2009 World of Coal Ash (WOCA) Conference - May 4-7, 2009 in Lexington, KY, USA
http://www.flyash.info/

Changing the Environment: An Alternative "Green" Concrete Produced without Portland Cement

Michael Berry[1], Doug Cross[1], and Jerry Stephens[1]

[1]Civil Engineering, Western Transportation Institute, Montana State University, 205 Cobleigh Hall, Bozeman, MT 59717-3900

KEYWORDS: 100% fly ash, recycled glass, structural performance, durability, mechanical properties

1 INTRODUCTION AND BACKGROUND

Concrete is the most commonly used construction material in the world because of its outstanding strength, durability, and availability. In fact, concrete is the world's most consumed man-made material[1] and its use is expected to increase substantially. However, the production of concrete is not environmentally friendly, and therefore significant environmental advantages may be realized if alternate, environmentally sensitive materials are identified for use in concrete.

While cement offers excellent performance as a binder in concrete, its manufacturing is an energy intensive process. This process consists of mining raw materials; crushing, blending, and heating these materials to temperatures of 1500˚C; and finally pulverizing the fired product to create finely divided cement powder. In addition to consuming large amounts of energy, the production of cement accounts for a significant portion of CO_2 emissions and other greenhouse gases. The production of cement reportedly accounted for 7% of worldwide greenhouse gas emissions in 2004 (from calcination of limestone and fuel combustion)[1]. Additionally, cement production and resulting emissions are expected to increase by 100% from the current level by 2020[1].

A material that resembles Portland cement both chemically and physically is fly ash, which is a byproduct of the combustion of coal to generate electricity at coal-fired power plants. Nationwide, 71 million tons of this material are produced annually. Fly ash has been used in concrete construction for years; however, variations in its properties related to the type of coal being burned and the nature of the combustion process at any given power plant have conservatively limited its use as a replacement for Portland cement. Typically, fly ash is used to replace less than 25% of the Portland cement in a concrete mixture. Thus, the cementitious binding capacity of many fly ashes is being underutilized. By better understanding its behavior, many fly ashes can potentially be used in higher dosages, thus reducing the environmental impact of both concrete construction and coal-fired power plants.

Over the past ten years, significant research has been conducted at Montana State University (MSU) on structural concretes in which 100% of the Portland cement was replaced with fly ash[2,3]. 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.

Additionally, over the past several years, MSU researchers have begun to look at alternative types of aggregates for use in concrete, one of which is recycled glass. In 2006, Americans generated 13.2 million tons of glass, of which 22% was recovered for recycling. Most of this recycled glass (90%) is used to make new containers, while the remaining 10% is used for secondary applications such as roadbed aggregates and fiberglass insulation. However, there is an increasing demand for alternative uses for pulverized glass because sources of high quality glass suited for the container industry (uniform type and color, uncontaminated) are becoming more sparse as many communities are turning to commingled collection strategies in an effort to save money[4]. Additionally, many communities must pay increasing transportation fees to ship recycled glass to the nearest container manufacturer. For other communities, it is not economical to transport recycled glass, and these communities are searching for alternative uses for their stockpiles or not collecting glass at all.

In 2000, researchers at MSU began investigating the use of pulverized glass in 100% fly ash concrete for nonstructural applications, such as countertops and other architectural surfaces. The concrete mixes resulting from this work showed promise for structural applications with similar set times, workability, and strengths of traditional concrete. Considerable testing subsequently was conducted to investigate fundamental engineering properties, durability, and the applicability of existing design procedures[5].

This paper highlights significant findings and resulting applications of MSU's research program on 100% fly ash concretes with traditional and glass aggregates. First, typical mix proportions are presented for select concrete mixtures. The mechanical properties, durability, and structural performance of these concrete mixtures are then summarized. Finally, details and difficulties encountered on several large-scale pilot projects built using these new concretes are presented and discussed.

2 MATERIALS AND MIXTURES

Although researchers at MSU have successfully demonstrated that multiple Class C fly ashes from the region are suitable for 100% fly ash concrete[6], a large portion of MSU's research has been conducted using a Class C fly ash from the Corette Power Plant in Billings, MT. The chemical composition of this fly ash is presented in Table 1. Note the high calcium content of this ash, which is critical with respect to the hydration reaction that occurs when water is added to the fly ash.

TABLE 1 Typical Properties of Corette Fly Ash

Chemical						Physical		
Silicon Dioxide	Aluminum Oxide	Iron Oxide	Sulfur Trioxide	Calcium Oxide	Loss on Ignition	Fineness, Retained on #325 Sieve	Soundness, Autoclave Expansion	Density
(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	
32.37	17.52	5.34	2.02	28.89	0.23	12.1	0.17	2.72

An impediment to the use of high calcium fly ash is the accelerated rate at which chemical reactions begin to occur when water is added, which leads to flash setting of the material. To avoid flash setting, borax was added to retard these reactions. For this project, commercially available 20 Team Mule Borax ($Na_2B_2O_3 \cdot 10H_2O$) was used as the set retarder.

With respect to aggregates, researchers at MSU have investigated 100% fly ash concrete mixes with both traditional aggregates (local sand and coarse aggregate) and pulverized recycled glass. The recycled pulverized glass used in MSU's research was of mixed color and was provided by the Montana Department of Environmental Quality. It was pulverized using an Andela crusher operated by Headwaters Recycling based in Helena, Montana. The glass particles were separated into two distinct size fractions, 3.175mm (1/8 inch) minus (fines) and 9.52mm (3/8 inch) to 3.175mm (1/8 inch) (coarse). To ensure uniformity with respect to set time and strength gain, all the pulverized glass was thoroughly washed prior to use in the concrete mixtures.

Typical proportions for 100% fly ash concretes made with traditional concrete aggregate and pulverized glass as aggregate are shown in Table 2. The concrete mixtures have water-to-cementitious-material (w/cm) ratios in the range of 0.20 to 0.24, and retarder dosage rates to provide approximately a 2.5-hour set time. These basic mixtures exhibit workability (10 to 15 cm slump, 4 to 6 inch) and strength (at least 27.6 MPa at 28 days, 4000 psi) consistent with concretes used in common construction.

The w/cm ratios for these mixes are noticeably lower than observed in a typical mix design for Portland cement concrete. While the chemical composition of the fly ash used in this investigation is similar to Portland cement, the spherical shape of the fly ash particles (as apposed to angular shape of Portland cement particles) allow for better workability at low w/cm ratios. A Portland cement mixture with a w/cm ratio of 0.20 would typically be unworkable.

TABLE 2 Proportions for 1 m^3 of Concrete

Concrete	Water (kg)	Fly Ash (kg)	Fines (kg)	Coarse (kg)	Borax (kg)
traditional aggregate	91.77	382.99	315.57	631.14	4.77
glass aggregate	120.23	601.27	274.83	274.83	7.49

3 MATERIAL PERFORMANCE

The mechanical properties, durability, and structural performance of 100% fly ash concretes have been systematically investigated by MSU researchers, with the ultimate goal of providing design professionals the information they need to begin specifying these new concretes on their projects[2,3,5,6]. This section provides highlights from these investigative efforts. It should be noted that while considerable information is available on testing the properties of Portland cement based concrete, little information is available on evaluating 100% fly ash concrete with or without glass aggregate. The various sampling and testing completed during this work was conducted as possible and appropriate in accordance with accepted procedures for Portland cement concrete with traditional aggregates, as described by the American Society for Testing and Materials[7].

The material properties and structural performance reported in this document are typical for 100% fly ash concretes researched at MSU over the past few years. This information is provided to indicate the capabilities of these new concretes. For more detailed descriptions of the tests performed and specific results obtained the reader is referred to the various citations made throughout this text.

3.1 Compressive and Tensile Strengths

With respect to concrete compressive strength, 100% fly ash concrete has demonstrated outstanding performance. Both the traditional aggregate and glass mixes have exhibited extraordinary early strength gain, often achieving strengths in excess of 27.6 MPa (4,000 psi) two days after casting. With respect to long-term strength gain, both mixes have demonstrated strengths of over 55.2 MPa (8,000 psi) after 84 days[5,6]. It is important to note that these strengths were achieved with very workable mixtures with no chemical admixtures (excluding set retarder).

Tensile tests on these concretes have found that this material may have slightly less tensile capacity than traditional Portland cement based concrete. For example, Stephens and Cross[3] reported that the average splitting tensile strength for their 100% fly ash concrete with traditional aggregate mix was approximately 7.5% of the reported compressive strength. The splitting tensile strength for Portland cement concretes is often estimated as 10% of the compressive strength[8]. Thus, the experimentally determined splitting tensile strength was approximately 25% below the value that would be predicted for similar Portland cement based concrete. Similar results were reported by Berry et. al.[5] for glass aggregate mixes.

3.2 Young's Modulus

The modulus of elasticity or Young's modulus of 100% fly ash concrete has been tested for both traditional aggregate mixes and glass aggregate mixes according to ASTM C469. A Young's modulus of 25.3 GPa (3,807 ksi) was determined for the fly ash concrete with conventional aggregates (with a corresponding unconfined compressive strength of 31 MPa (4,490 psi))[3]. This value closely matches (within 3%) the value determined using the empirical equation for Portland cement based concretes that relates Young's modulus (E in psi), to unit weight (w_c in lb/ft^3) and unconfined compressive strength (f_c' in psi) of the concrete ($E = 33 w_c \sqrt{f_c'}$)[8]. However, tests on the glass aggregate mixes indicate a lower elastic modulus for 100% fly ash concrete with this type of aggregate[9]. This result may be in part to the reduced stiffness of the glass aggregates relative to conventional aggregates used in traditional concrete. This result is currently being investigated further.

3.3 Alkali Silica Reactivity

The susceptibility of the 100% fly ash concretes to deleterious alkali-silica reactions (ASR) have been investigated following the protocols of ASTM C1260, Potential Alkali Reactivity of Aggregates (Mortar-Bar Method). While several methods are available to investigate ASR, ASTM C1260 is one of the more rapid and reliable of these methods. This test involves immersing mortar bars in an alkaline solution at 80° C for 16 days and monitoring their expansion. In using this test, it is important to note that the conditions the concrete is exposed to are severe, and the test has indicated unacceptable performance for cement-aggregate combinations known to have performed well in actual applications[7]. To provide some perspective on these results, note that according to ASTM C1260, expansion values that are smaller than 0.10% at the age of 16 days are indicative of innocuous behavior, and expansions greater than 0.20% at 16 days are indicative of deleterious behavior. Both the traditional and glass aggregate mixes performed well with respect to ASR with expansion values well below the 0.1% criteria at 16 days (0.015% and 0.053%, respectively)[5,6].

3.4 Freeze-Thaw Resistance

A primary mechanism of physical degradation of exposed concrete is prolonged exposure to cycles of freezing and thawing in a saturated state. This damage, which can occur at both a microscopic and macroscopic level, accumulates over time, eventually contributing to failure of the structure. The freeze-thaw resistance of both the traditional aggregate and glass aggregate concretes have been quantified according to ASTM C666 (Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing). This test consists of subjecting concrete specimens to multiple freeze-thaw cycles while fully saturated. Weight loss and change in dynamic modulus are monitored as a function of accumulated freeze-thaw cycles. As may be obvious, the degree of damage sustained by the concrete due to micro (as well as macro) cracking under freeze-thaw action is reflected by its attendant loss of weight and stiffness, where material stiffness can be non-destructively measured in terms of dynamic modulus. The relative dynamic moduli were calculated from fundamental transverse frequency measurements (ASTM C215, Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Resonant Frequencies of Concrete Specimens).

Overall, both the 100% fly ash concretes with traditional and glass aggregates without air entrainment perform well with respect to freeze-thaw resistance. For both mixes, the relative dynamic moduli at the completion of the tests were near 90% and the mass loss was less than 2%. For reference, a relative dynamic modulus of 80% or greater after 300 cycles is often assumed to indicate good freeze-thaw resistance.

3.5 Structural Performance

In almost all structural applications, concrete must be reinforced to provide the strength and/or ductility required in contemporary designs. While the behavior of conventional concrete coupled with reinforcing steel is well understood, this behavior is complex, and it is important to confirm by laboratory test how reinforced concrete elements made with fly ash as the binder behave. On a similar note, it is equally important to determine the effect of glass aggregates on element performance. Several research efforts at MSU have addressed these issues. Stephens and Cross[3] confirmed that 100% fly ash concrete made with conventional aggregates behave similar to elements made with traditional Portland cement concrete. Berry et. al.[5] observed similar performance from 100% fly ash members with glass aggregate. In both these research efforts, beams and columns were constructed with 100% fly ash concrete and tested until failure. The measured and calculated capacities were then compared in order to validate existing design procedures for elements made with this alternate material. In all cases, the predicted capacities according to ACI 318-05[10] were within 15% of the measured capacities.

4 PILOT PROJECTS

Although a significant amount of research must still be performed to fully characterize the behavior of 100% fly ash concrete, there is enough evidence to support the use of this material in nonstructural and structural elements beyond the laboratory setting. Both the 100% fly ash concretes with traditional aggregate and glass aggregate have been used in several large-scale pilot projects over the past 10 years. The following are brief descriptions of the key pilot projects that have been conducted. Several pictures from these pilot projects are provided below (Figures 1 to 5). The 100% fly ash concretes used in all these projects was produced using conventional concrete production equipment.

Jackson Hole Vault Toilet’s (2004): A 100% fly ash concrete with traditional aggregates was used in the construction of precast building panels in two Vault Toilet’s for a tourist facility near Jackson Hole, WY.

Orchard Gardens (2005): A 100% fly ash concrete with traditional aggregates was used in the foundation walls and footings of the Orchard Gardens building in Missoula, MT.

Missoula Federal Credit Union (2008): A 100% fly ash concrete with pulverized glass aggregates was used in the construction of a branch of the Missoula Federal Credit Union in Missoula, MT. This material was used in the foundation walls and footings, floor slab, two structural load-bearing beams, and various nonstructural elements such as architectural panels. This building achieved the highest LEED (Leadership in Energy and Environmental Design) rating possible (Platinum) and won the Montana Contractors Association’s Awards for Best Use of a Green Concrete in Construction and the Judges Choice Award for Concrete Construction.

Commercial Building in Billings (2008): A 100% fly ash concrete with pulverized glass aggregate was used in the floor slabs of an office building in Billings, MT. The concrete in this project was placed via a line pump.

Transcend Research Facility (2008): A 100% fly ash concrete with traditional aggregates was used in constructing the shop and various other buildings at the Transcend Research Facility in Lewistown, Montana. The material was used in the floor slabs, and foundation walls and footings. These elements have been instrumented to monitor the materials performance over time. Additionally, this project demonstrated that this concrete can be placed via a boom pump.

Figure 1: Load Bearing Beams at Various Stages During Construction (Missoula Federal Credit Union)

Figure 2: Foundation Walls and Footings (Missoula Federal Credit Union)

Figure 3: Placement of Glass Aggregate Mix via a Line Pump (Billings Commercial Building)

Figure 4: Discarded Concrete Mixes after Altered Batching Process

Figure 5: Pumping 100% Fly Ash Concrete with Traditional Aggregate (Lewistown, MT)

5 FACTORS HINDERING COMMERCIALIZATION OF 100% FLY ASH CONCRETE

The 100% fly ash concretes described in this paper have consistently been found to offer engineering performance similar to and often better than traditional Portland cement concretes. It has been shown that they can be produced in large volumes using conventional concrete equipment. Furthermore, they offer obvious environmental advantages relative to Portland cement concretes. So, what if any obstacles remain relative to their general acceptance and use by the construction industry? The most difficult recurring obstacles in all the above-mentioned pilot projects are related to human factors and the tendency of batch plant operators, contractors, and concrete finishers to treat this new material exactly the same as they would Portland cement based concrete. The following section discusses a couple of the more prominent difficulties encountered in this regard.

Adherence to specified batch procedures was one of the largest obstacles consistently observed in these projects. Although batching this material is similar to batching traditional concrete, the differences are significant enough to be disruptive to a standard batch plant's operations, and the level of quality control can be problematic relative to consistently producing good material. The current process for batching 100% fly ash concrete is very sensitive relative to the order in which the ingredients are introduced into the mixture, and the duration of the mixing process. This heightened sensitivity is due to the volatile nature of the hydrating fly ash and its tendency to flash set if a retarding agent is not present.

In order to ensure that this exact batching process was performed, meetings and trial pours were required prior to the actual pour. The pilot-projects mentioned before all used different batch plants; therefore, each project required its own set of trial pours and educational meetings. Often, despite the success of the batching process during closely a supervised trial pour, problems were encountered immediately when supervision was relaxed. Notably, due to its many similarities to Portland cement concrete, construction personnel would immediately revert to their traditional practices for Portland cement based concretes, even though they had been thoroughly instructed on the new procedures to be followed for 100% fly ash concrete. These personnel would freely alter the batching sequence, and mixing times based on their Portland cement experience, generally with negative consequences. Along these same lines, contractors and concrete truck operators have an inherent tendency to add water to a mix to improve workability. However, adding water can dilute the retarding agent in 100% fly ash concrete and can accelerate the set time, which in turn causes the mixture to ball up and stick to the fins of the ready mix truck.

In the concrete mixes containing recycled glass it is essential to wash the glass prior to mixing. If unwashed, the sugars and other chemicals on the surface of the glass can cause inconsistencies in the concrete mix, especially with respect to strength gain and set time. While washing sands and gravels to be used in concrete to remove deleterious materials is a common practice, concrete producers resisted using their conventional washing systems with pulverized glass, relying instead on ad hoc and imperfect methods to wash the glass. These methods either left contaminants in the glass, and/or resulted in unpredictable moisture contents of the glass. In either case, the quality of the 100% fly ash concrete was jeopardized, just as such a haphazard approach to washing aggregates for Portland cement based concrete would jeopardize the quality of that material.

The problems described above are related to the ability to simply follow good concrete practice as it is defined for 100 % fly ash concrete. Unlike Portland cement concrete, which is relatively forgiving relative to bad practices, the specified procedures for producing 100 % fly ash concrete must be followed as they are stated; use of short cuts or reliance on Portland cement based practices, will lead to problems, nearly every time.

6 SUMMARY AND CONCLUSIONS

The benefits of using 100% fly ash concrete are at least two fold: reduced environmental impacts from the production of cement, and reduced need for stockpiling of common waste-streams. Previous research at MSU has clearly demonstrated the use of 100% fly ash concrete with conventional aggregates and recycled pulverized glass aggregates for use in structural (and non-structural) applications. The fly ash concretes made throughout this research program have 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 at least 28 MPa (4,000 psi). With a few exceptions, the equations available to characterize the behavior of Portland cement based concrete were found to apply to the fly ash concretes. These new concretes offer good durability relative to ASR and freeze-thaw resistance. Reinforced structural elements made with fly ash concrete behaved as would be expected based on design equations for conventional Portland cement based concrete. Specifically, element behavior with respect to strength and ductility closely match that expected for similar Portland cement concrete elements. Thus, existing flexural design procedures can generally be employed when using these materials.

This research program has moved beyond the laboratory, and has been used in multiple pilot projects. These pilot projects used conventional equipment to batch the alternate concrete, and were successful at validating this concrete as an alternative to conventional Portland cement based concrete. However, these projects revealed several obstacles that must be overcome prior to widespread use of this material, a majority of which are related to human factors and the tendency of contractors, batch plan operators, and concrete finishers to underestimate the importance of differences between this material and traditional concrete. Current work is focused on simplifying the batching process and developing educational materials to distribute to all those involved in using these new materials. These educational materials will emphasize the importance of subtle, yet important differences between these materials.

This material is not intended to replace conventional Portland cement concrete; however it is a viable environmentally attractive option in appropriate situations. Additionally, this work was performed with a very specific fly ash from the Corette Power Plant near Billings, MT. More work is required and currently underway to expand the scope of this material to encompass other types of ashes.

ACKNOWLEDGMENTS

Multiple funding sources have been involved in sponsoring this fly ash based concrete research. The following is a list of the major contributors to this research effort: Combustion Byproducts Recycling Consortium (CBRC), the Missoula Federal Credit Union, the CE Dept. at MSU, and the Montana Department of Environmental Quality (through the efforts in particular of Dusti Johnson. Multiple students at MSU have participated in this research and their contributions have been very beneficial; work by Ray Gamradt, Geoff Wendt, and Alex Huffield, Benji Tornberg, and Zac Heideman was particularly important.

REFERENCES (NEED TO UPDATE THESE)

(1) Naik, T., Sustainability of Concrete Construction. *ASCE Practice Periodical on Structural Design and Construction*, Vol. 13 No. 2., 2008, pp. 98-103.

(2) Cross, J. and Stephens, J., An Alternative to Portland cement Concrete. *Proceedings, Third International Conference on Construction Materials: Performance, Innovations and Structural Implications*, Vancouver, BC, August 22-24, 2005.

(3) Cross, J., Stephens, J., and Vollmer, J., Structural Application of 100% Fly Ash Concrete. *Proceedings, World of Coal Ash*, Lexington, KY, April 11-15, 2005.

(4) *Glass,* Environmental Protection Agency Municipal Solid Waste Division, January 31, 2008, http://www.epa.gov/garbage/glass.htm, Accessed August 1, 2008.

(5) Berry, M., Cross, D., and Stephens, J. (2008). Performance of 100% Fly Ash Concrete with 100% Recycled Glass Aggregate. *Proceedings, TRB 2009 Annual Meeting*.

(6) Cross, J. and Stephens, J., Evaluation of the Durability of 100 Percent Fly Ash Concrete. *CBRC Final Report for Project No. 05-CBRC-W08, 2008.*

(7) ASTM, *Annual Book of ASTM Standards,* American Society for Testing and Materials, 2007.

(8) Park, R. and Paulay, T., *Reinforced Concrete Structures*, John Wiley and Sons, New York, NY, 1975.

(9) Huffield, A., *Moment and Shear Analysis for Beams with 100% Fly Ash, 100% Glass Aggregate Concrete*, Master's Student Professional Paper, Montana State University, Bozeman, 2008.

(10) ACI 318-05, Building *Code Requirements for Structural Concrete*, American Concrete Institute, 2005.