

Center for By-Products Utilization

ENHANCED MATERIALS FOR CONCRETE CONSTRUCTION USING FOUNDRY BY- PRODUCTS

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Enhanced Materials for Concrete Construction Using Foundry By-Products

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Synopsis: This research was carried out to develop concrete mixtures incorporating used foundry sand. Eleven concrete mixtures including a reference concrete mixture were proportioned to obtain the 28-day compressive strength of 31 MPa (4,500 psi). Foundry sands (clean or used) were used to replace regular concrete sand. A Class C fly ash was used as an additional cementitious material up to 25% of total cementitious materials used. Density, compressive strength, flexural strength, modulus of elasticity, and abrasion resistance for all concrete mixtures were measured. Based on the results obtained in this investigation, it was concluded that structural-grade concrete can be manufactured using up to 40% used or clean foundry sand with or without Class C fly ash.

Keywords: By-products, compressive strength, clean foundry sand, concrete, flexural strength, fly ash, modulus of elasticity, used foundry sand.

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INTRODUCTION

Large volumes of foundry by-products are generated in the U.S.A. Wisconsin alone produces about 800,000 tons of used foundry sand. Foundry by-products are composed of used or spent foundry sand, slag, broken core-butt, dust-collector fines, etc. Used foundry sand forms the major component. Molding and coremaking operations account for over 75% all by-products

generated in foundry industries. These operations require large amounts of sand, binder materials, and additives. Silica sand comprises about 50 to 95% of the total material used in manufacture of sand molds.

Numerous feasibility studies [1-18] have been conducted in the past to determine suitability of foundry sand as a constituent of construction materials. These studies have indicated that used foundry sand has significant potential for various applications including portland cement concrete [1, 2, 5, 9-11, 15-18], asphalt concrete [1, 2, 6, 8, 15], Controlled Low Strength Materials (CLSM) [3, 4, 12], masonry products [1, 2, 5, 9, 10, 11, 16], and other miscellaneous applications [1, 2, 6, 13, 14, 16]. However, currently a large portion of the used foundry sand generated in the U.S.A. is landfilled. This may be due to insufficiently developed high-volume use technologies for used foundry sand, non-uniform quality of available used foundry sand materials, and/or regulatory constraints.

The UWM Center for By-Products (CBU) Utilization started research in 1989 [1] to establish applications of used foundry sand in cement-based materials. The CBU has developed low-cost used foundry sand containing concrete [2, 4, 5, 9, 10, 11, 16-18], CLSM [2, 3, 4, 12], and masonry products [9, 10, 11, 16]. This investigation is a part of the research completed at CBU pertaining to development of low-cost, durable concrete incorporating large amounts of used foundry sand.

Previous investigations [2, 9, 10] have shown that the application of used foundry sand causes a reduction in the strength of concrete. This was partly attributed to finer sand particles increasing water demand in concrete and presence of impurities in the used foundry sand compared to the regular concrete sand. The investigation described here was undertaken to solve the problems associated with the decrease in the strength of concrete made with used foundry sand and to establish technology for manufacturing of high-volume foundry sand (HVFS) concrete systems.

RESEARCH SIGNIFICANCE

This research was performed to establish concrete mixture proportions and to determine the effects of used foundry sand with and without fly ash on mechanical properties and abrasion resistance of concrete. Application of used foundry sand in concrete will lead to diversion of large amounts of used foundry sand from landfilling to manufacturing of concrete and other cement-based products.

EXPERIMENTAL PROGRAM

Two series of experiments were conducted. The first series of experiments were conducted to establish the effects of used and clean foundry sands on mechanical properties and abrasion resistance of concrete. The second series of tests were conducted to establish the combined influence of the foundry sands and fly ash on mechanical properties and abrasion resistance of concrete.

Materials

Sand -- Three types of sand, one used foundry sand (UFS), one clean foundry sand (CFS) and one regular concrete sand (CS), were used in this investigation. All physical properties, except for soundness, of these sands were determined using appropriate ASTM standards (Table 1). A modified ASTM C 88 was employed to measure soundness of the foundry sands. Per ASTM C 88 test standards, the test sample shall be such that it contains 100 grams of all materials retained on each of No. 4 (4.75 mm), No. 8 (2.36 mm), No. 16 (1.18 mm), No. 30 (600 μm), and No. 50 (300 μm) sieves, and respectively passing through sieves 9.5 mm (3/8 in.), No. 4 (4.75 mm), No. 8 (2.36 mm), No. 16 (1.18 mm), and No. 30 (600 μm). Because foundry sand was finer than No. 30 sieve, only about 0.2 to 2.1 percent of the sands was retained on No. 4 (4.75 mm) to No. 30 (600 μm) sieve. As a result, the ASTM sample requirement was modified to evaluate the soundness of the foundry sands for this work. For this investigation, one sample was utilized (100 grams passing through No. 30 (600 μm) sieve and retained on No. 50 (300 μm) sieve) for measurement of soundness.

The physical properties data for the sand materials are given in Table 1. The properties of used foundry sand varied depending upon the type of metal cast and foundry processing equipment used, type of additive for mold making, the number of times the sand is recycled in the process, and the type and amount of binder used. The unit weight of the used sand was greater than that of the clean sand. This is probably due to attached particles of materials such as steel pellets bonded to the sand during the foundry process. Both the clean and used foundry sands exhibited high absorption values compared to the regular concrete sand. However, the difference between the values for clean and used foundry sands was small. The material finer than No. 200 (75 μm) sieve was slightly higher for the used foundry sand, relative to the clean foundry sand. The difference in the results probably was due to the presence of clay binders in the used foundry sand. The results for the sand used for this project showed low values of clay lumps and friable particle for all sands tested; all the values were less than the allowable ASTM limit. However, the used foundry sand had the

highest value of all the sands tested. This is primarily because of the presence of clay binder in the used foundry sand, which probably dissolved during the soaking in water for 24 hours and was washed away when sieved in accordance with ASTM C 142.

The mass losses suffered were 9.8% for the regular concrete sand and 10.5% for the clean foundry sand when subjected to the soundness test in accordance with ASTM C 88. Thus, both the sands showed values below the ASTM limit of 12 percent. However, the loss for the used foundry sand was very high (50.6%). This occurred because the used sand particles were weakened due to the temperature shock that occurs during molding operations. This led to cracking and quicker deterioration of the used sand particles in the chemicals used for the soundness test per ASTM.

The sieve analysis grading curves for the sands are plotted in Fig. 1. These curves show that both the clean foundry sand and the used foundry sand are finer and they are outside the ASTM limits. The grading curves exhibit that the foundry sands contain predominantly finer particles compared to those of regular sand. About 50 to 60 percent of the clean and used foundry sands passed through the No. 50 sieve (95 to 100 percent passed No. 30 sieve).

Cement -- A Type I cement secured from one source was used throughout this investigation. Its physical and chemical properties were determined in accordance with applicable ASTM test methods. The test data on the cement are given in Table 2. The cement conformed to the ASTM C 150 specification for Type I cement.

Fly Ash -- An ASTM Class C fly ash obtained from one source in Wisconsin, was used in this work. Its physical and chemical properties were determined in accordance with ASTM C 311. The test data on the fly ash are shown in Table 2. The fly ash conformed to the ASTM C 618 requirements for Class C fly ash, except the sodium oxide content was slightly higher than allowable per ASTM C 618.

MIXTURE PROPORTIONS

Eleven concrete mixtures were developed for this investigation. A reference mixture (R0+0) containing no by-product materials was proportioned to attain a compressive strength of 31 MPa (4,500 psi) at the age of 28 days. Four mixtures were proportioned to contain used or clean foundry sand as a replacement of 20 to 40% regular concrete sand. The remaining six mixtures were proportioned with used or clean foundry sand as a replacement of concrete sand, and with fly ash as an additional cementitious material. The water to

cement ratio (W/C) was kept at about 0.48 ± 0.01 for all mixtures. The water to cementitious materials ratio (W/C_m) for fly ash concrete mixtures was 0.39 ± 0.03 . These mixtures were air-entrained to maintain air content of about $6\% \pm 0.5\%$, using an air entraining agent (ASTM C 260). The mixture proportion data are presented in Table 3.

CONCRETE MIXING, PREPERATION OF SPECIMENS, AND TESTING OF SPECIMEN

All concrete mixtures were mixed in a 0.14 m^3 (5 ft^3) capacity electric tilting-drum type rotating mixer. The fine aggregate, coarse aggregate, foundry sand, cement, and fly ash were mixed dry for two minutes. Then water and air-entraining agent were added and the concrete was mixed for an additional period of three minutes followed by a period of three-minute rest, and then followed by a period of two more minutes of mixing. Fresh concrete properties such as slump (ASTM C 143), unit weight (ASTM C 138), air content (ASTM C 231), and concrete temperature (ASTM C 1060) were measured. Ambient air temperature was also recorded.

All test specimens were prepared and cured in accordance with ASTM C 192. Cylindrical specimens $150 \times 300 \text{ mm}$ ($6 \times 12 \text{ in.}$) were made for measurements of compressive strength (ASTM C 39) and modulus of elasticity (ASTM C 469). Beam specimens of $75 \times 100 \times 300 \text{ mm}$ ($3 \times 4 \times 12 \text{ in.}$) were made for flexural strength (ASTM C 78) determinations.

Test specimens of $300 \times 300 \times 100 \text{ mm}$ ($12 \times 12 \times 4 \text{ in.}$) were cast for abrasion resistance determination. An accelerated test method, a modified ASTM C 944, as described in detail elsewhere [17, 18,], was used to measure abrasion resistance of concrete. In this method, a rotating cutter was equipped with washer having smaller diameter relative to the dressing wheels. Furthermore, an equal amount of silica sand ("Ottawa Sand") was added to the concrete surface during exposure to abrasion at one-minute intervals. One level teaspoon of sand was added each time. At each wear location (circle of wear), for each wear time, three readings were taken along two lines in the worn circle; and, the average of these six readings were recorded as one reading for each experimental condition.

RESULTS AND DISCUSSIONS

Fresh Concrete Properties

The fresh concrete properties such as slump, air content, temperature, density, and ambient air temperature are given in Table 3. The slump of the concrete mixtures varied between 75 to 160 mm (3 to 6 ½ in.). Air content of the mixtures varied between 5.1 and 6.3%. Inclusion of fly ash in the concrete mixtures decreased the water to cementitious materials ratio to a marked extent. The fresh concrete properties were not greatly affected by inclusion of either used or clean foundry sand.

Hardened Concrete Properties

Concrete Density -- The hardened densities of concrete mixtures were generally higher than their respective fresh densities. This was attributed to the densification of concrete matrix. Addition of fly ash increased the density of mixtures containing up to 20% used foundry sand. However, densities of the mixtures made with 40% foundry sands (used or clean) were not considerably affected due to the inclusion of fly ash up to 25%.

Compressive Strength of Concrete -- Test data on compressive strength are presented in Fig. 2. The results showed that the compressive strength of concrete was not greatly influenced by inclusion used or clean foundry sand up to 40% as a replacement of concrete sand. However, concrete made with 40% clean sand showed slightly higher compressive than the reference mixture. The compressive strengths of the reference mixture were about 23.1 MPa (3350 psi) at 3 days, 25.6 MPa (3710 psi) at 7 days, 32.1 MPa (4650 psi) at 28 days, 38.3 MPa (5550 psi) at 91 days, and 39.5 MPa (5730 psi) at 182 days. The compressive strengths of concrete mixtures containing up to 40% foundry sand varied from 21.6 to 25.9 MPa (3130 to 3750 psi) at 3 days, from 25.0 to 30.3 MPa (3620 to 4400 psi) at 7 days, from 30.9 to 36.8 MPa (4480 to 5340 psi) at 28 days, from 36.8 to 42.2 MPa (5340 to 6120 psi) at 91 days, and from 38.5 to 43.2 MPa (5590 to 6270 psi) at 182 days.

The compressive strengths of mixtures containing up to 40% foundry sands and fly ash up to 25% ranged from 25.7 to 30.3 MPa (3730 to 4390 psi) at 3 days, 28.3 to 34.5 MPa (4110 to 5010 psi) at 7 days, 36.4 to 42.4 MPa (5280 to 6150 psi) at 28 days, 41.1 to 49.0 MPa (5960 to 7110 psi) at 91 days, and 42.0 to 50.5 MPa (6090 to 7320 psi) at 182 days.

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. This was attributed to generation of additional C-S-H crystals resulting from cementitious and pozzolanic reactions of the fly ash. Although the use of large amounts of used foundry sand did not decrease compressive strength in this investigation, previous studies [9-11, 16] had recorded reduction in strength of concrete due to incorporation of used foundry sand above 20% compared to the reference concrete containing regular concrete sand. Since variation occurs in the quality of used foundry sand, it would be desirable to add fly ash in design of concrete mixtures to compensate for variation in the potential decrease in the strength. Additionally, as indicated before, the use of fly ash would also result in a better quality structural-grade foundry sand concrete compared to the reference concrete without any by-product material.

Flexural Strength --The flexural strength data for the concrete mixtures are shown in Fig. 3. The concrete mixtures containing up to 20% used or clean foundry sand exhibited flexural strength equivalent to the reference mixture. Application of 40% used foundry sand diminished the flexural strength slightly while the use of 40% clean foundry increased it slightly relative to the reference mixture. However, all mixtures with and without foundry sand attained high flexural strengths appropriate for structural applications. The control mixture showed flexural strength values of 4.2 MPa (610 psi) at 7 days, 4.9 MPa (715 psi) at 28 days, and 5.2 MPa (750 psi) at 91 days. The flexural strength values for the mixtures incorporating clean or used foundry sand varied from 3.9 to 4.4 MPa (570 to 635 psi) at 7 days, 4.4 to 5.1 MPa (645 to 740 psi) at 28 days, and 4.2 to 5.7 MPa (615 to 820 psi) at 91 days.

Inclusion of fly ash improved the flexural strength of concrete similar to that observed for compressive strength. However, significant improvement in the flexural strength was noticed for fly ash content above 17%. The flexural strengths of the mixtures containing clean and used foundry sands up to 40% and fly ash up to 25% ranged from 4.3 to 5.5 MPa (630 to 795 psi) at 7 days, from 4.4 to 5.6 MPa (645 to 810 psi) at 28 days, and from 5.0 to 5.8 MPa (720 to 835 psi) at 91 days.

Modulus of Elasticity --The modulus of elasticity data are shown in Fig. 4. All concrete mixtures containing up to 40% of clean or used foundry sand showed modulus of elasticity values equivalent to the reference mixture. The modulus of elasticity values for the reference mixtures were 21.4 GPa (3.1×10^6 psi) at 3 days, 23.4 GPa (3.4×10^6 psi) at 7 days, 26.2 GPa (3.8×10^6 psi) at 28 days, 29.0 GPa (4.2×10^6 psi) at 91 days, and 30.3 GPa (4.4×10^6 psi) at 182 days. The modulus of elasticity concrete mixtures containing up to 40% foundry sands

ranged from 21.4 to 25.5 GPa (3.1×10^6 to 3.7×10^6 psi) at 3 days, from 22.8 to 25.5 GPa (3.3×10^6 to 3.7×10^6 psi) at 7 days, from 24.1 to 29.0 GPa (3.5×10^6 to 4.2×10^6 psi) at 28 days, from 27.6 to 30.3 GPa (4.0×10^6 to 4.4×10^6 psi) at 91 days, and 29.6 to 31.0 GPa (4.3×10^6 to 4.5×10^6 psi) at 182 days.

Inclusion of foundry sands (used or clean) with fly ash did not cause appreciable effect on the modulus of elasticity of concrete within the experimental range. The modulus of elasticity values of concrete mixtures containing foundry sands up to 40 % and fly ash up to 20% ranged from 20.7 to 24.8 GPa (3.9×10^6 to 3.6×10^6 psi) at 3 days, 23.4 to 24.8 GPa (3.4×10^6 to 3.6×10^6 psi) at 7 days, 27.6 to 31.0 GPa (3.9×10^6 to 4.5×10^6 psi) at 28 days, 27.6 to 31.1 GPa (4.0×10^6 to 4.5×10^6 psi) at 91 days, and 29.0 to 31.0 MPa (4.2×10^6 to 4.5×10^6 psi) at 182 days.

Abrasion Resistance --The depth of abrasion data for the concrete mixtures are shown in Fig. 5 through 7. The depth of wear of concrete is inversely proportional to its compressive strength. No definite trend could be established concerning the effects of age and mixture proportions on concrete resistance to abrasion. Mixtures U20+20 (2.1 mm), U30+22 (2.4 mm), U40+25 (2.3 mm) exceeded 2.0 mm depth of abrasion while the remaining mixtures attained depth of abrasion less than 2 mm at the age of 28 days. Beyond 28 days, all mixtures made with or without foundry sands of fly ash exhibited depth of abrasion values less than 2.0 mm. Thus, all concrete mixtures with or without foundry sand attained high resistance to abrasion.

CONCLUSIONS

Based on the data recorded in this work, the following major conclusions may be drawn.

1. Both foundry sands (used or clean) did not pass all ASTM C 33 requirements for fine aggregate for use in concrete. These foundry sands contained higher amounts of fine particles relative to regular concrete sand.
2. Inclusion of used foundry sand up to 40% replacement of regular concrete sand produced compressive strength equivalent to the reference mixture. The 40% clean foundry sand mixture showed slightly higher strength than the reference mixture.
3. Inclusion of fly ash improved compressive strength of concrete mixtures incorporating up to 40% foundry sand (clean or used). All concrete mixtures with up to 40% foundry sands (used or clean) and up to 25% fly ash outperformed the reference mixture.

4. The effect of foundry sands and fly ash on the flexural strength of the concrete mixtures was similar to that observed for the compressive strength.
5. The modulus of elasticity concrete was not considerably affected by inclusion of used foundry sand or Class C fly ash within the experimental range.
6. All concrete mixtures with and without foundry sand exhibited high resistance to abrasion.
7. All the concrete mixtures proportioned with up to 40% used foundry sand with or without fly ash exhibited strength properties appropriate for most structural applications.

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Table 1 Physical Properties of Fine Aggregates

	As Received Moisture Content, %	Unit Weight, kg/m ³ (lb/ft ³)	Bulk Specific Gravity	Bulk Specific Gravity, SSD	Apparent Specific Gravity	SSD Absorption, %
ASTM	C 566	C 29	C 128	C 128	C 128	C 128
Sand 1	0.39	1762 (110)	2.66	2.70	2.76	1.4
Sand 2	0.19	1730 (108)	2.38	2.50	2.70	4.5
Sand 3	0.25	1785 (111.4)	2.44	2.57	2.79	5.0
Coarse Aggregate	0.25	1487 (92.8)	2.68	2.69	2.71	0.5

	Percent void, %	Fineness Modulus	Clay Lumps & Friable Particles, %	Soundness of Aggregates Loss of, %	Material Finer than #200 Sieve, %
ASTM	C 29	C 136	C 142	C 88	C 117
Sand 1	33.7	3.57	0.2	9.8	1.35
Sand 2	33.8	2.33	0.3	10.3	0.17
Sand 3	34.8	2.32	0.6	50.6	1.08
Coarse Aggregate	44.7	NA	0.3	NA	NA

Sand 1: Regular Concrete Sand

Sand 2: Badger Clean Sand

Sand 3: Maynard Used Sand

NA = Not Available

Table 2 Properties of Cement and Fly Ash Used

Chemical composition (%)	Cement	ASTM C 150, Type I	Fly Ash	ASTM C 618, Class C Fly Ash
Silicon dioxide, SiO ₂	19.4	-	30.7	-
Aluminum oxide, Al ₂ O ₃	4.3	-	16.7	-
Ferric oxide, Fe ₂ O ₃	2.6	-	5.4	-
Total, SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃	26.3	-	52.8	50.0 min.
Sulfur trioxide, SO ₃	2.4	3.0 max.	0.0	5.0 max.
Calcium oxide, CaO	64.7	-	29.7	-
Magnesium oxide, MgO	1.8	6.0 max.	4.6	-
Titanium dioxide, TiO ₂	0.0	-	1.5	-
Potassium oxide, K ₂ O	0.7	-	0.4	-
Sodium oxide, Na ₂ O	0.1	-	1.8	1.5 max.
Moisture content	-	-	0.1	3.0 max.
Loss on ignition	1.4	3.0 max.	0.3	6.0 max.
Physical Properties of Cement				
Air content (%)	8.7	12 max.	-	-
Fineness (m ² /kg)	383	280 min.	-	-
Autoclave expansion (%)	0.02	0.8 max.	-	-
Specific gravity		-	-	-
Compressive strength MPa				
1-day	13.0	-		
3-day	25.7	-	-	-
7-day	31.3	12.4 min.	-	-
28-day	37.5	19.3 min.	-	-
Vicat time of initial Set (min)	163	45 min. 375 max.	-	-
Physical Properties of Fly ashes				
Fineness retained on No. 325 sieve (%)	-	-	15.4	34 max.
Pozzolanic activity index with cement, 28-day (% of control)	-	-	75	75 min.
Water requirement (% of control)	-	-	99.8	105 max.
Autoclave expansion (%)	-	-	0.01	0.8 max.
Specific gravity	-	-	2.2	-

Table 3 Mixture Proportion Data

Mix Number*	R0+0	U20+0	U40+0	C20+0	C40+0
Design Strength, MPa (psi)	31 (4500)	31 (4500)	31 (4500)	31 (4500)	31 (4500)
Cement, kg/m ³ (lbs/cu yd)	336 (567)	336 (566)	335 (565)	336 (566)	340 (574)
Fly Ash, kg/m ³ (lbs/cu yd)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Water, kg/m ³ (lbs/cu yd)	163 (274)	166 (279)	164 (276)	163 (274)	162 (273)
Sand, SSD, kg/m ³ (lbs/cu yd)	797 (1343)	635 (1071)	476 (803)	636 (1072)	487 (820)
Foundry Sand, SSD, kg/m ³ (lbs/cu yd)	0 (0)	160 (269)	318 (535)	159 (268)	323 (545)
¾" Aggregates SSD, kg/m ³ (lbs/cu yd)	997 (1680)	997 (1680)	993 (1673)	997 (1680)	1010 (1703)
Slump, mm (inches)	133 (5 ¼)	159 (6 ¼)	152 (6)	104 (4)	76 (3)
W/C Ratio	0.48	0.49	0.49	0.48	0.47
W/Cm Ratio	0.48	0.49	0.49	0.48	0.47
Air Content, %	5.8	6.3	6.3	5.9	5.1
Air Temperature, °C (°F)	22 (72)	24 (75)	23 (73)	22 (72)	22 (72)
Concrete Temperature, °C (°F)	21 (70)	23 (73)	24 (75)	26 (78)	27 (80)
Fresh Concrete Density, kg/m ³ (lb/ft ³)	2290 (143)	2290 (143)	2290 (143)	2290 (143)	2323 (145)
Hardened Concrete Density, kg/m ³ (lb/ft ³)	2387 (149)	2355 (147)	2371 (148)	2339 (146)	2371 (148)

* R_{i+j} , U_{i+j} , and C_{i+j} are reference mixture, mixtures containing used foundry sand, and mixtures containing clean foundry sand, respectively. The number i refer to percent of regular concrete sand replacement and j refers to percent of fly ash addition.

Table 3 Mixture Proportion Data (cont'd.)

Mix Number	U10+17	U20+20	U30+22	U40+25	C20+14	C40+14
Design Strength, MPa (psi)	31 (4500)	31 (4500)	31 (4500)	31 (4500)	31 (4500)	31 (4500)
Cement, kg/m ³ (lbs/cu yd)	327 (551)	332 (560)	207 (549)	323 (545)	327 (551)	329 (554)
Fly Ash, kg/m ³ (lbs/cu yd)	68 (114)	82 (138)	94 (158)	106 (178)	53 (90)	54 (91)
Water, kg/m ³ (lbs/cu yd)	161 (271)	160 (270)	155 (262)	158 (267)	157 (265)	162 (273)
Sand, SSD, kg/m ³ (lbs/cu yd)	694 (1170)	599 (1010)	5389 (908)	460 (776)	619 (1043)	460 (775)
Foundry Sand, SSD, kg/m ³ (lbs/cu yd)	77 (130)	158 (267)	231 (390)	307 (517)	155 (261)	312 (526)
¾" Aggregates SSD, kg/m ³ lbs/cu yd	969 (1633)	983 (1657)	971 (1636)	956 (1611)	970 (1635)	972 (1638)
Slump, mm (inches)	127 (5)	102 (4)	102 (4)	102 (4)	127 (5)	95 (3 ¾)
W/C Ratio	0.49	0.48	0.46	0.49	0.48	0.49
W/Cm Ratio	0.41	0.39	0.38	0.36	0.42	0.42
Air Content, %	5.5	5.5	5.2	5.4	6.2	6.2
Air Temperature, °C (°F)	23 (73)	24 (75)	22 (72)	22 (72)	22 (72)	23 (73)
Concrete Temperature, °C (°F)	26 (78)	24 (76)	10 (50)	25 (77)	24 (76)	22 (72)
Fresh Concrete Density, kg/m ³ (lb/ft ³)	2290 (143)	2323 (145)	2339 (146)	2307 (144)	2275 (142)	2290 (143)
Hardened Concrete Density, kg/m ³ (lb/ft ³)	-	-	2371 (148)	2339 (146)	-	2339 (146)

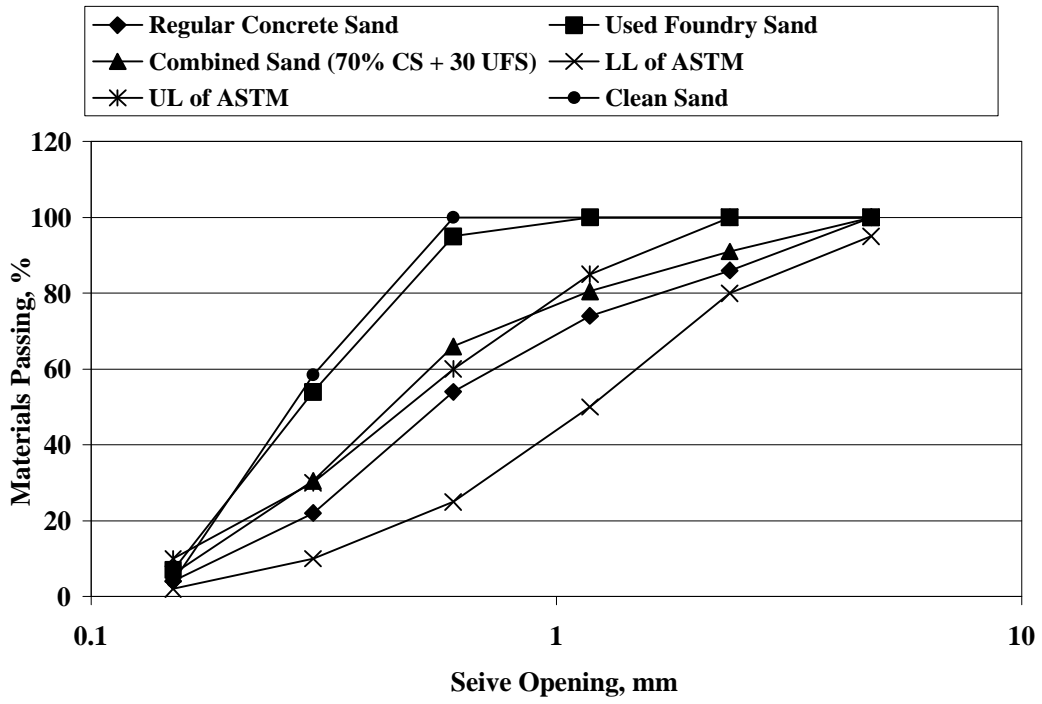


Fig 1 - Sieve Analysis Envelope for Sands

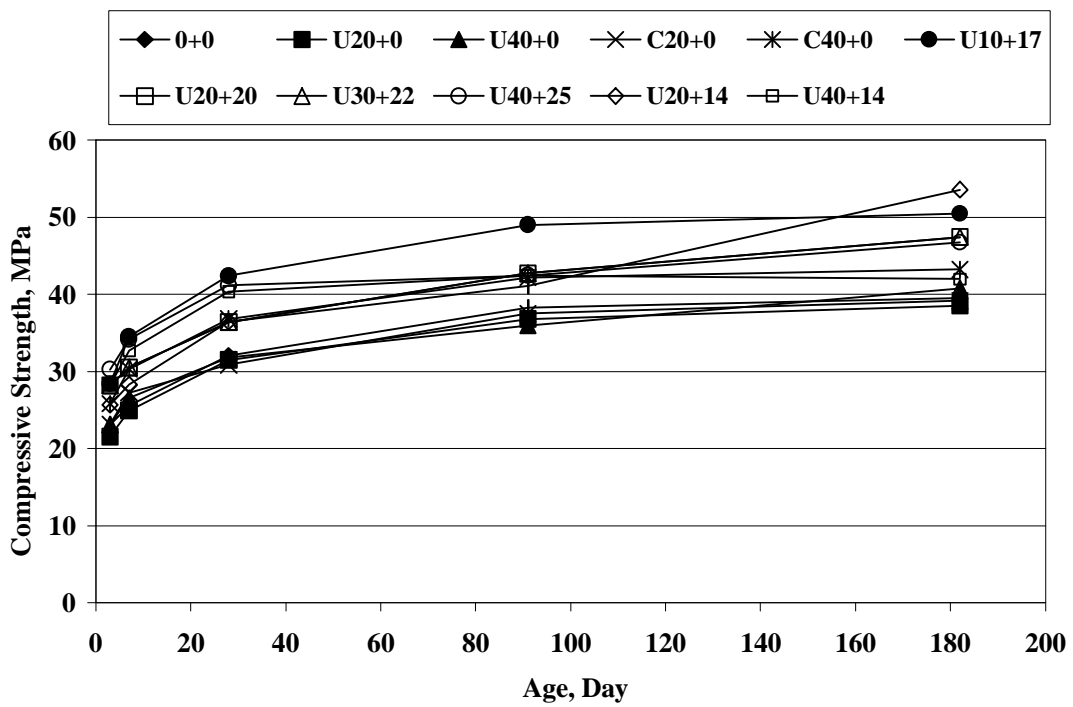


Fig. 2 - Compressive Strength of Concrete vs. Age

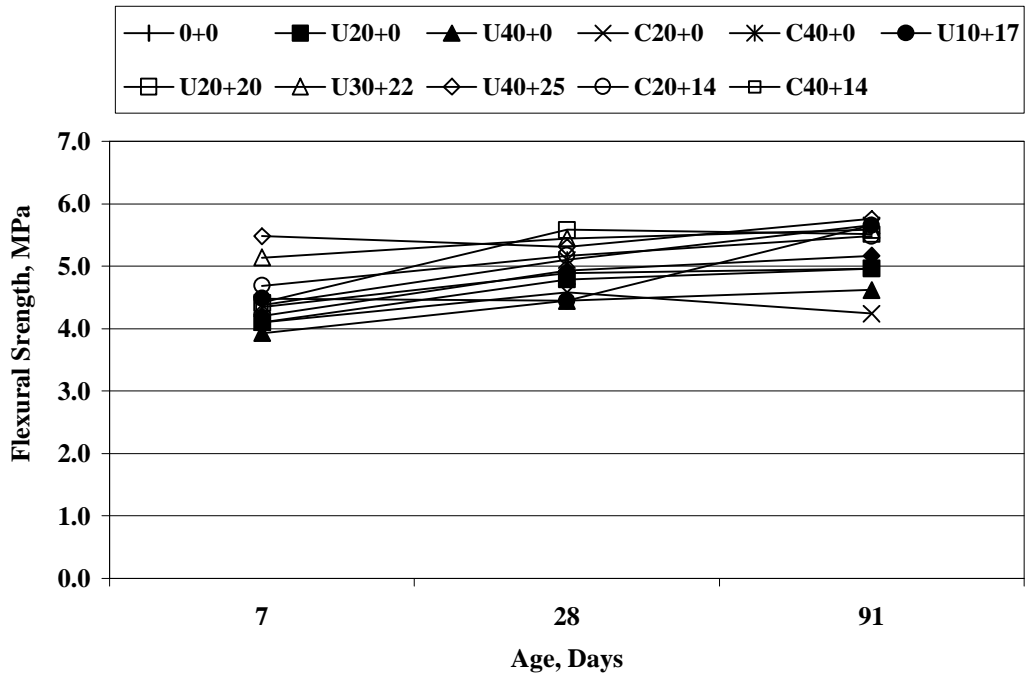


Fig. 3 - Flexural Strength of Concrete vs. Age

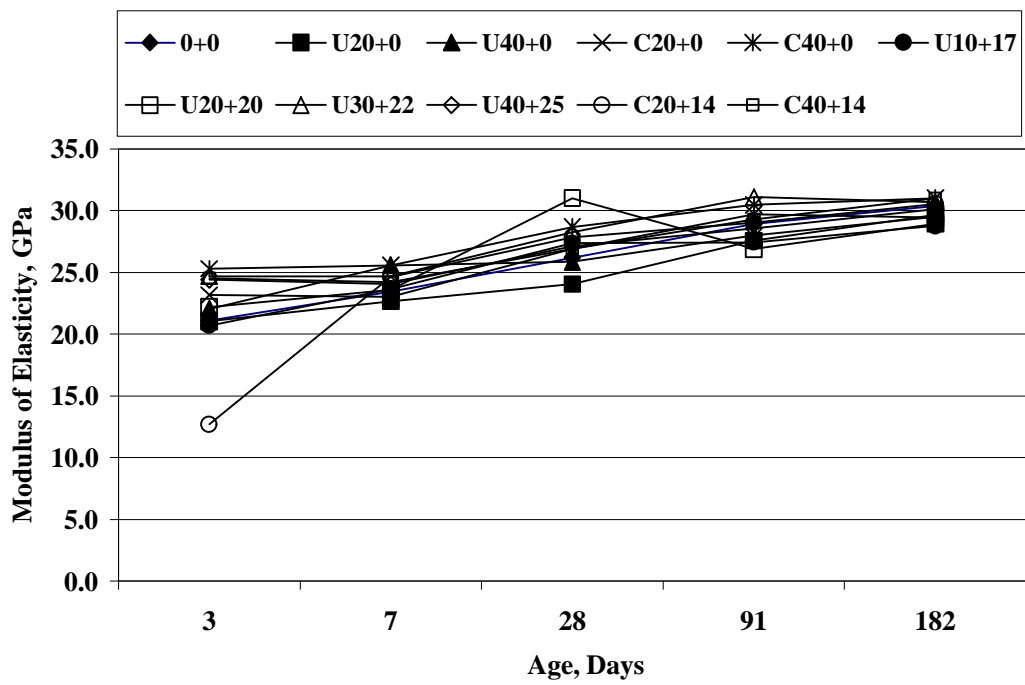


Fig. 4 - Modulus of Elasticity vs. Age

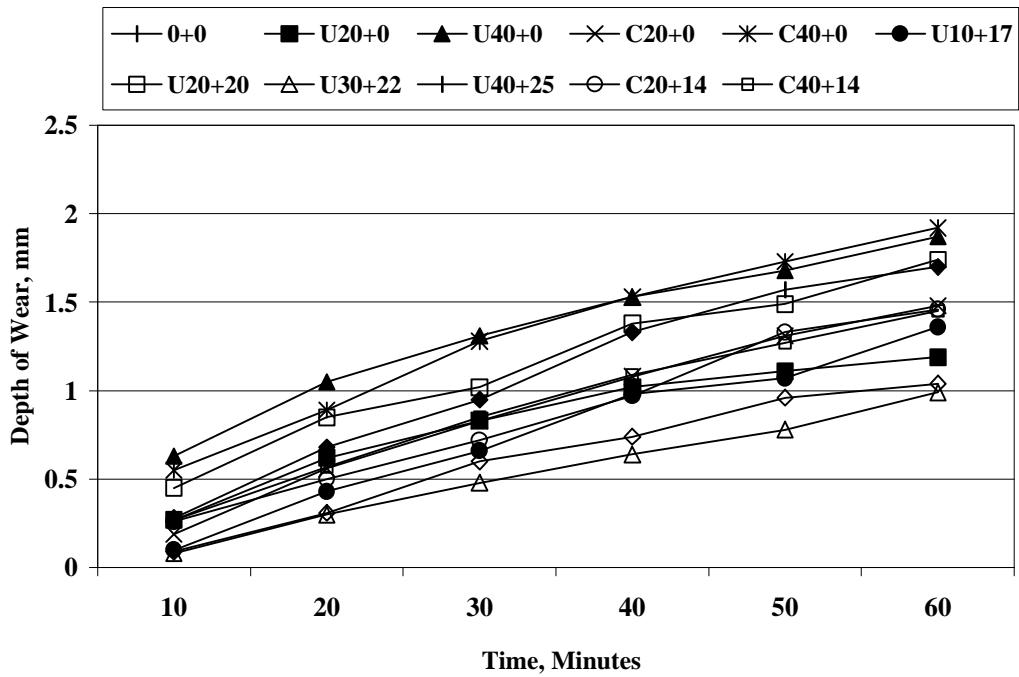


Fig. 5 - Abrasion Resistance of Concrete vs. Time at 91-Day Age

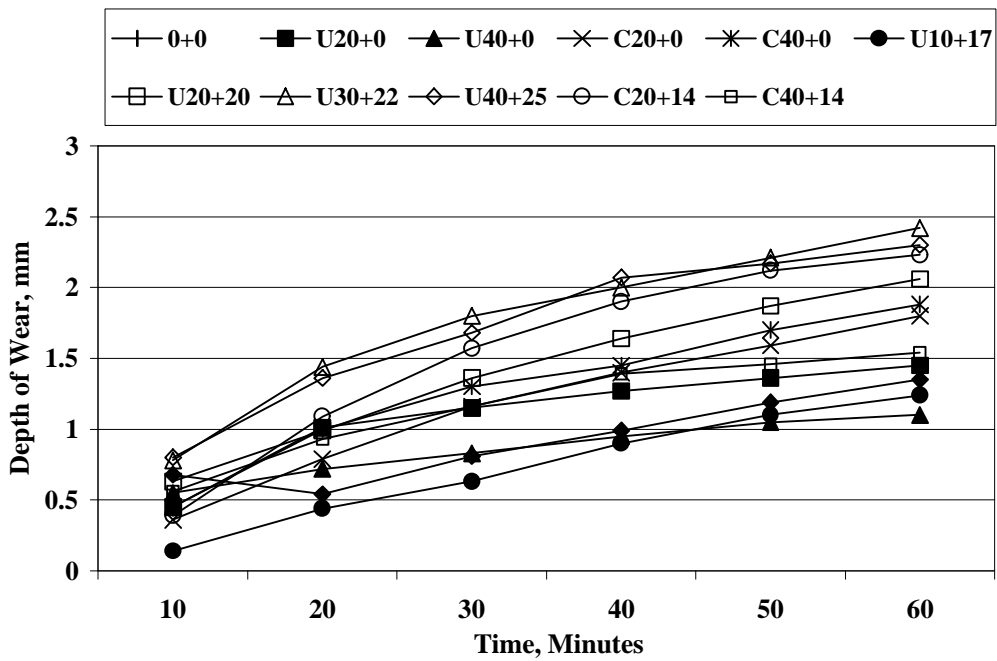


Fig. 6 - Abrasion Resistance of Concrete vs. Time at 28-Day Age

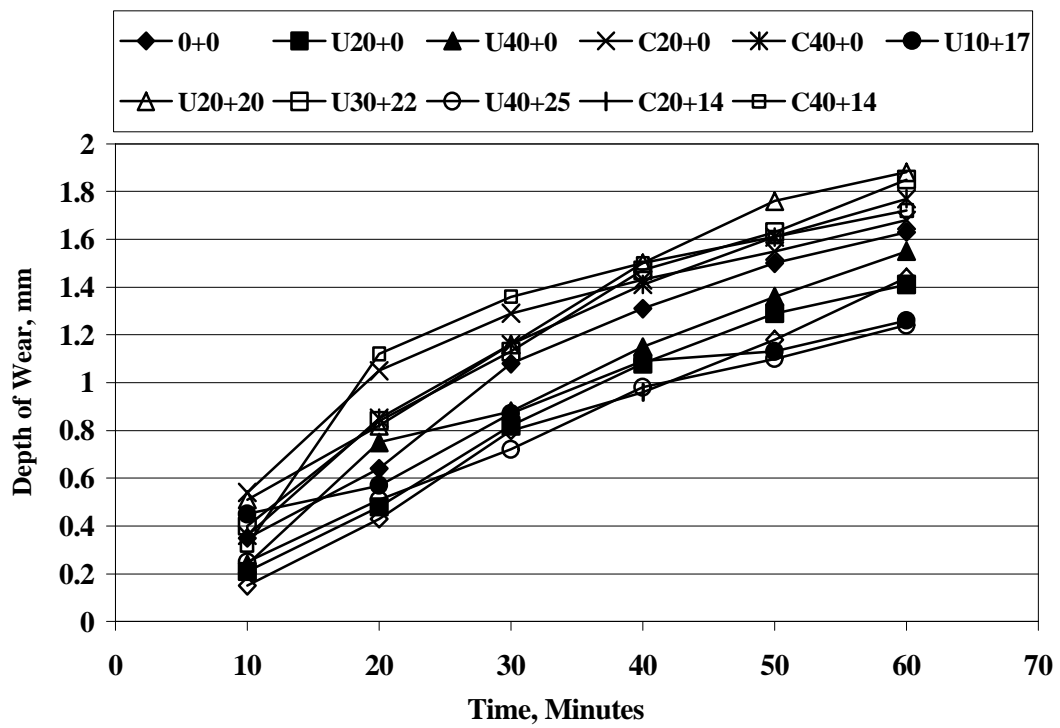


Fig. 7 - Abrasion Resistance of Concrete vs. Time at 182-Day Age