Case Study

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 its product without using any fly ash. The argument is that using fly ash would reduce the early release strength of the concrete mix. This paper shows research to dispute that claim and then illustrates the monetary and environmental savings that could be achieved if fly ash is used as a cement substitute. **DOI: 10.1061/(ASCE)MT.1943-5533.0000243.**

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Introduction

In the United States, more than 1,100 manufacturing facilities primarily burn coal for energy, and more than 600 coal-fired electric-generating plants operate. Additional coal-fired electrical power plants are in the construction or planning phase. More than 1 billion t (1.2 billion short tons) of coal were used in the United States in 2008, and use is forecasted to rise.

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

Burning coal creates a number of coal combustion products (CCPs). Fly ash is the largest component of the coal CCPs, averaging to approximately 57%. In 2007, approximately 60 million t of fly ash were produced in the United States, but only 26 million t (44%) were beneficially used (Fig. 1).

Of the 26 million t of fly ash used, about 14.5 million t were used either directly as a cement replacement in concrete or in the production of cement itself. Using fly ash as a partial 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.

Replacing portland cement with fly ash reduces green house gas emissions. For every ton of cement manufactured, 1 t of green house gases is produced. For every ton of cement made, 1.7 t of raw materials must be mined and moved. The supply of suitable raw materials near cement-manufacturing facilities is reduced every year, resulting in higher transportation energy use and costs.

One major user of concrete that underuses fly ash is the prestressed concrete industry. This paper documents two projects in the Milwaukee 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 (Figs. 2–4). This building used 1,057 m^3 (1,382 cu yd) of concrete for the precast wall panels and the prestressed columns and beams.

The prestressed concrete manufacturer used no fly ash in the mix; the mix was very rich, having 469 kg of cement per cubic meter of concrete (790 lb/cu yd). The total amount of cement used for the walls, beams, and columns was 495 t. 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 lb/cu yd). The cement used in the hollow core plank was 422 t. Adding the plank cement to the wall, beam, and column cement results in a total quantity of cement exceeding 918 t. In the United States, cement costs approximately $115 per short ton, so the cement used in this building cost more than $116,000. The production of this cement also created more than 918 t of green house gases (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 had been replaced with fly ash, approximately 272 t of cement would have been saved, and an equal amount of GHGs would not have been produced. Because fly ash typically costs one-third that of concrete, approximately $23,000 would have been saved.

The second building to be analyzed for potential savings is a 14-story multiuse 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 also having clear spans of up to 21 m (70 ft). To meet these goals, the building uses 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. (Fig. 5). The truss in the building construction is shown in Fig. 6.

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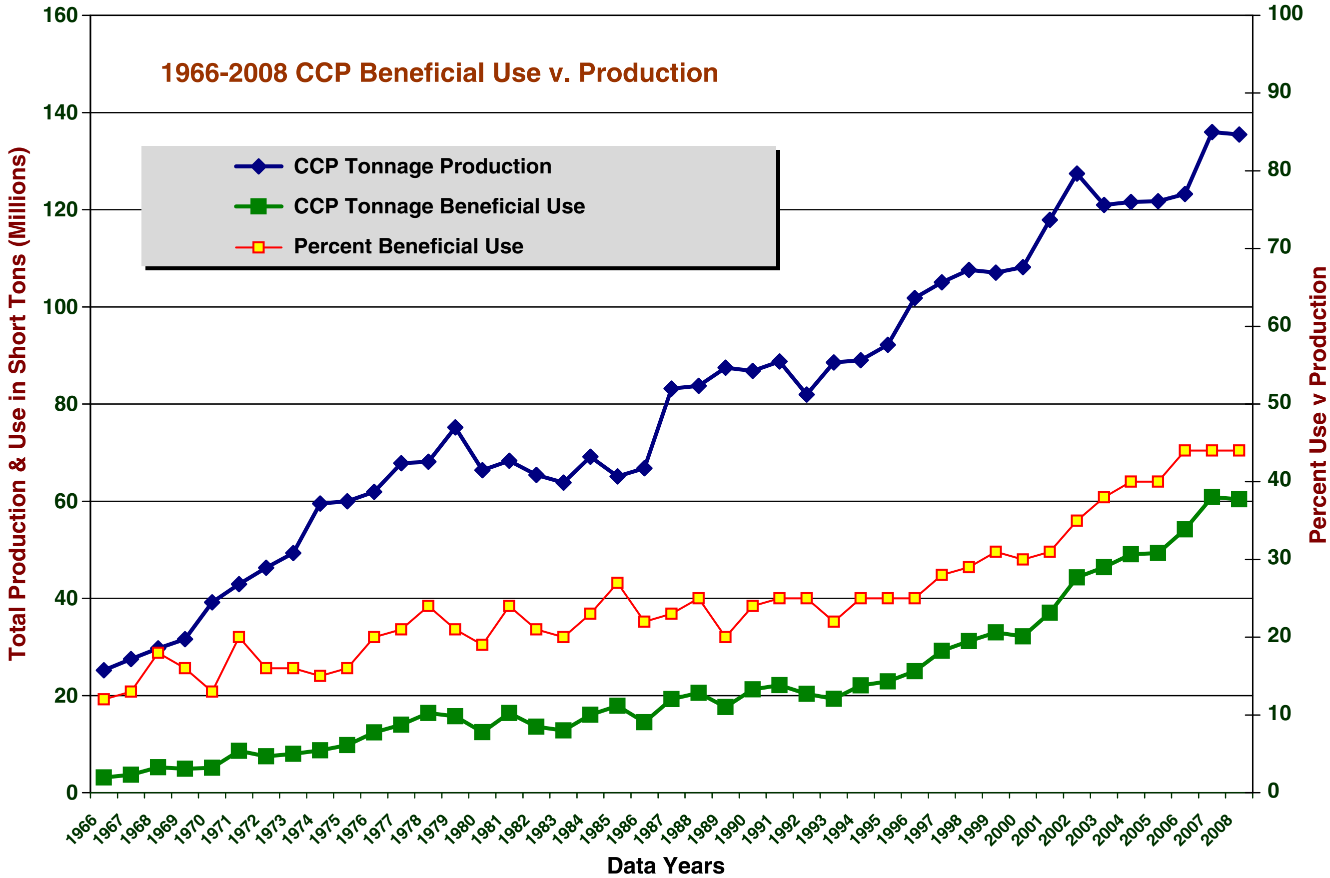

Fig. 1. Beneficial use of coal combustion products versus production [used with permission from the American Coal Ash Association (ACAA)]

Fig. 2. Precast example: Structure 1 (photo by J. Zachar)

Fig. 3. Precast example: Structure 1 (photo by J. Zachar)

This building used approximately 1,500 t (1,650 short tons) of cement. As mentioned previously, cement in the United States costs approximately $115 per short ton, so the cement used in this building cost approximately $190,000. The production of this cement created almost 1,500 t of GHGs.

If 30% of the cement had been replaced with fly ash, it would have saved approximately 450 t (495 short tons) of cement and an equivalent amount of GHGs. Approximately $38,000 would have been saved.

In just these two buildings, more than $61,000 could have been saved if fly ash had been used as a cement replacement; in addition, GHG emissions could have been reduced by more than 720 t.

Experimental Investigation

Why do some precast concrete manufacturers resist using fly ash? The common argument is that adding fly ash increases the set time

Fig. 4. Precast example: Structure 1, plank beams, and columns (photo by J. Zachar)

Fig. 5. Precast truss fabrication (photo courtesy of the Spancrete Group, Inc.)

and reduces the early strength. For precast/prestressed concrete, it is very important to have high early strength because the forms are typically stripped within 24 h.

This concern about reduced early strength is common; however, research (Naik and 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 in Pleasant Prairie, Wisconsin. This fly ash is a by-product of Western United States subbituminous coal combustion. The fly ash is captured by electrostatic precipitators from flue gas before discharge by exhaust chimneys, and it meets all the requirements of the ASTM C618 Class C designation (Table 1). Until approximately 30 years ago, most of the fly ash available from coal-burning power plants in the United States was of the Class F (low calcium) variety. However, the introduction of low-sulfur western subbitumous coal in the 1970s 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. Therefore, Class C fly ash can

Fig. 6. Precast truss erection (photo by J. Zachar)

Table 1. Chemical Properties of Pleasant Prairie Class C Fly Ash (Data from Naik and Ramme 1990)

Chemical composition	Average (%) (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

be used in higher proportions than the 15–20% range typically used for the Class F fly ash for structural quality concrete.

Mix proportions were developed for producing concrete with the substitution of 1.25 parts of fly ash to one part cement (by weight). Substitutions were made in the amount of 0, 10, 15, 20, 25, and 30%. Six different mix proportions of 55 MPa (8,000 psi) nominal compressive-strength concrete were developed. Mix proportions and test data for the 12 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 C94 test designation.

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 mixes and averaged to about 15 cm. Other researchers have reported that fly ash in concrete improves workability, and the data drawn from this project confirm this because although the water-to-cementitious ratio decreased as the fly-ash content was increased, excellent workability was maintained.

As shown in Table 2, Mix 1 is the concrete without fly ash. Mix 2, which had 10% fly-ash replacement, had a strength gain of 8, 14, 17, and 11% for the ages of 19 h, 22 h, 3 days, and 7 days, respectively, when compared with Mix 1.

Table 2. Mix Design (Data from Naik and Ramme 1990)

Components and ages	Mix 1	2	3	4	5	6
Component						
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
Water/(cement + fly ash)	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
Age	Compressive strengths (MPa) (6.9 MPa = 1,000 psi)					
19 h	18.6	21	22.8	28.3	23.4	21.4
22 h	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

Note: All mixes were for 55-MPa (8,000-psi) concrete and used approximately 610 kg (1,344 lb) of sand and 862 kg (1,900 lb) of course aggregate. The air temperature was 39°C (70°F). 2,662 cm^3 (90 fl oz) of WRDA-19 (water-reducing admixture; calcium naphthalene sulfonate) superplasticizer was added to all mixes. The average slump was 15 cm.

When the amount of fly-ash replacement was increased further, the strength gain at early age was more pronounced. For example, Mix 4, which had 20% fly-ash replacement, had a strength gain of 53, 48, 51, and 50% for the ages of 19 h, 22 h, 3 days, and 7 days, respectively, when compared to Mix 1. Also, the reduction in air content with increasing fly ash shows a decreasing permeability of the mix.

Mix 6, which had the highest fly-ash replacement of 30%, had an even higher strength gain of 65% at the 7-day age.

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 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% cement replacement.

Conclusions

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

1. Improved economics—This is a result of reduced raw-material costs, resulting in more competitive products over a wider geographical region.
2. Reduced environmental impact—There is a direct relationship between reduced cement usage and reduced GHG production.

Also, other research not directly cited in this paper has consistently shown that fly-ash usage in concrete increases the quality of products by giving higher density with reduced permeability.

References

Naik, T. R., and Ramme, B. (1990). "High early strength fly ash concrete for precast/prestressed products." *PCI J.*, 35(6), 72–78.