

# **Center for By-Products Utilization**

## **DURABILITY OF CAST-CONCRETE PRODUCTS UTILIZING RECYCLED MATERIALS**

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## **Durability of Cast-Concrete Products Utilizing Recycled Materials**

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**Synopsis:** The major aim of this investigation was to develop technology for manufacturing of cast-concrete products using fly ash, bottom ash, and used foundry sand. A total of 18 mixture proportions were developed for bricks, blocks, and paving stones using these by-products. A reference mixture without any by-product materials for each type of cast-concrete masonry product was also proportioned. For bricks and blocks, 25% and 35% of portland cement was replaced with fly ash. Bottom ash and used foundry sand were used as a partial replacement of cement at replacement levels of 25 and 35% of regular sand. Paving stones contained fly ash as a replacement of cement at the rate of replacement of 15% and 25%. All cast-concrete products were tested for compressive strength, density, absorption, freezing and thawing resistance, drying shrinkage, and abrasion resistance.

Analysis of test data revealed that bricks with 25% replacement of cement with fly ash are suitable for use in both cold and warm climates. However, other brick mixtures were appropriate for building interior walls in cold regions and both interior and exterior walls in warm regions. None of paving stone mixtures including control mixtures strictly conform to the ASTM requirements. Masonry blocks with up to 25% replacement of regular sand with either bottom ash or used foundry sand could be used for building exterior walls in cold regions. The rest of the concrete mixtures for blocks could be used for building interior walls in cold regions and both interior and exterior walls in warm regions.

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

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## **INTRODUCTION**

Fly ash and bottom ash are generated from the combustion of coal in steam generating power plants. The annual production of fly ash and bottom ash in the United States is estimated to be about 20 and 60 million short tons in 1997, respectively. Of these, only 32% of the total materials produced were utilized in various applications. Therefore, large volumes of these by-products are still landfilled. Numerous applications of fly ash including for concrete, waste stabilization, structural fills, road base/subbase, mining application, controlled low strength materials (CLSM), etc. are well known and well established. The use of fly ash in concrete products accounted for about 49% of the total fly ash used in 1997. This translates to 16% of the total fly ash produced in the United States in 1997 [11]. Beneficial applications of bottom ash include structural fills, road base/subbase, snow

and ice control, concrete, waste stabilization, mining applications, blasting grit/roofing granules, and mineral filler [12]. The use of bottom ash in concrete accounts for about 12% of total bottom ash generated in 1997. This translates to only 3.6% of the total bottom ash produced in the United States in 1997 [11].

A basic foundry process produces castings by pouring molten metal into sand molds. The molds consist usually of molding sand and core sand. After hardening, the castings are removed in a shakeout process, cleaned, inspected, and shipped for delivery. The foundry by-product materials are generated because the raw materials used in mold making lose their required characteristics for manufacturing processes after a few times of reuse. Foundries are typically classified as ferrous or non-ferrous foundries. Ferrous foundries include gray iron, ductile iron, steel foundries, etc. Non-ferrous foundries include aluminum, brass/bronze foundries, etc. [13]. Over 92% (873,000 tons) of Wisconsin foundry by-products were landfilled in 1996 [14].

Currently, large volumes of fly ash, bottom ash, and used foundry sand are disposed of in landfills. Because of the increasing disposal cost and the difficulty in locating new landfill sites and the potential liability associated with landfills, beneficial utilization options for these industrial by-products is an important issue for the industry and the public [12, 13, 15, 16, 17].

The primary reasons for low utilization rate for the above by-products may be quality of the by-product materials, regulatory restrictions, and unavailability of sufficiently developed high-volume use technologies. Large-scale use of these by-products in construction materials, especially in cement-based materials, will consume most of the by-products generated in the USA. This project was primarily undertaken to develop high-volume use technologies for fly ash, bottom ash, and used foundry sands in manufacture of cast-concrete bricks, blocks, and paving stones.

## **RESEARCH SIGNIFICANCE**

In this work, the effects of inclusion of fly ash (FA), bottom ash (BA), and used foundry sand (UFS) on strength and durability-related properties of masonry products such bricks, blocks, and paving stones were investigated. The data obtained in this investigation will be used to establish mixture proportions and production technology for masonry products incorporating substantial amounts of fly ash, bottom ash, and used foundry for construction applications.

## **TESTING PROGRAM**

### **MATERIALS**

The following ingredients were used in the manufacture of concrete masonry products.

#### **Portland Cement**

Type I portland cement from one source was used in this work. The cement met the standard requirements for ASTM Type I cement. However, it showed a little higher SO<sub>3</sub> content than the standard chemical requirements of ASTM.

#### **Fly Ash**

ASTM Class F fly ash from the Wisconsin Electric Power Company's Oak Creek Power Plant (OCPP) was used in this research. The fly ash met both the physical and the chemical requirements of ASTM for Class F fly ash.

#### **Regular Sand**

Regular concrete sand was used as a fine aggregate. The sand met all ASTM requirements for fine aggregate for concrete.

#### **Used Foundry Sand**

Used foundry sand (ferrous green sand) supplied by a foundry in Neenah, WI was used in this investigation. The UFS was used as a partial replacement of regular sand. The used green sand exhibited about 14% lower unit weight, 20% lower SSD absorption, 60% lower fineness modulus, and over five times larger percentage of materials finer than 75- $\mu$ m relative to regular concrete sand. The used green sand did not meet the grading and materials finer than 75- $\mu$ m requirements of ASTM C33 for fine aggregates for use in concrete. Clay lumps and friable particles test and soundness test for UFS results showed 9% clay lumps and friable particles and 39% weight loss due to soundness test.

#### **Bottom Ash**

Bottom ash was obtained from the Oak Creek Power Plant of the Wisconsin Electric Power Company. It was sieved over a 9.5 mm sieve and only the portions finer than 9.5 mm was used in this project. The bottom ash was used as a partial replacement of regular fine aggregate. The bottom ash

exhibited a slightly higher percentage of clay lumps and friable particles than the requirement of ASTM. It met all the other requirements of ASTM.

### **Coarse Aggregate**

Crushed limestone chips with a 9.5-mm maximum size were used as coarse aggregate. The coarse aggregates did not meet the materials finer than 75- $\mu$ m requirement of ASTM for coarse aggregates. The coarse aggregates used did not meet all the gradation requirements.

## **MIXTURE PROPORTIONS AND MANUFACTURING OF MASONRY PRODUCTS**

### **Mixture Proportions**

A total of 18 masonry mixtures, six each for bricks, paving stones, and blocks were proportioned. For brick and block mixtures, fly ash was used as a replacement of cement at levels of 25% and 35% of cement by mass. For paving stone mixtures, fly ash was used as a replacement of cement at levels 15% and 25% by mass. Also, 25% and 35% of regular sand by mass was replaced with either bottom ash or used foundry sand. Bottom ash and used foundry sand were not used simultaneously in the same mixture. Crushed limestone chips with 9.5-mm maximum size were used as a coarse aggregate. Cementitious materials (cement + fly ash) content in paving stone mixtures were almost two times that of brick or block mixtures. Control mixtures for bricks, paving stones, and blocks without fly ash, bottom ash, or used foundry sand were also proportioned. Mixture proportions for bricks, paving stones, and blocks are presented in Tables 1 through 3, respectively.

### **Mixing Procedure**

Regular fine aggregate (sand) and coarse aggregate (crushed limestone chips), and bottom ash or used foundry sand were blended in a standard, fixed-drum, mixer, for three minutes. Then, cement and fly ash were added. After mixing for three more minutes, a gentle stream of water was added. Mixing and adding water were repeated until desired moisture content for these mixtures 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 density. After the casting, the products were transported via conveyor belts and steams cured for 16 to 20 hours at 52°C and at atmospheric pressure. Several days later, these masonry products were shipped to the laboratories of the University of Wisconsin-Milwaukee (UWM). Initially, they were stored outdoors. Bricks and paving stones were stored outdoors for almost two months (June and July). Blocks were stored outdoors for about two weeks (in July). Then, bricks, paving stones, and blocks were moved into the UWM Concrete Laboratory for indoor storage at ambient temperature of  $22 \pm 2$  °C and relative humidity of  $50 \pm 10$  %, 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. Each specimen of bricks and paving stones had a “frog”, that is 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 397-mm x 192-mm.

### **Testing of Specimens**

Tests for compressive strength, water absorption, and moisture content of bricks, paving stones, and blocks were performed in accordance with ASTM C 140. Three to six compression specimens and three absorption and moisture content specimens were tested for each brick or paving stone mixture at 5, 28, 56, 91, and 288 days. Three compression specimens and three absorption and moisture content specimens were tested for each block mixture at 7, 14, 28, and 91 days. Testing for freezing and thawing resistance of bricks, paving stones, and blocks was carried out in accordance with ASTM C 1262 using five specimens for each masonry block 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 mixture.

## **RESULTS AND DISCUSSION**

### **Compressive Strength of Bricks**

The compressive strength for DR1 (control), DR2 (25% FA), DR3 (25% FA and BA), DR4 (35% FA and BA), DR5 (25% FA and UFS), and DR6 (35% FA and UFS) bricks were 25.2, 23.2, 16.3, 12.9, 21.9, and 20.8 MPa, respectively, at the age of five days. At this age, DR1 (control) bricks

exceeded the minimum compressive strength requirement for Grade N (Table 15) bricks (24 MPa) by about 5%. At five days, DR2, DR5, and DR6 dry-cast bricks exceeded the strength requirement for Grade S bricks (17 MPa) by about 34%, 27%, and 21%, respectively. The respective compressive strength values for brick mixtures DR1, DR2, DR3, DR4, DR5, and DR6 increased to 31.2, 32.1, 18.9, 21.6, 27.8, and 27.2 MPa at 28 days; 34, 36.5, 22.1, 24.1, 34.1, and 33.1 MPa, at 56 days; 30.3, 38.1, 20.8, 24.3, 34.2, and 29.3 MPa at 91 days; and 41.8, 41, 20.5, 30, 41.6, and 37 MPa at 288 days of age.

The above results indicate that the early-age strength of brick mixtures containing fly ash was lower compared to the reference mixture. The rate of strength gain for the fly ash mixture became greater than that for the reference mixture at later ages. Thus the difference in strength of the fly ash mixtures and the control mixture reduced with increasing age. A lower strength values were obtained for DR3 and DR4 mixtures incorporating both fly ash and bottom ash. This was attributed to the dilution effects of fly ash, and lower relative strength of bottom ash particles compared to concrete sand particles used in these concrete mixtures. Except mixtures DR3 and DR4, all mixtures met the ASTM strength requirement for grade N bricks. DR3 and DR4 met the ASTM strength requirement for Grade S bricks. At later ages relative performance of 35% fly ash and bottom ash mixture (DR4) was better than 25% fly ash and bottom ash mixture (DR3). This is attributed to higher contribution of the pozzolanic effect of the class F fly ash in this project.

### **Density and Absorption**

The average density values for DR1 (control), DR2 (25% FA), DR3 (25% FA and BA), DR4 (35% FA and BA), DR5 (25% FA and UFS), and DR6 (35% FA and UFS) bricks were 2098, 2098, 1922, 1906, 2114, and 2114 kg/m<sup>3</sup>, respectively. DR2 (25% FA) bricks showed the same density as DR1 (control) bricks. DR3 (25% FA and bottom ash) and DR4 (35% FA and bottom ash) bricks showed about 8% and 9%, respectively, lower density than DR1 (control) bricks. This is attributed to the partial replacement of regular sand with lighter bottom ash. DR5 (25% FA and UFS) and DR6 (35% FA and UFS) bricks showed density equivalent to DR1 (control) bricks.

DR3 (25% FA and BA) and DR4 (35% FA and BA) bricks were classified as medium weight bricks per ASTM C 55. All other bricks (DR1, DR2, DR5, and DR6) were classified as normal weight bricks. The average absorption values for DR1, DR2, DR3, DR4, DR5, and DR6 bricks were 169.8, 150.6, 193.8, 184.2, 149, and 149 kg/m<sup>3</sup>, respectively. DR2 (25% FA) bricks showed about 11% lower absorption than DR1 (control) bricks. DR3 (25% FA and BA) and DR4 (35% FA and BA) bricks showed about 14% and 8%,

respectively, higher absorption than DR1 (control) bricks. This is believed to be primarily due to more porous microstructure of bottom ash versus normal sand that it reflected in these mixtures. DR1 (control) met the maximum absorption requirement for Grade S bricks ( $208 \text{ kg/m}^3$ ) for normal weight bricks. All other bricks (DR2, DR3, DR4, DR5, and DR6) met the absorption requirement for Grade N bricks (maximum  $160 \text{ kg/m}^3$  for normal weight bricks and  $208 \text{ kg/m}^3$  for medium weight bricks). The above results indicate that the lowest absorption was obtained for DR2, DR5, and DR6. This was primarily attributed to improved microstructure of these bricks resulting from pozzolanic reactions of fly ash.

### **Freezing and Thawing Resistance of Bricks**

DR2 bricks with 25% replacement of cement with FA showed the lowest freezing and thawing weight loss. In this work a weight loss of 0.20% was taken as the critical value. The critical value of weight loss (0.20%) was reached by DR1, DR2, DR3, DR4, DR5, and DR6 bricks at about 92, 150, 30, 18, 40, and 12 cycles of freezing and thawing, respectively.

On the basis of number of freezing and thawing cycles before reaching the critical value of weight loss for DR1 (control) bricks, DR2 (25% FA) bricks had about 63% longer freezing and thawing life than DR1 (control) bricks. DR3 (25% FA and BA) and DR4 (35% FA and BA) bricks had about 67% and 80%, respectively, shorter freezing and thawing life than DR1 (control) bricks. DR5 (25% FA and UFS) and DR6 (35% FA and UFS) bricks had about 57% and 87%, respectively, shorter freezing and thawing life than DR1 (control) bricks. The above results suggest that the freezing and thawing resistance of dry-cast bricks substantially decreased with the increase in percent replacement of regular fine aggregate with either BA or UFS. This was attributed to decrease in the strength of bricks when these by-products were added to the brick mixtures.

### **Drying Shrinkage of Bricks**

All bricks (DR1 through DR6) met the maximum drying shrinkage requirement of ASTM for Type II nonmoisture-controlled brick units (less than 0.065%) per ASTM C55. This means that all of the bricks could also be used as Type I moisture-controlled brick units if they are dried to meet the maximum moisture content requirements for Type I moisture-controlled brick units. The drying shrinkage values for DR1 (control), DR2, DR3, DR4, DR5, and DR6 bricks were approximately 0.023%, 0.040%, 0.031%, 0.034%, 0.041%, and 0.036%, respectively. These values were 35%, 62%,

48%, 52%, 63%, and 55%, respectively, of the maximum drying shrinkage requirement for Type II nonmoisture-controlled brick units (less than 0.065%).

## **PAVING STONES**

### **Compressive Strength of Paving Stones**

The respective compressive strength values for mixtures DS1 (control), DS2 (15% FA), DS3 (15% FA and 25% BA), DS4 (25% FA and 35% BA), DS5 (15% FA and 25% UFS), DS6 (25% FA and 35% UFS) were 38.3, 53.8, 26.5, 15.7, 30.1, and 24 MPa at the age of five days. These values are about 69%, 98%, 48%, 28%, 55%, and 44%, respectively, of the minimum compressive strength requirement of ASTM for paving stones (55 MPa). The respective compressive strength values for DS1 (control), DS2 (15%FA), DS3 (15% FA and 25% BA), DS4 (25% FA and 35% BA), DS5 (15%FA and 25% UFS), DS6 (25% FA and 35% UFS) were increased to 33.8, 47.4, 35, 22, 29.2, and 26.2 MPa at 28 days, 48.5, 58.3, 39.6, 22.7, 41.9, and 32.6 MPa at 56 days; 54.1, 54.5, 41.7, 25.4, 33.7, and 35.5 MPa at 91 days; 43.6, 48.3, 46.2, 31.5, 42.3, and 45.9 MPa at 288 days of age.

The rate of compressive strength development for paving stone mixtures followed the same general trend as described previously for brick mixtures. The peak compressive strength was observed for paving stone mixture DS2 containing 15% fly ash at all test ages. The above results revealed that none of the paving stone mixtures met the ASTM strength (55 MPa) requirement. This was partly related to the type of mold used; a brick mold was used due to non-availability of molds for paving stones at the manufacturing facility. Since DS2 exhibited strength equivalent to the control mixtures, it can also be recommended for commercial manufacture of paving stone for typical construction work.

### **Density and Absorption of Paving Stones**

The average density values for paving stones were 2098 kg/m<sup>3</sup> for DS1 (control), 2195 kg/m<sup>3</sup> for DS2 (15% FA), 2002 kg/m<sup>3</sup> for DS3 (15% FA and 25% BA), 1874 kg/m<sup>3</sup> for DS4 (25% FA and 35% BA), 2082 kg/m<sup>3</sup> for DS5 (15% FA and 25% UFS), and 2066 kg/m<sup>3</sup> for DS6 (25% FA and 35% UFS). The density of DS2 (15% FA) paving stones was about 5% higher than that of DS1 (control) paving stones. The density values for DS3 (15% FA and 25% BA) and DS4 (25% FA and 35% BA) paving stones were about 5% and 11%, respectively, lower than that of DS1 (control). The density values for DS5 (15% FA and 25% UFS) and DS6 (25% FA and 35% UFS) paving stones were equivalent to the value shown by control mixture DS1.

The average absorption values for DS1 (control), DS2 (15% FA), DS3 (15% FA and 25% BA), DS4 (25% FA and 35% BA), DS5 (15% FA and 25% UFS), and DS6 (25% FA and 35% UFS) paving stones were 131.4, 96.1, 137.8, 176.2, 129.8, 131.4 kg/m<sup>3</sup>, respectively. These values are about 64%, 20%, 72%, 120%, 62%, and 64%, respectively, higher than the maximum absorption requirement for paving stones (80 kg/m<sup>3</sup>). The absorption values for DS2 (15% FA), DS3 (15% FA and 25% BA), DS4 (25% FA and 35% BA), DS5 (15% FA and 25% UFS), and DS6 (25% FA and 35% UFS) paving stones were about 27% lower, 5% and 34% higher, 1% lower, and 0% lower than that of DS1 (control) paving stones.

### **Freezing and Thawing Resistance of Paving Stones**

DS2 (15% FA) paving stone mixture showed the highest resistance to freezing and thawing among all mixtures tested. The freezing and thawing weight loss

of DS1 (control) paving stones was equivalent to DS2 paving stones up to about 250 cycles of freezing and thawing. However, DS1 (control) paving stones ruptured after 250 cycles of freezing and thawing.

DS1 (control), DS2, DS3, DS4, DS5, and DS6 paving stones reached the critical value of weight loss (0.20%) at about 190, 200, 150, 120, 95, and 45 cycles of freezing and thawing, respectively. Thus, the paving stones showed much longer freezing and thawing life than that achieved by the bricks discussed previously. This was probably due to the higher cementitious materials (cement + FA) contents of paving stones which resulted in higher values of compressive strength compared to bricks.

### **Abrasion Resistance of Paving Stones**

Abrasion coefficient represent the volume loss from sand blasted area of paving stones. The abrasion coefficient values for DS1 (control), DS2 (15% FA and 25% UFS), DS3 (15% FA and 25% BA), DS4 (25% FA and 55% BA), DS5 (15% FA and 25% UFS), and DS6 (25% FA and 35% FA) paving stones were 4.75, 3.68, 5.72, 7.32, 6.83, and 8.53 mm<sup>3</sup>/mm<sup>2</sup>, respectively. The abrasion coefficient values for DS2 (15% FA), DS3 (15% FA and 25% BA), DS4 (25% FA and 35% BA), DS5 (15% FA and 25% UFS), and DS6 (25% FA and 35% UFS) paving stones were about 22% lower, and 20%, 54%, 44%, and 80% higher than that of DS1 (control) paving stones. The highest abrasion resistance of DS2 (15% FA) was attributed to its highest compressive strength amongst all paving stones mixtures tested.

## **BLOCKS**

### **Compressive Strength of Blocks**

The compressive strength values for DL1 (control), DL2 (25% FA), DL3 (25% FA), DL4 (35% FA and BA), DL5 (25% FA and UFS), and DL6 (35% FA and UFS) dry-cast blocks were 19.2, 20.6, 14.8, 9.7, 18.2, and 15.4 MPa, respectively at the age of 7 days. These values are about 46%, 57%, 13% higher, 26% lower, and 39% and 18% higher than the minimum compressive strength requirement for load-bearing concrete blocks (13 MPa). Therefore, except DL4 (35% FA and BA), all block mixtures exceeded the minimum compressive strength requirement at the age of seven days. The respective compressive strength values for DL1 (control), DL2 (25% FA), DL3 (25% FA), DL4 (35% FA and BA), DL5 (25% FA and UFS), and DL6 (35% FA and UFS) dry-cast blocks increased to 21.7, 19.9, 20.4, 12.5, 18.9, and 20.2 MPa at 14 days; 22.7, 25.4, 21.4, 15.3, 24.4, and 22.3 MPa at 28 days; 23.1, 29.2, 22.5, 16.1, 28.1, and 25.4 MPa at 91 days of the age.

### **Density, and Absorption of Blocks**

The average density values for DL1 (control), DL2 (25% FA), DL3 (25% FA and BA), DL4 (35% FA and BA), DL5 (25% FA and UFS), and DL6 (35% FA and UFS) dry-cast blocks were 2163, 2211, 2034, 1938, 2227, and 2227 kg/m<sup>3</sup>, respectively. The density values for DL2 (25% FA), DL3 (25% FA and BA), DL4 (35% FA and BA), DL5 (25% FA and UFS), and DL6 (35% FA and UFS) blocks were about 2% higher, 6% and 10% lower, and 3% and 3% higher compared to DL1 (control). DL4 (35% FA and BA) blocks were classified as medium weight blocks. All the other blocks were classified as normal weight blocks.

The average absorption values for DL1 (control), DL2 (25% FA), DL3 (25% FA and BA), DL4 (35% FA and BA), DL5 (25% FA and UFS), and DL6 (35% FA and UFS) blocks were 134.6, 123.3, 152.2, 171.4, 123.3, and 129.8 kg/m<sup>3</sup>, respectively. These values are 35%, 41%, 27%, 29%, 41%, and 38% lower than the applicable maximum ASTM water absorption requirement. The respective absorption values for DL2 (25% FA), DL3 (25% FA and BA), DL4

(35% FA and BA), DL5 (25% FA and UFS), and DL6 (35% FA and UFS) blocks were about 8% lower, 13% and 27% higher, and 8% and 4% lower relative to DL1 (control) blocks.

### **Freezing and Thawing Resistance of Blocks**

The freezing and thawing resistance results exhibited the lowest weight loss for the blocks made with DL2 (25% FA). DL1 (control), DL3 (25% FA and BA), and DL5 (25% FA and UFS) blocks showed comparable freezing and thawing weight loss with each other up to about 80 cycles of freezing and thawing. However, from about 100 cycles, DL5 blocks began to show larger weight loss than DL3 or DL1 (control) blocks. From about 160 cycles, DL3 blocks began to show larger weight loss than DL1 (control) blocks. DL6 (35% FA and UFS) and DL4 (35% FA and BA) blocks showed very large freezing and thawing weight loss from the early freezing and thawing cycles. DL6 (35% FA and UFS) blocks showed smaller weight loss than DL4 (35% FA and BA) blocks.

DL1 (control), DL3, DL4, DL5, and DL6 blocks reached the critical value of weight loss (1.1%) at about 250, 200, 10, 170, and 30 cycles, respectively. Based on the plot shown in Fig. 8, DL2 (25% FA) blocks would have reached the critical value of weight loss at about 350 cycles of freezing and thawing if the freezing and thawing tests were continued.

Therefore, based on the critical value of weight loss, DL2 (25% FA), DL3 (25% FA and BA), DL4 (35% FA and BA), DL5 (25% FA and UFS), and DL6 (35% FA and UFS) blocks had about 40% longer, and 20%, 96%, 32%, and 88% shorter freezing and thawing life compared to DL1 (control) blocks. The blocks with up to 25% replacement of regular sand with either BA or UFS exhibited freezing and thawing resistance comparable to DL1 (control) blocks.

### **Drying Shrinkage of Blocks**

All blocks met the maximum drying shrinkage requirement of ASTM for Type II nonmoisture-controlled block units (less than 0.065%). This means that all of the blocks could also be used as Type I moisture-controlled block units if they were dried to meet the moisture content requirement for Type I moisture-controlled block units. The drying shrinkage values for DL1 (control), DL2 (25% FA), DL3 (25% FA and BA), DL4 (35% FA and BA), DL5 (25% FA and UFS), and DL6 (35% FA and UFS) were 0.023%, 0.020%, 0.031%, 0.028%, 0.038%, and 0.040%, respectively. DL3 (25% FA and BA) and DL4 (35% FA and BA) blocks exhibited about the same drying shrinkage. The respective drying shrinkage values for DL2 (25%

FA), DL3 (25% FA and BA), DL4 (35% FA and BA), DL5 (25% FA and UFS), and DL6 (35% FA and UFS) blocks were about 13% lower, and 35%, 22%, 65%, and 74% higher than that of DL1 (control) blocks.

## **SUMMARY AND CONCLUSION**

This investigation was undertaken to develop mixture proportion for manufacturing of cast-concrete products using fly ash, bottom ash, and used foundry sand. Details of test results of this investigation are reported elsewhere [8]. ASTM Class F Fly Ash (FA) was used as a partial replacement of portland cement at replacement levels of 15%, 25%, and 35%. UFS (used foundry sand, specifically ferrous green sand) and BA (bottom ash) were used as partial replacements of regular fine aggregates (sand) at replacement levels of 25% and 35%. Six brick mixtures were produced: DR1 (control), DR2 (25% FA), DR3 (25% FA and 25% BA), DR4 (35% FA and 35% BA), DR5 (25% FA and 25% UFS), and DR6 (35% FA and 35% UFS). For these masonry products, BA and UFS were not used simultaneously in the same mixture. Six paving stone mixtures were produced: DS1 (control), DS2 (15% FA), DS3 (15% FA and 25% BA), DS4 (25% FA and 35% BA), DS5 (15% FA and 25% UFS), and DS6 (25% FA and 35% UFS). The cement content of paving stones was about two times the cement content of bricks due to higher compressive strength and durability requirements. Paving stones were produced using brick molds. Six block mixtures were produced: DL1 (control), DL2 (25% FA), DL3 (25% FA and 25% BA), DL4 (35% FA and 35% BA), DL5 (25% FA and 25% UFS), and DL6 (35% FA and 35% UFS). The mixture proportions for blocks were similar to those for bricks.

Based on the data presented, the following conclusions can be drawn.

1. In general concrete masonry mixtures containing Class F fly ash showed lower early-age compressive strength compared to reference masonry mixture for each masonry product. The compressive strength difference between fly ash containing mixtures and reference concrete mixtures decreased with age. This was attributed to improvement in microstructure of the material due to additional calcium silicate hydrate (C-S-H) resulting from pozzolanic reactions of the fly ash in addition to C-S-H generation from portland cement reaction.
2. Partial replacement of regular sand with either BA or UFS resulted in reduction in compressive strength, freezing and thawing resistance, and abrasion resistance of these masonry products.

3. Partial replacement of cement with FA resulted in improvement in compressive strength, freezing and thawing resistance, and abrasion resistance of these masonry products.
4. In general, products made with UFS showed higher compressive strength than those with BA.
5. Products made with BA showed better freezing and thawing resistance and abrasion resistance and lower drying shrinkage than those with made UFS.
6. In warm regions, all the bricks (DR1 through DR6) could be used for building both interior and exterior walls. In cold regions, only DR1 (control) and DR2 (25% FA) bricks could be used for building exterior walls. All the other bricks (DR3 through DR6) could be used for building interior walls in cold regions.
7. In warm regions, all of the blocks (DL1 through DL6) could be used for building both interior and exterior walls. In cold regions, DL1 (control), DL2 (25% FA), DL3 (25% FA and BA), and DL5 (25% FA and UFS) blocks could be used for building exterior walls. DL4 (35% FA and BA) and DL6 (35% FA and UFS) blocks could be used for building interior walls in cold regions.
8. None of the paving stones, including control paving stones, met the compressive strength and the water absorption requirements of ASTM for concrete paving stones. However, paving stone mixture DS2 (15% FA) showing strength and absorption equivalent to the control paving stone mixture is suitable for typical construction work.

## REFERENCES

11. American Coal Ash Association, "1997 Coal Combustion Product (CCP) Production and Use," Alexandria, VA, 1998, 2 pages.
12. "Coal Combustion Byproduct (CCB) Production & Use: 1966-1993: Report for Coal Burning Electric Utilities in the United States", American Coal Ash Association, Alexandria, VA, April 1995, 68 pages.
13. Naik, T. R., "Foundry Industry By-Products Utilization," University of Wisconsin-Milwaukee, Department of Civil Engineering and Mechanics, Center for By-Products Utilization, Report No. CBU-1989-01, February 1989, 23 pages.
14. "Wisconsin Cast Metal Association 1996 Foundry Survey Results," Wisconsin Cast Metal Association, 1997, 4 pages.
15. "Final Report on Alternate Utilization of Foundry Waste Sand," A Report Prepared for Illinois Department of Commerce and Community Affairs, American Foundrymen's Society, Chicago, IL, August 1991, pp. 39-41.
16. Ramme, B. W., and Kohl, T. A., "Wisconsin Electric's Coal Combustion Products Utilization Program," Proceedings of the 1998 60th Annual American Power Conference, Illinois Institute of Technology, Chicago, IL, Vol. 60, No. 2, 1998, pp. 887-894.
17. Blackstock, T., "Coal Combustion By-Products: Opportunities for Utilization," Proceedings of the 1997 59th Annual American Power Conference, Illinois Institute of Technology, Chicago, IL, Vol. 59, No. 2, 1997, pp. 1151-1154.
18. Naik, T. R., Kraus, R. N., Chun, Y.-M., Ramme, B. R., and Singh, S. S., "Strength and Durability of Cast-Concrete Products Utilizing Recycled Materials," Submitted to ACI Materials Journal.

**Table 1: Mixture Proportions for Bricks**

Plant: Best Block Co., Racine, WI

Mixture Number	DR1	DR2	DR3	DR4	DR5	DR6
Cement, kg/m <sup>3</sup>	199	157	145	128	157	136
Fly Ash, kg/m <sup>3</sup>	0	65	59	89	65	95
Water kg/m <sup>3</sup> *	86	95	118	163	110	131
Sand, SSD, kg/m <sup>3</sup>	1388	1415	987.8	860	1068	922
9.5 mm Bottom Ash, SSD, kg/m <sup>3</sup>	0	0	285	406	0	0
Used Foundry Sand, SSD, kg/m <sup>3</sup>	0	0	0	0	365	510
9.5 mm Coarse Aggregates, SSD, kg/m <sup>3</sup>	463	484	448	445	484	481
Density of Freshly Cast Bricks, kg/m <sup>3</sup>	2131	2211	2050	2098	2242	2275

\*Estimated by the microwave test procedure

**Table 2: Mixture Proportions for Paving Stones**

Plant: Best Block Co., Racine, WI

Mixture Number	DS1	DS2	DS3	DS4	DS5	DS6
Cement, kg/m <sup>3</sup>	383	332	303	252	314	267
Fly Ash, kg/m <sup>3</sup>	0	74	68	107	68	113
Water kg/m <sup>3</sup>	95	107	122	122	104	104
Sand, SSD, kg/m <sup>3</sup>	1305	1329	911	745	949	792
9.5 mm Bottom Ash, SSD, kg/m <sup>3</sup>	0	0	273	350	0	0
Used Foundry Sand, SSD, kg/m <sup>3</sup>	0	0	0	0	323	436
9.5 mm Coarse Aggregates, SSD, kg/m <sup>3</sup>	445	451	412	389	430	412
Density of Freshly Cast Paving Stones, kg/m <sup>3</sup>	2227	2291	2082	1970	2195	2131

\*Estimated by the microwave test procedure

**Table 3: Mixture Proportions for Blocks**

Plant: Best Block Co., Racine, WI

Mix. No.	DL1	DL2	DL3	DL4	DL5	DL6
Cement, kg/m <sup>3</sup>	217	166	157	131	166	134
Fly Ash, kg/m <sup>3</sup>	0	68	65	89	68	92
Water kg/m <sup>3</sup>	95	101	101	119	148	157
Sand, SSD, kg/m <sup>3</sup>	1448	1469	1044	863	1092	890
9.5 mm max. Bottom Ash, SSD, kg/m <sup>3</sup>	0	0	309	421	0	0
Used Foundry Sand, SSD, kg/m <sup>3</sup>	0	0	0	0	380	504
9.5 mm Coarse Aggregates, SSD, kg/m <sup>3</sup>	498	507	481	460	507	478
Concrete Density, kg/m <sup>3</sup>	2259	2307	2147	2082	2371	2259

\*Estimated by the microwave test procedure