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High-Volume Fly Ash Structural Grade Concrete for Use in Transmission Structure Foundations

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ABSTRACT

This paper presents results of technology transfer efforts for design and construction practice with research performed to identify and recommend mixture proportions for high-volume fly ash content 4,500 psi (31 MPa) structural grade concrete utilizing ASTM-C618, Class C fly ash.

The transmission structure foundations were constructed in Wisconsin with cold weather considerations. Many transmission structure foundations are of sufficient size where mass concrete considerations (with respect to minimizing thermal cracking from excess heat of hydration) are important considerations.

This paper describes the development of high-volume fly ash concrete for construction with an emphasis on environmental sustainability in providing long life structures,
reducing CO_2 emissions, making use of a co-product of electric power generation, conservation of natural resources, and energy conservation. This paper also shows a significant cost savings through the increased use of fly ash.

INTRODUCTION

Electric power transmission lines provide the vital link from generation facilities to distribution substations in forming our nation's power grid infrastructure. Electric generation facilities are currently in an expansion mode in the USA and in many parts of the world. Both base load generation fueled by clean coal technologies and renewable energy sources are being added to the existing generation infrastructure.

The American Transmission Company (ATC) constructs, operates, and maintains transmission facilities in Wisconsin and the Upper Peninsula of Michigan in delivering power generated at nuclear and coal fueled generating stations, landfill and natural gas combustion turbines, hydroelectric generating stations, wind turbine farms, solar generation, biomass fueled power plants, and miscellaneous other generating units. The wide geographic distribution of renewable energy sources and base load power plants have both created a need for additional transmission facilities. Transmission structures come in a wide array of designs to accommodate structural loads and environmental conditions.

Concrete is used primarily for steel structure foundations for high tension transmission line support, and for associated transmission substation structures. In some regions, specialty precast pre-stressed concrete structures are also in use.

A large volume of concrete is used for cast-in-place reinforced concrete foundations. This significant construction need presented an opportunity in changing company construction standards to provide more sustainable concrete while reducing both cost and the associated environmental impacts. Change in engineering and construction is often slowed by the need for demonstrated proven performance for use in critical infrastructure facilities.

This paper describes the process of change to higher volume ASTM C618, Class C fly ash concrete for transmission structure foundations. Fly ash was increased from 15% to 30% of the cementitious content in the concrete mixtures.

BACKGROUND

ATC was formed in 2001 by combining the management of electric power transmission assets of several Midwest utilities. ATC owns, operates and maintains 9,400 circuit miles of transmission lines and 510 substations. The values of assets under ATC's ownership are $2.5 billion dollars. In the next 10 years, ATC is planning on $2.5 billion dollars in new construction. ATC currently has thousands of drilled pier foundations in service.

Each utility had it's own design and construction standards, and a standards group was formed to identify the best practices for use by the transmission company. Of course, this presented many challenges in change management. Coincidentally, thermal cracking was identified in some large diameter concrete drilled pier foundations.

Reducing the amount of portland cement and replacing it with fly ash in concrete mixtures is a proven method of reducing the heat of hydration and associated thermal cracking. This situation provided the opportunity to review the use of fly ash specified in ATC's construction standards in solving a problem and moving towards improved sustainable construction practices.

RELEVANT PUBLICATIONS

A literature review was conducted and some important publications are provided in the list of references found at the end of this paper [Malhotra 1994] [Malhotra 2006] [Mehta 1998] [Naik 2006] [Ramme 2008] [Ramme 2004] [Ramme 2008]. The We Energies Coal Combustion Products Utilization Handbook [Ramme and Tharaniyil 2004] was particularly useful in providing detailed information on the performance of locally produced ASTM C618, Class C fly ash in high-volume fly ash concretes.

MATERIALS UTILIZED IN HIGHER VOLUME FLY ASH CONCRETE MIXTURES

Typical chemical and physical test data are shown on Table 1 for the Class C fly ash and portland cement cementitious materials used for construction of transmission structure foundations. Locally available concrete-quality sand and stone were provided by ready mixed concrete producers. Water, air entraining, and water-reducing admixtures were used to target a 4 to 6 in (10 to 15 cm) and 7 to 9 in (18 to 23 cm) slump and provide a durable concrete product.

MIXTURE PROPORTIONS SELECTION PROCESS

A large 345-kV transmission project was experiencing cracking on the surface of new drilled pier foundations. This construction phase of the project was scheduled to last two

Table 1. Chemical analysis of cementitious materials.

Parameters	Portland Cement	Class C Fly Ash
SiO_2	20.20%	34.11%
Fe_2O_3	2.93%	5.76%
Al_2O_3	4.90%	18.63%
CaO	63.20%	21.20%
MgO	3.70%	4.93%
SO_3	3.82%	3.01%
K_2O	1.21%	0.68%
Na_2O	0.17%	4.48%
Loss on Ignition	0.80%	0.80%
Insoluble Residue	0.25%	NR
Total Alkali as Na_2O	0.97%	2.87%
Moisture Content	NR	0.05%

to three years and would install more than 800 foundations. ATC construction uses two primary types of mixtures. The first is a 'standard' mix that is used for dry holes. The second is a 'tremie' mix that is used for wet holes. All concrete mixtures were designed for a 28-day minimum compressive strength of 3,500 psi (24 MPa) concrete. The construction specification was requiring 3,500 psi (24 MPa) for the standard mix and 4,000 psi (28 MPa) for the tremie mix. The existing concrete mixture proportions are shown on Table 2 to provide 3,500 psi (24 MPa) concrete and 4,000 psi (28 MPa) concrete. In reviewing compressive strength testing records, it was found that significant excess strength was routinely being achieved. However, thermal cracking was sometimes also being experienced. The mixture proportions were changed to significantly reduce the portland cement content and add fly ash to the concrete mixtures. The new concrete mixtures are shown on Table 3. The following arguments and considerations were used to promote the change:

- Reduced water demand.
- Reduced heat of hydration and solution to associated thermal cracking.
- The mixture attained sufficient strength to meet project schedules.
- Equivalent or improved workability for placement during construction.
- Reduced cost. Fly ash sells for approximately one-half the cost of portland cement.
- Improved environmental performance. (Approximately one ton of CO_2 and other combustion emissions are avoided for each ton of cement clinker replaced with fly ash or GGBF slag. Typical portland cement is produced in a high temperature with up to 6 million Btu's of energy conserved for each ton of cement reduced. Mines and quarries supplying raw materials for manufacturing portland cement are conserved for use by future generations for each ton of cement replaced by fly ash. The land associated with fly ash disposal and cement raw materials mining are also conserved).
- Proven long-term structural performance [Ramme and Jacobsmeyer 2008].

HIGH-VOLUME FLY ASH CONCRETE COMPRESSIVE STRENGTH

The construction schedule for building transmission lines is very important. It is not uncommon to have electric load dependent on radial lines during construction or to have to dispatch more expensive generation. Also, the transmission utility typically is not able to collect rates for the new asset until it is in service; thus, transmission lines need to be

Table 2. Standard concrete mixture proportions – existing.

Parameters	Existing Dry Hole Mixture	Existing Tremie Mixture
Specified Design Strength (psi)	3,500 psi (24 MPa)	4,000 psi (28 MPa)
Cement, lbs.	516 lbs (234 kg)	516 lbs (234 kg)
Fly Ash, lbs.	95 lbs (43 kg)	95 lbs (43 kg)
Water, lbs.	287 lbs (130 kg)	244 lbs (111 kg)
Sand, SSD lbs.	1,304 lbs (591 kg)	1,355 lbs (615 kg)
1-1/2 or 3/4" Aggregates, lbs.	1,661 lbs (753 kg)	1,725 lbs (782 kg)
Slump, inch	5 to 7 in. (10 to 15 cm)	7 to 9 in. (18 to 23 cm)
Air Content %	5 to 7 %	5 to 7 %
Average Cost	$85/cu yd ($111/cu m)	$92/cu yd ($120/cu m)

Table 3. Standard concrete mixture proportions – new.

Parameters	New Dry Hole Mixture	New Tremie Mixture
Specified Design Strength (psi)	4,000 psi (28 MPa)	4,500 psi (31 MPa)
Cement, lbs.	395 lbs (179 kg)	395 lbs (179 kg)
Fly Ash, lbs.	170 lbs (77 kg)	170 lbs (77 kg)
Water, lbs.	232 lbs (105 kg)	232 lbs (105 kg)
Sand, SSD lbs.	1,199 lbs (544 kg)	1,199 lbs (544 kg)
1-1/2 or 3/4" Aggregates, lbs.	1,892 lbs (858 kg)	1,892 lbs (858 kg)
Slump, inch	4 to 6 in. (10 to 15 cm)	7 to 9 in. (18 to 23 cm)
Air Content %	5 to 7 %	4 to 7 %
Average Cost	$67/cu yd ($88/cu m)	$75/cu yd ($98/cu m)

constructed in as timely a manner as possible. Strength development in the foundations can have an affect on the schedule. A specified compressive strength is needed to set the transmission structures on the foundations and a higher compressive strength is needed to install the conductors. Table 4 and Figure 1 show the "before" and "after" concrete compression strength results for the specified 4,000 psi (27 MPa) and 4,500 psi (31 MPa) concrete at an age of 28 days. Note the significant reduction in portland cement used with associated economic and environmental benefits described earlier. Thermal cracking was also significantly reduced.

ECONOMICS

Regionally, fly ash sells for approximately one-half the cost of portland cement. The change in mixture proportions shown in Tables 2 and 3 translated to a net savings of $11.50 per cubic yard of concrete. When reviewing a 93-structure line section, the average amount of concrete used per foundation was 30 cu yd (23 cu m). Add to that a 15% waste and overrun, the total amount of concrete needed for this section was 3,203 cu yd (2,449 cu m) of concrete. This translates to a savings on this section of line of nearly $37,000 and about $396 per transmission structure foundation. The entire project was 100 mi (161 km) long. Approximately 800 structures will be needed. This represents a projected savings of nearly $317,000 for the project.

Table 4. Compressive strength development.

	Existing Dry Hole Mixture	Existing Tremie Mixture
Specified Design Strength (psi)	3,500 psi (24 MPa)	4,000 psi (28 MPa)
Average 3 day strength	3,940 psi (27 MPa)	6,026 psi (42 MPa)
Min 3 day strength	2,610 psi (18 MPa)	2,780 psi (19 MPa)
Average 7 day strength	5,046 psi (35 MPa)	7,224 psi (50 MPa)
Min 7 day strength	4,270 psi (29 MPa)	4,510 psi (31 MPa)
Average 14 day strength	NA	NA
Min 14 day strength	NA	NA
Average 28 day strength	5,963 psi (41 MPa)	8,517 psi (59 MPa)
Min 28 day strength	5,110 psi (35 MPa)	5,510 psi (38 MPa)
Average Ambient Temperature	58° F (14°C)	65° F (18°C)
	New Dry Hole Mixture	New Tremie Mixture
Specified Design Strength (psi)	4,000 psi (28 MPa)	4,500 psi (31 MPa)
Average 3 day strength	3,528 psi (24 MPa)	3,841 psi (26 MPa)
Min 3 day strength	2,890 psi (20 MPa)	3,580 psi (25 MPa)
Average 7 day strength	4,225 psi (29 MPa)	4,272 psi (29 MPa)
Min 7 day strength	3,420 psi (24 MPa)	3,380 psi (23 MPa)
Average 14 day strength	4,974 psi (34 MPa)	5,133 psi (35 MPa)
Min 14 day strength	4,140 psi (29 MPa)	3,980 psi (27 MPa)
Average 28 day strength	5,498 psi (38 MPa)	5,631 psi (39 MPa)
Min 28 day strength	4,460 psi (31 MPa)	4,220 psi (29 MPa)
Average Ambient Temperature	77° F (25°C)	78°F (26°C)

SUSTAINABILITY

Benefits included:

- Reduced heat of hydration and associated thermal cracking will result in a longer in service life for the foundation.

- Attained sufficient (but not excess) strength to meet project schedules by conserving cementitious materials for use on other infrastructure projects. Using smaller quantities of cement with fly ash decreases the need to construct additional portland cement kiln capacity, and makes use of a coal combustion co-product.
- Equivalent or improved workability for placement during construction has benefits in worker safety and conserves energy used to pump, place, and finish concrete.
- Reduced cost that can be applied to benefit society. Fly ash sells for approximately one-half the cost of portland cement.
- Improved environmental performance. Approximately one ton of CO_2 and other air emissions are avoided for each ton of portland cement that is replaced with fly ash. Portland cement is produced in a kiln with up to 5.26 million Btu's (5.5 million kjoules) of energy conserved for each ton of cement reduced. Mines and quarried materials used to produce portland cement are conserved for use by future generations for each ton replaced by fly ash. The land that would otherwise be associated with fly ash disposal and cement raw materials mining are conserved.
- High volume fly ash concrete is proven to provide long-term structural performance required for infrastructure projects with service lives of 100 years or more [Ramme and Jacobsmeyer 2008].

The change in mixture proportions by both reducing the cement content and incorporating the use of higher volumes of fly ash (as shown in Tables 2 and 3) also results in a reduction of SO_X and NO_X, PM, CO, VOC's, and TRI substances that would be released from the manufacture of portland cement that would be otherwise produced.

CONCLUSIONS AND FUTURE WORK

The use of ASTM C618, Class C fly ash in production of high-volume fly ash concrete is proven, and can be employed successfully in transmission structure foundations. Changing standards in critical infrastructure systems must be applied with caution. The development of additional fly ash concrete mixtures for cold weather conditions, high early strength and 56 day strengths with reduced cement contents is currently in progress. Changing to sustainable construction practices combined with required short-term and long-term performances are clearly the right economic and environmental choice for the future.

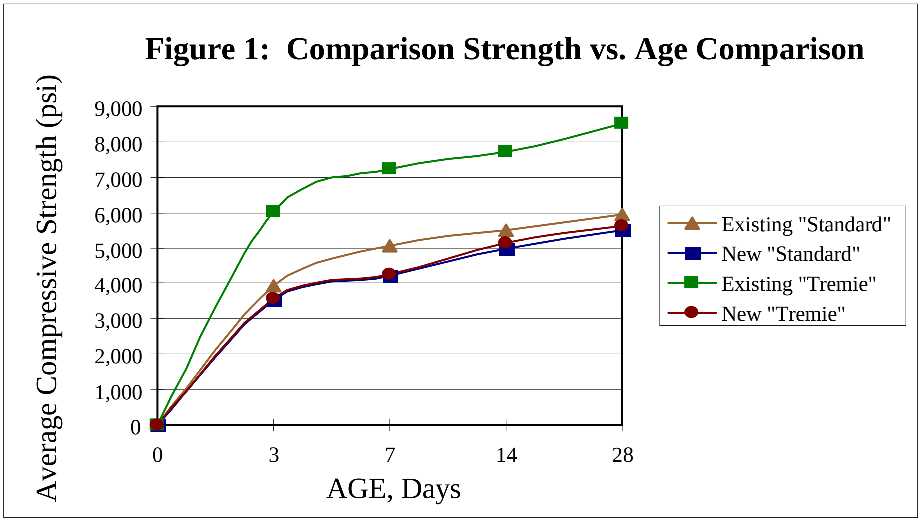

Figure 1. Comparison Strength Vs. Age Comparison.

Note: 145 psi = 1 MPa

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