Mortar Mix Design for Roofing Applications

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Abstract — *The following information is about the results on experimental tests of a mortar containing fly ash used on roofing application. These results are based on compressive strength, air permeability and specific gravity. Physical and chemical characterization for the fly ash produced is not evaluated this time, but it will in the future. The main purpose of this research is to deal with a common rainwater leakage problem of concrete roofs in Puerto Rico. With this document, Polytechnic University of Puerto Rico evaluated the suitability of several proportions mixtures in a mortar containing fly ash to be used as a topping to prevent water leakages in roofs. It contains cement, water, and aggregate. The fly ash tested is nearly a Class C because it exceeds the maximum allowed for Sulfur Trioxide. The utilization of fly ash concrete mixtures helps to reduce the environmental impact due to the use of aggregates from natural resources like rivers.*

Key Terms — *air permeability, chemical characterization, fly ash, specific gravity.*

INTRODUCTION

This report summarizes the result of experimental tests evaluating some of the mechanical properties of a mortar containing fly ash to be used as roofing application. The fly ash used is a byproduct of the AES power plant facility in Guayama, Puerto Rico. These tests conducted include: compressive strength, air permeability and specific gravity. Physical and chemical characterization for the fly ash produced in AES is not evaluated in this work, but it is necessary in the future to complement the results obtained here. The main objective of this research was to deal with a very common problem in Puerto Rico for concrete roofs exhibiting rainwater leakage problems. There is a large industry in the island dedicated to preventing and fixing these problems. With this document, Polytechnic University of Puerto Rico (PUPR) evaluated the suitability of several proportions mixtures in a mortar containing fly ash to be used as a topping to prevent water leakages in roofs. Mortars have similar characteristics to concrete in that it contains cement, water, and aggregate (only graded sand). The AES fly ash tested is nearly a Class C (it exceeds the maximum allowed for SulfurTrioxide). Class C of cement at ordinary temperatures to form compounds of cementitious properties when in a finely divided form and in the presence of moisture [1]. As sustainability moves to the forefront of construction, the utilization of fly ash fly ash has cementitious properties in addition to pozzolanic properties. Pozzolans are siliceous or siliceous and aluminous materials which in themselves possess little or no cementitious property, but they can react with calcium hydroxide concrete mixtures to reduce CO_2 emissions and cement consumption per unit volume of concrete placed is receiving renewed interest. Concrete mixtures in which the fly ash replaces a portion of the Portland cement are both economically and technically viable helping to reduce the environmental impact due to the use of aggregates from natural resources like rivers [2].

LITERATURE REVIEW AND DEFINITIONS

Fly ash is the finely divided mineral that results from the combustion of pulverized coal produced during the steam generation process in the power plant. The fly ash particles solidify while suspended in the exhaust gases and are collected by electrostatic precipitations. The physical and chemical characteristics of fly ash can vary greatly and will mainly depend on the combustion method and coal properties used at a particular power plant. Fly ash is commonly used as a pozzolan, reacting in the presence of water with calcium hydroxide at ordinary temperatures to produce cementitious compounds. The pozzolanic properties of fly ash can be stabilized with cement or lime [3].

According to the American Society for Testing and Materials [4], fly ash is classified in two main types as follow: Class C, a fly ash with high calcium content (>20% by weight) and Class F, a low calcium fly ash (<10% by weight). The principal factors that influence the classification of fly ash are the percentages of silica (SiO_2), alumina (Al_2O_3), and ferric oxide (Fe_2O_3). Table 1 shows the characteristics for both types of fly ash.

Table 1
Chemical Requirements for Fly Ash [4]

	Class	
Chemical	**F**	**C**
SiO2+Al2O3+Fe2O3 min%	70	50
SiO3 max%	5	5
Moisture content max%	3	3
Loss in ignition max%	6	6

According to an elaborate chemical analysis performed in 2005 and carried out by SGS North America Inc. from a sample obtained on December 16, 2004, AES fly ash complies with most of the chemical requirements for a Class C fly ash with only a deviation in the content of sulfur trioxide (SO_3) of 12.57% that exceeds the 5% maximum percentage specified by ASTM [4]. Table 2 summarizes the main characteristics of AES fly ash, evaluated in this research.

Physical Properties of Fly Ash

Typically, fly ash consists of spherical silt-sized particles finer than Portland cement and lime, i.e., particle sizes ranging between 10 and 100 microns. Fly ash is usually dark gray in color, but this depends on its chemical composition and mineral constituents (e.g., fly ash with high calcium content usually is cream colored, and fly ash from bituminous coal is gray colored due to its high carbon content). Approximately 80% of fly ash consists of tiny glass spheres. The other 20% is composed of quartz, mullite, hematite and magnetite. The specific gravity of most fly ash is between 1.9 and 2.5. Its dry density in a compacted state can vary between 70 and 115 lb/ft3. The friction angle of fly ash is typically of the order of 30^o, but values between 20^o and 40^o have been reported [3].

Table 2
Chemical Composition for AES Fly Ash

Analysis of fly ash	Result
Silica, SiO2 (% by Weight)	39.41
Alumina, Al2O3 (% by Weight)	12.59
Ferric Oxide, Fe2O3 (% by Weight)	4.35
SiO2 + Al2O3 + Fe2O3 (% by Weight)	56.35
Titania, TiO2 (% by Weight)	0.51
Lime, CaO (% by Weight)	27.02
Magnesia, MgO (% by Weight)	1.27
Potassium Oxide, K2O (% by Weight)	1.17
Sodium Oxide, Na2O (% by Weight)	0.44
Sulfur Trioxide, SO3 (% by Weight)	12.57
Phosphorus Pentoxide, P2O5 (% by Weight)	0.28
Strontium Oxide, SrO (% by Weight)	0.14
Barium Oxide, BaO (% by Weight)	0.23
Manganese Oxide, Mn3O4 (% by Weight)	0.02

Data from SGS North America for AES Puerto Rico.

Another benefit obtained from the use of fly ash in mortar mixtures includes the insulative characteristics. Because the density of fly ash can be as much as one-third less than that of cement, fly ash concretes may exhibit a reduced thermal conductivity, making them more insulative than conventional concretes [2].

OBJECTIVE

The objective of this project was to develop a mortar mixture containing the fly ash suitable to be used as a roof topping to prevent and fix leakages. To achieve this objective, the physical and mechanical properties of different mortar mixtures containing fly ash were tested. The fly ash used was the byproduct of AES Puerto Rico.

METHODOLOGY

This section describes the methodology that was used to carry out the proposed project. Initially, the specific gravity of the materials used in the experiment was determined. Afterwards, six (6) trial mixtures were designed. The designs were based on replacing portions of the typical materials included in mortar with fly ash obtained as a sub-product by AES. Table 3 describes the six mixtures evaluated for the test proposed in this research.

Table 3
Mixture Design Descriptions

Batch Number	Description
1	10% of Portland cement volume substituted by fly ash.
2	50% of Portland cement volume substituted by fly ash.
3	30% of Portland cement volume substituted by fly ash.
4	Control mix without fly ash addition for comparison purposes.
5	50% of fine aggregate volume substituted by fly ash.
6	30% of Portland cement volume substituted by fly ash and 25% of fine aggregate volume substituted by shredded tires.

From each of the designs, one batch was prepared to fabricate samples to test each mixture for compressive strength and specific gravity according to the standards of ASTM [5]. Also, samples were developed to test the mixtures for permeability and air content using a P-6050 Poroscope Plus instrument manufactured by NDT James Instruments Inc. Table 4 indicates the ASTM standards that were applied and the required number of specimens necessary to conduct each of the tests. In addition, from each batch, a small sample was used to cover a small section of a roof to observe how the mixture behaves when exposed to the elements.

Table 4
Proposed Tests

Tests	ASTM Standard	No. of Samples per batch
Compressive Strength	C 109/C109 M-08	12
Density	C-642-06	3
Permeability and Air Content	N/A	1

Mortar Mix Design and Preparation of Specimens

First the specific gravities of the materials to be used in the experiments were determined. Figure 1 shows an example of the testing performed to determine the specific gravity of the materials, while Table 5 presents the values obtained.

Figure 1
Determination of Specific Gravity

Table 5
Specific Gravity of Materials used in Project

Material	Specific Gravity
Cement	3.14
Aggregate	2.57
Fly Ash	2.48
Shredded Tire	1.13

Six (6) trial mix proportions were designed. From each proportion, a batch was prepared to fabricate the test specimens. These designs are presented in Table 6. It can be seen that Batch 4 contained no fly ash. Batch 4 was used as the control mixture because it represents typical design used for mortar concrete. Its design was based on Standard Specification for Mortar for Unit Masonry [6]. Batches 1 to 3 were based on substituting 10%, 50% and 30%, respectively, of the volume of cement with fly ash. For Batch 5, the full amount of the cement was used, but 50% of the volume of the aggregate was substituted with fly ash. For Batch 6, 30% of the volume of cement was substituted with fly ash while 25% of the volume of the aggregate was replaced with shredded tires. For substitution in any case, the amount of volume substituted was replaced with an equal amount of the volume of the substituting material.

Table 6
Trial Mix Design

Batch	Cement (lb)	Water (lb)	Aggre-gate (lb)	Fly Ash (lb)	Shredded Tire (lb)
1	143	86	391	13	-
2	80	86	391	63	-
3	111	86	391	38	-
4	159	86	391	-	-
5	159	86	274	113	-
6	111	86	293	38	43

Compressive Strength

These experiments were performed in accordance to Standard Test Method for Compressive Strength of Hydraulic Cement Mortars [7]. For each batch, a total of twelve cubes of 2 inches were prepared. At each of the ages of 24-hrs, 3 days, 7 days and 28 days, three cubes from each batch were tested in the Construction Materials Laboratory of the Civil and Environmental Engineering Department. Figure 2 shows a cube being tested using the Forney Concrete Compression Machine and Figure 3 shows the compression load capacity of a tested cube being recorded.

Figure 2
Compression tested performed on a 2-in cube of Batch 1

Figure 3
Recording of Compression Load Capacity on a 2-in Cube of Batch 1

Density

The density of each mortar was tested in accordance to the Standard Test Method for Density, Absorption, and Voids in Hardened Concrete [8]. For each batch, four cubes of 6 inches were prepared to determine the density. Figure 4 shows the cubes for specific gravity testing of Batches 4 to 6.

Figure 4
Cubes used for determination of density of Batches 4 to 6

Air Content and Permeability

From each batch a 2-ft x 2-ft x 6-in slab was fabricated. After 28 days of age, three holes were drilled into each slab to test for air content and permeability using a P-6050 Poroscope Plus instrument manufactured by NDT James Instruments. This instrument injects air into a test hole and measures the time it takes to change from a pre-defined air pressure to another. Figure 5 shows the slabs prepared from each of the six batches, with the slab of Batch 4 being tested for permeability.

Figure 5
Slabs used to determine Air Content and Permeability

Exposure to Elements

A portion of each batch was used to cover a 3-ft x 3-ft roof area with a 1.5-in thick topping to observe how each mortar behaves when exposed to the elements, as shown in Figure 6. Principally, in this test attention was paid to the formation of cracks.

Figure 6
Testing for Exposure to the Elements

RESULTS AND ANALYSIS

In this section, the results from the compressive strength, density and air permeability tests are presented and discussed.

Compressive Strength

From the test results presented in both Table 7 and Figure 7, it can be observed that compressive strength decreased in the first three batches proportionally inverse to the addition of fly ash as Portland cement substitute. Control Batch (Batch 4) shows the greater compressive strength at 24 hours, 3 and 7 days (Figure 7). Batch 5, in which fine aggregate was substituted by fly ash in a thirty percent (30%) proportion, shows the greater compressive strength at 28 days of all the evaluated batches, meaning that fly ash used as substitute of fine aggregate is ideal for compressive purposes gaining strength as they age. Substitution of fine aggregate by shredded tire shows the lower compressive resistance of all the evaluated batches.

Table 7
Compressive Strength Results

Batch number	Compressive Strength (psi)			
	24_ HOURS	3_ DAYS	7_ DAYS	28_ DAYS
1	1097.5	1909.6	2351.3	3636.3
2	195.0	407.9	969.2	2227.5
3	403.3	1062.5	1609.6	2846.3
4	1510.4	2340.4	3253.3	3975.4
5	598.8	1417.5	2588.3	5210.0
6	390.8	772.9	1298.3	2206.7

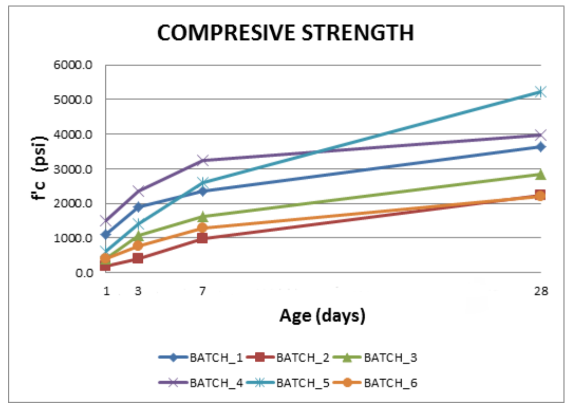

Figure 7
Compressive Strength Results

Density

According to ASTM [8], several measures of density can be computed from the same sample. Both Table 8 and Figure 8 summarize the density results including bulk density, bulk density after immersion, bulk density after immersion and boiling, apparent density and volume of permeable pore space. It can be seen from the results that all the batches showed similar density results with inversely proportional increase as fly ash addition. In this sense, Batch 1 and Batch 3 with substitution of ten and thirty percent, respectively, have greater bulk dry density results compared with Batch 2 with a fifty percent of fly ash substitution. As expected, Control Batch had the higher density and Batch 6 (with fly ash substitution by cement and shredded tire by fine aggregate) had the lower density. Density results can be correlated to other fly ash mixtures properties. In this sense, the lower density of fly ash concretes may exhibit a reduced thermal conductivity, making them better insulators than conventional concretes.

Table 8
Density Results

Batch #	Bulk Density Dry (lb/ft^3)	Bulk Density after Immer-sion (lb/ft^3)	Bulk Density after Immer-sion and Boiling (lb/ft^3)	Apparent Density (lb/ft^3)	Volume of Permeable Pore Spaces (Voids) %
1	118.44	131.69	132.26	152.13	58.97
2	113.84	128.51	129.08	150.60	58.55
3	116.98	128.95	129.34	145.87	57.21
4	121.10	132.35	132.74	148.87	58.07
5	115.04	126.08	126.46	140.81	55.67
6	108.61	119.69	120.95	135.38	53.89

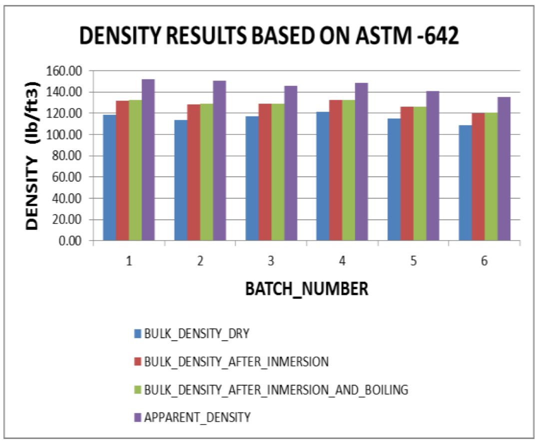

Figure 8
Density Results Based on ASTM [8]

Air Permeability

The air permeability results obtained using a P-6050 Poroscope Plus after 28 days of age are presented in Table 9. In accordance to the instrument's User Manual, an Air Exclusion Rating (AER) is calculated and then compared with the value ranges established by the manufacturer in order to classify the protective quality of the mixture.

Only Batches 1, 4 and 5 demonstrated a Good Protective Quality in all three test holes. Batch 1 had the two highest AER values (test holes 1 and 3) of all the test holes measures, but had a value that was lower (test hole 2) than any of the measurements taken for Batches 4 and 5. Still, Batch 1 had the highest average of AER with 174.6. Batches 4 and 5 have virtually the same AER average (146.2 and 145.1, respectively). So there was a significant increase in impermeability when 10% of the cement was substituted with fly ash, but the results were not very good with 30% nor 50% substitutions. When 30% of the fine aggregate was substituted with fly ash, the impermeability practically remained unchanged.

In the case of Batch 6 (in which 30% of cement was substituted with fly ash and 25% of fine aggregate was substituted with shredded tires), the results showed a not very good protective quality, meaning that shredded tire increased permeability when compared to Batch 2.

Exposure to elements Figure 9 shows a top view of each of the toppings applied for these experiments. Meanwhile, Figure 10 shows the thickness of the toppings (this view is used to observe how deep surface cracks were). These pictures were taken three months after all toppings were applied.

The following observations were made after examining the toppings:

- Batch 1 exhibited cracks with width measurements greater than 0.1-in, which were the largest cracks observed in all the samples. Meanwhile, Batches 2 and 3 exhibited cracks with width measurements up to 0.035-in and 0.030-in, respectively. In these three batches, in which portions of cement were substituted with fly ash, the cracks were observed to penetrate the thickness of the topping from top to bottom.
- Batch 4 exhibited cracks with a width of less that 0.015-in that did not penetrate the thickness of the topping.
- Batch 5 exhibited cracks with a width of less that 0.005-in that did not penetrate the thickness of the topping. It is also observed that this topping has the lightest color of all the samples.
- Batch 6 exhibited very interesting results. It was observed that it had no cracks, but some abrasions were observed due to weathering.

Table 9
Air Permeability Results

Batch Number	Test Hole	AER* (s/ml)	Protective Quality**
1	1	233.7	Good (75-250)
	2	90.2	Good (75-250)
	3	199.8	Good (75-250)
2	1	14.1	Not very good (8-25)
	2	82.9	Good (75-250)
	3	51.6	Fair (25-75)
3	1	158.7	Good (75-250)
	2	20.1	Not very good (8-25)
	3	110.8	Good (75-250)
4	1	179.2	Good (75-250)
	2	156.4	Good (75-250)
	3	102.9	Good (75-250)
5	1	118.8	Good (75-250)
	2	140.7	Good (75-250)
	3	176.4	Good (75-250)
6	1	13.7	Not very good (8-25)
	2	15.7	Not very good (8-25)
	3	19.4	Not very good (8-25)

* AER = Air exclusion rating.

**According to P-6050 Poroscope Plus instrument manual, manufactured by NDT James.

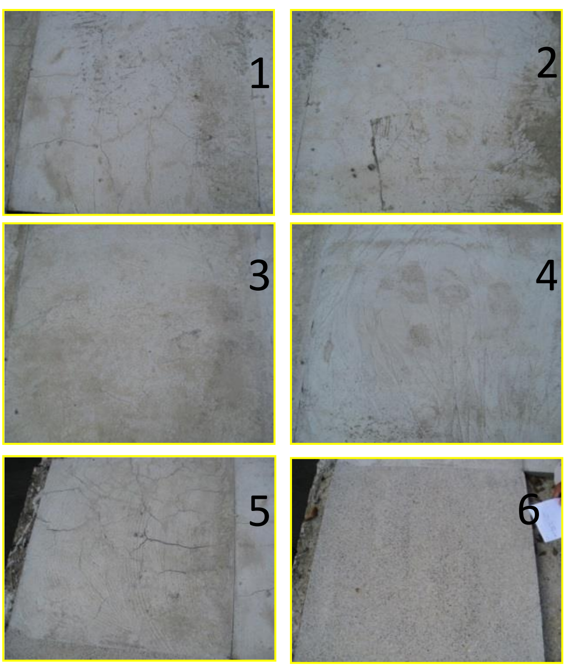

Figure 9
Top view of roof toppings after three months of exposure (Batches 1 to 6)

Figure 10
Thickness of each roof topping (Batches 1 to 6)

CONCLUSIONS

After evaluating all the results, it is clear that the mixture of Batch 5 (in which 30% of the fine aggregate was replaced with fly ash) was the most optimal mortar mixture evaluated in this project. This batch had the highest compressive strength (over 1,200 psi larger than the control mixture) and the second lowest density, while exhibiting a good protective quality in the Poroscope tests and superficial cracks with a width of less that 0.005-in. With a 28-day compressive strength of over 5000 psi, the mix design used for Batch 5 might be useful for other applications besides roofing.

In Puerto Rico and the world, the excessive use of natural resources including fine and coarse aggregates taken from rivers for construction purposes, represents a stress to natural conditions producing a lot of negative effects in the ecosystem and eventually in civil engineering structures (scour at bridges, excessive sediment transport, etc). The use of fly ash as substitute of fine aggregates (as it was done for Batch 5) could minimize those adverse effects, reutilizing a waste product from coal combustion.

Very interesting results were obtained with Batch 6 in which both shredded tires and fly ash were included in the mixture. Although it had the lowest compressive strength and a "not very good" protective quality, it had the lowest density and no cracks were observed to develop in the topping prepared with this batch. There is probably other applications other than roofing in which a lightweight mortar in which no cracks develop might be very useful. It could be of great benefit to identify it.

The substation of cement with fly ash was unsuccessful, as it can be appreciated from the results obtained using Batches 1 to 3. These batches exhibited larger and deeper cracks than the other mixtures, which make them inappropriate for rooting applications.

FUTURE WORK

The results obtained in this research constitute a first attempt to evaluate the mechanical and physical characteristics of mortars used as roofing applications. The six mixtures evaluated show the need to refine the results in order to obtain the best combination for the established purposes. In this sense, additional test are proposed in order to validate and improve the preliminary results obtained in this research through a combination of sustainable materials and additional proportions of fly ash in substitution of fine aggregates.

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