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Synopsis: This investigation was conducted to establish database for manufacturing of concrete masonry products incorporating high volumes of ASTM Class F fly ash. A total of 15 mixture proportions for bricks, blocks, and paving stones, including reference mixture for each type of masonry product, was proportioned. The fly ash content was varied from 20 to 50% for brick and block mixtures, and from 15 to 30% for paving stone mixtures All masonry products were tested for compressive strength, density, absorption, freezing and thawing resistance, drying shrinkage, and abrasion resistance. Test results indicated that bricks and blocks with up to 30% fly ash are suitable for use in both cold and warm climates. Other brick and block mixtures containing up to 50% fly ash were appropriate for building interior walls in cold regions and both interior and exterior walls in warm regions. None of the paving stone mixtures, including the control mixture, strictly conformed to all ASTM requirements. However, all the paving stone mixtures with and without fly ash are suitable for normal construction applications.

Keywords: blocks, bricks, cast-concrete products, fly ash, masonry products, and paving stones.

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INTRODUCTION

Currently every year in the US approximately 90 million tonnes (100 million tons) of coal combustion products are generated from conventional and advanced combustion technologies [1]. Fly ash forms the major component of these by-products. The annual production of fly ash in the United States was estimated to be about 55 million tonnes (60 million tons) in 1997, of which only 25% is being utilized. Therefore, large volumes of fly ash are continuously being disposed in landfills. However, due to environmental concerns, escalating landfill costs, and loss in resource and energy conservation, land filling is an unacceptable alternative for the management of coal ash.

Several applications of fly ash including concrete, waste stabilization, structural fills, road base/sub base, mining application, controlled low strength materials (CLSM), etc. are well known. The use of fly ash in concrete products accounted for about 49% of the total fly ash used in 1997, which translates to 16% of the total fly ash produced in the United States in 1997 [1]. The primary reasons for low utilization rate for fly ash are due to several factors including availability of low-cost virgin materials, quality of fly ash, regulatory restrictions, and unavailability of sufficiently developed high-volume use technologies. It is estimated that large-scale use of fly ash in construction materials, especially in cement-based materials, can consume most of the fly ash generated in the USA.

More recent investigations [2-5] have shown that large amounts of coal combustion and other by-products can be used in manufacture of concrete masonry products. This project was primarily undertaken to develop high-volume Class F fly ash use technologies for manufacture of bricks, blocks, and paving stones using commercial facilities.

RESEARCH SIGNIFICANCE

This research involved establishing the effects of inclusion of fly ash on strength and durability of cast-concrete products such bricks, blocks, and paving stones. The results derived from this investigation will be used to establish mixture proportions and production technology for commercial manufacturing of these masonry products by incorporating high volumes of fly ash. Successful completion of this investigation will lead to the diversion of fly ash from land filling to manufacture of the masonry products.

TESTING PROGRAM

Materials

Type I portland cement obtained from one source was used throughout this work. The cement was tested for its physical, chemical, and mineralogical properties in accordance with applicable ASTM or other standards. It met the standard requirements for ASTM Type I cement (ASTM C 150).

A low-calcium F fly ash derived from one source in Illinois was used in this research. The fly ash was tested for its physical, chemical, and mineralogical properties in accordance ASTM or other applicable standards. The fly ash met the requirement of Class F fly ash in accordance with ASTM C 618 (Tables 1 and 2).

Both coarse and fine aggregates were obtained from the Best Block Co., Racine, WI. The coarse aggregates were crushed limestone of 9.5 mm (3/8") maximum size. The fine aggregates were natural sand. Both coarse and fine aggregates met the ASTM C 33 requirements.

MIXTURE PROPORTIONS AND MANUFACTORING OF MASORNY PRODUCTS

Mixture Proportions

A total of 15 masonry mixtures, consisting of five bricks, six blocks, and four paving stones, were proportioned. The major aim of this investigation was to demonstrate the use of high volumes of fly ash in the manufacture of masonry products using commercial manufacturing facilities. The reference mixture for each masonry product used in this study was the same as that used by the Best Block Company, Racine, Wisconsin. Therefore, attempt was not made to optimize mixture proportions for production of bricks, blocks, and paving stones for this investigation. Fly ash was used as a replacement of portland cement on one to one mass basis. Standard commercial manufacturing processes used for production of bricks, blocks, and paving stones by the Best Block Company were also used for production of test specimens for this work. Thus, no attempts were made to change the level or mode of pressure applied in compacting bricks, blocks, or paving stones. Various cement replacement levels used were three (20, 30, and 50%) for bricks, five (10, 20, 30, 40, and 50%) for blocks, and three (15, 25, and 30%) for paving stones. Fly ash was used on a 1:1 ratio by mass of cement replaced. In this paper, nominal fly ash content is expressed as percentage of cement replacement. Control mixtures for bricks, blocks, and paving stones without fly ash were also proportioned based on the production mixtures available from the Best Block Co. Mixture proportions for bricks, blocks, and paving stones are presented in Tables 3 through 5, respectively.

Mixing Procedure

The normal production facilities of the Best Block Co. were used for each batch of these three types of masonry mixtures. Regular fine aggregate, coarse aggregate, and cement were batched and weighed automatically. Fly ash was manually weighed separately. All the materials were fed into the mixer and then dry mixed for three to four minutes. After mixing, a gentle stream of water was added. Mixing and adding water was repeated until the desired moisture content for each mixture was achieved. Then the mixture was discharged into a hopper, which lifted it up and dumped it into the top of a masonry product-manufacturing machine at the Best Block Company's plant in Racine, WI.

Test Specimens

From each brick or paving stone mixture, four representative specimens were taken and weighed for determining approximate density of the freshly cast concrete bricks or paving stones. From each block mixture, one representative specimen was taken for measuring the density. After casting, the products were transported via a conveyor system and steams cured overnight at atmospheric pressure. A few days later, these masonry products were shipped to the laboratories of the University of Wisconsin-Milwaukee (UWM). The bricks, blocks, and paving stones were moved into the UWM Concrete Laboratory for indoor storage at ambient temperature of 22 ± 2 °C (72 ± 3 °F) and relative humidity of 50 ± 10%, until the time of test.

Typical dimensions (width, length, and height) of bricks and paving stones were 92-mm x 194-mm x 57-mm (3.625" x 7.625" x 2.250"). Each specimen of bricks and paving stones had a "frog", i.e. a groove, on its bottom-bearing surface. For this project, dry-cast paving stones were produced using brick molds. The blocks were three web hollow blocks with typical dimensions of 194-mm x 395-mm x 194-mm (7.625" x 15.563" x 7.625").

Testing of Specimens

Tests for compressive strength, water absorption, and moisture content of bricks, blocks, and paving stones were performed in accordance with ASTM C 140. Three absorption and moisture content specimens were tested for each brick, block or paving stone mixture at the ages of 5, 28, 56, and 91 days. Test for freezing and thawing resistance of bricks, blocks, and paving stones were carried out in accordance with ASTM C 1262 using five specimens for each masonry mixture. Drying shrinkage of bricks and blocks was measured in accordance with ASTM C 426 using three specimens for each mixture. Test for abrasion resistance of paving stones was carried out in accordance with ASTM C 418 using three specimens for each paving stone mixture.

RESULTS AND DISCUSSION

Test results for compressive strength, density, absorption, freezing and thawing resistance, drying shrinkage for bricks, blocks, and paving stones are presented in the following sections.

Compressive Strength of Bricks

The compressive strength data for brick mixtures are presented in Fig. 1. In general, the compressive strength of the brick mixtures increased with increasing age (Fig. 1). The early-age strength of brick mixtures containing fly ash was lower relative to the control mixture without fly ash. The rate of strength gain for the fly ash mixtures was higher compared to the control mixture with increasing age. Consequently, the difference in strengths for the fly ash mixtures and the control mixture diminished with increasing age (Fig. 1). Compressive strength of masonry products is important soon after manufacturing. Therefore, the compressive strength at the age of 7 days was compared with the no-fly ash control mixtures for masonry products manufactured. The compressive strength values for brick Mixtures 2 (control, 0% FA), 3 (20% FA), 4 (30% FA), and 5 (50% FA) were 26.8 (3890), 22.6 (3280), 23.0 (3330), and 20.4 (2965) MPa (psi), respectively, at the age of five days. At this age, Mixture 2 (control) bricks exceeded the minimum compressive strength requirement for ASTM Grade N bricks (24 MPa, 3500 psi). At the age of five days, all fly ash containing masonry mixtures exceeded the strength requirement for ASTM Grade S bricks (17 MPa, 2500 psi). The respective compressive strength values for brick Mixtures 2, 3, 4, and 5 increased to 27.7 (4015), 28.5 (4135), 25.4 (3690), and 21.4 (3105) MPa (psi) at 7 days. At the age of 7 days, all brick mixtures except Mixture 5 exceeded the compressive strength requirement for Grade N bricks. At the 91-day age, all brick mixtures met Grade N requirement for compressive strength.

Density and Absorption of Bricks

The values of bulk density and absorption were determined at the ages of 5, 7, 28 and 91 days (Figs. 2 and 3). The average dry density values for the brick mixtures did not vary much with either age or fly ash content within the experimental range. The density of the brick mixtures ranged from 2034 to 2115 kg/m^3 (127 to 132 lb/ft^3).

The absorption of the brick mixtures decreased with age (Fig. 3). The absorption values decreased from 13.0 to 10.7% for Mixture 2 (0% FA), from 12.6 to 9.8% for Mixtures 3 (20% FA), from 12.9 to 9.5% for Mixture 4 (30% FA), and from 13.8 to 10.0% for Mixture 5 (50% FA) when age increased from 5 days to 91 days. This was primarily attributed to improved microstructure of these bricks resulting from increased pozzolanic activity of the material. Bricks containing fly ash up to 30% met the ASTM absorption requirement for Grade S bricks 208 kg/m^3 (13 lb/ft^3) at 5 days and bricks containing 50% fly ash met this requirement at 28 days.

Freezing and Thawing Resistance of Bricks

The weight loss in bricks due to freezing and thawing (F & T) actions is shown in Fig. 4. The weight loss increased with increasing fly ash content and number of cycles of F & T. The weight loss was quite small for the mixtures containing up to 30% fly ash. At 50% fly ash content, the rate of weight loss increased substantially with increasing cycles of F & T. All brick mixtures containing up to 30% fly ash met the ASTM C 1262 for F & T resistance as their weight loss remained less than 1% at 100 cycles of F & T (Fig. 4). However, Mixture 5 (50% FA) failed this requirement.

Drying Shrinkage of Bricks

The drying shrinkage of the brick mixtures decreased with increasing fly ash content (Fig. 5). This was probably attributed to the increased formation of the densified stable solids from the hydration reactions of fly ash with increasing fly ash content. The drying shrinkage varied between 0.047 and 0.056% for the brick mixtures between 50% and 0% fly ash. All brick mixtures (Mixtures 2 through 5) met the maximum drying shrinkage requirement of ASTM for Type II no moisture-controlled brick units (less than 0.065%) per ASTM C 55.

Compressive Strength of Blocks

The compressive strength data of the block mixtures were recorded at the ages of 3, 7, 28, 56, and 91 days. The strength data for the block mixtures (Mixtures 6 through 11) followed the same general trend as observed for the brick mixtures (Fig. 6). The compressive strength values of blocks were 19.9 (2890), 12.5 (1810), 13.7 (1980), 15.3 (2220), 8.4 (1220), and 11.0 (1590) MPa (psi) for Mixtures 6 (0% FA), 7 (10% FA), 8 (20% FA), 9 (30% FA), 10 (40% FA), and 11 (50% FA), respectively, at the 3-day age. The corresponding compressive strength values were 23.9 (3460), 17.4 (2520), 17.0 (2460), 15.0 (2180), 10.9 (1580), and 13.2 (1910) MPa (psi) at the age of 7 days. All block mixtures, with exception of Mixture 10 (40% FA), met the ASTM strength requirement of 13 MPa (1900 psi) at the age of 7 days. Strength increased with the density of the block mixtures did not vary with age (Fig. 7). Inclusion of fly ash caused slight decrease in density of the bloincreasing age for all mixtures with and without fly ash.

Density and Absorption of Blocks

The density of the block mixtures did not vary with age (Fig. 7). Inclusion of fly ash caused slight decrease in density of the block mixtures relative to the control mixture. However, the effect of amount of fly ash (up to 50% FA content) on density of the block mixtures was insignificant. The density of the control block mixture varied between 2147-2211 kg/m^3 (134-138 lb/ft^3) while it varied between 2115-2163 kg/m^3 (132-135 lb/ft^3) for the fly ash block mixtures.

The absorption of the block mixtures did not vary significantly with fly ash content (Fig. 8). The absorption of the block mixtures decreased slightly beyond 28 days. The absorption values ranged from 7.7 to 8.9% up to 28 days, and from 6.8 to 8.6% up to 91 days. All block mixtures (Mixtures 6 through 11) met the ASTM requirement for absorption 208 kg/m^3 (13 lb/ft^3) at the ages of 5 days and beyond.

Freezing and Thawing Resistance of Blocks

The weight loss due to freezing and thawing action exhibited the same general trend as obtained for the brick mixtures. All block mixtures except Mixture 11 (50% FA) showed weight loss of less than 1% at 100 cycles of F&T (Fig. 9). Thus, the block mixtures containing up to 30% fly ash attained satisfactory resistance to freezing and thawing in accordance with ASTM C 1262. The 50% fly ash block mixtures failed the F&T resistance test as it exceeded the weight loss of 1% and all test specimens made with 50% fly ash fractured after 60 cycles of F&T.

Drying Shrinkage of Blocks

The drying shrinkage of the block mixtures generally decreased with increasing fly ash content (Fig. 10). This was probably attributed to the increased formation of the densified stable products from the hydration reactions with increasing fly ash content. The values of drying shrinkage varied between 0.042 and 0.057% for blocks mixtures between 50% and 0% fly ash. All block mixtures met the maximum drying shrinkage requirement of ASTM for Type II non-moisture-controlled block units (less than 0.065%).

Compressive Strength of Paving Stones

The compressive strength data for the paving stone mixtures (Mixtures 12 through 15) were obtained at the ages of 3, 7, 28, 56, and 91 days. The results for these mixtures exhibited essentially the same general trend as that obtained for the brick mixtures (Fig. 11). The compressive strength values were 46.5 (6750), 41.0 (5940), 37.6 (5460), and 35.1 (5090) MPa (psi) for

Mixtures 12 through 15, respectively, at the 3-day age. The corresponding compressive strength values were 51.4 (7460), 42.6 (6185), 39.9 (5790), and 35.9 (5210) MPa (psi) at the age of 7 days. The above results demonstrated that none of the paving stone mixtures met the ASTM C 936 requirement for compressive strength (55 MPa, 8,000 psi) at the age of 7 days. The lower strength may be partly related to the type of mold used and direction of the compressive force versus the direction of casting these specimens. This might have caused deviation from the required compaction level and specimen geometry for paving stones.

Density and Absorption of Paving Stones

The general trend of the paving stone density data followed a similar trend as observed for brick mixtures (Fig. 12). The density values varied between 2163-211 kg/m^3 (135-138 lb/ft^3) for the reference paving stone mixture and between 2035-2131 kg/m^3 (127-133 lb/ft^3) for the fly ash paving stone mixtures. The similar density values as bricks of the paving stone mixtures revealed that adequate compaction probably was not achieved for the paving stone mixtures for obtaining the desired strength and durability.

The average absorption values for paving stones were found to vary between 8.2 and 9.0% at 7 days, 6.1 and 7.4% at 28 days, 5.6 and 6.6 at 91 days (Fig. 13). Therefore, none of the paving stone mixtures met the ASTM C 936 requirement for absorption (5% maximum).

Freezing and Thawing Resistance of Paving Stones

The weight loss increased slightly with increasing fly ash content and number of cycles of F&T (Fig. 14). However, amount of weight loss was small for the paving stone mixtures up to 100 cycles of F&T. All paving stone mixtures (Mixtures 12 through 15) exhibited the weight loss less than 1% at 100 cycles of F & T (Fig. 14), similar to brick mixtures. Thus, these paving stone mixtures made with and without fly ash met the ASTM C 1262 freezing and thawing resistance requirement.

Abrasion Resistance of Paving Stones

The abrasion coefficient was determined in accordance with ASTM C 418. It is expressed as volume of the test specimen abraded per unit area of surface abraded. The abrasion coefficient values for paving stone mixtures are shown in Fig. 15. The abrasion resistance decreased (i.e., abrasion coefficient increased) slightly with increasing fly ash content. This was primarily attributed to a decrease in compressive with increasing fly ash content.

However, all paving stone mixtures made with and without fly ash met the ASTM C 936 requirement for abrasion as their abrasion coefficient remained less than 0.3 cm^3/cm^2. The highest abrasion resistance was obtained for the reference mixture without fly ash and the least was observed for the 30% fly ash mixture.

CONCLUSIONS

Considering the above data presented, the following general conclusions can be drawn.

1. All masonry mixtures containing Class F fly ash attained lower early-age compressive strength relative to the reference masonry mixture for each masonry product. The compressive strength difference between masonry mixtures containing fly ash and reference masonry mixtures without fly ash decreased noticeably with age.
2. Inclusion of fly ash did not cause significant reduction in density of the masonry products.
3. All masonry products containing fly ash up to 30% exhibited adequate resistance to F&T in accordance with ASTM C 1262.
4. Inclusion of fly ash caused reductions in the drying shrinkage of masonry products.
5. Based on the freeze thaw results, it is clear that in warm regions, all the bricks (Mixture 2 through 5) could be used for building both interior and exterior walls. In cold climates, on the other hand, all bricks (Mixtures 2 through 4) incorporating up to 30% fly ash can be used for exterior walls and the 50% fly ash mixture can be used for building interior walls in cold regions.
6. In warm regions, all of the block mixtures (Mixtures 6 through 11) could be used for building both interior and exterior walls. In cold regions, block Mixtures 6 through 9 could be used for building exterior walls. Block Mixtures 10 (40% FA) and 11 (50% FA) could be used for building interior walls in cold region.
7. Abrasion resistance of the paving stone mixtures was proportional to its compressive strength.
8. Abrasion resistance of paving stones containing fly ash was slightly lower than the reference paving stone mixture. However, all paving stone mixtures with and without fly ash met the ASTM requirement for abrasion resistance.
9. All paving stone mixtures (Mixtures 12 through 15) manufactured in this investigation did not meet the compressive strength and the water absorption requirements of ASTM for concrete paving stones. This was primarily attributed to the lower cementitious materials factor and the mold design used which resulted in insufficient compaction of the paving stones

made in this investigation. However, all paving stone exhibited sufficient strength and durability for use in normal construction work.

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REFERENCES

(1) American Coal Ash Association, “1997 Coal Combustion Product (CCP) Production and Use,” Alexandria, VA, 1998, 2 pages.

(2) Chun, Yoon-Moon, "Manufacture of Cast Concrete Products Using Fly Ash, Bottom Ash, and Used Foundry Sand," M. S. Thesis, University of Wisconsin—Milwaukee, 1999, 165 pages.

(3) Naik, T. R., Kraus, R. N., Chun, Y.-M., Ramme, B. W., and Singh, S. S., “Durability of Cast-Concrete Products Utilizing Recycled Materials,” Report No. CBU-2000-07, UWM Center for By-Products Utilization, University if Wisconsin-Milwaukee, January 2000, 41 pages.

(4) Wei, L., Naik, T. R., and Golden, D. M., “Construction Materials Made with Coal Combustion By-Products, “ ASTM Cement, Concrete, & Aggregates, Vol. 16, No. 1, June 1994, pp. 36-42.

(5) Chopada, P.P., “Low-Cost, High-Performance Construction Materials Using Coal Combustion By-Products,” M.S. Thesis, University of Wisconsin-Milwaukee, May 1998, 136 pages.

Table 1 - Physical Properties of Fly Ash

Test	Class F Fly Ash	ASTM C 618 Class F (%)
Fineness, retained on No. 325 Sieve, (%)	15.7	34 max
Strength activity index with cement at 28 days, (% of control)	87%	75 min
Water requirement (% of control)	101	105 maximum
Autoclave expansion, (%)	0.02	±0.8
Specific gravity	2.27	-

Table 2 - Chemical Analysis of Fly Ash

Chemical Composition	Class F Fly Ash (%)	ASTM C 618 Class F (%)
Silicon dioxide, SiO_2	54.6	--
Ferric oxide, Fe_2O_3	4.1	--
Aluminum oxide, Al_2O_3	23.2	--
Total SiO_2+Al_2O_3+Fe_2O_3	81.8	70 minimum
Calcium oxide, CaO	3.0	--
Magnesium oxide, MgO	1.3	5.0 maximum
Titanium oxide, TiO_2	0.7	--
Potassium oxide, K_2O	1.0	--
Sodium oxide, Na_2O	2.4	
Sulfur trioxide, SO_3	1.0	5.0 maximum
Moisture content	0.1	3.0 maximum
Loss on ignition	1.0	6.0

Table 3 - Mixture Proportions for Bricks

Mixture Number	1	2	3	4	5
Fly Ash (%)	0	0	20	30	50
Cement, kg/m^3 (lbs/yd^3)	200 (337)	196 (330)	161 (272)	146 (246)	106 (178)
Fly Ash, kg/m^3 (lbs/yd^3)	0 (0)	0 (0)	42 (70)	62 (105)	106 (178)
Water kg/m^3 (lbs/yd^3)	75 (126)	66 (111)	71 (120)	72 (122)	75 (126)
W/(C + FA)	0.37	0.34	0.35	0.35	0.35
Sand, SSD, kg/m^3 (lbs/yd^3)	1371 (2311)	1344 (2266)	1336 (2251)	1346 (2269)	1314 (2214)
9.5 mm Coarse Aggregates, SSD, kg/m^3 (lbs/yd^3)	454 (766)	446 (752)	443 (746)	445 (750)	435 (734)
Dry Density, kg/m^3 (lbs/ft^3)	2098 (131)	2051 (128)	2051 (128)	2067 (129)	2035 (127)

Table 4 - Mixture Proportions for Blocks

Mixture Number	6	7	8	9	10	11
Fly Ash (%)	0	10	20	30	40	50
Cement, kg/m^3 (lbs/yd^3)	211 (355)	201 (339)	164 (277)	142 (240)	101 (171)	121 (204)
Fly Ash, kg/m^3 (lbs/yd^3)	0 (0)	25 (42)	52 (87)	77 (129)	126 (213)	100 (168)
Water kg/m^{3*} (lbs/yd^3)	75 (126)	89 (150)	86 (145)	87 (147)	87 (146)	91 (154)
W/(C + FA)	0.35	0.44	0.40	0.40	0.38	0.41
Sand, SSD, kg/m^3 (lbs/yd^3)	1418 (2390)	1385 (2334)	1382 (2330)	1368 (2305)	1362 (2295)	1373 (2315)
9.5 mm (3/8”) Coarse aggregates, SSD, kg/m^3 (lbs/yd^3)	491 (827)	470 (792)	471 (805)	478 (797)	470 (793)	466 (786)
Dry Density, kg/m^3 (lbs/ft^3)	2195 (137)	2147 (134)	2163 (135)	2147 (134)	2147 (134)	2131 (133)

Table 5 - Mixture Proportions for Paving Stones

Mixture Number	12	13	14	15
Fly Ash (%)	0	15	25	30
Cement, kg/m^3 (lbs/yd^3)	332 (559)	274 (461)	245 (413)	231 (390)
Fly Ash, kg/m^3 (lbs/yd^3)	0 (0)	48 (81)	81 (137)	100 (168)
Water kg/m^{3*} (lbs/yd^3)	100 (169)	84 (141)	93 (156)	92 (155)
W/(C + FA)	0.30	0.26	0.28	0.28
Sand, SSD, kg/m^3 (lbs/yd^3)	1360 (2292)	1260 (2124)	1250 (2107)	1255 (2115)
9.5 mm Coarse Aggregates, SSD, kg/m^3 (lbs/yd^3)	444 (748)	418 (704)	415 (699)	416 (701)
Dry Density, kg/m^3 (lbs/ft^3)	2211 (138)	2083 (130)	2083 (130)	2099 (131)

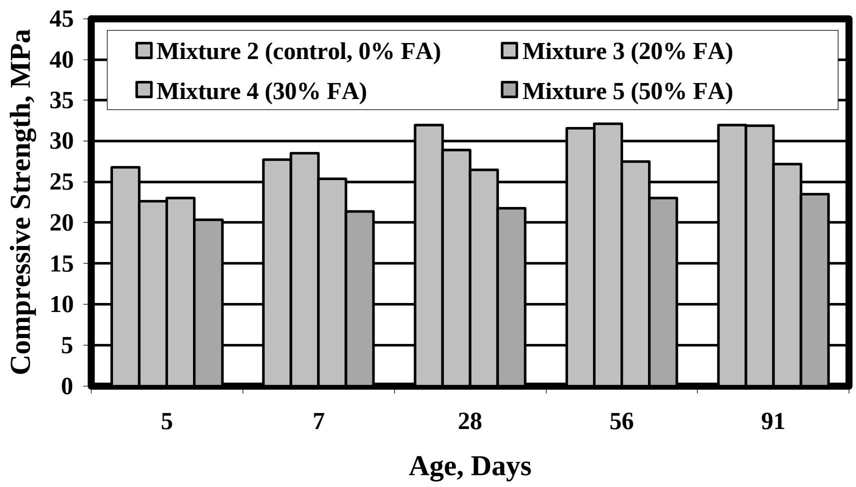

Fig. 1 - Compressive Strength versus Age for Brick Mixtures

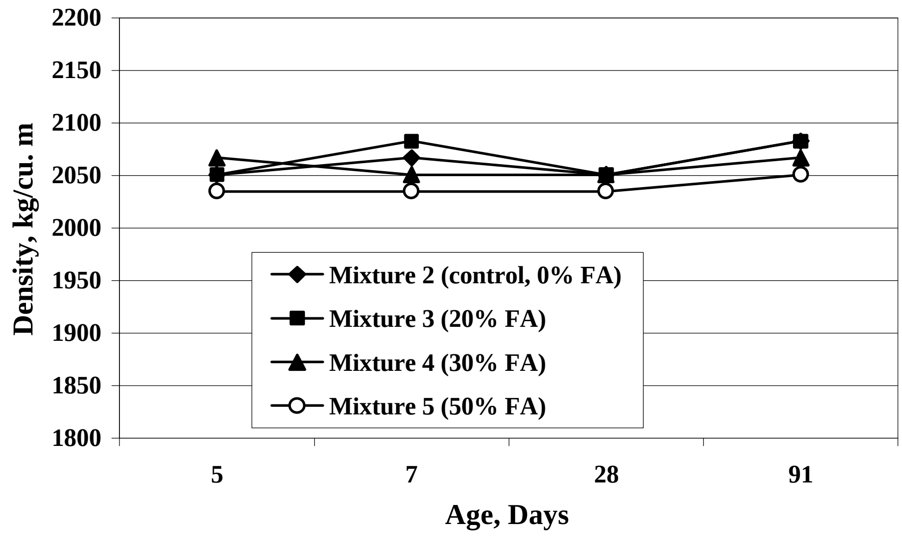

Fig. 2 - Density versus Age for Brick Mixtures

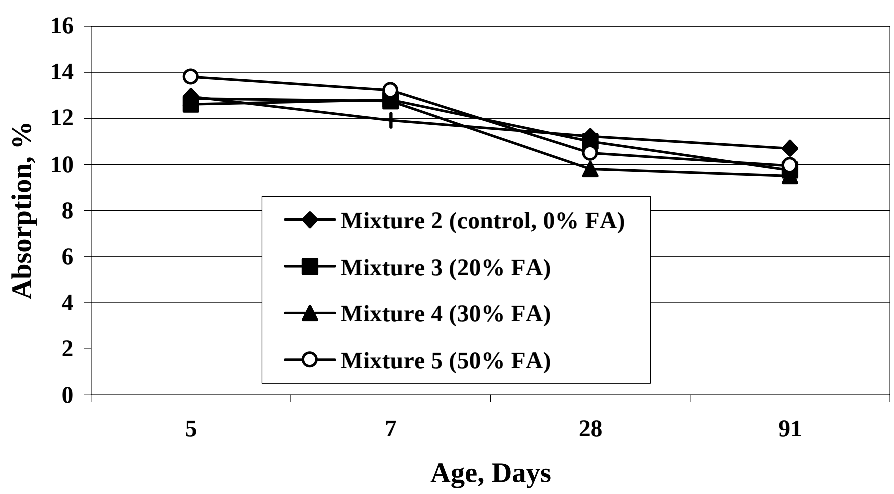

Fig. 3 - Absorption versus Age for Brick Mixtures