Center for By-Products Utilization

DEVELOPMENT OF DRY-CAST AND WET-CAST CONCRETE PRODUCTS UTILIZING FLY ASH, BOTTOM ASH, AND USED FOUNDRY SAND

By:
Tarun R. Naik, Rudolph N. Kraus, and Bruce W. Ramme

Report No. CBU-1998-01

Submitted for presentation and publication at the CANMET/ACI Joe Cabrera Symposium, Bangkok, Thailand, June 1998

Department of Civil Engineering and Mechanics

College of Engineering and Applied Science
THE UNIVERSITY OF WISCONSIN - MILWAUKEE

DEVELOPMENT OF DRY-CAST AND WET-CAST CONCRETE PRODUCTS UTILIZING FLY ASH, BOTTOM ASH, AND USED FOUNDRY SAND

by Tarun R. Naik, Rudolph N. Kraus, and Bruce W. Ramme

Synopsis: This paper deals with the manufacture and testing of wet-cast and dry-cast concrete products containing fly ash, bottom ash, and used foundry sand. Test specimens for all dry-cast and wet-cast concrete mixtures have been evaluated for compressive strength, absorption, density, moisture content, and resistance to freezing and thawing as a function of age. A total of 18 dry-cast concrete products mixtures, consisting of six dry-cast brick, six dry-cast block, and six dry-cast paving stone, were manufactured. The dry-cast bricks, blocks, and paving stones were produced using standard manufacturing equipment utilized in the production of dry-cast concrete products. A total of six wet-cast concrete products mixtures, consisting of three wet-cast brick and three wet-cast paving stone mixtures, were also manufactured. Mixtures were manufactured in a conventional manner in a mixer with one cubic yard capacity used for daily concrete production.

One reference mixture without fly ash, bottom ash, or used foundry sand was produced for each dry-cast product. Two mixtures of dry-cast bricks, blocks, and paving stones were produced by incorporating two ash by-product materials into each mix: fly ash as a partial replacement of cement and bottom ash as a replacement of normal concrete sand. The two remaining mixtures of each dry-cast product incorporated fly ash as a replacement of cement and used foundry sand as a replacement of normal concrete sand. Dry-Cast concrete mixtures contained up to 41% fly ash, 33% bottom ash and 36% foundry ash. Wet-cast concrete mixtures contained up to 40% fly ash, 32% bottom ash, and 36% used foundry sand.

One reference wet-cast mixture was proportioned without fly ash, bottom ash, or used foundry sand for both the wet-cast brick and paving stone mixtures. Two wet-cast concrete brick and two wet-cast concrete paving stone mixtures were also proportioned to utilize all three by-product materials: foundry sand and bottom ash as a partial replacement of normal concrete sand and fly ash as a partial replacement for cement.

Keywords: bricks, blocks, bottom ash, concrete, durability, fly ash, paving stones, used foundry sand.

Dr. Tarun R. Naik is Director of the UWM Center for By-Products Utilization and Associate Professor of Civil Engineering at the University of Wisconsin-Milwaukee, WI. He is an active member of ACI and ASCE. He is a member of ACI Committee 232, "Fly Ash and Natural Pozzolans in Concrete", Committee 228, "Nondestructive Testing of Concrete", Committee 214, "Evaluation of Results of Strength Tests of Concrete", and Committee 123, "Research". He is also chairman the ASCE technical committee "Emerging Materials".

ACI member Rudolph N. Kraus is Assistant Director, UWM Center for By-Products Utilization, Milwaukee, WI. He has been involved with numerous projects on the use of by-product materials including utilization of used foundry sand and fly ash in CLSM (Controlled Low Strength Materials), evaluation and development of CLSM utilization lightweight aggregate, and use of by-product materials in the production of dry-cast concrete products.

Bruce W. Ramme is the Manager of Combustion By-Products Utilization for Wisconsin Electric Power Company, Milwaukee, WI and a member of ACI. He is currently Chairman of ACI Committee 229 on Controlled Low Strength Materials; and also serves on Committee 231C on By-Product Lightweight Aggregates, Committee 213 on Lightweight Concrete, and Committee 232 on Fly Ash in Concrete.

INTRODUCTION AND BACKGROUND

Statement of Objectives

The major aim of this project was: (1) to introduce manufacturers of cast concrete products in the use of recycled industrial materials (fly ash, bottom ash, and used foundry sand) in manufacturing dry-cast and wet-cast concrete products; and, (2) to develop mixtures with predictable strength and durability properties for future manufacturing. The success of this project should increase utilization of under-utilized industrial by-product materials in Wisconsin. Wisconsin currently generates approximately 1.2 tons of coal ash and 800,000 tons of used foundry sand per year, most of which goes to landfills because there is no economical use for currently available options. Used foundry sand and coal ashes are also becoming more of a disposal problem due to shrinking landfill space and unknown future environmental and economic liability. The results of this project will benefit both industry and the environment. It will also lead to further development of the market for fly ash, bottom ash, and foundry by-products. A significant amount of work has been previously performed by Naik[1-5] and the UWM Center for By-Products Utilization related to the development of masonry products utilizing recycled industrial materials such as fly ash and used foundry sand. The full scale production and the basis for the mixtures for this project were developed from previous laboratory research at UWM-CBU.

EXPERIMENTAL PROCEDURES

Materials

The components of the dry-cast and wet-cast concrete masonry products used for this project were tested in accordance with standard ASTM test methods found in reference 6. Fly Ash (ASTM C

618) was characterized for chemical properties including oxides, elements, mineralogical, and the following physical tests: fineness (ASTM C 430), strength activity index with cement (ASTM C 109), water requirements (ASTM C 109), Autoclave expansion (ASTM C 151), and specific gravity (ASTM C 188). Bottom ash was also used for this study. Cement from each manufacturer was tested per ASTM C 150 requirements for air content (ASTM C 185), fineness (ASTM C 204), autoclave expansion (ASTM C 151), compressive strength (ASTM C 109), time of setting (ASTM C 191), and specific gravity (ASTM C 188). Type I Portland cement (ASTM C 150) was used throughout this work. Fine and coarse aggregates including used foundry sand and bottom ash were tested per ASTM C 33 requirements for the following physical properties: unit weight (ASTM C 29), specific gravity and absorption (ASTM C 128), fineness (ASTM C 136), material finer than #200 sieve (ASTM C 117), organic impurities (ASTM C 40), and soundness (ASTM C88). The fine aggregate was natural sand with 6.4 mm (1/4-in.) normal maximum size. Used foundry sand was obtained from an iron foundry from Wisconsin. The used foundry sand utilized for the project was a green foundry sand which used kaolin clay as the primary binder. The coarse aggregate for the dry-cast concrete mixtures was crushed limestone with a 9.5 mm (3/8-in.) maximum size. The coarse aggregate for the wet-cast mixtures was gravel with a 9.5 mm (3/8-in.) maximum size. The air entraining admixture utilized in the wet-cast paving stone mixtures was Axim Concrete Technology's Catexol A.E. 260.

Mixture Proportions

A total of 18 dry-cast concrete products mixtures, consisting of six dry-cast brick (Table 1), six dry-cast block (Table 2), and six dry-cast paving stone mixtures (Table 3) were prepared. The dry-cast products were manufactured at the facilities of the Best Block Company in Racine, Wisconsin. The dry-cast bricks, blocks, and paving stones were produced using standard manufacturing equipment utilized in the manufacture of dry-cast concrete products. Best Block Company is one of the primary manufacturers of dry-cast concrete blocks, retaining wall units, and bricks in southeastern Wisconsin.

One reference mixture without fly ash, bottom ash, or used foundry sand was proportioned for each dry-cast product (Mixture BR-1, bricks; BL-1, blocks; and, PS-1, paving stones). One mixture of dry-cast bricks and blocks was also produced with up to 30% fly ash by weight of total cementitious materials and without used foundry sand or bottom ash (Mixture BR-2, bricks; BL-2, blocks; and, PS-2, paving stones). Two mixtures of dry-cast bricks, blocks, and paving stones were produced by incorporating two by-product materials into each mix; fly ash as a partial replacement of cement and bottom ash as a partial replacement of normal concrete sand (Mixtures BR-3, BR-4 bricks; BL-3, BL-4 blocks; and, PS-3, PS-4 paving stones). The two remaining mixtures of each dry-cast product incorporated fly ash as a partial replacement of cement and used foundry sand as a partial replacement of normal concrete sand (Mixtures BR-5, BR-6 bricks; BL-5, BL-6 blocks; and, PS-5, PS-6 paving stones).

All wet-cast concrete brick and paving stone mixtures were batched at the facilities of the Advance Cast Stone Company, Random Lake, Wisconsin. A total of six ready-mixed concrete mixtures, including three wet-cast concrete brick mixtures (Table 4) and three wet-cast concrete paving stone mixtures (Table 5) were proportioned. The wet-cast mixtures were proportioned to maintain a

slump in the range of approximately 50 to 100 mm. One reference wet-cast mixture was proportioned without fly ash, bottom ash or used foundry sand for both the wet-cast brick and wet-cast paving stone mixtures (Mixture BRW-1, bricks; and, PSW-1, paving stones). Two wet-cast concrete brick and two wet-cast concrete paving stone mixtures were also proportioned to utilize all three by-product materials; foundry sand and bottom ash as a partial replacement of normal concrete sand and fly ash as a partial replacement for cement (Mixtures BRW-3, BRW-4 bricks; and, PSW-3, PSW-4 paving stones).

Manufacturing of Concrete Mixtures

All dry-cast and wet-cast concrete making ingredients, except fly ash, bottom ash, and used foundry sand, were automatically batched. The dry-cast concrete was mixed utilizing the mixer at the Best Block Company. Each batch of concrete was minimum 0.4 m. Fly ash was manually weighed and loaded into the mixer prior to the addition of the cement. The bottom ash and foundry sand were loaded prior to the addition of the coarse aggregate. Additional water was added in the mixture as needed for achieving the desired level of workability. Whenever additional water was added to obtain the desired fresh concrete characteristics, the concrete mixture was again mixed for an additional five minutes. All concrete mixing was conducted in accordance with ASTM C 94 procedures. The dry-cast concrete was discharged into a hopper and then automatically conveyed to the dry-cast brick/block/paving stone manufacturing equipment.

The wet-cast concrete was mixed in one cubic yard batch size mixer at the facilities of the Advance Cast Stone Company. The required amount of the fly ash was manually weighed and loaded into the mixer prior to the addition of the cement. The bottom ash and foundry sand were loaded into the mixer prior to the addition of the coarse aggregate. The resulting wet-cast "ready-mixed" concrete was discharged into a hopper and moved by an overhead crane to the location where fresh concrete tests were performed and test specimens were cast. Additional water was added in the mixture as needed for achieving the desired level of workability, prior to discharging the concrete from the mixer. Whenever additional water and/or air entraining admixture was added to obtain the specified fresh concrete characteristics, the concrete was mixed for an additional five minutes. All concrete mixing was done in accordance with ASTM C 94.

Specimen Preparation and Testing

Fresh concrete properties of the dry-cast brick, block, and paving stone mixtures were obtained. These tests included unit weight (ASTM C 138), total moisture content (utilized for determining total water content of the mixture), and temperature (ASTM C 1064).

Dry-cast concrete brick, block, and paving stone test specimens were manufactured for each mixture by the manufacturing equipment of the Best Block Company. These included specimens for compressive strength, absorption, resistance to freezing and thawing, shrinkage, and abrasion resistance tests. All test specimens were cast utilizing the standard dry-cast concrete molds and vibratory-compaction equipment of the Best Block Company. The test specimens were then typically steam cured for 6 ± 2 hours at about $52° \pm 5°C$ at the Best Block Company Plant. They

were then brought to the UWM-CBU lab for storage and testing. Test specimens were then placed in the UWM-CBU concrete test lab room maintained at 23° ± 2°C and 50° ± 10% R.H. until the time of test.

Fresh concrete properties, including; air content (ASTM C 231), workability (ASTM C 143), unit weight (ASTM C 138), and temperature (ASTM C 1064), were measured for wet-cast brick and paving stone mixtures.

Wet-cast concrete brick and paving stone test specimens were prepared for each of the designated mixture. They included brick and paving stone specimens for compressive strength, absorption, resistance to freezing and thawing, shrinkage, and abrasion resistance tests. All test specimens were cast in accordance with ASTM C 31. These specimens were typically cured for one day in their molds at about 21° ± 5°C at the Advance Cast Stone Company indoor plant. They were then brought to the UWM-CBU lab for further curing and testing. For additional curing, these specimens were demolded and placed in a standard moist-curing room maintained at 100% R.H. and 22° ± 2°C until the time of test.

Compressive strength, density and absorption of dry-cast bricks, blocks and paving stones and wet-cast brick and paving stone mixtures were conducted in accordance with ASTM C 140. Resistance to freezing and thawing of all dry-cast and wet-cast mixtures were conducted per ASTM C 1262.

RESULTS

Compressive Strength

Dry-Cast Bricks, Blocks, and Paving Stones-- The reference dry-cast concrete brick mixture (Mix BR-1) attained a strength of approximately 33 MPa at the 56-day age (Fig. 1). Other brick mixtures attained compressive strength in the range of 22 to 36 MPa at the age of 56 days. The results obtained up to 56 days indicate that three dry-cast brick test mixtures, BR-2 (29% fly ash), BR-5 (29% fly ash, 25% used foundry sand), and BR-6 (41% fly ash, 36% used foundry sand), out-performed the reference mixture at the 56-day age. At the 55 days age, these mixtures would meet the ASTM C 55 compressive strength requirements of 24.1 MPa for grade N-I and N-II bricks. Mixtures containing bottom ash had lower compressive strengths than the reference mixture. However, these bricks would still meet the ASTM C 55 compressive strength requirement (17.3 MPa) for Grade S-I and S-II. The compressive strength of Mix BR-3 and BR-4 were significantly lower than the other mixtures. This reduction in strength can be attributed to the bottom ash utilized in the mixtures. The bottom ash had a significantly lower unit weight than the normal aggregate used for dry-cast products 769 kg/m^3 vs. 1585 kg/m^3 for crushed limestone. The compressive strength of bottom ash was also lower than limestone.
Compressive strength results of dry-cast concrete block mixtures are shown in Fig. 2. The compressive strength at the 91-day age attained by the block mixtures ranged from 23 MPa for the reference mixture to 29 MPa for Mix BL-2 at 91-day age. All mixtures except for mix BL-4 (40% fly ash, 33% bottom ash) met the ASTM C 90 compressive strength requirement (13.1

MPa) at the first age tested (7-days). At the age of 28 days and later, all mixtures exceeded the ASTM C 90 compressive strength requirements. The reference paving stone mixture attained a strength of approximately 52 MPa at the 91-day age (Fig. 3). Other dry-cast concrete paving stone mixtures attained compressive strength in the range of 25.5 to 54 MPa at the age of 91 days (Fig. 3). The results obtained up to 91 days show that the dry-cast paving stone mixture with 18% fly ash (PS-2) out-performed the reference mixture.

Wet-Cast Bricks and Paving Stones-- Compressive strength data of wet-cast brick mixtures are shown in Fig. 4. The compressive strength of all three mixtures met the ASTM C 55 Grade N-I and N-II requirement (24.1 MPa) at the age of 91 days and later. At the 28-day age, Mix BRW-1 (control) and BRW-2 (26% used foundry sand, 30% fly ash, 26% bottom ash) met the requirements for Grade N-I and N-II bricks while Mix BRW-3 (40% fly ash, with bottom ash and used foundry sand) met Grade S-I and S-II compressive strength requirements (17.3 MPa).

Compressive strength data of wet-cast paving stone mixtures are shown in Fig. 5. None of the values reached the strength required by ASTM C 936 (55 MPa). A slightly higher cementitious materials, or lower w/cm would be used in the future. Compressive strengths of the mixtures ranged from 16.5 to 44.8 MPa at the 29-day age. Due to the pozzolonic contributions of the fly ash, the percentage difference between the reference mixture (PSW-1) and the mixtures containing used foundry sand, bottom ash, and fly ash (PSW-2, PSW-3) decreased with age. This becomes apparent when comparing results at the 3-day age with the 182-day test results.

Density and Absorption

Dry-Cast Bricks, Blocks, and Paving Stones-- Density and absorption of dry-cut brick mixtures did not change significantly with age. However these properties did vary when components of the mixtures included used foundry sand or bottom ash. Utilization of fly ash up to 29% (Mix BR-2) did not affect the density. Density of the reference Mix BR-1 varied from 2066 to 2114 kg/m^3 while that for mixtures containing used foundry sand increased slightly to 2114 to 2130 kg/m^3 and the density of mixtures containing bottom ash decreased to 1858 to 1954 kg/m^3. All dry-cast brick mixtures tested met the ASTM C55 Grade S-I and S-II requirement for absorption (208 kg/m^3 maximum) with the least absorption, 112.1 to 160.2 kg/m^3, was exhibited by mixtures containing used foundry sand and fly ash (Mix BR-5 and BR-6). The mixtures containing used foundry sand and fly ash or the 29% fly ash Mix BR-2 also met the more stringent ASTM C55 Grade N-I and N-II requirement (160 kg/m^3 maximum).

Similar to dry-cast brick mixtures, density and absorption of dry-cast block did not change with increasing age. All mixtures produced met the ASTM C 90 requirement for absorption (208 kg/m^3 maximum). Absorption of dry-cast concrete block varied between 96 to 176 kg/m^3. Mixtures containing bottom ash (Mix BL-3 and BL-4) exhibited the highest absorption. All dry-cast block mixtures produced were classified as normal weight block per ASTM C 90 designation with the exception of Mix BL-4. This mixture contained 40% fly ash and 33% bottom ash. The density of Mix BL-4 was approximately 192 kg/m^3 which is considered to be a medium weight block per ASTM C 90 designation (1680-2000 kg/m^3).

Absorption of all dry-cast paving stone mixtures, including the reference mixture, did not meet ASTM C 936 requirements for absorption (5% maximum). All mixtures with the exception of Mix PS-4 had absorption similar to the reference mixture (Mix PS-1). Mix PS-4 (30% fly ash, 33% bottom ash) slightly exceeded the absorption of the reference mixture 10 to 11% versus 6 to 8% for Mix PS-1.

Wet-Cast Bricks and Paving Stones-- Density of wet-cast bricks and paving stone mixtures did not change with age. As-expected reference mixtures without bottom ash had the highest density 2130 kg/m^3 for the wet-cast brick reference Mix BRW-1 and 2162 kg/m^3 for the wet-cast paving stone Mix PSW-1. As the amount of bottom ash increased for the brick and paving stone mixtures, density decreased (1922 to 2002 kg/m^3 for wet-cast brick and 1810 to 1938 kg/m^3 for wet-cast paving stones).

Resistance to Freezing and Thawing

Dry-Cast Bricks, Blocks, and Paving Stones-- The resistance to freezing and thawing of dry-cast mixture are shown in Figs. 6 to 8. The dry-cast brick mixtures (Fig. 6) that exhibited the least resistance to freezing and thawing were Mix BR-6 (36% used foundry sand and 41% fly ash content) and Mix BR-4 (41% fly ash and 33% bottom ash content). Mix BR-2 (29% fly ash content) had the greatest resistance to freezing and thawing. No significant weight loss was exhibited for this mix up to 170 cycles of freezing and thawing. This was a significant improvement over the reference Mix BR-1 which began to show weight loss of approximately 1.5% at 120 cycles. Preliminary results of dry-cast block mixtures (Fig. 7) indicate a general trend of results similar to that of dry-cast bricks. At 20 cycles, Mix BL-6 (36% used foundry sand and 40% fly ash content) and BL-4 (40% fly ash and 33% bottom ash content) had a much greater weight loss than the remaining mixtures. Freezing and thawing resistance of dry-cast paving stones are shown in Fig. 8. The two mixtures with the lowest resistance to freezing and thawing are the two mixtures containing used foundry sand, Mix PS-5 and PS-6. Similar to the other dry-cast materials, the mixture exhibiting the highest resistance to freezing and thawing is Mix PS-2 containing 18% fly ash.

Wet-Cast Bricks and Paving Stones-- Results of freezing and thawing tests for wet-cast bricks and paving stones are shown in Figs. 9 and 10. Test results of these mixtures indicate that including all three by-products (used foundry sand, fly ash and bottom ash) in percentages of 25% and above will reduce the resistance to freezing and thawing. Weight loss of Mix BRW-3 and PSW-3 (36% used foundry sand, 40% fly ash and 32% bottom ash content) were approximately 7% and 1.7%, respectively. Test samples of these mixtures are expected to break prior to reaching 80 cycles of freezing and thawing.

CONCLUSIONS AND RECOMMENDATIONS

Strength Properties

The compressive strength of dry-cast brick mixtures were determined for ages up to 56 days. Compressive strength increased with age, however, the rates of strength gain for mixtures

containing fly ash were higher than the reference mixtures. As a result, the difference in the strength properties of fly ash concrete mixtures and the reference mixture decreased with age and in some mixtures out-performed the reference mixture starting at the 28-day age. The increased gain in compressive strength of mixtures containing fly ash is due to the pozzolanic reaction of the fly ash causing improved microstructure of concrete. At the age of 28 days and beyond, mixtures containing fly ash and used foundry sand, BR-5, and BR-6, and the fly ash Mix BR-2 met ASTM requirements for Grade N bricks. Grade N bricks are used as architectural veneer and for units in exterior walls and applications requiring high strength and high resistance to moisture penetration and severe frost action. The mixture containing bottom ash, BR-3 and BR-4, would still meet requirements for Grade S bricks. Grade S bricks are used in general construction where moderate strength and resistance to frost action and moisture penetration are required.

Compressive strength of the dry-cast concrete block mixtures met the ASTM C 90 strength requirements at the age of 28 days and beyond for load bearing concrete monetary units. The compressive strength of these mixtures are suitable for standard structural applications. Dry-cast paving stones mixtures produced for this project did not meet the ASTM C 936 compressive strength requirement for standard paving stone applications. However, the mixtures attained compressive strengths appropriate for other structural applications at the age of 28 days and beyond. The mixture containing 18% fly ash out performed the reference mixture.

Wet-cast brick mixtures containing up to 26% used foundry sand, 30% fly ash, and 26% bottom ash met the compressive strength requirement of Grade N bricks at the age of 28-days and later. Mixtures incorporating up to 36% used foundry sand, 40% fly ash, and 26% bottom ash met this strength requirement at the age of 91-days and later. Wet-cast paving stones, including the reference mixture did not meet ASTM requirements for paving stones. However, the strength obtained by a mixture containing up to 25% used foundry sand, 29% fly ash, and 23% bottom ash at the age of 28 days would be suitable for most structural applications.

Substantial amounts of data concerning resistance to freezing and thawing of all dry-cast and wet-cast concrete mixtures were collected. The dry-cast concrete brick, block and paving stone mixtures containing fly ash without the addition of used foundry sand or bottom ash showed the most encouraging results. The dry-cast concrete brick mixture incorporating 29% fly ash showed improved resistance to freezing and thawing over the standard reference mixture without fly ash.

Other durability data concerning abrasion resistance (ASTM C 418) and shrinkage (ASTM C 426) are being finalized. The results concerning these parameters will be reported in the future.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to the Wisconsin Electric Power Company, Milwaukee, WI, and the University of Wisconsin System Applied Research Grant Program for their financial support of this study. Gratitude is also expressed to Neenah Foundry, Neenah, WI; Wisconsin Electric Power Co.; Best Block Company, Racine, WI; and Advanced Cast Stone, Random Lake, WI for providing materials and manufacturing facilities required for the project. This project was conducted by the Center for By-Products Utilization. The Center was established

by a generous grant from the Dairyland Power Cooperative, La Crosse, WI; Madison Gas and Electric Company, Madison, WI; National Minerals Corporation, St. Paul, MN; Northern States Power Company, Eau Claire, WI; Wisconsin Eclectic Power Company, Milwaukee, WI; Wisconsin Power and Light Company, Madison, WI; and Wisconsin Public Services Corporation, Green Bay, WI. Manitowoc Public Utilities, Manitowoc, WI, also generously supported UWM-CBU for many years. Their continuing support, and support from Manitowoc Public Utilities is gratefully acknowledged.

REFERENCES

1. Naik, T.R., Production of Masonry Blocks for Developing Countries, Presented at the 7th ASCE Structure Congress, American Society of Civil Engineers, San Francisco, CA May 1989.

2. Naik, T.R., Utilization of Fly Ash in the Manufacture of Bricks, Technical Report, Center for By-Product Utilization, Department of Civil Engineering and Mechanics, College of Engineering and Applied Science, University of Wisconsin-Milwaukee, 1984-1985.

3. Wei, L. and T.R. Naik. 1992. Utilization of Coal Combustion By-Products for Masonry Construction. EPRI Report no. TR-100707, Electric Power Research Institute, Palo Alto, California.

4. Naik, T.R., Patel, V.M., Parikh, D.M. and Tharaniyil, M.P., Utilization of Used Foundry Sand: Characterization and Products Testing, Report prepared for Wisconsin Department of Natural Resources; and, Badger Mining Corp., Falk Corp., Maynard Steel Casting, Inc., Waupaca Foundry, Inc., and Wisconsin Power and Light Co., June 1992.

5. Naik, T.R., Kolbeck, H.J., Singh, S.S., and Wendorf, R.B., Low-Cost, High Performance Materials Using Illinois Coal Combustion By-Products, Technical Report to Illinois Clean Coal Institute, May 1997.

6. National Concrete Masonry Association (NCMA). 1997. Concrete Masonry Standards. ASTM, National Concrete Masonry Association, Herndon, Virginia.

Table 1: Dry-Cast Concrete Brick Mixtures

Mix No.	BR-1	BR-2	BR-3	BR-4	BR-5	BR-6
Used Foundry Sand, [FS/(S + FS)] (%)	0	0	0	0	25	36
Fly Ash, [A/(C + A)] (%)	0	29	29	41	29	41
Bottom Ash, [BA/(S + BA)] (%)	0	0	23	33	0	0
Cement, C (kg/m^3)	203	153	144	126	156	135
Fly Ash, A (kg/m^3)	0	65	59	88	65	94
Net Water, W (kg/m^3)	85	94	112	153	109	129
[W/(C + A)]	0.43	0.43	0.55	0.72	0.49	0.57
SSD Fine Aggregate, S (kg/m^3)	1373	1391	973	856	1061	914
SSD Used Foundry Sand, FS (kg/m^3)	0	0	0	0	362	506
SSD Bottom Ash, BA (kg/m^3)	0	0	188	415	0	0
SSD 3/8" Crushed Limestone Aggregate (kg/m^3)	467	473	441	441	479	476
Moisture Content of Mixture, %	5.6	5.9	7.8	10.1	6.5	7.5
Unit Weight (kg/m^3)	2128	2176	2017	2080	2239	2255
Test Batch Yield (m^3)	0.46	0.46	0.46	0.46	0.46	0.46

Table 2: Dry-Cast Concrete Block Mixtures

Mix No.	BL-1	BL-2	BL-3	BL-4	BL-5	BL-6
Used Foundry Sand, [FS/(S + FS)] (%)	0	0	0	0	26	36
Fly Ash, [A/(C + A)] (%)	0	30	29	40	30	40
Bottom Ash, [BA/(S + BA)] (%)	0	0	23	33	0	0
Cement, C (kg/m^3)	203	156	144	126	144	135
Fly Ash, A (kg/m^3)	0	65	59	88	59	94
Net Water, W (kg/m^3)	95	94	112	153	112	129
[W/(C + A)]	0.36	0.43	0.54	0.71	0.54	0.57
SSD Fine Aggregate, S (kg/m^3)	1352	1385	1044	841	964	903
SSD Used Foundry Sand, FS (kg/m^3)	0	0	0	0	368	509
SSD Bottom Ash, BA (kg/m^3)	0	0	291	420	0	0
SSD 3/8" Crushed Limestone Aggregate (kg/m^3)	467	479	443	450	485	485
Moisture Content of Mixture, %	5.9	5.9	6.5	10.1	6.5	7.5
Unit Weight (kg/m^3)	2176	2176	2017	2080	2239	2255
Test Batch Yield (m^3)	0.46	0.46	0.46	0.46	0.46	0.46

Table 3: Dry-Cast Concrete Paving Stone Mixtures

Mix No.	PS-1	PS-2	PS-3	PS-4	PS-5	PS-6
Used Foundry Sand, [FS/(S + FS)] (%)	0	0	0	0	25	35
Fly Ash, [A/(C + A)] (%)	0	18	18	30	18	29
Bottom Ash, [BA/(S + BA)] (%)	0	0	24	33	0	0
Cement, C (kg/m^3)	382	329	300	250	315	268
Fly Ash, A (kg/m^3)	0	74	68	106	71	112
Net Water, W (kg/m^3)	94	106	115	112	163	103
[W/(C + A)]	0.25	0.26	0.31	0.31	0.27	0.27
SSD Fine Aggregate, S (kg/m^3)	1297	1314	906	738	944	788
SSD Used Foundry Sand, FS (kg/m^3)	0	0	0	0	323	435
SSD Bottom Ash, BA (kg/m^3)	0	0	279	356	0	0
SSD 3/8" Crushed Limestone Aggregate (kg/m^3)	441	447	409	382	426	412
Moisture Content of Mixture, %	5.7	6.1	7.6	8.0	6.2	6.3
Unit Weight (kg/m^3)	2207	2270	2080	1937	2176	2112
Test Batch Yield (m^3)	0.48	0.47	0.51	0.54	0.49	0.51

Table 4: Wet-Cast Concrete Brick Mixtures

Mix No.	BRW-1	BRW-2	BRW-3
Used Foundry Sand, [FS/(S + FS)] (%)	0	26	36
Fly Ash, [A/(C + A)] (%)	0	30	40
Bottom Ash, [BA/(S + BA)] (%)	0	26	32
Cement, C (kg/m^3)	326	223	185
Fly Ash, A (kg/m^3)	0	94	126
Net Water, W (kg/m^3)	250	262	247
[W/(C + A)]	0.76	0.82	0.79
SSD Fine Aggregate, S (kg/m^3)	1164	556	335
SSD Used Foundry Sand, FS (kg/m^3)	0	285	382
SSD Bottom Ash, BA (kg/m^3)	0	244	332
SSD 3/8" Natural Gravel Aggregate (kg/m^3)	476	453	435
Slump (mm)	58	45	51
Air Content, %	5.9	4.0	3.9
Unit Weight (kg/m^3)	2218	2118	2044
Test Batch Yield (m^3)	0.65	0.69	0.48

Table 5: Wet-Cast Concrete Paving Stone Mixtures

Mix No.	PSW-1	PSW-2	PSW-3
Used Foundry Sand, [FS/(S + FS + BA)] (%)	0	25	36
Fly Ash, [A/(C + A)] (%)	0	29	40
Bottom Ash, [BA/(S + BA + FS)] (%)	0	23	32
Cement, C (kg/m^3)	373	253	209
Fly Ash, A (kg/m^3)	0	109	138
Net Water, W (kg/m^3)	229	262	256
[W/(C + A)]	0.61	0.73	0.74
SSD Fine Aggregate, S (kg/m^3)	1117	523	312
SSD Used Foundry Sand, FS (kg/m^3)	0	265	356
SSD Bottom Ash, BA (kg/m^3)	0	232	309
SSD 3/8" Natural Gravel Aggregate (kg/m^3)	470	426	412
Air Entraining Admixture ($4m^3$)	0.19	1.15	1.96
Slump (mm)	96	71	71
Air Content (%)	8.1	6.4	6.8
Air Temperature (°C)	22	19	19
Concrete Temperature (°C)	24	25	26
Unit Weight (kg/m^3)	2188	2079	1990
Test Batch Yield (m^3)	0.46	0.54	0.54

Table 9: Density and Absorption of Dry-Cast Concrete Bricks

Mixture No.	Used Foundry Sand (%)	Fly Ash (%)	Bottom Ash (%)	Test Age					
				5-day		28-day		56-day	
				Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption(lb/ft^3)
BR-1	0	0	0	128	11	132	11	130	11
BR-2	0	29	0	129	10	132	10	131	10
BR-3	0	29	23	122	12	120	13	118	13
BR-4	0	41	33	116	12	120	11	120	11
BR-5	25	29	0	134	7	133	9	132	10
BR-6	36	41	0	130	10	133	9	133	9

Table 10: Density and Absorption of Dry-Cast Concrete Blocks

Mixture No.	Used Foundry Sand (%)	Fly Ash (%)	Bottom Ash (%)	Test Age							
				7-day		14-day		28-day		91-day	
				Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)
BL-1	0	0	0	134	9	135	8	135	9	135	8
BL-2	0	30	0	138	8	138	8	139	8	139	8
BL-3	0	29	23	127	153	127	10	127	10	129	9
BL-4	0	40	33	121	168	120	11	120	11	122	10
BL-5	26	30	0	141	107	137	8	139	8	140	8
BL-6	36	40	0	140	92	139	9	139	9	140	9

Table 11: Density and Absorption of Dry-Cast Concrete Paving Stones

Mixture No.	Used Foundry Sand (%)	Fly Ash (%)	Bottom Ash (%)	Test Age									
				5-day		8-day		28-day		56-day		91-day	
				Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)
PS-1	0	0	0	134	7	-0.0021	-0.000092	-0.002	-0.000122	-0.002	-0.000122	-0.002	8
PS-2	0	18	0	137	5	-0.0021	-0.000092	-0.0021	-0.000092	-0.002	-0.000092	-0.002	5
PS-3	0	18	24	124	8	-0.0019	-0.000137	-0.0019	-0.000122	-0.002	-0.000122	-0.002	8
PS-4	0	30	33	115	11	-0.0018	-0.000153	-0.0018	-0.000168	-0.002	-0.000168	-0.002	10
PS-5	25	18	-1e + 304	134	6	-0.002	-0.000122	-0.002	-0.000137	-0.002	-0.000107	-0.002	8
PS-6	35	29	-1e + 304	130	7	-0.002	-0.000092	-0.002	-0.000122	-0.002	-0.000122	-0.002	8

Table 12: Density and Absorption of Wet-Cast Concrete Bricks

Mixture No.	Used Foundry Sand (%)	Fly Ash (%)	Bottom Ash (%)	Test Age									
				3-day		7-day		28-day		91-day		182-day	
				Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)
BRW-1	0	0	0	135	9	137	7	135	10	134	11	134	12
BRW-2	26	30	26	125	11	129	10	127	10	126	12	123	14
BRW-3	36	40	32	119	13	121	11	121	12	119	14	120	14

Table 13: Density and Absorption of Wet-Cast Concrete Paving Stones

Mixture No.	Used Foundry Sand (%)	Fly Ash (%)	Bottom Ash (%)	Compressive Strength (psi)									
				3-day		7-day		29-day		91-day		182-day	
				Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)
PSW-1	0	0	0	133	7	131	7	132	13	132	8	133	9
PSW-2	25	29	23	121	10	121	10	122	10	120	11	120	12
PSW-3	36	40	32	114	12	114	12	113	8	113	14	113	14

Table 1: Physical Properties For Fine and Coarse Aggregate : (ASTM C33)

Material		Unit Weight (lb/ft^3)	Bulk Specific Gravity	Bulk Specific Gravity (SSD)	Apparent Specific Gravity	SSD Absorption (%)	Percent Void (%)	Fineness Modulus	Organic Impurity for Fine Aggregate
ASTM Specification Number		C 29	C 127/C 128				C 29	C 136	C 40
Wet-Cast Brick	Sand	108	2.71	2.73	2.77	.74	36	1.68	Pass
	Foundry Sand	96	2.14	2.16	2.2	1.32	28	1.19	Pass
	Bottom Ash	57	1.88	2.01	2.18	7.33	52	3.37	Pass
	Pea Gravel	110	2.73	2.76	2.82	1.08	35	5.46	NA
Wet-Cast Paving Stone	Sand	112	2.72	2.72	2.77	.74	34	1.62	Pass
	Foundry Sand	96	2.14	2.14	2.2	1.32	28	1.19	Pass
	Bottom Ash	57	1.88	1.88	2.18	7.33	52	3.37	Pass
	Pea Gravel	112	2.74	2.74	2.82	1.08	35	5.68	NA
Dry-Cast Brick / Paving Stone	Sand	111	2.63	2.67	2.73	1.42	32	2.57	Pass
	Foundry Sand	96	2.14	2.16	2.2	1.32	28	1.19	Pass
	Bottom Ash	48	1.89	1.98	2.09	5.14	59	3.34	Pass
	Crushed Limestone	99	2.70	2.74	2.82	1.59	41	4.94	NA

Table 1: Cement - Analysis for Oxides, SO_3, and Loss on Ignition

OXIDES, SO_3, AND LOSS ON IGNITION ANALYSIS, (%)		
Analysis Parameter	Cement (Dry Cast)	Cement (Wet Cast)
Silicon Dioxide, SiO_2	20.32	20.88
Aluminum Oxide, Al_2O_3	4.33	5.24
Iron Oxide, Fe_2O_3	2.6	2.22
SiO_2 + Al_2O_3 + Fe_2O_3	27.25	25.34
Calcium Oxide, CaO	62.1	62.63
Magnesium Oxide, MgO	4.19	2.85
Titanium Oxide, TiO_2	0	0.015
Potassium Oxide, K_2O	1.08	0.88
Sodium Oxide, Na_2O	0.11	0.21
Sulfite, SO_3	3.87	3.98
Loss on Ignition, LOI (1000 C)	1.38	1.09
Moisture (%)	0.1	0.45
Available Alkali, Na_2O, (ASTM C-311)	--	--

Table 2: Chemical Analysis of Fly Ash and Bottom Ash

OXIDES, SO_3, AND LOSS ON IGNITION ANALYSIS, (%)				
Analysis Parameter	Bottom Ash	Fly Ash	ASTM C-618 Fly Ash Requirements	
			Class C	Class F
Silicon Dioxide, SiO_2	83.11	50.96	--	--
Aluminum Oxide, Al_2O_3	21.81	23.25	--	--
Iron Oxide, Fe_2O_3	7.14	7.05	--	--
$SiO_2 + Al_2O_3 + Fe_2O_3$	112.06	81.26	50.0 Min	70 Min
Calcium Oxide, CaO	8.37	11.09	--	--
Magnesium Oxide, MgO	1.92	2.71	--	--
Titanium Oxide, TiO_2	0.89	1.13	--	--
Potassium Oxide, K_2O	0.93	1	--	--
Sodium Oxide, Na_2O	1.17	1.14	--	--
Sulfite, SO_3	--	0.56	5.0 Max	5.0 Max
Loss on Ignition, LOI (@ 1000 C)	2.64	1.1	6.0 Max	6.0 Max
Moisture	1.29	0.05	3.0 Max	3.0 Max
Available Alkali, Na_2O, (ASTM C-311)	--	--	1.5 Max	1.5 Max

Table 3: Mineralogy of Fly Ash and Cement

MINERALOGY, (% by Weight)			
Analysis Parameter	Cement (Dry Cast)	Cement (Wet Cast)	Fly Ash
Quartz, SiO_2	--	--	7
Dicalcium Silicate (C_2S) $2Ca0Si0_2$	13.8	17.5	--
Tricalcium Silicate (C_3S) $3CaOSi0_2$	42.8	43.9	--
Tricalcium Aluminate (C_3A) $Ca_3Al_20_6$	3.2	8.7	1.8
Tetracalcium Aluminoferrite (C_4AF) $4CaOAl_2O_3Fe_2O_3$	7.4	2.5	--
Anhydrite, $CaSO_4$	--	--	0
Periclase, MgO	0	4.2	--
Lime, CaO	--	--	--
Amorphous	32.8	31.35	82.5

Table 2: Cement - Analysis for Oxides, SO_3, and Loss on Ignition

OXIDES, SO_3, AND LOSS ON IGNITION ANALYSIS, (%)		
Analysis Parameter	Cement (Dry Cast)	Cement (Wet Cast)
Silicon Dioxide, SiO_2	20.32	20.88
Aluminum Oxide, Al_2O_3	4.33	5.24
Iron Oxide, Fe_2O_3	2.6	2.22
$SiO_2 + Al_2O_3 + Fe_2O_3$	27.25	25.34
Calcium Oxide, CaO	62.1	62.63

Magnesium Oxide, MgO	4.19	2.85
Titanium Oxide, TiO_2	0	0.015
Potassium Oxide, K_2O	1.08	0.88
Sodium Oxide, Na_2O	0.11	0.21
Sulfite, SO_3	3.87	3.98
Loss on Ignition, LOI (1000 C)	1.38	1.09
Moisture (%)	0.1	0.45
Available Alkali, Na_2O, (ASTM C-311)	tbr	tbr

* tbr = to be repeated

Physical Test Requirements of Fly Ash per ASTM C 618

TEST	FLY ASH	ASTM C 618 Requirements	
		CLASS C	CLASS F
Retained on No.325 sieve, (%)		34 max	34 max
Strength Activity Index with Cement at 7 days, (% of Control)		75 min	75 min
Water Requirement (% of Control)		105 max	105 max
Autoclave Expansion, (%)		± 0.8	± 0.8
Specific Gravity		-	-
Variation from Mean, (%) Fineness Specific Gravity		 5 max 5 max	 5 max 5 max

Chemical Analysis of Fly Ash and Bottom Ash

OXIDES, SO_3, AND LOSS ON IGNITION ANALYSIS, (%)				
Analysis Parameter	Bottom Ash	Fly Ash	ASTM C-618 Requirement	
			Class C	Class F
Silicon Dioxide, SiO_2	83.11	50.96	--	--
Aluminum Oxide, Al_2O_3	21.81	23.25	--	--
Iron Oxide, Fe_2O_3	7.14	7.05	--	--
SiO_2 + Al_2O_3 + Fe_2O_3	112.06	81.26	50.0 Min	70 Min
Calcium Oxide, CaO	8.37	11.09	--	--
Magnesium Oxide, MgO	1.92	2.71	--	--
Titanium Oxide, TiO_2	0.89	1.13	--	--
Potassium Oxide, K_2O	0.93	1	--	--
Sodium Oxide, Na_2O	1.17	1.14	--	--
Sulfite, SO_3	nr	0.56	5.0 Max	5.0 Max
Loss on Ignition, LOI (@ 1000 C)	2.64	1.1	6.0 Max	6.0 Max
Moisture	1.29	0.05	3.0 Max	3.0 Max
Available Alkali, Na_2O, (ASTM C-311)	nr	tbr	1.5 Max	1.5 Max

* nr = analysis not requested
* tbr = to be repeated

Mineralogy of Fly Ash and Cement

MINERALOGY, (% by Weight)					
Analysis Parameter	Cement (Dry Cast)	Cement (Wet Cast)	Fly Ash		Bottom Ash
Quartz, SiO_2			7		
Hematite, Fe_2O_3					
Dicalcium Silicate (C_2S) $2Ca0Si0_2$	13.8	17.45			
Tricalcium Silicate (C_3S) $3CaOSi0_2$	42.8	43.85			
Tricalcium Aluminate (C_3A) $Ca_3Al_20_6$	3.2	8.65	1.8		
Tetracalcium Aluminoferrite (C_4AF) $4CaOAl_2O_3Fe_2O_3$	7.4	2.5			
Anhydrite, $CaSO_4$			0		
Periclase, MgO	0	4.2			
Lime, CaO					
Amorphous	32.8	31.35	82.5		

Table 1: Dry-Cast Concrete Brick Mixtures

Mix No.	BR-1	BR-2	BR-3	BR-4	BR-5	BR-6
Used Foundry Sand, [FS/(S + FS)] (%)	0	0	0	0	25	36
Fly Ash, [A/(C + A)] (%)	0	29	29	41	29	41
Bottom Ash, [BA/(S + BA)] (%)	0	0	23	33	0	0
Cement, C (kg/m^3)	203	153	144	126	156	135
Fly Ash, A (kg/m^3)	0	65	59	88	65	94
Net Water, W (kg/m^3)	85	94	112	153	109	129
[W/(C + A)]	0.43	0.43	0.55	0.72	0.49	0.57
SSD Fine Aggregate, S (kg/m^3)	1373	1391	973	856	1061	914
SSD Used Foundry Sand, FS (kg/m^3)	0	0	0	0	362	506
SSD Bottom Ash, BA (kg/m^3)	0	0	188	415	0	0
SSD 3/8" Crushed Limestone Aggregate (kg/m^3)	467	473	441	441	479	476
Moisture Content of Mixture, %	5.6	5.9	7.8	10.1	6.5	7.5
Unit Weight (kg/m^3)	2128	2176	2017	2080	2239	2255
Test Batch Yield (m^3)	0.46	0.46	0.46	0.46	0.46	0.46

Table 2: Dry-Cast Concrete Block Mixtures

Mix No.	BL-1	BL-2	BL-3	BL-4	BL-5	BL-6
Used Foundry Sand, [FS/(S + FS)] (%)	0	0	0	0	26	36
Fly Ash, [A/(C + A)] (%)	0	30	29	40	30	40
Bottom Ash, [BA/(S + BA)] (%)	0	0	23	33	0	0
Cement, C (kg/m^3)	203	156	144	126	144	135
Fly Ash, A (kg/m^3)	0	65	59	88	59	94
Net Water, W (kg/m^3)	95	94	112	153	112	129
[W/(C + A)]	0.36	0.43	0.54	0.71	0.54	0.57
SSD Fine Aggregate, S (kg/m^3)	1352	1385	1044	841	964	903
SSD Used Foundry Sand, FS (kg/m^3)	0	0	0	0	368	509
SSD Bottom Ash, BA (kg/m^3)	0	0	291	420	0	0
SSD 3/8" Crushed Limestone Aggregate (kg/m^3)	467	479	443	450	485	485
Moisture Content of Mixture, %	5.9	5.9	6.5	10.1	6.5	7.5
Unit Weight (kg/m^3)	2176	2176	2017	2080	2239	2255
Test Batch Yield (m^3)	0.46	0.46	0.46	0.46	0.46	0.46

Table 3: Dry-Cast Concrete Paving Stone Mixtures

Mix No.	PS-1	PS-2	PS-3	PS-4	PS-5	PS-6
Used Foundry Sand, [FS/(S + FS)] (%)	0	0	0	0	25	35
Fly Ash, [A/(C + A)] (%)	0	18	18	30	18	29
Bottom Ash, [BA/(S + BA)] (%)	0	0	24	33	0	0
Cement, C (kg/m^3)	382	329	300	250	315	268
Fly Ash, A (kg/m^3)	0	74	68	106	71	112
Net Water, W (kg/m^3)	94	106	115	112	163	103
[W/(C + A)]	0.25	0.26	0.31	0.31	0.27	0.27
SSD Fine Aggregate, S (kg/m^3)	1297	1314	906	738	944	788
SSD Foundry Sand, FS (kg/m^3)	0	0	0	0	323	435
SSD Bottom Ash, BA (kg/m^3)	0	0	279	356	0	0
SSD 3/8" Crushed Limestone Aggregate (kg/m^3)	441	447	409	382	426	412
Moisture Content of Mixture, %	5.7	6.1	7.6	8.0	6.2	6.3
Unit Weight (kg/m^3)	2207	2270	2080	1937	2176	2112
Test Batch Yield (m^3)	0.48	0.47	0.51	0.54	0.49	0.51

Table 4: Wet-Cast Concrete Brick Mixtures

Mix No.	BRW-1	BRW-2	BRW-3
Used Foundry Sand, [FS/(S + FS)] (%)	0	26	36
Fly Ash, [A/(C + A)] (%)	0	30	40
Bottom Ash, [BA/(S + BA)] (%)	0	26	32
Cement, C (kg/m^3)	326	223	185
Fly Ash, A (kg/m^3)	0	94	126
Net Water, W (kg/m^3)	250	262	247
[W/(C + A)]	0.76	0.82	0.79
SSD Fine Aggregate, S (kg/m^3)	1164	556	335
SSD Used Foundry Sand, FS (kg/m^3)	0	285	382
SSD Bottom Ash, BA (kg/m^3)	0	244	332
SSD 3/8" Natural Gravel Aggregate (kg/m^3)	476	453	435
Slump (mm)	58	45	51
Air Content, %	5.9	4.0	3.9
Unit Weight (Kg/m^3)	2218	2118	2044
Test Batch Yield (m^3)	0.65	0.69	0.48

Table 5: Wet-Cast Concrete Paving Stone Mixtures

Mix No.	PSW-1	PSW-2	PSW-3
Used Foundry Sand, [FS/(S + FS + BA)] (%)	0	25	36
Fly Ash, [A/(C + A)] (%)	0	29	40
Bottom Ash, [BA/(S + BA + FS)] (%)	0	23	32
Cement, C (kg/m^3)	373	253	209
Fly Ash, A (kg/m^3)	0	109	138
Net Water, W (kg/m^3)	229	262	256
[W/(C + A)]	0.61	.73	.74
SSD Fine Aggregate, S (kg/m^3)	1117	523	312
SSD Used Foundry Sand, FS (kg/m^3)	0	265	356
SSD Bottom Ash, BA (kg/m^3)	0	232	309
SSD 3/8" Natural Gravel Aggregate (kg/m^3)	470	426	412
Air Entraining Admixture ($4m^3$)	0.19	1.15	1.96
Slump (mm)	96	71	71
Air Content (%)	8.1	6.4	6.8
Air Temperature (°C)	22	19	19
Concrete Temperature (°C)	24	25	26
Unit Weight (kg/m^3)	2188	2079	1990
Test Batch Yield (m^3)	0.46	0.54	0.54

Table : Density and Absorption of Dry-Cast Concrete Bricks

Mixture No.	Field Mix No.	Used Foundry Sand (%)	Fly Ash (%)	Bottom Ash (%)	Test Age					
					5-day		28-day		56-day	
					Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorptio(lb/ft^3)
BR-1	1	0	0	0	128	11	132	11	130	11
BR-2	3	0	29	0	129	10	132	10	131	10
BR-3	8	0	29	23	122	12	120	13	118	13
BR-4	10	0	41	33	116	12	120	11	120	11
BR-5	7	25	29	0	134	7	133	9	132	10
BR-6	9	36	41	0	130	10	133	9	133	9

Table : Density and Absoption of Dry-Cast Concrete Blocks
(Based Upon Average Net Area)

Mixture No.	Field Mix No.	Used Foundry Sand (%)	Fly Ash (%)	Bottom Ash (%)	Test Age							
					7-day		14-day		28-day		91-day	
					Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (%)	Density (lb/ft^3)	Absorption (lb/ft^3)
BL-1	13	0	0	0	134	9	135	8	135	9	135	8
BL-2	14	0	30	0	138	8	138	8	139	8	139	8
BL-3	16	0	29	23	127	10	127	10	127	10	129	9
BL-4	18	0	40	33	121	11	120	11	120	11	122	10
BL-5	15	26	30	0	141	7	137	8	139	8	140	8
BL-6	17	36	40	0	140	6	139	9	139	9	140	9

Table : Density and Absorption of Dry-Cast Concrete Paving Stones

Mixture No.	Field Mix No.	Used Foundry Sand (%)	Fly Ash (%)	Bottom Ash (%)	Test Age									
					5-day		8-day		28-day		56-day		91-day	
					Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)
PS-1	2	0	0	0	134	7	135	6	131	8	131	8	131	8
PS-2	4	0	18	0	137	5	137	6	137	6	137	6	139	5
PS-3	6	0	18	24	124	8	124	9	126	8	126	8	126	8
PS-4	11	0	30	33	115	11	118	10	117	11	116	11	117	10
PS-5	5	25	18	0	134	6	131	8	128	9	132	7	129	8
PS-6	12	35	29	0	130	7	130	6	131	8	127	8	129	8

Table : Density and Absorption of Wet-Cast Concrete Bricks

Mixture No.	Field Mix No.	Used Foundry Sand (%)	Fly Ash (%)	Bottom Ash (%)	Test Age									
					3-day		7-day		28-day		91-day		182-day	
					Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)
BRW-1	A	0	0	0	135	9	137	7	135	10	134	11	134	12
BRW-2	B	26	30	26	125	11	129	10	127	10	126	12	123	14
BRW-3	C	36	40	32	119	13	121	11	121	12	119	14	120	14

Table : Desnsity and Absorption of Wet-Cast Concrete Paving Stones

Mixture No.	Field Mix No.	Used Foundry Sand (%)	Fly Ash (%)	Bottom Ash (%)	Compressive Strength (psi)									
					3-day		7-day		29-day		91-day		182-day	
					Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)	Density (lb/ft^3)	Absorption (lb/ft^3)
PSW-1	D	0	0	0	133	7	131	7	132	13	132	8	133	9
PSW-2	E	25	29	23	121	10	121	10	122	10	120	11	120	12
PSW-3	H	36	40	32	114	12	114	12	113	8	113	14	113	14

Table 6: Compressive Strength of Dry-Cast Concrete Bricks

Mixture No.	Field Mix No.	Used Foundry Sand (%)	Fly Ash (%)	Bottom Ash (%)	Compressive Strength (psi)					
					5-day		28-day		56-day	
					Act.	Ave.	Act.	Ave.	Act.	Ave.
BR-1	1	0	0	0	3255	3660	4005	4530	4480	4750
					3830		4345		4730	
					3895		4485		4735	
					--		4525		5055	
					--		4850		--	
					--		4935		--	
BR-2	3	0	29	0	2740	3360	3855	4650	490	5300
					3365		4645		5025	
					3970		4659		5220	
					--		4780		5550	
					--		4880		5785	
					--		5065		--	
BR-3	8	0	29	23	2260	2360	2530	2740	2600	3210
					2360		2610		3285	
					2460		2705		3305	

					--		2810		3375	
					--		2880		3480	
					--		2930		--	
					1690		2835		2650	
					1770		3130		3570	
					2140		3175		3635	
					--		3190		3700	
					--		3225		3910	
BR-4	10	0	41	33	--	1870	3230	3130	--	3490

Table 6 (continued): Compressive Strength of Dry-Cast Concrete Bricks

Mixture No.	Field Mix No.	Used Foundry Sand (%)	Fly Ash (%)	Bottom Ash (%)	Compressive Strength (psi)					
					5-day		28-day		56-day	
					Act.	Ave.	Act.	Ave.	Act.	Ave.
					3065		3225		3765	
					3190		4085		4860	
					3295		4160		4955	
					--		4175		5480	
					--		4185		5665	
BR-5	7	25	29	0		3180	4345	4030	--	4940
					2710		3460		4535	
					3045		3680		4610	
					3320		3920		4695	
					--		4095		4835	
					--		4110		5355	
BR-6	9	36	41	0	--	3020	4355	3940	--	4800

Table 7: Compressive Strength of Dry-Cast Concrete Blocks
(Based Upon Average Net Area)

Mixture No.	Field Mix No.	Used Foundry Sand (%)	Fly Ash (%)	Bottom Ash (%)	Compressive Strength (psi)							
					7-day		14-day		28-day		91-day	
					Act.	Ave.	Act.	Ave.	Act.	Ave.	Act.	Ave.
BL-1	13	0	0	0	2605	2780	2825	3150	2850	3290	3240	3350
					2775		3290		3415		3360	
					2955		3345		3610		3460	
BL-2	14	0	30	0	2830	2990	2805	2880	3405	3690	4200	4240
					3055		2880		3545		4215	
					3080		2950		4115		4300	
BL-3	16	0	29	23	2075	2150	2875	2960	3030	3100	3130	3260
					2190		2875		3110		3225	
					2195		3125		3150		3435	
BL-4	18	0	40	33	1315	1410	1790	1810	2040	2220	2075	2340
					1405		1805		2220		2260	
					1520		1825		2390		2695	
BL-5	15	26	30	0	2570	2640	2510	2740	3215	3540	3910	4080
					2670		2735		3560		4135	

					2680		2975		3840		4180	
BL-6	17	36	40	0	2195	2240	2690	2930	3140	3240	3305	3680
					2230		3020		3190		3830	
					2280		3085		3395		3890	

Table 8: Compressive Strength of Dry-Cast Concrete Paving Stones

Mixture No.	Field Mix No.	Used Foundry Sand (%)	Fly Ash (%)	Bottom Ash (%)	Compressive Strength (psi)									
					5-day		8-day		28-day		56-day		91-day	
					Act.	Ave.	Act.	Ave.	Act.	Ave.	Act.	Ave.	Act.	Ave.
					3820		7100		4460		5515		7050	
					5805		7630		4855		5745		7495	
					7025		8095		4950		7515		8235	
					--		--		5020		8075		--	
					--		--		5040		8365		--	
PS-1	2	0	0	0	--	5550	--	7610	5085	4900	--	7040	--	7595
					7745		7020		5640		7120		7700	
					7770		7265		5645		7895		7735	
					7880		7950		6645		8075		7790	
					--		--		6655		8985		7920	
					--		--		8195		--		8385	
PS-2	4	0	18	0	--	7800	--	7410	8520	6880	--	8020	--	7790
PS-3	6	0	18	24	3510	3840	3575	3870	5005	5310	5390	5740	5420	6050
					3935		3750		5015		5660		5775	
					4065		4295		5080		5725		6030	

					--		--		5565		5935		6035	
					--		--		5865		5975		6975	
					2080		2945		2865		2820		3435	
					2440		2815		3080		3245		3545	
					2295		2520		3155		3285		3675	
					--		--		3215		3350		3875	
					--		--		3385		3765		3925	
PS-4	11	0	30	33	--	2270	--	2760	3445	3190	--	3290	--	3690

Table 8 (continued): Compressive Strength of Dry-Cast Concrete Paving Stones

Mixture No.	Field Mix No.	Used Foundry Sand (%)	Fly Ash (%)	Bottom Ash (%)	Compressive Strength (psi)									
					5-day		8-day		28-day		56-day		91-day	
					Act.	Ave.	Act.	Ave.	Act.	Ave.	Act.	Ave.	Act.	Ave.
					4115		3155		3865		4320		4830	
					4445		4085		4370		5490		5365	
					4510		4295		4525		6190		5450	
					--		--		4780		6995		5985	
PS-5	5	25	18	0	--	4360	--	3840	5035	4520	7340	6070	--	5410
					2950		3530		3275		3865		4185	
					3520		4415		3550		4350		4867	
					3980		4540		3820		4520		5434	
					--		--		3945		5245		5560	
					--		--		4155		5655		5695	
PS-6	12	35	29	0	--	3480	--	4160	4365	3850	--	4730	--	5150

Table 9: Compressive Strength of Wet-Cast Concrete Bricks

Mixture No.	Field Mix	Used Foundry	Fly Ash	Bottom Ash	Compressive Strength (psi)				
					3-day	7-day	28-day	91-day	182-day

	No.	Sand (%)	(%)	(%)	Act.	Ave.	Act.	Ave.	Act.	Ave.	Act.	Ave.	Act.	Ave.
					4385		3635		6100		6880		6990	
					4865		4955		6775		6975		7375	
BRW-1	A	0	0	0		4630	5485	4690	6910	6590	7645	7170	7590	7320
					2350		2745		4330		5135		6435	
					2380		2385		4475		6085		6570	
BRW-2	B	26	30	26		2370	2410	2510	4530	4450	6325	5850	6610	6540
					1290		1575		2740		4175		5375	
					1395		1635		2905		4275		5390	
BRW-3	C	36	40	32	1150	1380	1655	1620	2915	2850	4365	4270	5410	5390

Table 10: Compressive Strength of Wet-Cast Concrete Paving Stones

Mixture No.	Field Mix No.	Used Foundry Sand (%)	Fly Ash (%)	Bottom Ash (%)	Compressive Strength (psi)									
					3-day		7-day		29-day		91-day		182-day	
					Act.	Ave.	Act.	Ave.	Act.	Ave.	Act.	Ave.	Act.	Ave.
PSW-1	D	0	0	0	4780	4880	5345	5800	6145	6490	6870	7010	7480	7820
					4905		6025		6385		6920		7965	
					4970		6040		6950		7230		8005	
PSW-2	E	25	29	23	2260	2330	2730	2810	3850	4120	5445	5550	5900	5950
					2350		2785		4170		5525		5955	
					2385		2905		4335		5680		6000	
PSW-3	H	36	40	32	1135	1150	1365	1380	2380	2390	3300	3520	4135	4350
					1155		1390		2395		3600		4400	
					1165		1395		2405		3650		4525	

Table : Cylinder Compressive Strength of Wet-Cast Concrete Brick Mixtures

Mixture No.	Field Mix No.	Used Foundry Sand (%)	Fly Ash (%)	Bottom Ash (%)	Compressive Strength (psi)									
					3-day		7-day		28-day		91-day		182-day	
					Act.	Ave.	Act.	Ave.	Act.	Ave.	Act.	Ave.	Act.	Ave.
BRW-1	A	0	0		2380	2510	2245	2560	3075	3470	4500	4650	4965	5050
					2515		2700		3150		4685		5006	
					2630		2720		4180		4780		5185	
BRW-2	B	34	30		1045	1140	985	1130	2215	2300	3360	3500	4245	4260
					1155		1180		2320		3465		4260	
					1230		1214		2370		3675		4275	
BRW-3	C	53	59		660	690	625	800	1285	1480	2140	2420	3395	3470
					705		885		1560		2560		3425	
					715		885		1590		2575		3580	

Table : Cylinder Compressive Strength of Wet-Cast Concrete Paving Stone Mixtures

Mixture No.	Field Mix No.	Used Foundry Sand (%)	Fly Ash (%)	Bottom Ash (%)	Compressive Strength (psi)									
					3-day		7-day		29-day		91-day		182-day	
					Act.	Ave.	Act.	Ave.	Act.	Ave.	Act.	Ave.	Act.	Ave.
PSW-1	D	0	0		17	17.5	17.2	17.2	23	25.5	29.1	31.4	35.3	36.2
					17		18.5		26.6		32.1		35.7	
					19		23.7		26.9		33		37.5	
PSW-2	E	34	30		9.4	9.72	10	10.6	19.5	19.9	27	27.9	31.4	32.2
					9.7		10.6		19.6		27.5		31.8	
					10		11.3		20.5		28.9		33.4	
PSW-3	H	53	40		4.3	4.5	4.6	4.9	8.3	9.5	15.9	16.5	22.3	22.5
					4.5		4.6		9.8		16.6		22.7	
					4.6		5.5		10.4		16.9		--	