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More Sustainable and Economical Concrete Using Fly Ash, Used Foundry Sand, and Other Residuals

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ABSTRACT

The use of fly ash, used foundry sands and cupola slag as a replacement for cement, and fine and coarse aggregates in concrete is examined in this paper. Using these products reduces the carbon foot-print of concrete and leads to more sustainable concrete construction, as well as a reduction in the cost of concrete production. A positive environmental and economical impact is established by the increased use of these recyclable materials in producing structural-grade concrete. This paper looks at a recent construction project and examines the projected savings in cost, raw materials, and greenhouse-gas emissions as a result of using these recyclable materials .

INTRODUCTION

The use of fly ash in concrete has been widely shown to be an effective way to minimize the cost of the concrete by means of partial cement replacement. Using fly ash as a cement replacement also reduces the proportional amounts of Green House Gas (GHG) production and other environmental effects of cement production.

The use of fly ash as a cement replacement also improves the performance of concrete that is made with other recycled by-products.

This paper will examine the potential monetary and environmental savings of combining two by-products. In addition to using fly ash as a cement replacement, the paper will examine the use of recycled foundry sand as a partial replacement for regular fine aggregate. .

FOUNDRY SANDS

The basic processes in a typical foundry include coremaking, molding, melting, pouring, cleaning and inspection. Coremaking and molding usually produce 75% of the various by-products generated by foundries. The remainder is generated mainly by melting operations with minor contributions from cleaning and dust collectors. Typical amounts of total by-products materials from foundries range between 227 to 2270 kg (500 to 5000 pounds) per ton of produced metal castings [Heine, Loper, Santa Maria, Nanninga 1975].

The foundry industry is diverse and complex. Although there are differences in some specific operations, the basic foundry processes vary only slightly from one foundry to another. The main foundry process produces metal or alloy castings by pouring molten metal into molds. The molds may be made of molding sand and core sand or may be of a permanent type made of metal and a refractory lining. After hardening, the castings are removed from the molds, processed and finished. The raw materials (sands) used for making foundry molds are usually recycled. However, after multiple uses, they lose their characteristics, thereby becoming unsuitable for further use in manufacturing processes, and all the raw materials are then discarded as waste. [Naik, Patel 1992] [Greer, Vondracek, Ham, and Oman, 1989].

Sand is used in to make molds for multiple reasons: it can easily withstand the heat of molten metal, it does not chemically react with the metal, and it is permeable enough to allow gasses to escape when the molten metal is poured. Molding sand is compacted and shaped according to the pattern that is going to be produced. This molding sand is typically called “green” sand. Green sands are composed of three major ingredients: silica sand, clay, and water. Silica sand comprises the majority of the materials in a molding [Jain 2003].

Clay acts as a binder for the green sand. Clays form approximately 4 to 10 percent of the green sand mixture. When the green sand is used and reused for molding, the clay particles can fuse and lose their bonding properties. New clay must be added to the green sand during each molding cycle. Reconditioning of sand is one of the most difficult steps.

Sand additives or carbonaceous materials may be added to the molding sand mixture for improving some special features such as surface finish, easier cleaning, burned sand prevention, etc. Many materials are used as molding sand additives. These include coal, wood flour, and silica flour. The selection of a given additive depends on the specific desired properties in the sand mixture.

Core sands are used to produce desired cavities which are not practical to produce by normal molding operations. Core sands are composed essentially of silica sand, without the clay binder but mixed with small percentages of other binders. These binders include oils such as linseed oil, soybean oil, or mineral oil, or synthetic resins. Occasionally, high early strength portland cement is used as a binder.

POTENTIAL USES OF USED FOUNDRY SAND

Portland Cement Production

Portland cement is manufactured by heating a mixture of finely divided calcareous and argillaceous materials in a rotary kiln. The process of manufacturing cement consists essentially of grinding the raw materials, mixing them in required proportions and heating them at about 2500 °F (1370 °C) to sinter and partially fuse the raw materials into balls known as clinkers. This clinker is cooled and ground to a fine powder, with some gypsum, in a ball mill to produce portland cement.

The American Foundrymen's Society (AFS) [American Foundrymen's Society, Inc, 1991] investigated the feasibility of using used foundry sand as a feed material for cement kilns. They carried out a chemical analysis on the used foundry sand using x-ray fluorescence. The results indicated that used sand could be an alternate raw material for cement production.

The AFS produced clinkers in a simulated kiln with raw materials having 0%, 4.5%, 8.9% and 13.4% of used foundry sand. These clinkers were then ground with gypsum to produce cement. These cements were tested for their compressive strength development over 28 days. Tests indicated that inclusion of used foundry sand increased the compressive strength of cement by a small magnitude.

Fine Aggregate Replacement in Concrete

Typical concrete is a mixture of portland cement, coarse and fine aggregates, water, admixtures and additives. In general about 416 to 520 Kg of fine aggregates are used per cubic meter (1200 to 1500 pounds per cubic yard) of concrete. The AFS recommended that fine aggregates could be replaced by 33% of used foundry sands in a batch of normal weight concrete.

The Center for By Products Utilization (CBU) at the University of Wisconsin - Milwaukee ran multiple tests of concrete made with used foundry sand as a replacement for regular sand. The data from three of those tests will be used in this report.

In one test [Naik, Patel, Parikh and Tharaniyil. 1992], the CBU decided to make and test two batches of concrete with 25% and 35% foundry sand to normal sand replacement percentages. Table 1 describes the mix quantities. Mix 1 is the control mix, with no foundry sand. Mix 2 and 3 had "used" foundry sand (foundry sand that has been used in molding). All the mixes were proportioned to achieve a 28 day compressive strength of 38 MPa (5.5 Ksi). Three cylinders were tested at each age.

Table 1. Mix and test data [Naik, Patel, Parikh and Tharaniyil. 1992]

Materials: All mixes designed for a 28 day strength of 38 Mpa (5.5 Ksi).	Mix Number		
	1	2	3
Cement (Kg / M^3)	362	362	362
Water (Kg / M^3)	173	173	173
19 mm Coarse Aggregate (Kg / M^3)	1,074	1,074	1,074
New Concrete Sand (Kg / M^3)	859	644	558
Used Foundry Sand (Kg / M^3)	0	215	300
Measured slump (mm)	152	32	29
Test age (days)	Average Compressive Strength (MPa)		
7	36.9	27.9	26.9
28	43.8	33.6	30.7

The results show that mixes with used foundry sand had substantially lower values of slump. The tests also showed that foundry sand gave a strength that was substantially lower that the non foundry sand mix. Both of these effects are believed to be caused by the presence of the binders (primarily clay) used in the foundry sand.

To research this effect further, the CBU performed another set of tests [Naik, Singh, Tharaniyil, and Wendorf. 1996]. The mix is defined in Table 2. These tests were run with used foundry sand from two different foundries at a 35% replacement to regular concrete sand. As before, these tests showed that the inclusion of used foundry sand as a replacement for regular sand resulted in a lower compressive strength.

Table 2. Mix and test data [Naik, Singh, Tharaniyil, and Wendorf. 1996]

All mixes designed for a 28 day strength of 55 Mpa (8 Ksi)			
Materials	Mix Number		
	1	2	3
Cement (Kg / M^3)	481	481	481
Water (Kg / M^3)	136	136	136
19 mm Coarse Agg. (Kg / M^3)	600	600	600
New Concrete Sand (Kg / M^3)	1216	790	790
Used Foundry Sand (Kg / M^3)	0	426	426
Test age (days)	Average Compressive Strength (MPa)		
7	40.5	40.4	38.9
28	53.4	43.2	41.1

Many tests have shown that the addition of fly ash results in an increased compression strength. Researchers at the CBU decided to combine fly ash with used foundry sand to see if the fly ash improved the strength of the concrete. Table 3 illustrates the mix design for these tests [Naik, Singh, Kraus, Ramme, and Domann 2001]. In this study, fly ash was added as an additional cementitious material. In general, inclusion of the fly ash improved concrete performance significantly. Fly ash content was varied from 14% to 25% of total cementitious materials used. All concrete mixtures up to 40% foundry sand (clean or used) with fly ash contents up to 25% outperformed the reference concrete (mix 1). This was attributed to generation of additional C-S-H crystals resulting from cementitious and pozzolanic reactions of the fly ash. This test also reinforced the long established principle that concrete with fly ash increases strength with age more than concrete made with just cement.

Table 3. Mix and test data [Naik, Singh, Kraus, Ramme, and Domann 2001]

All quantities in Kg / M^3, all mixes designed for 31 Mpa (4.5 Ksi)							
Mix	1	2	3	4	5	6	7
Cement	336	327	332	207	323	327	329
Water	163	161	160	155	158	157	162
Fly Ash	0	68	82	94	106	53	54
19 mm Agg.	997	969	983	971	956	970	972
New Sand	797	694	599	539	460	619	460
Used Foundry Sand	0	77	158	231	307	155	312
Slump (mm)	133	127	102	102	102	127	95

Tested Compressive Strength (MPa) (1 MPa = 0.145 Ksi)		
Time of test	Mix1	Mixes 2-7
3 days	23	22 to 26
7 days	26	25 to 30
28 days	32	31 to 37
91 days	38	41 to 49
182 days	40	42 to 51

To illustrate the economic and environmental benefits that could be achieved by the combination of fly ash and used foundry sand, two buildings recently constructed in the Milwaukee area are examined.

COMPARISON STRUCTURE 1

Johnson Controls Inc., a leader in manufacturing heating and cooling controls for buildings, recently has undertaken a $45 million expansion and upgrade of its international headquarters. They wanted this building to be a prototype for sustainable environmental design. Johnson Controls is headquartered at 5757 N. Green Bay Ave, Glendale, WI USA. Glendale is a northern suburb of Milwaukee.

The expansion plans were unveiled in August 2007 and construction was completed in the spring of 2009. Three new structures were built: an office building, a parking garage and a amenity building that will be a fitness center and a cafeteria for employees.

The new office building is a two-story structure that can be expanded to four. The structure had a cast in place basement level (Figures 1) and a 2 story steel structure above grade with floors of concrete on metal deck. This structure used about 9,150 m^3 of concrete. The concrete had different mix designs for the different structural elements as shown in Table 4. What can first be seen from Table 4 is that all the concrete mixes incorporated fly ash. Most of the structural mixes had 20% fly ash, the footings had 25% fly ash, and the low strength structural fill had 62% fly ash. For the entire structure, we can see that this saved over 600,000 Kg of cement which amounts to a monetary savings of over $50,000 and an environmental savings from the 600,000 Kg of Green Houses Gases (GHG's) that did not have to be produced to make this cement.

Table 4. Mix data from Johnson Controls Office Building

Mix 1, Footings designed for 21 MPa (3 Ksi) Mix 2, Int Beams, Cols, Slabs 27.5 MPa (4 Ksi) Mix 3, Ext Columns 31 MPa (4.5 Ksi) Mix 4, Lean Fill 10 MPa (1.5 Ksi)				
Mix	1	2	3	4
Cement (Kg / M^3)	209	256	307	71
Water (Kg / M^3)	142	142	133	152
Fly Ash. (Kg / M^3)	71	65	77	119
19 mm Agg. (Kg / M^3)	1116	1157	1068	1127
Sand (Kg / M^3)	890	837	736	801

Fig. 1. Johnson Controls Footings and Flowable Fill

Fig. 2 Johnson Controls Precast parking structure

The use of fly ash in all the cast in place concrete mixes is a commendable step in the right direction. However, if this concrete would have also used foundry sand at a 40% replacement ratio, this building could have saved the cost of nearly 1,500 m^3 of sand (about $3,500) along with the environmental savings of excavation and transportation. Since fly ash was already present, the inclusion of foundry sand would not have reduced the finished strength of the concrete. Comparing Tables 3 and 4, it can be seen that the actual mix used in the Johnson Controls project is very similar to some of the test mixes and the resultant strength is greater than specified for the project.

The 300-car parking garage (Figure 2) has three decks but also can be expanded. It was fabricated of all precast - prestressed concrete members. In contrast to the office building, this precast structure used no fly ash or other by products in the mix. The precast concrete members used 989,000 Kg (nearly 1,100 tons) of cement. Cement in the USA costs about $115 dollars per ton, so the cement in the precast cost about $126,500. If fly ash were substituted for cement at the 30% replacement level, it would have saved nearly $25,000 and also reduced the production of GHG's about 300,000 Kg (330 tons).

These buildings were designed with many energy conservation measures such as green roofs, wind turbines, solar panels and even a geothermal field. All were included in the design to save money and energy in the future. The office building saved money and reduced GHG's by the use of fly ash. However, if the engineers had done a little more work on the cast in place and precast mix designs, this building could have doubled the savings in both money and GHG's. This would also have eliminated the need to dispose of the fly ash and foundry sand which would have been beneficially used instead.

COMPARISON STRUCTURE 2:

The Park Lafayette condominiums in Milwaukee WI, USA. This project is composed of twin 20 story towers. Each floor has 7 or 8 condominium units (figures 3-5). This structure is constructed entirely of cast in place concrete. This building used fly ash in all of its mixes as shown in Table 5. There is a wide variety of concrete strengths, from a low of 27.5 MPa (4 Ksi) to a high of 69 MPa (10 Ksi). The percent of fly ash used decreased as the concrete strength increased. There is a common misconception that high strength concrete cannot be produced with a high percentage of fly ash. Research, however, has shown this assumption to be wrong, but that issue is not being addressed in this paper.

Table 5. Mix data from Park Lafayette Building

Mix 1, Shear walls, beams 27.5 Mpa (4 Ksi) Mix 2, Structural flat slabs, beams 34 Mpa (5 Ksi) Mix 3, Pile caps, grade beams, exterior columns 42 Mpa (6 Ksi) Mix 4, High strength concrete for interior columns 69 MPa (10 Ksi)				
Mix	1	2	3	4
Cement (Kg / M^3)	251	307	349	564
Water (Kg / M^3)	142	142	152	204
Fly Ash. (Kg / M^3)	59	71	71	44
Fly Ash / Cement (%)	19.1	18.8	16.9	7.3
19 mm Agg. (Kg / M^3)	1068	1127	1068	1068
Sand (Kg / M^3)	914	801	777	504

This building used about 21,660 m^3 (28,330 Cu Y) of concrete. The amount of fly ash used averaged about 15.8%. This represents a total of 3,400 m^3 of fly ash used and cement saved. Using this volume of fly ash means that nearly $433,000 and 5,200,000 Kg of CO2 and other GHG's were saved because of cement replacement.

This building also used over 16,500,000 Kg of sand. Based on the research cited earlier, and since fly ash is already present in the mix, the mix designers could have substituted used foundry sand for regular sand at a 30% replacement. This would create the savings of nearly 5,000,000 Kg of sand. This represents over 3,000 m^3 of new sand that would not have to be mined and transported, and 3,000 m^3 of used foundry sand that would not have to be land filled.

Fig. 3 Park Lafayette Rendering.

Fig. 5 Park Lafayette Construction

Fig. 4 Park Lafayette Construction.

ADDITIONAL BY-PRODUCTS THAT COULD BE INCORPORATED

Cupola Slag:

Foundries for the metal-casting industry generate cupola slag during melting operations. Cupola slag can be used as coarse aggregate in concrete. The density (1280 Kg/m3 [80 lb/ft3]) of cupola slag is between that of normal weight aggregate (1600 kg/m3 [100 lb/ft3]) and structural lightweight aggregate (1120 Kg/m3 [70 lb/ft3]). The water absorption of cupola slag is lower than that for the structural lightweight aggregate [Naik, Singh, Kraus, Ramme, and Domann (2001)]. This slag could have been combined with fly ash and used foundry sand and incorporated in the Johnson Controls low strength fill mix shown in table 4.

SUMMARY

Engineers and suppliers are aware that the use of fly ash in concrete is a proven way to increase strength and durability while decreasing costs and GHG emissions. The next logical step is to educate these engineers in the potential savings from the use of two or more by-products in the mix design. This paper has illustrated the savings in money and GHGs that could have been realized with the combination of fly ash and used foundry sand.

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