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More Sustainable and Economical Precast and Prestressed Concrete Using Fly Ash as a Cement Replacement

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ABSTRACT

Precast, prestressed concrete is used to construct a variety of structures. The primary Milwaukee area precast supplier chooses to make their product without the use of any fly ash. Their argument is that using fly ash would reduce the early release strength of the concrete mix. This paper will show research to dispute that claim and then illustrate the monetary and environmental savings that could be achieved if fly ash were used as a cement substitute.

INTRODUCTION

In the United States, there are more than 1,100 manufacturing facilities that primarily burn coal for energy, and more than 600 coal-fired electric generating plants operating. Additional coal-fired electrical power plants are in the construction or planning phase. Over 1 billion tonnes (1.2 billion US tons) of coal were used in the U.S. in 2008, and use is forecast to rise.

Even though there are fewer electrical power plants than manufacturing facilities, the electrical plants burn about 92% of all the coal used in the United States.

Fly ash is the largest component of the CCPs, averaging about 57%. In 2007, about 60 million tonnes (MT) of fly ash were produced in the USA, but only 26 MT (44 %) were beneficially used. About 11.4 MT of fly ash was used directly in the production of concrete as a cement replacement, and another 3 MT was used in cement manufacturing.

Using fly ash as a cement replacement in concrete is effective on many levels. For example, fly ash reduces the permeability of concrete, reduces the heat of hydration, and increases the strength.

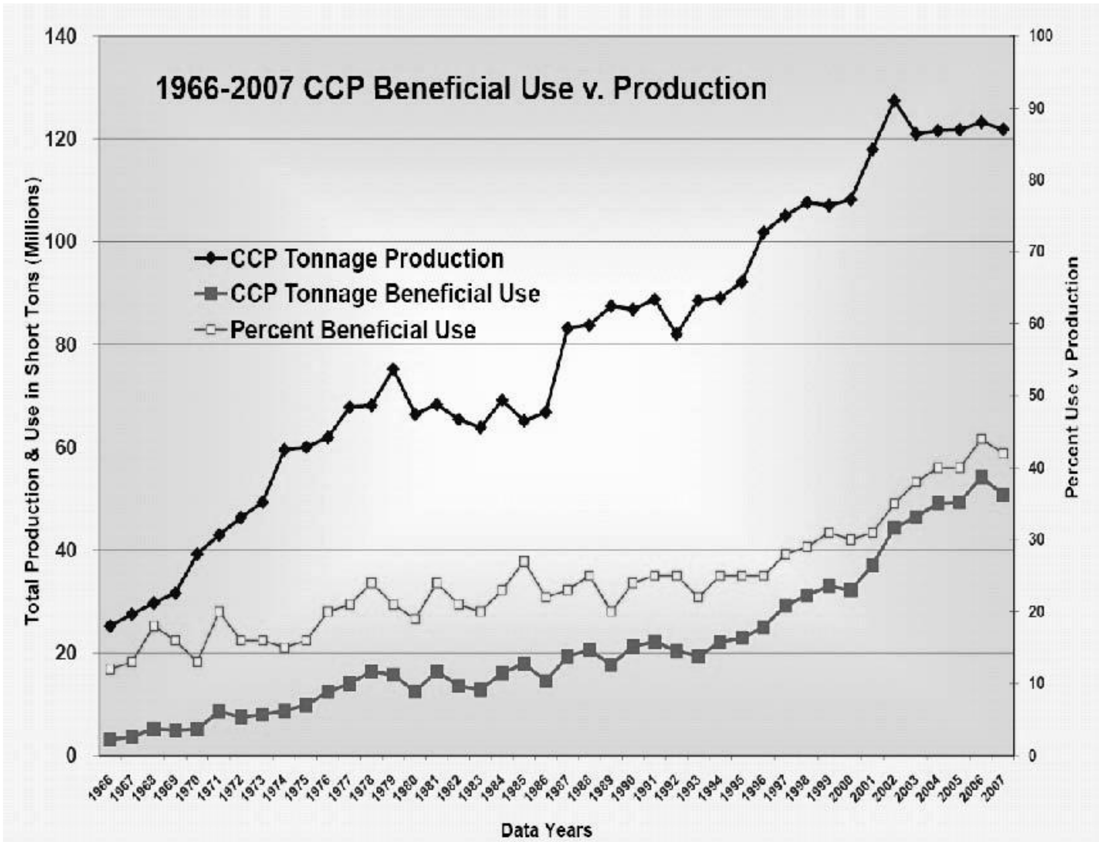

Fig. 1 Beneficial use of Coal Combustion Products versus Production

Replacing cement with fly ash helps reduce green house gas emissions. For every tonne of cement manufactured, one tonne of green house gasses are produced. For every tonne of cement made, 1.7 tonnes of raw materials must be mined and moved. The supply of suitable raw materials near cement manufacturing facilities is being reduced every year, resulting in higher transportation energy use and costs.

One major user of concrete that underutilizes the use of fly ash is the prestressed concrete industry. This paper documents two projects in the Milwaukee, Wisconsin USA area that were built primarily of prestressed concrete and used no fly ash. This paper calculates the savings in cement, money, and carbon dioxide that would have been achieved if fly ash had been used.

COMPARISON STRUCTURES

The first building examined is a 3 story office building. The walls are precast panels, the floors are prestressed hollow core plank, and the beams and columns are also prestressed concrete (Figures 2-4). This building used 1,057 m^3 (1,382 cubic yards) of concrete for the precast wall panels and the prestressed columns and beams.

The prestressed manufacturer used no fly ash in the mix, and the mix was very rich, having 469 Kg/m^3 of concrete (790 pounds per cubic yard). The total amount of cement used for the walls, beams and columns was 495,000 Kg. The floors of the building were made of hollow core plank. The plank was made with a slightly richer mixture of 475 Kg/m^3 (800 pounds pcy). The cement used in the hollow core plank was 422,400 Kg. Adding the plank cement to the wall, beam and column cement gives a total cement exceeding 918,000 Kg. In the USA, cement costs about $115 per ton, so the cement used in this building cost more than $116,000. The production of this cement also created over 918,000 Kg of GHGs.

Cement can be replaced by fly ash in various percentages. This report will show that a 30% replacement rate produces concrete that is very suitable for a prestressed / precast operation. If 30% of the cement would have been replaced with fly ash, about 272,000 Kg of cement would have been saved and 272,000 Kg of GHG's would not have been produced. Since fly ash typically costs 1/3 that of concrete, about $23,000 would have been saved.

Fig. 2 Precast Example Structure 1

Fig. 3 Precast Example Structure 1

Fig. 4 Precast Example Structure 1, Plank Beams, Columns

The second building to be analyzed for potential savings is a 14 story multi use business, hotel, condominium constructed with a very novel prestressed structural system. The design team faced a daunting challenge posed by the owner's project requirements. The hurdle was to find a structural system that maintained the shallow floor-to-floor heights synonymous with flat plate construction while achieving clear spans of up to 21 m (70 ft). To achieve that, the building employs a new structural precast concrete truss that allows alternating floors to remain completely free of interior columns. This system is called the "ER Post "and it was patented by Ericksen Roed engineers of Minneapolis Minnesota USA. (Figure 5). A picture of the truss in the building construction is shown in Figure 6.

This building used a total of 1,494,000 Kg (1,650 tons) of cement. As said before, cement in the USA costs about $115 per ton, so the cement used in this building cost about $190,000. The production of this cement created almost 1,500,000 Kg of GHGs.

If 30% of the cement had been replaced with fly ash, it would have saved about 450,000 Kg (495 tons) of cement and an equivalent amount of GHG's would not have been produced. About $38,000 would have been saved.

So, in just these two buildings, the total monetary savings that could have been realized if fly ash had been used as a cement replacement is over $61,000; in addition, GHG emissions could have been reduced by nearly 800,000 Kg.

A Spancrete employee at the Valders plant works on production of the ER Post™ Structural System.

Fig. 5 Precast Truss Fabrication

Fig 6: Precast Truss Erection

EXPERIMENTAL INVESTIGATION

Why do some precast concrete manufacturers resist using fly ash? The common argument is that adding fly ash increases the set time and reduces the early strength. For precast / prestressed concrete, it is very important to have high early strength since the forms are typically stripped within 24 hours.

This worry about reduced high early strength is common; however, research [Naik, Ramme 1990], has shown that a high volume fly ash mix can have the same or better early strength as regular concrete while also maintaining workability.

The Naik-Ramme research used class C Fly Ash from a coal-fired electric power plant located in Pleasant Prairie, Wisconsin, USA. This fly ash is a by-product of Western United States sub-bituminous coal combustion. The fly ash is captured by electrostatic precipitators from flue gas prior to discharge by exhaust chimneys, and meets all the requirements of the ASTM C618 Class C Designation, (Table 1). Until about thirty years ago, most of the fly ash available from coal burning power plants in the U.S. was of the Class F (low calcium) variety. However, the introduction of low sulphur western sub-bitumous coal in the 1970's made Class C (high calcium) fly ash more readily available. Class C fly ash has higher lime content than Class F fly ash and possesses some cementitious properties of its own.

Table 1. Chemical Properties of Pleasant Prairie Class C Fly Ash

Chemical Composition	Average % (from 7-9 samples)	ASTM Requirement
Silicon Dioxide (SiO_2)	34.4	Combined Silicon plus Aluminum > 50%)
Aluminum Oxide (Al_2O_2)	17.7	
Iron Oxide (Fe_2O_3)	7	No requirement
Sulfur Trioxide (SO_3)	3.1	maximum of 5
Calcium Oxide (CaO)	27.5	No requirement
Moisture Content	0.12	Maximum of 3
Loss On Ignition	0.38	Maximum of 6
Magnesium Oxide (MgO)	4.6	Maximum of 5
Available Alkali (Na_2O)	1.1	Maximum of 1.5

Therefore, the Class C fly ash can be used in higher proportions than the 15 to 20 percent range typically used for the Class F fly ash for structural quality concrete.

Mix proportions were developed for producing concrete on a 1.25 parts (by weight) of fly ash to 1 part cement (by weight) substitutions in the amount of 0, 10, 15, 20, 25 and 30 percent. Six different mix proportions of 55 MPa (8000 psi) nominal compressive strength concrete were developed. Mix proportions and test data for the twelve mixes are given in Table 2. The concrete was produced at a precast/prestressed concrete plant in 1.52 m^3 (2 cu.yd.) test batches. Based on the preliminary mix proportions developed, the final mix proportions were completed in consultation with the concrete producer. All mixes were made with Type I Cement. Standard batching and mixing procedures for ready-mix concrete were followed, in accordance with the ASTM Test Designation C-94.

Workability was observed and no adverse concerns were found throughout the project. All of the concrete produced was homogeneous and cohesive irrespective of the amount of fly ash replacement. Slump readings showed no significant difference between the different mixes. Other researchers have reported that fly ash concrete improves workability, and the data

Table 2: Mix design: All mixes were for 55 Mpa (8,000 psi) concrete All mixes used approx 610 Kg (1344 pounds) of sand and 862 Kg (1900 pounds) of course aggregate. The air temperature was 70 degrees F (39 C). 2,662 cc (90 fluid ounces) of WRDA-19 superplasticizer was added to all mixes.

MIX	1	2	3	4	5	6
Cement (kg)	299	269	254	239	224	210
Fly Ash (kg)	0	36	54	72	90	108
Water (kg)	135	124	116	112	108	104
W / (C+FA)	0.45	0.41	0.38	0.36	0.34	0.33
Air Content (%)	5.4	4.5	2.4	2.0	2.1	1.6
Compressive strengths (MPa) { 6.9 MPa = 1,000 Psi)						
19 hours	18.6	21	22.8	28.3	23.4	21.4
22 hours	19.3	21.4	26.2	28.3	23.4	22.8
3 days	22.1	26.2	28.3	33.8	35.2	30.3
7 days	26.2	29	37.9	38.6	43.4	42.7
14 days	29	32.4	45.5	42.7	49	50.3
28 days	33.1	37.2	46.9	55.8	57.9	57.2

drawn from this project confirms this fact because even though the water to cementitious ratio decreased as the fly ash content was increased, excellent workability was maintained.

Mix 1 is for the no fly ash concrete. Mix No. 2, which has 10 percent fly ash replacement, had a strength gain of 8%, 14%, 17%, and 11% for the 19-hrs., 22-hrs., 3-day, and 7-day ages, respectively, when compared to the non-fly ash concrete (Mix No. 1).

When the amount of fly ash replacement was increased further, the strength gain at early age was more pronounced. For example, Mix No. 4, which had 20 percent fly ash replacement, had a strength gain of 53%, 48%, 51% and 50% for the 19-hrs, 22-hrs, 3-day, and 7-day ages, respectively, when compared to Mix No.1. Also, the reduction in air content with increasing fly ash shows a decreasing permeability of the mix.

Mix No. 6, which has the highest fly ash replacement, 30 percent, had even a higher strength gain at the 7-day age, 65 percent.

These results clearly indicate that Class C fly ash usage increases the early age strength of concrete. Therefore, this fly ash can be used to produce the high early strength concrete typically used in the prestressed / precast concrete industry. This experiment showed this to be true in quantities of up to 30 percent cement replacement.

CONCLUSIONS

Precast/prestressed product suppliers not using Class C fly ash should consider the advantages of using this material in their daily production. Advantages are:

(1) Improved Economics -This is a result of reduced raw material costs resulting in more competitive products over a wider geographical region.

(2) Higher Quality -Fly ash usage in concrete provides higher quality products including higher density with reduced permeability, increased strength and other properties.

(3) Increased Productivity -Fly ash concrete mixes are handled more easily because of improved workability. Faster release of prestressing tendons is also possible because of increased early age strength with use of fly ash.

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