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High-percentage replacement of cement with fly ash for reinforced concrete pipe

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Abstract

Fly ash is commonly used as a substitute for cement within concrete in various applications. Manufacturers of reinforced concrete products commonly limit the quantity of fly ash used to 25% or less by weight. Test cylinders with varying percentages of Class C (25–65%) and Class F (25–75%) fly ash and a water-reducing admixture (WRA) were created under field manufacturing conditions and tested for 7-day compressive strength. Seven-day compressive strength for the concrete/fly ash/WRA was found to be highest when the concrete mix included approximately 35% Class C or 25% Class F fly ash. However, substitution ratios of up to 65% Class C or 40% Class F fly ash for cement met or exceeded American Society for Testing and Materials (ASTM) strength requirements for manufacture of Class I, II and III reinforced concrete pipe (RCP).
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1. Introduction

The production of fly ash as a by-product of coal-fired electric power plants in the United States was 51.9×10^{6} kg in the year 2000 [1]. Only about 20% of this fly ash was utilized in various commercial applications [2], while the remainder was placed in landfills. Current U.S. environmental regulations have increased the expense associated with landfill disposal of fly ash to about US$3.30 per 1000 kg [3]. Maximizing the use of fly ash to create useable products has been and will continue to be the goal of numerous studies and incentives. A high percentage of the cement within concrete can be replaced by fly ash without adversely affecting concrete properties for specific applications. However, high-percentage replacement of cement by fly ash may result in concrete that has such low workability that it is unusable in common manufacturing processes.

Manufacture of reinforced concrete pipe (RCP) is an application where large volumes of fly ash could be used as a replacement for Portland cement. In addition to providing a means of disposal for a significant quantity of fly ash, use of fly ash in the manufacture of RCP also reduces the quantity of cement required to create each pipe section, which reduces production cost and saves energy. The most commonly manufactured RCP is Class III 450-mm-diameter culvert [4]. Concrete Industries of Lincoln, NE (USA) produced approximately 50,000 sections of Class III 450-mm culvert during the 2002 calendar year [5]. A comparatively low level of Class C fly ash (25% replacement of Portland cement) was used by Concrete Industries for production of this RCP [6].

The American Society for Testing and Materials (ASTM) divides fly ash into two classes, Class F and Class C [7]. Class F fly ash is produced by combustion of anthracite and bituminous coals, while Class C fly ash is a product of combustion of lignite and subbituminous coals. Both classes of fly ash have pozzolanic properties, while Class C fly ash also displays cementitious properties.

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Table 1
Concrete industries mix design (per m^3) for RCP

Sand (kg)	Rock (kg)	Fly ash (kg)	Cement (kg)	Water (kg)	WRA (L)
1510	448	73.5	294	98.9	7.06

Replacement of cement with fly ash in the manufacture of RCP has been shown to provide many significant benefits, including: [8–10]

- Decreases permeability of concrete.
- Improves the resistance of RCP to weak acids and sulfates.
- Improves the workability of concrete.
- Enables pipe production equipment (wings and long bottoms) to last longer due to the lubricating effects of fly ash.
- Increases the cohesiveness of concrete when forms must be removed early.
- Reduces the amount of inside surface hairline cracking due to decreased heat of hydration.

High-percentage replacement of cement with fly ash is recommended only in situations where early compressive strength is not required [11]. Concrete with high percentages of fly ash has been reported to exhibit lower durability with some testing procedures [12], but comprehensive engineering performance test data on concrete with high percentages of fly ash have yet to be published. Researchers in Australia and at the Canada Center for Material and Energy Technology (CANMET) have shown that high percentages of Class F and Class C fly ash can be mixed with water-reducing admixtures (WRAs) and cement to create concrete having the following advantages when compared to mixes without WRAs [13–15]:

- Increased workability.
- Adequate early strength.
- Greater 28-day strength (40 MPa).
- Higher elastic modulus.
- Better long-term durability in chemically aggressive environments.

There have been many studies completed pertaining to fly ash substitution for cement in concrete mixes over the past half century, but no documentation could be found which defines the limits for substitution at the low water/cement ratios commonly used in the manufacture of RCP. This research duplicated as closely as possible the unique processes used in manufacturing RCP in a laboratory setting by using identical mix designs and a vibrating table to consolidate the dry, cementitious mix into compacted cylinders. Cylinders were subsequently removed from the molds immediately after consolidation to duplicate removal of RCP sections from the molding machinery immediately following the manufacturing process.

The objective of this study was to determine limits for concrete mix design using fly ash replacement of cement in the RCP manufacturing process with regards to 7-day compressive strength and to maximize the percentage of fly ash in the RCP manufacturing process through use of a WRA.

2. Materials and methods

2.1. Materials

The base concrete mix was identical to the concrete mix used for Class III RCP mix design (Table 1) at Concrete Industries, which contains 25% ASTM Class C fly ash as a percentage of the total weight of cementitious material. This mix design was developed to provide concrete (containing Class C fly ash) with a minimum compressive strength of 27.6 MPa in accordance with requirements of ASTM C 76(02). Subsequent experimental mixes replaced 25–75% of the Portland cement with Class C or Class F fly ash and a WRA. The WRA was the same type and was used in the same percentage required in the commercial RCP manufacturing process.

ASTM Type I/II cement was used for all concrete mixes. No major compressive strength difference has been documented between the concrete made with ASTM Type I cement whether a WRA is added or not. Concrete made with ASTM Type V cement has been documented to exhibit lower compressive strength when a WRA has been added [16]. The coarse aggregate used in all mixes was crushed limestone. Gradation of coarse aggregate used is shown in Table 2. Fine aggregate used in all mixes was coarse concrete sand. Class C Fly ash used in the concrete mixes was obtained from a coal-fired power plant near Omaha, NE, while Class F fly ash was obtained from a power plant in West Virginia. Fly ash used in all concrete mixes was certified as meeting the standards by class as specified within ASTM C 618.

WRA was added to improve the workability of the fresh concrete and to allow the cylinders to maintain integrity once the molds were removed. The quantity of WRA was based upon the manufacturer's suggested ratio for volume of liquid admixture based upon mass of cement in the mix.

Table 2
Gradation of coarse aggregate

Screen size (mm)	12.5	9.5	4.75	2.36	1.18	0.85	0.074
Min/max specification (%)	0/10	30/60	85/100	95/100	96/100	97/100	98/100
Sample % retained	5	40	96	98	98	98	99

Table 3
Average unit weight (kg/m^3) of concrete mix samples

F/(F+C)	Class C fly ash concrete	Class F fly ash concrete
0.25	–	2387
0.35	2439	2412
0.45	2406	2391
0.55	2423	2352
0.65	2411	2323
0.75	–	2306
Average unit weight	2420	2362

Workability of fresh concrete changes sharply as the quantity of WRA approaches 1.9–2.1% of the weight of cement [17]. Some research suggests that there is no major difference in the compressive strength of concrete regardless of the quantity of WRA added [16], while other research seems to indicate that the compressive strength of concrete containing Type I cement mixed with fly ash decreases when the percentage of WRA is greater than 2% [18]. For this study, the percentage of WRA was limited to a maximum of 2% of the weight of cement in the mix.

2.2. Methods

Based on the Concrete Industries mix design, quantities of materials were scaled to produce sufficient material to create seven 100 mm×20 cm concrete cylinders from each batch of concrete. Batches of concrete were mixed in the laboratory between March and June of 2002 using an electric mixer. The resulting mix was very stiff and had a slump approaching zero. The concrete mix was moved into cylindrical molds and compacted on a vibrating table to duplicate the effects of the revolving compaction tool used in RCP manufacturing process. Samples were removed from cylindrical molds shortly after compaction, corresponding to RCP sections being removed from the molding machinery immediately after compaction during the manufacturing process. Concrete samples were then cured inside a building at room temperature for 7 days. Samples were subsequently capped before being measured, weighed and compression tested to failure.

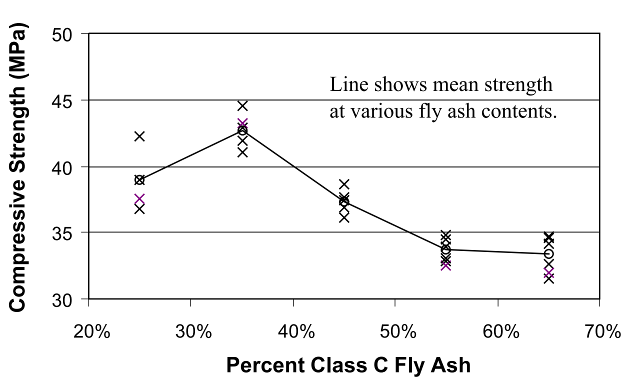

Fig. 1. Compressive strength of concrete with varying percentages of Class C fly ash.

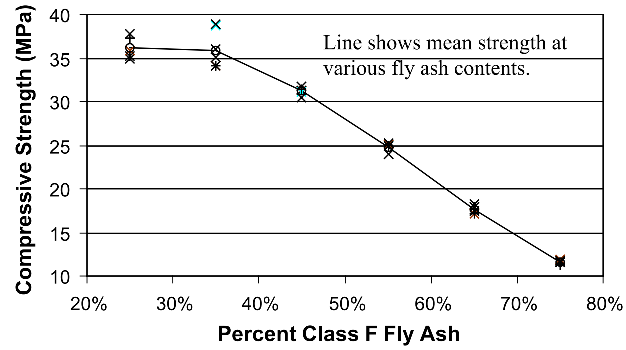

Fig. 2. Compressive strength of concrete with varying percentages of Class F fly ash.

3. Results and discussion

As shown in Table 3, there are no significant differences in unit weight of Class C specimens that can be correlated directly to the different percentages of fly ash contained within. Unit weight of Class F fly ash–concrete specimens peaks between fly ash concentrations of 35% and 45%. This peak corresponds to minimum void ratio, and suggests that maximum compressive strength may lie between these fly ash percentages as well.

Maximum compressive strength was found at a fly ash replacement percentage of 35% for concrete containing Class C fly ash. The mean value of compressive strength for 35% type C fly ash was slightly above 41.5 MPa as shown in Fig. 1. The maximum compressive strength for concrete where cement was replaced with Class F fly ash was at 25% replacement. Maximum compressive strength for concrete containing type F fly ash was approximately 36.0 MPa as shown in Fig. 2.

4. Conclusions

The maximum 7-day compressive strength for concrete containing Class C fly ash was obtained at approximately 35% replacement of cement by fly ash, while Class F fly ash achieved maximum compressive strength at approximately 25% cement replacement. Requirements for Class I, II and III RCP from ASTM C 76(02) mandate concrete with a minimum compressive strength of 27.6 MPa. The 7-day compressive strength of concrete cylinders containing Class C fly ash remains at or above 27.6 MPa until the percentage of fly ash is above 65%. When Class F fly ash is used as a replacement for cement, the 7-day compressive strength remains at or above 27.6 MPa until the percentage of fly ash is approximately 45%. These percentages represent the approximate limits where minimum compressive strength and integrity of the concrete pipe sections (immediately after removal of the forms) can be achieved.

The authors recommend further durability and strength tests on concrete mixes containing 65% replacement of cement by Class C fly ash and 40% replacement of cement by Class F fly ash under actual manufacturing conditions. An increase by 15% in the percentage of Class C fly ash used for cement replacement ratio would require an additional 6600 tons of fly ash per year at Concrete Industries Lincoln manufacturing facility. If a 40% replacement rate of cement by Class C fly ash were used throughout the United States in RCP production, additional fly ash consumed would approach 1.2 million tons annually. A small increase in the percentage of fly ash used in the manufacture of RCP could provide significant benefits, both economically and in the quality of product.

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