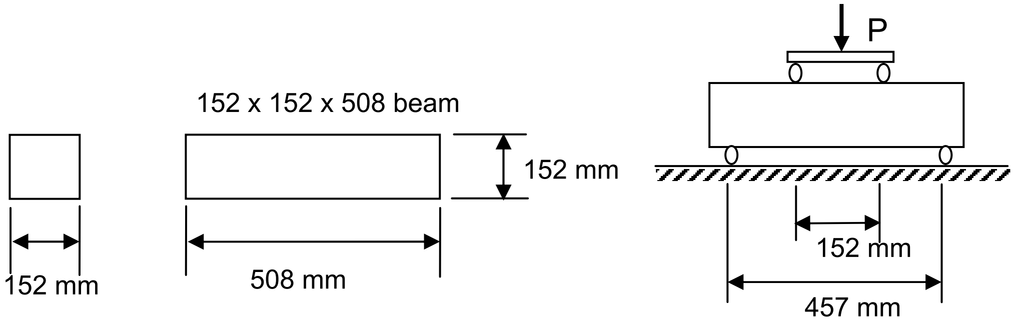
Results – An average value for Young's modulus of 25.3 GPa (3807000 psi) was determined for the fly ash concrete mixtures (with a corresponding unconfined compressive strength of 31 MPa (4490 psi)). The values determined by test closely matched (within 3 percent) those determined using the equation for Portland cement



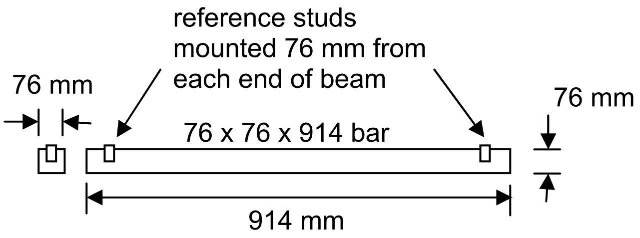
(a) Young's Modulus



(b) Splitting Tensile Strength



(c) Modulus of Rupture



(d) Shrinkage

Figure 1. Tests Conducted to Determine Engineering Properties of Concrete

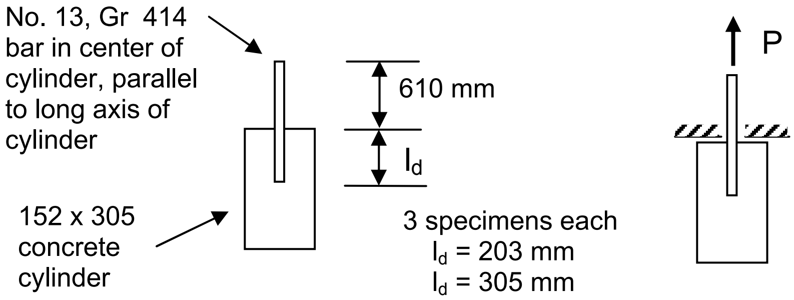


Figure 2. Bar Pullout Test

concrete that relates Young's modulus (E in psi), to unit weight ($w_c$ in lbs/ft$^3$) and unconfined compressive strength ($f'_c$ in psi) of the concrete[4]:

$$E = 33\, w_c^{1.5} \sqrt{f'_c}$$

The average tensile splitting strength of the fly ash concrete was 2.22 MPa (323 psi). The splitting tensile strength for Portland cement concretes can be estimated as one-tenth of the compressive strength[5]. Thus, the experimentally determined splitting tensile strength was 30 percent below the value predicted by this method.

The average modulus of rupture for the fly ash concrete was found from test to be 2.87 MPa (417 psi). This value was 16 percent below the value predicted for the compressive strength using the equation relating these parameters developed for Portland cement concrete[5]:

$$f'_r = K \sqrt{f'_c}$$

in which K often is taken as 7.5 out of range of possible K values of 6 to 12 (for $f'_r$ and $f'_c$ in psi).

Both the splitting tensile strength and the modulus of rupture of the fly ash concrete were below the values that were predicted from the compressive strength using relationships developed for Portland cement concrete. These results indicate that the tensile strength of the fly ash concrete may be relatively lower than the compressive strength compared to the relationship between these strengths for Portland cement concrete.

The fly ash concrete exhibited nominal expansive behavior. After 7days of moist cure, the fly ash concrete specimens expanded approximately 0.03 percent from their original size. Over the next few days, the specimens further expanded to 0.045 percent of their initial size. They subsequently shrank over the next 1 ½ months, returning to the 0.03

percent expansion observed when they first were removed from the moist cure environment. These dimensional changes are nominally smaller in magnitude than those expected for Portland cement concrete, and they are opposite in direction. Portland cement based concretes generally exhibit ultimate shrinkage in the range of 0.02 to 0.06 percent[5]. For the specific elapsed time, relative humidity, and concrete mixture used in this investigation, a Portland cement based concrete specimen would have been expected to shrink 0.05 percent[5].

Relative to bar anchorage, the fly ash and Portland cement concrete performed similarly, although the results of the tests are somewhat equivocal (full results are presented in Table 2). All the specimens ultimately failed through splitting of the concrete cylinders in which the bars were anchored. According to MacGregor and Wight[6], the applied tensile load at splitting failure (P) can be estimated in terms of the unconfined compressive strength of the concrete ($f'_c$), the diameter of the reinforcing bar ($d_b$), the length of embedment ($l_d$), the distance from the bar to the surface of the concrete (c), and the ratio of the average to the maximum splitting stress (K), using the equation:

$$P = 6\sqrt{f'_c}\,K\left(\frac{c}{d_b} - \frac{1}{2}\right)\pi\, d_b\, l_d$$

In this case, since all of the specimens failed through splitting, this equation should predict the failure load, independent of any other possible failure mechanisms (i.e.,

Table 2. Pullout Test Results

| Test Specimen | Actual $f'_c$, MPa | Embedment Length for Test, mm | Predicted Failure Load, kN | Actual Failure Load, kN |
|---|---|---|---|---|
| FA-P-1 | 33.8 | 305 | 48.4 | 49.5 |
| FA-P-2 | | | | 48.9 |
| FA-P-3 | | | | 44.7 |
| FA-P-4 | | 203 | 32.3 | 41.5 |
| FA-P-5 | | | | 45.5 |
| FA-P-6 | | | | 43.7 |
| PC-P-1 | 53.7 | 305 | 62.3 | 62.3 |
| PC-P-2 | | | | 68.5 |
| PC-P-3 | | | | 52.1 |
| PC-P-4 | | 203 | 41.5 | 63.6 |
| PC-P-5 | | | | 86.9 |
| PC-P-6 | | | | 62.0 |

traditional bond failure in which the bar is dragged out of the concrete, or tensile failure of the reinforcing steel). Failure loads calculated by this equation, assuming a K value of 0.125, are presented in Table 2. Note that for an edge distance, c, of 1.5 $d_b$, MacGregor and Wight assumed a K value of 0.5. As the edge distance increases relative to the bar diameter, $d_b$, it seems logical that K will decrease. A K value of 0.125 generated reasonable results for the 305 mm (12 in) Portland cement based embedment depth used in this investigation.

Referring to Table 2, the fly ash concrete specimens with a 305 mm (12 in) length of embedment offered an average anchorage resistance within 2 percent of the resistance predicted by the equation developed for bar anchorage in Portland cement based concrete. The close agreement between the actual and predicted anchorage strengths in this case, however, must be viewed with some reservations, as the anchorage test results at 203 mm (8 in) of embedment appear to be unreasonable relative to those from the 305 mm (12 in) embedment tests. Notably, significantly higher anchorage resistances were observed for the Portland cement based concretes at an embedment length of 203 mm (8 in) relative to 305 mm (12 in). For the fly ash based concrete, anchorage resistances at 203 mm (8 in) of embedment were 90 percent of those observed at 305 mm (12 in) of embedment, while the analysis would predict that the resistance should decrease in direct proportion to the embedment length (in this case, 203/305, or 67 percent of the 305 mm (12 in) value). In light of these anomalies in behavior, further evaluation is necessary before the bar anchorage properties of fly ash concrete can be definitely established.

## BEHAVIOR OF STRUCTURAL ELEMENTS MADE WITH FLY ASH CONCRETE

Many investigations of new cementitious building materials terminate with the generation of a mix design based on workability and compressive strength. This project went further, first in looking at additional engineering properties as discussed above, and second, in looking at the performance of these materials in reinforced beam and column elements. Cementitious building materials must be reinforced in contemporary designs to provide strength in tension and more importantly, ductility under overloads. Therefore, tests were conducted on simple beam and column elements to look at these two features of their performance. The equations developed to predict the capacity of these elements for Portland cement based concretes were evaluated relative to their applicability to fly ash based concrete elements.

Beam Elements – Three fly ash beams singly reinforced in accordance with ACI Building Code[4] requirements were tested to failure under monotonically increasing transverse loads. The test specimens and the test setup are described in Figure 3. The basic test specimens were simply supported beams, approximately 2.360 m (93 in) long, 254 mm (10 in) deep, and 152 mm (6 in) wide. The beams were normally reinforced with conventional, Grade 414 (60) reinforcing steel at a steel ratio of 0.007. Shear reinforcement was provided along the entire length of each beam spaced at 102 mm (4 in) on center (approximately one-half of the effective depth of the beams, d). The

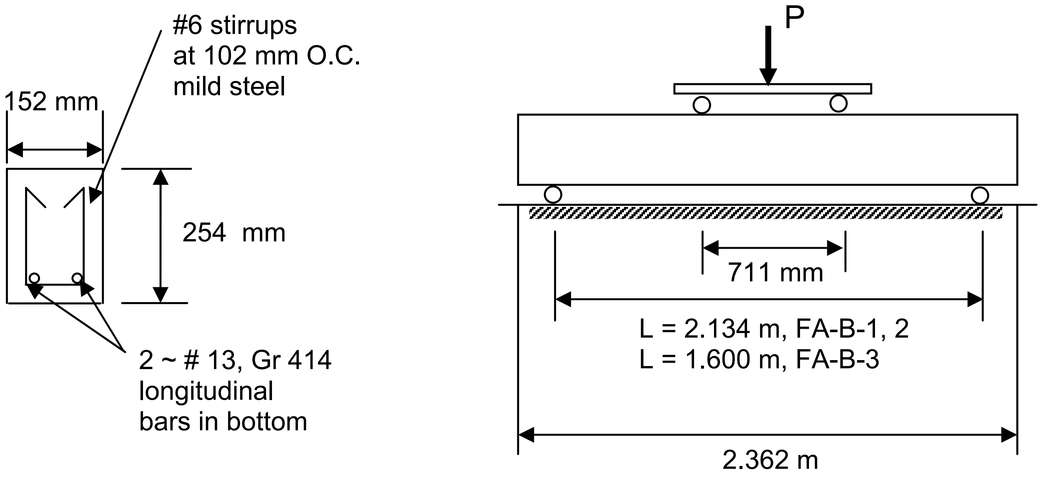


Figure 3. Beam Test Setup

beams were loaded with two symmetrically placed point loads of equal magnitude (Figure 3). Two of the beams were subjected to 1/3 point loads applied vertically on a simply supported span of 2.130 m (84 in). One beam was tested using a span of 1.600 m (63 in) to increase the shear demands experienced by the beam. Note that all the beams, including the one tested on a 1.600 m (63 in) span, were predicted to yield in flexure (as discussed further below). Applied load and center point deflection were measured in each test.

All of the beams performed satisfactorily in flexure. In all tests, the first distress consisted of flexural tensile cracks on the bottom of the beam in the center of the span. These cracks widened and propagated toward the top of the beams as the load increased. While initially the vertical deflection of each beam increased proportionally with the applied load, a point was reached in each test at which the beam began to move down without an increase in the applied load. Based on conventional reinforced concrete beam theory, this point corresponds to the point at which the reinforcing steel in the beam yielded. The yield point in each test can be readily identified in the load versus displacement plots presented in Figure 4. Eventually, as the beams continued to deflect vertically, the fly ash concrete at the top of the beams in the center of the span began to spall off, and the load carrying capacity of the beams began to decrease as this compressive failure propagated horizontally and vertically in extent (Figure 5). Throughout all the beam tests, there was no evidence of any anchorage problems with the primary flexural or shear reinforcement.

The beam behavior described above closely matches that predicted by theory for conventional reinforced Portland cement concrete beams with respect to both the yield strength and the post-yield ductility. The internal moment at which the beams first yielded in each test is reported in Table 3. These moments were calculated from the load at yield, as determined from the load deflection response reported in Figure 4. The observed yield moments in the beams with 2.230 and 1.600 m (84 and 63 in) spans were within 6 and 14 percent, respectively of the predicted flexural capacities of these

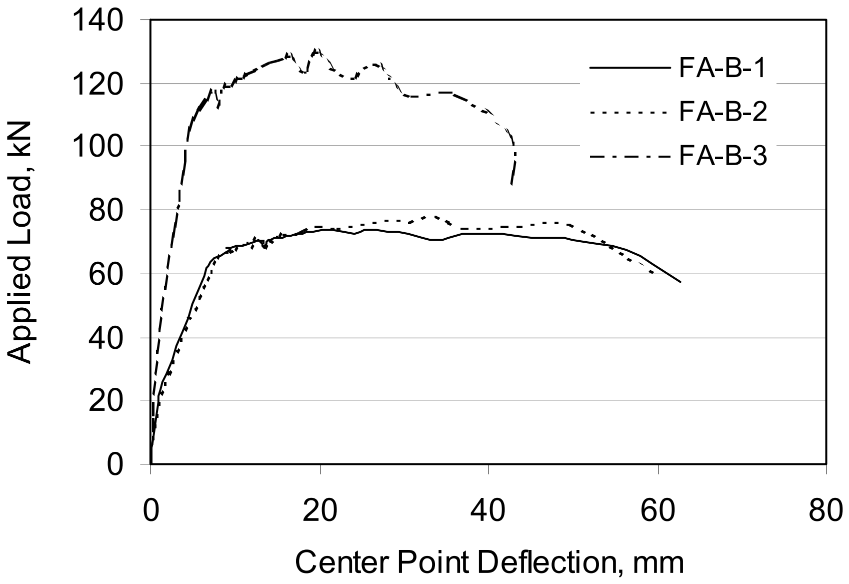


Figure 4. Load – Deflection Behavior, Beams

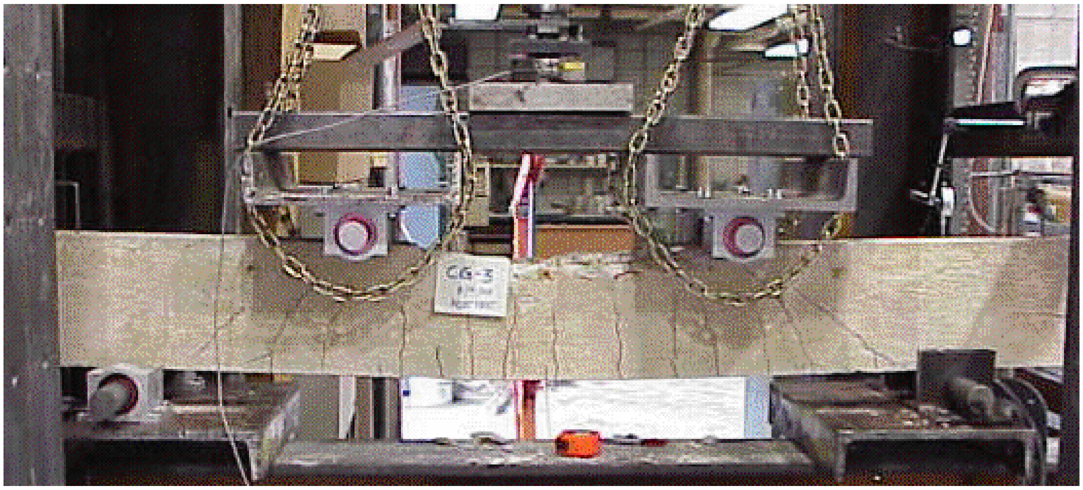


Figure 5. Typical Beam Distress

beams calculated using the plastic moment equation for conventional Portland cement concrete. This well established equation for moment capacity ($M_n$) is based on the compressive strength of the material ($f'_c$), the width of the cross-section (b), the location of the reinforcing steel (d), the area of steel ($A_s$), and the yield strength of the steel ($f_y$)[6]:

$$M_n = A_s\ f_y\ \left(d - \left(0.59\ A_s\ f_y\right)/\left(f'_c\ b\right)\right)$$

Table 3. Beam Test Matrix and Results

| Test Specimen | Span, m | Actual $f'_c$, MPa | Predicted Moment Capacity, N-m | Actual Moment Capacity, N-m |
|---|---|---|---|---|
| FA-B-1 | 2.130 | 34 | 22.4 | 23.7 |
| FA-B-2 | 2.130 | 31 | 22.4 | 23.7 |
| FA-B-3 | 1.600 | 31 | 22.4 | 25.8 |

All of the beams demonstrated adequate shear resistance, although they were not challenged to failure in shear in these tests. That is, no shear failures were expected based on the shear capacity of these beams calculated using equations developed for Portland cement concrete, and none occurred. Shear capacities, $V_n$ (in lbs), were calculated from the strength of the material ($f'_c$ in psi); the width of the beam (b in inches), and effective depth (d in inches), of the cross section; and the spacing of the shear reinforcement (s in inches), its yield strength ($f_y$ in psi), and its cross-sectional area ($A_v$ in square inches), using the equation[4]:

$$V_n = 2\sqrt{f'_c}\, b\, d + \left(A_v\, f_y\, d\right)/ s$$

The highest shear demands occurred in the 1.600 m (63 in) span beam. The maximum load in this test produced a shear demand in the beam equal to 94 percent of the predicted shear capacity. At this load, the beam exhibited hairline shear cracks in the end panel zones, as the shear demand was shared between the material and the shear reinforcement. Shear capacity of concrete-like materials is related to the material's tensile strength, and thus consideration should be given to researching more thoroughly the shear capacity of the fly ash concrete (in that early results indicated that its tensile strength is less than expected relative to its compressive strength). A series of beam tests designed to challenge this material in shear have already been planned and will be conducted in the near future.

With respect to ductility, the fly ash concrete beams exhibited displacement ductility ratios on the order of magnitude of 7. The displacement ductility ratio was calculated for each beam as the ratio of the displacement at final loss of load carrying capacity divided by the displacement at initial yield. These displacements were estimated for each test from the load versus displacement data presented in Figure 4. Note that similar beams made with Portland cement concrete generally have ductility ratios between 5 and 10. Displacement ductility ratios of 3 to 5 are typically required to provide adequate seismic response[5].

<u>Column Elements</u> – Fly ash concrete columns approximately 152 mm (6 in) in diameter and 457 mm (18 in) long were tested in uniaxial compression to failure (Figure 6). These columns, constructed generally in accordance with ACI Building Code[4] requirements, were all identically reinforced with deformed longitudinal steel bars

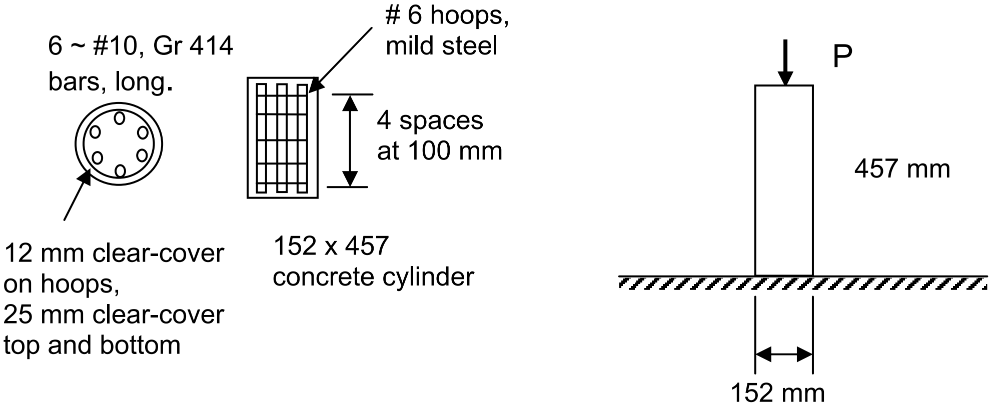


Figure 6. Column Test Setup

confined by discrete hoops, as detailed in Figure 6. Applied load and deformation were measured in each test.

The behavior of the fly ash concrete columns matched that expected based on conventional Portland cement concrete theory. Complete results of the column tests are summarized in Table 4. The column capacities were calculated using an equation developed for Portland cement concrete columns expressed in terms of the area of the concrete ($A_c$) and steel ($A_s$) and the basic stresses in the concrete ($f'_c$) and steel ($f_y$)[4]:

$$P_n = 0.85\, f'_c\, A_c + A_s\, f_y$$

The reinforced fly ash concrete columns failed at loads ranging from 88 to 113 percent of the predicted values. While these results give the impression that the columns did not perform according to the prediction, data collected previously at Montana State University on the capacity of columns constructed with Portland cement based concrete have also exhibited considerable scatter with respect to their predicted capacity. This scatter has been attributed in part to the short specimen length, and thus the possibility of irregularities at the ends of the columns significantly influencing the test results.

For the tie spacing used, the columns exhibited the ductility expected based on experience with similarly reinforced Portland cement concrete elements[5]. A typical failed column is shown in Figure 7. Load as a function of axial deformation is plotted for the columns in Figure 8 (note that problems were encountered in collecting the data for one of the columns). While the load carrying capacity of the columns rapidly diminished after the peak resistance was achieved, this behavior is consistent with that observed in similarly reinforced columns made with Portland cement concrete[5]. A tie spacing on the order of magnitude of 38 mm (1.5 in) would have been required to generate significant post yield ductility.

Table 4. Column Test Matrix and Results

| Test Specimen | Actual f'$_c$, MPa | Predicted Load at Initial Crushing, kN | Actual Load at Crushing, kN |
|---|---|---|---|
| FA-C-1 | 35 | 654 | 603 |
| FA-C-2 | 34 | 633 | 647 |
| FA-C-3 | 29 | 568 | 643 |

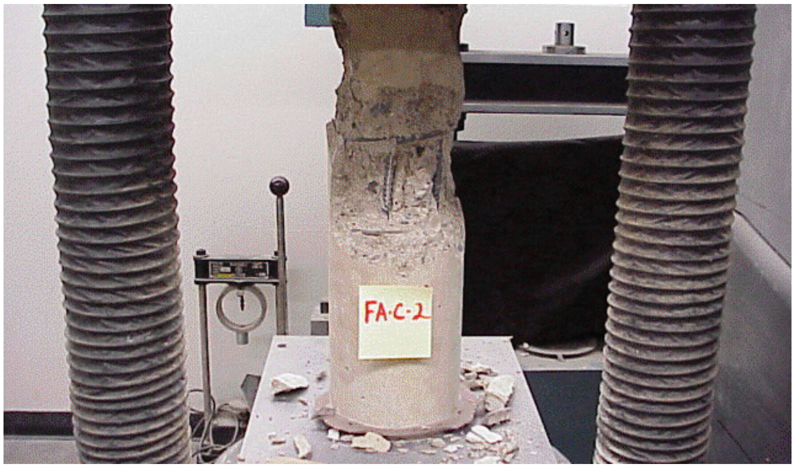


Figure 7. Typical Column Distress

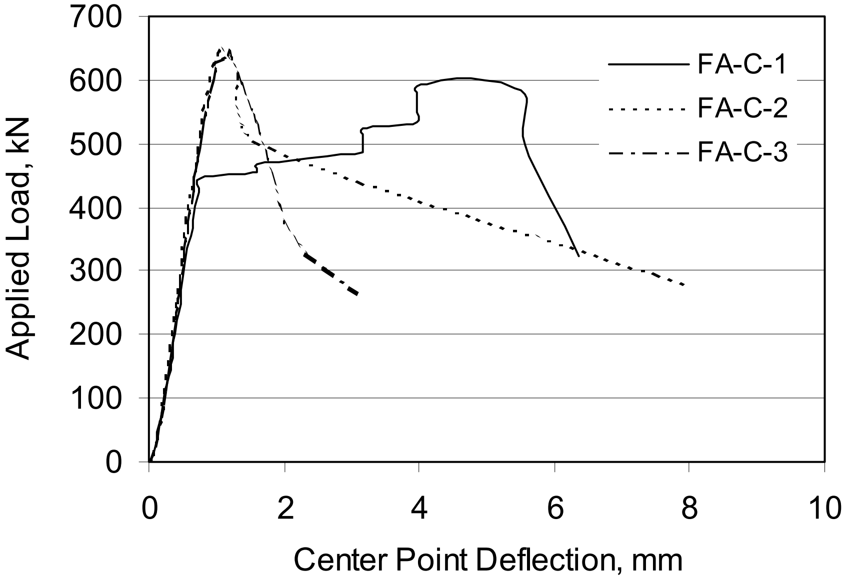


Figure 8. Load – Deflection Behavior, Columns

## FIELD TRIALS

Upon completing the requisite laboratory testing, the next task was to determine if this material could be produced using standard concrete equipment. Two field trials were conducted in this regard, one utilized conventional ready mix equipment and the other utilized more sophisticated equipment commonly found in modern precast concrete plants.

Ready-Mix Application - The objective of the first scale up attempt was to determine if results generated in the laboratory adequately represented what would happen in the field using ready-mix equipment (such as would be used in constructing footers, stem walls, etc. in the field using this material). A little over 2.2 $m^3$ (3 $yd^3$) of 100 percent fly ash concrete were batched in a ready mix truck at Norsioux Redimix in Billings Montana. The concrete was used to cast a landscape block, a wainscoting panel, and a reinforced concrete beam (Figure 9).

The mix used in this trial had three target performance objectives: 1) there had to be adequate workability to place the freshly mixed material (minimum slump 102 to 152 mm (4 to 6 in)), 2) the set time had to be long enough to allow for placement (minimum of 3 hours), and 3) the strength upon curing (28 days) had to be adequate for general construction applications (28 MPa (4000 psi)). The mix design that was used to satisfy these criteria was directly patterned after the mix designs used for the laboratory tests described above. Note that in the laboratory mixtures, a small quantity of lime had been added (0.3 percent or less of the total fly ash weight) to improve the finishability of the concrete. One draw back to adding lime was that the set times became less predictable. For this reason, lime was left out of the scale up mixture. The mix design for the trial ready-mix scale up project consisted of 40 percent paste (water and fly ash), 40 percent coarse aggregate (19 mm (0.75 in) minus, ASTM C-33), and 20 percent fine aggregate (ASTM C-33), with a w/fa ratio of 0.24.

This first scale up effort was an unqualified success. The concrete met all the performance requirements, without any unusual effort. The slump was 8.5 inches, which was a little higher than what had been observed in the laboratory, but the mix showed no signs of segregation. The 2, 7, and 28-day strengths of the concrete averaged 20, 23, and 33 MPa (2900, 3300, and 4800 psi), respectively. One-year compressive strength for the concrete averaged 55 MPa (8000 psi). The overall performance was very comparable to that of a Portland cement concrete designed to satisfy the same criteria.

Precast Application - Researchers form MSU collaborated with Missoula Concrete construction to fabricate two vault toilet systems to be placed along the Snake River outside of Jackson, Wyoming. The only cementitious material used to construct the wall panels was Class C fly ash. Missoula Concrete, a precast concrete company in Missoula, Montana, was contracted to build the bathrooms. Relative to the operation of their plant, it was important that the use of 100 percent fly ash concrete in these bathrooms not disrupt their overall production schedule, or require any extraordinary

a) Batching

b) Placing

c) Finishing

Figure 9. Production of Fly Ash Concrete in a Ready-Mix Truck

effort from them. To meet these constraints, two criteria had to be met, first, the fly ash concrete needed to have a slump greater than 102 mm (4 in) and a set time of 1 to 2 hrs. Two hours was abundant time to place the concrete in the form and trowel finish the top surface. From a process standpoint, introducing the retarder (borax) into the mixture required a sequence of steps that departs from conventional Portland cement based concrete mixing methodology. After completing six trial mixes with 100 percent fly ash concrete, procedures were developed so that the retarder could be introduced into the mixer with the least amount of effort while still experiencing the full affect of the given dosage. Introduction of borax into the mixer was the biggest obstacle to overcome during this project.

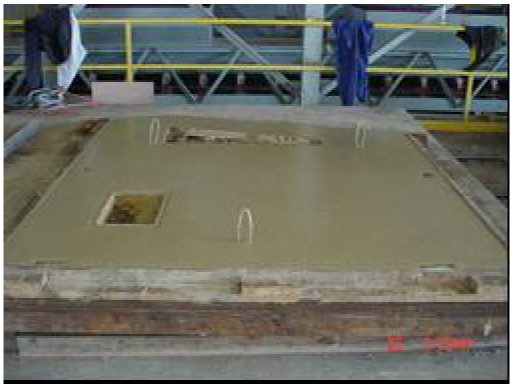
The second criteria the concrete had to meet was achieving an 18-hour unconfined compressive strength of at least 19 MPa (2800 psi); with this strength, the work crew could pick up and move the wall panels the following morning so a new job could be started.

Previous work at MSU with respect to 100 percent fly ash concrete provided the required background information (such as mixing procedures, retarder dosage rates, and strength data) necessary to successfully complete this project. The mixing equipment for this project differed considerably from that used in the scale up effort described above, as well as from the equipment used in the laboratory. Thus, it was evident that the mix sequence would have to be altered from the laboratory established procedures. The mixer for this project was a stationary high energy rotating paddle mixer (Figure 10a). This particular mixer is not absolutely water tight; therefore, if water is the only material in the mixer, a small amount will leak out through the discharge door. The single biggest concern using this mixer was whether enough of the mix water dosed with borax would remain in the mixing drum long enough for the borax to go into solution. The water loss problem was mitigated by adding water to the mixer with the coarse and fine aggregate already in the mixing tub. Only small amounts (4 l (1 gal) or less) of water leaked out when the ingredients were charged into the mixer in this order. The aggregate, water, and borax were mixed for 4 minutes. Note that in the laboratory, the borax typically was added to the mix water along with a small amount of the total aggregate and allowed to mix for 10 minutes (prior to adding the remaining aggregate and the fly ash). The effectiveness of the borax is directly related to how much borax goes into solution before the fly ash is added. Given the small amount of borax required to achieve a given set time, if any of the water-borax solution is lost (e.g., due to leaks in the mixer) prior to the ash being added, the material will set earlier than expected.

A total of 4.6 $m^3$ (6 $yd^3$) of 100 percent fly ash concrete were produced in 1.2 $m^3$ (1.5 $yd^3$) batches for the vault toilet project. The mix design for this project consisted of 45 percent paste, 35 percent coarse aggregate, and 20 percent fine aggregate. The paste volume was increased (by 5 percent over what had been used in the laboratory and in the previous scale up effort) to, among other things, insure that the detail from the wood grain form liner was picked up in the finish. Each of the mixtures had good workability with the average slump of 127 mm (5 in) and an average set time of 120 minutes. The average 18 hour strength was 19 MPa (2790 psi) and the average 90-day strength was

a) Mixer at Precast Plant

b) Placing Concrete



c) Finished Wall Panel

Figure 10. Fly Ash Concrete Vault Toilet Project

32 MPa (4577 psi). The work crews who placed the fly ash concrete into the wall panels and trowel finished the interior side of the panels remarked at how nicely the material placed and finished (Figures 10b and10c). The willingness of the participants to conduct several trial mixtures before actually casting the final product certainly contributed to the success of this project. The trial mixes also helped educate the staff at Missoula Concrete on how this material behaves in the plastic state.

## CONCLUSIONS

The fly ash concrete reported on herein is a promising alternative to traditional Portland cement concrete in building construction applications. This concrete fundamentally consists of a conventional concrete mixture in which the Portland cement has been completely replaced by fly ash as the binder. The fly ash concretes made in the course of this investigation had slumps from 102 to 216 mm (4 to 8.5 in), set times of approximately 120 minutes, and 28 day unconfined strengths on the order of magnitude of 28 MPa (4000 psi). With a few exceptions, the equations available to characterize the behavior of Portland cement based concrete were found to apply to fly ash concrete. The notable exception to this observation is for the tensile strength of fly ash concrete. The tensile strength of fly ash concrete appears to be 15 to 30 percent lower then would be expected based on its compressive strength (using equations relating these parameters developed for Portland cement concrete). With respect to anchorage (development length) requirements for reinforcing steel in fly ash concrete, the results from this investigation are somewhat inconclusive. At an embedment length of 305 mm (12 in), bars embedded in fly ash concrete specimens behaved as expected based on anchorage equations developed for Portland cement concretes. On the other hand, bars embedded at a shorter development length in both Portland cement and fly ash concrete specimens failed at loads significantly different from the predicted values. Additional research needs to be conducted on fly ash concretes to definitively establish its bar anchorage characteristics.

Reinforced beam and column elements made with fly ash concrete behaved substantially as would be expected based on the equations used to predict the behavior of such elements made with Portland cement concrete. Specifically, element behavior with respect to strength and ductility closely matched that expected for similar Portland cement concrete elements. Thus, existing flexural design procedures can generally be employed when using these materials (with the exception of embedment lengths). Note that while shear behaviors were not directly investigated in this project, no shear related problems in performance were observed.

Finally, this research was scaled up in two demonstration projects. Landscape blocks, structural beams, and wainscoting panels were fabricated from this material at a ready mix yard in Billings, MT. A more ambitious project was the production of vault toilets that have been installed on US Forest Service land along the Snake River outside of Jackson, Wyoming. Both of these field trials were successful, with the fly as concrete achieving the workability, set time, and strength required for the specific application, without the need for special equipment or methods.

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