

Center for By-Products Utilization

MANUFACTURE OF WET CAST-CONCRETE PRODUCTS USING INDUSTRIAL BY-PRODUCTS

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ABSTRACT

This research was directed toward establishing high-volume reuse technologies for fly ash, bottom ash, and used foundry sand in manufacture of cast concrete products. Mixture proportion and production technology were developed for wet-cast concrete masonry products such as bricks and paving stones. Two reference mixtures; one for bricks and the other for paving stones, without fly ash, bottom ash, and foundry sand were proportioned. ASTM Class F fly ash (FA) was used as partial replacement of portland cement. Bottom ash (BA) and used foundry sand (UFS) were used as a replacement of regular concrete sand. For wet-cast masonry products, 50% and 70% of regular concrete sand was replaced with both bottom ash and used foundry sand. Compressive strength, freezing and thawing resistance, drying shrinkage, and abrasion resistance tests were conducted on the cast-concrete products manufactured in this work. Based on strength and durability evaluations, it was concluded that all wet-cast bricks could be used for both exterior and interior walls in warm climates and for interior walls in cold climates. None of wet-cast paving stone mixtures including the reference mixture met the ASTM requirements for paving stones.

INTRODUCTION

Fly ash and bottom ash are generated due to combustion of coal in electric power plants. The annual production of fly ash and bottom ash by coal-burning power plants in the United States are estimated to be about 19 and 47 tonnes (21 and 52 tons) in 1999, respectively [1]. Of these, only 33% of these materials were utilized in various applications, and thus large volumes of these by-products are still landfilled. Numerous applications of fly ash including in concrete, waste stabilization, structural fills, road base/subbase, mining application, controlled low strength materials (CLSM), etc. are well known. Beneficial applications of bottom ash include in structural fills, road base/subbase, snow and ice control, concrete, waste stabilization, mining applications, blasting grit/roofing granules, and mineral filler [2].

A basic foundry process produces castings by pouring molten metal into molds. The molds consist usually of molding sand and core sand. After hardening, the castings are removed in the 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 use in the process after a few times of recycling. Foundries can be classified as ferrous or non-ferrous foundries. Ferrous foundries include gray iron, ductile iron, and steel foundries. Non-ferrous foundries include aluminum, brass/bronze foundries, etc.

Currently, large volumes of fly ash, bottom ash, and used foundry sand are disposed of in landfills. Because of the increasing disposal costs and the difficulty in locating new landfill site and the liability associated with the use of landfill, beneficial utilization options for these industrial by-products are an important issues for the industry and the public [1, 2, 3, 4, 5]. The primary

reasons for low utilization rate for the above by-products include quality of materials, regulatory restrictions, and unavailability sufficiently developed high-volume reuse 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 projects was primarily undertaken to develop high-volume use technologies for fly ash, bottom ash, and used foundry sand in manufacture of cast-concrete products such as bricks and paving stones.

RESEARCH SIGNIFICANCE

In this work, the effects of inclusion of fly ash, bottom ash, and used foundry sand on strength and durability-related properties of wet-cast concrete bricks and paving stones were investigated. The data obtained in this investigation will be used to establish mixture proportions and production technologies for these products incorporating fly ash, bottom ash, and used foundry for commercial applications.

PREVIOUS WORK

Although, the amount of fly ash in typical structural concrete applications ranges from 15 to 35 percent by mass of cement, large amounts of fly ash (up to 70 percent), are used for manufacture of concrete road bases, and dams [6, 7]. Ghafoori et al. [6,7] reported that concrete containing 50% bottom ash of the total dry volume of natural fine aggregate exhibited compressive strength and depth of wear identical to that of portland cement concrete (PCC) [6,7]. Bakoshi et al. [8] reported that compressive strength of concrete increased slightly with the increase of replacement ratio for fine aggregate with bottom ash in the range of 10 to 40%. However, the freezing and thawing resistance of bottom ash concrete was inferior to that of PCC [7]. Steam-cured fly ash blocks made with about 55% fly ash, 20% lime, and 25% gypsum showed compressive strengths

of up to about 5 MPa (740 psi) [9]. Wei [9] reported that inclusion of bottom ash caused significant decreases in compressive strength and density of mini size concrete blocks.

Several constructive use options as a material for USF include landfill cover, geotechnical fill, asphalt pavement, rock wool mineral fibers, smelting flux, and portland cement. Javed et al. [10] concluded that 15% foundry sand (used green sand, chemically bonded sand, and shell sand) can be used as a replacement level of regular fine aggregate in asphalt concrete mixture without compromising performance. An investigation by American Foundrymen's Society [5] indicated that that a concrete mixture containing 45% waste shell sand from iron foundry achieved compressive strength, flexural strength, modulus of elasticity, and Poisson's ratio equivalent to those achieved by PCC.

Investigations by researchers [11,12,13] at the UWM Center for By-Products Utilization (CBU) at the University of Wisconsin-Milwaukee revealed that properties of foundry sand concrete vary significantly with type and amount of UFS (e.g. green sand, crushed core shell sand, chemically bonded sand, etc.). Generally incorporation of UFS in concrete caused reduction in slump of fresh concrete, and compressive strength and tensile strength of hardened concrete with increasing UFS in the range of 20 to 40% [11,12]. Addition of Class C fly above 17% resulted in higher compressive and flexural strengths of concrete relative to PCC [13].

Studies [12] at The CBU-UWM showed that replacement of 35% of regular sand with crushed core sand resulted in 47% reduction in compressive strength of mini size concrete masonry blocks at the age of 28 days. Inclusion of 35% of regular sand with laundry/backing sand resulted in 23% reduction in 28-day compressive strength of full-size laboratory made concrete paving stones [11]. Inclusion of 35% of wheelabrator sand as a replacement of fine aggregate resulted in 28% reduction in 28-day compressive strength of mini size blocks. Addition of 35% chemically bonded

sand resulted in 19% reduction in compressive strength of full-size laboratory made concrete paving stones at the age of 28 days [14].

TESTING PROGRAM

Materials

Various constituent materials for manufacture of cast concrete products used in this research include portland cement, fine and coarse aggregates, used foundry sand, and bottom ash.

ASTM Type I portland cement from one source was used. Physical and chemical properties of these by-products were determined using the applicable ASTM standards or other applicable standards. The cement met the standard physical and chemical properties requirements of ASTM for Type I portland cement with exception of exception of SO_3 (Table 1). A Class F fly conformation to ASTM C 618 requirements was used (Table 1).

A regular concrete sand from one sources were used as a fine aggregate. The regular sand met all the ASTM requirements with exception of grading requirement (Table 2). A used green foundry sand supplied by a ferrous foundry in Wisconsin was used in this work. This foundry sand was used as a partial replacement of regular fine aggregate. The physical and chemical properties of the used foundry sand are given in Tables 2.

The UFS exhibited about 14% lower unit weight, 20% lower SSD absorption, 50% lower fineness modulus, and six times larger percentage of materials finer than 75- μm as compared with regular concrete sand. The UFS did not meet the grading and materials finer than 75- μm requirements of ASTM for fine aggregates for use in concrete. Clay lumps and friable particles test and soundness test of this type of sand were determined in a previous study [12]. The results showed 9% clay lumps and friable particles (ASTM C 1142), and 39% weight loss in soundness

test (ASTM C 88). A bottom ash from Oak Creek Power Plant of the Wisconsin Electric Power Company was used in this research. Bottom ash was sieved on a 9.5 mm sieve and only the portions finer than 9.5 mm was used in this research. Bottom ash was used as a partial replacement of regular fine aggregate. The chemical, physical properties, and gradation of the bottom ash are presented in Table 3. The bottom ash exhibited a slightly higher percentage of clay lumps and friable particles than the requirement of ASTM.

Pea gravel with a 9.5 mm (3/8 in.) maximum size was used for manufacture of masonry products. The physical properties of the coarse aggregate did not meet the ASTM requirement for materials finer than 75- μ m for coarse aggregates. The physical properties and gradation of coarse aggregate is shown in Table 4.

MIXTURE PROPORTIONS AND MANUFACTURING PROCEDURE

Mixture Proportions

Three wet-cast brick mixtures and three wet-cast paving stone mixtures were proportioned. Fly ash was used as a replacement 25% and 35% of portland cement by mass. Bottom ash and used foundry sand were used as a replacement of 25% and 35% of regular sand by mass. Since both bottom ash and used foundry sand were combined to replace fine aggregate in the mixtures, 50% or 70% of regular sand was replaced with both bottom ash and used foundry sand in each mixture. Pea gravel with 9.5 mm (3/8 in.) maximum size was used as coarse aggregate. A high-range water-reducing admixture (HRWRA), also called superplasticizer, was used to produce 50 to 100 mm slump concrete. Air-entraining admixture (AEA) was added only to the wet-cast

paving stone mixtures. Except the use of AEA, the wet-cast paving stone mixture proportions were similar that of the wet-cast brick mixture proportions. Additionally, paving stone concrete mixtures had a slightly higher cementitious materials (cement + fly ash) content and a slightly lower aggregate content compared to the wet-cast brick concrete mixtures. Two reference mixtures, one for brick and one for paving stone were also produced given in Tables 5 and 6.

Manufacture of Concrete

Regular fine aggregate (sand), coarse aggregate (pea gravel), bottom ash, and used foundry sand were blended in a commercial concrete mixer. Then cement and fly ash were added, and the batch was mixed further. Then, water was added. After the mixture became consistent and uniform, HRWRA was added until 50 to 100 mm (2 to 4 in.) slump for the concrete batch was achieved. In the paving stone mixtures, air-entraining agent was also added to entrain 6 to 8% air content. Fresh concrete data for wet-cast brick concrete and wet-cast paving stone concrete are included in Tables 5 and 6, respectively.

Preparation Test Specimens

For each concrete mixture, 100x400 mm (4x8 in.) concrete cylinders were cast for compressive strength tests. The wet-cast brick and paving stone specimens were cast in wooden molds and compacted by mechanical vibrators (a rod insertion-type and form vibrators). All mixtures exhibited good workability. Typical dimensions (width, length, and height) of wet-cast bricks were 92 x 194 x 59 mm (3.625" x 7.650" x 2.325"). Typical dimensions of wet-cast paving stones were 99 x 192 x 59 mm (3.900" x 7.575" x 2.325"). After the casting, the molds with specimens were covered with large plastic sheets and cured inside of the cast concrete plant (at about 22 °C, 72 °F) for 24 hours without disturbance. Then the molds with specimens in them

were moved to the UWM concrete laboratory and the specimens were demolded and stored in a moist curing room until the time of testing. For compression test, the top and bottom bearing surfaces of bricks and paving stones were capped with gypsum to ensure uniform distribution of loading stress during compression test. Tests for freezing and thawing resistance of bricks and paving stones were carried out in accordance with ASTM C 1262 [16]. Five specimens were tested for each brick and paving stone mixture. Testing for drying shrinkage of bricks was carried out in accordance with ASTM C 426. Testing for abrasion resistance of paving stones was carried out in accordance with ASTM C 418. Before being subjected to sandblasting, the abrasion specimens were immersed in water for 24 hours. Inside a sand blasting machine, a metal shield with 645 mm^2 (1 in^2) circular opening was placed on the top bearing surface of a paving stone. Then, a sand blasting nozzle was placed 75 mm (3 inches) apart from the surface of the specimen to be tested. The specimen was blasted with sand for 1 minute. This was repeated at eight different spots on the surface. Then the abrasion cavities were filled with oil base modeling clay, and the abraded volume was determined.

TEST RESULTS AND DISCUSSION

Compressive Strength of Concrete Specimens

Compressive Strength of concrete cylinder for various concrete mixtures are shown in Figure 1. As expected, concrete compressive strength increased with age for all mixtures. The compressive strengths of WR1 (control), WR2 (25% fly ash, 25% bottom ash, 25% used foundry sand), and WR3 (35% fly ash, 35% bottom ash, 35% used foundry sand) were 17.3, 7.9, and 4.8 MPa (2510, 1140, and 690 psi), respectively at the age of three days. The respective compressive strengths of these concrete mixtures (WR1, WR2, WR3) were increased to 17.7, 7.8, and 5.5 MPa (2560, 1130 and 8000 psi) at seven days; 23.9, 15.9, and 10.2 MPa (3470, 2300, and 1480

psi) MPa at 28 days; 32.1, 24.1, and 16.7 MPa (4650, 3500, and 2420 psi) at 91 days; and 34.8, 29.4, and 23.9 MPa (5050, 4260, and 3470 psi) at 182 days.

It is a well-known fact that concrete with fly ash exhibits lower rate of compressive strength development compared to PCC at early ages. This is primarily due to the dilution effects of the fly ash in the cementitious mixtures. Because of this property of concrete with fly ash, the relative compressive strengths of Mixture WR2 (25% fly ash, 25% bottom ash, 25% used foundry sand) and Mixture WR3 (35% fly ash, 35% bottom ash, 35% used foundry sand) concrete were much lower compared to Mixture WRI (control). However, rate of compressive strength development becomes greater than control at later ages due to significant formation of pozzolanic C-S-H [10, 25,26]. This resulted in a decreased difference in compressive strength of control Mixture WR1 and the fly ash concrete mixtures (WR2 and WR3). However, still compressive strengths of Mixtures WR2 and WR3 were lower compared to Mixture WR1 even at 182 days. This was primarily due to lower amounts of total C-S-H produced due to both cementitious and pozzolanic reactions because pozzolanic contributions of fly ash did not compensate for the decrease in the amount of C-S-H resulting from lower amounts of cement content in the mixtures. Moreover, inclusion of bottom ash as a replacement of regular concrete sand caused further decrease in strength. This happens probably due to weaker particles of bottom ash compared to the sand particles. However, compressive strengths of Mixtures WR2 and WR3 were sufficient to meet the minimum compressive strength requirement of ASTM at early ages.

Compressive Strength of Wet-Cast Bricks

The compressive strength of control brick mixture (WR1) met the minimum compressive strength requirement of ASTM for Grade N bricks (24 MPa, 3500 psi) even before 3 days of moist curing (Figure 2). The compressive strength of control wet-cast bricks was 31.9 MPa (4630 psi) at the age of three days which is 32% higher than the compressive strength requirement for Grade N bricks (24 MPa, 3500 psi). The corresponding 3-day cylinder compressive strength of WR1 (control) was 17.3 MPa (2510 psi). This indicates that wet-cast bricks exceeding the minimum compressive strength requirement for Grade N bricks (24 MPa, 3500 psi) can be manufactured using reference Mixture WR1 concrete with cylinder compressive strength of about 17.3 MPa (2510 psi).

Bricks made with Mixture WR2 (25% fly ash, 25% bottom ash, and 25% used foundry sand) met the minimum compressive strength requirement for Grade N bricks (24 MPa, 3500 psi) at about 18 days of moist-curing. The corresponding 18-day cylinder compress strength of WR2 was about 11.9 MPa (1730 psi) (Figure 2). This suggest that wet-cast bricks meeting the minimum compressive strength requirement for Grade N bricks (24 MPa, 3500 psi) can be produced using mixture WR2 with cylinder compressive strength of approximately 11.9 MPa (1730 psi). Wet-cast bricks made with Mixture WR3 (35% fly ash, 35% bottom ash, and 35% used foundry sand) met the minimum compressive strength requirement for Grade N bricks (24 MPa, 3500 psi) at about 57 days of moist-curing (Figure 2). The corresponding 57-day cylinder compressive strength was about 13.2 MPa (1910 psi) (Fig.1). Therefore, wet-cast bricks meeting the minimum compressive strength requirement for Grade N bricks (24 MPa, 3500 psi) can be produced using WR3 concrete mixture with cylinder compressive strength as low as 13.2 MPa (1910 psi).

Wet-cast bricks made with Mixture WR2 met the compressive strength requirement for Grade S bricks (17 MPa, 2500 psi) at about 7 days of moist-curing. The corresponding 7-day cylinder compressive strength of Mixture WR2 was 7.8 MPa (1130 psi). Thus, wet-cast bricks meeting the minimum compressive strength requirement for Grade S bricks (17 MPa, 2500 psi) can be produced using WR2 concrete mixture with cylinder compressive strength of about 7.8 MPa (1130 psi). Wet-cast bricks made with Mixture WR3 met the minimum compressive strength requirement for Grade S bricks (17 MPa, 2500 psi) at about 22 days of moist-curing (Fig. 2). The corresponding 22-day cylinder compressive strength was about 8.9 MPa (1290 psi). This means that it is possible to produce wet-cast bricks that meet the minimum compressive strength requirement for Grade S bricks (17 MPa, 2500 psi) using WR3 concrete with cylinder compressive strength of about 8.9 MPa (1290 psi).

As explained above, all mixtures made with and without fly ash, bottom ash and used foundry sand met the ASTM strength requirement for production of masonry bricks. However, the minimum moist-curing time necessary for wet-cast bricks to achieve the minimum compressive strength requirements for Grade S (17 MPa, 2500 psi) and Grade N (24 MPa, 3500 psi) bricks considerably increased with amounts of fly ash, bottom ash, and used foundry sand. Therefore, for commercial manufacturing, it is required to accelerate the strength development of the by-product containing material mixtures.

Density, and Water Absorption Of Wet-Cast Bricks

The density of wet-cast brick mixtures did not change appreciably with age [15]. The respective average densities of wet-cast bricks made with Mixture WR2 (2019 kg/m³, 126 lb/ft³) concrete

and Mixture WR3 (1922 kg/m^3 , 120 lb/ft^3) concrete were 8% and 12% lower than that for bricks made with Mixture WR1 (2163 kg/m^3 , 135 lb/ft^3) concrete. The lower weights of bricks made with Mixtures WR2 and WR3 relative to bricks made with Mixture WR1 are primarily associated with the partial replacement of cement with fly ash, and regular sand with bottom ash because fly ash is lighter than cement and bottom ash is lighter than regular concrete sand. Use of lighter bricks is known to improve construction productivity compared to normal weight bricks.

The ASTM C 55 absorption requirements are given in Table 7. The respective water absorption values of wet-cast bricks made with concrete Mixtures WR2 and WR3 were about 17% and 29%, respectively, higher than that of wet-cast bricks made with Mixture WR1 (Table 8). This was attributed to the increased porosity of the materials made with Mixtures WR2 and WR3 resulting from increased amounts of porous bottom ash aggregate, and decreased amounts of C-S-H due to the cement replacement with the fly ash.

Wet-cast bricks made with Mixtures WR1 and WR3 met the absorption requirement for Grade N bricks and wet-cast bricks made with Mixture WR2 concrete met the absorption requirement for Grade S bricks (Table 8). As expected absorption decreased with increasing density or compressive strength.

Freezing and Thawing Resistance of Wet-Cast Bricks

The result showed the freezing and thawing resistance of wet-cast bricks decreased with increasing the amount of the three by-product materials (fly ash, bottom ash, and used foundry sand) (Fig 3). WR1 (control) wet-cast bricks and WR2 wet-cast bricks showed about the same weight loss after 150 cycles of freezing and thawing. Due to large weight loss, the freezing and thawing test on WR3 wet-cast bricks was terminated at 60 freezing and thawing cycles (Fig. 3).

Drying Shrinkage of Wet-Cast Bricks

In general, the drying shrinkage increased with increasing amounts of fly ash, bottom ash, and used foundry sand in the concrete mixture (Fig. 4). All of the wet-cast bricks met the maximum drying shrinkage requirement of ASTM for Type II nonmoisture-controlled brick units (0.065%).

Compressive Strength of Cylinder Made with Paving Stone Concrete Mixtures

As expected, compressive strengths of the paving stone concrete mixtures made with fly ash, bottom ash, and used foundry sand (WS2 and WS3) were lower compared to the control (WS1) at all test ages (Fig. 5). The values of compressive strength were 17.5 MPa (2540 psi) for WS1, 9.7 MPa (1410 psi) for WS2 and 4.5 MPa (650 psi) at the age of 3 days.

The compressive strengths of Mixtures WS2 and WS3 were about 56% and 26% of that of WS1 (control), at three days. The compressive strengths for the respective mixtures increased to 19.8, 10.6, and 4.9 MPa (2870, 1540 and 710 psi) at 7 days; 25.5, 19.9, and 9.5 MPa (3700, 2880 and 1380 psi) at 28 days; 31.4, 27.9, and 16.5 MPa (4550, 4050, and 2390 psi) at 91 days; and 36.2, 32.2, and 22.5 MPa (5250, 4670 and 3260 psi) at 182 days. The effects of the by-product materials on the strength development of the paving stone concrete followed the same general trend as explained for the brick concrete mixtures.

Compressive Strength of Wet-Cast Paving Stones

The compressive strengths of Mixtures WS1, WS2, and WS3 were 33.6, 16.1, and 7.9 MPa (4880, 2330, and 1150 psi), respectively at the age of 3 days (Fig. 6). These values were about 61%, 29%, and 14% of the compressive strength requirement for paving stones 55.2 MPa (8000 psi).

The compressive strength of respective mixtures (WS1, WS2, and WS3) increased to 40.0, 19.4, and 9.5 MPa (5800, 2810, and 1380 psi) at 7 days; 44.7, 28.4, and 16.5 MPa (6490, 4120, and 2390 psi), at 28 days; 48.3, 38.3, and 24.3 MPa (7010, 5550, and 3520 psi) at 91 days; and 54.0, 41.0, and 30.0 MPa (7820, 5950, and 4350 psi) at 182 days of curing. Even after 182 days of moist-curing, the compressive strengths of Mixtures WS1, WS2, and WS3 were 98%, 74%, and 54% of the minimum compressive strength requirement for paving stones 55.2 MPa (8000 psi).

For producing paving stones to meet the ASTM strength requirement, the use of increased amounts of cementitious materials content and coarse aggregates is needed. For commercial production, early-age strength needs to be increased. This can be accomplished through the use of low water to cementitious materials content superplasticized concrete with accelerating admixture.

Density, and Absorption of Wet-Cast Paving Stones

The density and absorption of wet-cast paving stones were not significantly affected by age. The average density of mixtures were 2115 kg/m³ (132 lb/ft³) for WS1, 1938 kg/m³ (121 lb/ft³) for mixtures WS2, and 1826 kg/m³ (114 lb/ft³) for mixtures WS3. The paving stones made with by-product containing mixtures WS2 and WS3 were 8% and 14% lighter than control mixture WS1.

The respective absorption values for mixtures WS1, WS2, and WS3 were 123, 171, and 207 kg/m³ (7.7, 10.7, and 12.9 lb/ft³). These three values are about 54%, 114%, and 158%, respectively, higher than the maximum ASTM water absorption requirement for paving stones (80

kg/m³ 5 lb/ft³). Thus, none of the wet-cast paving stones, including control wet-cast paving stones, met the absorption requirement of ASTM.

Freezing and Thawing Resistance of Wet-Cast Paving Stones

The results showed that the significant amount of loss occurred in paving stone specimens between 60 to 140 cycles of freezing and thawing due to surface scaling (Fig 7). Slightly more weight loss occurred in the wet-cast paving stone specimens between 140 and 270 cycles and the freeze-thaw test was terminated at 270 cycles. WS2 wet-cast paving stones showed generally larger values of weight loss than the WS1 wet-cast paving stones.

At 270 cycles of freezing and thawing, the weight loss of WS2 wet-cast paving stones was about 2.5 times that of WS1 (control) wet-cast paving stones. WS3 wet-cast paving stones exhibited a much larger values of weight loss due to freezing and thawing cycling compared to WS2. Due to the large weight loss of WS3 wet-cast paving stones, the freezing and thawing testing was terminated after completion of 150 cycles of testing.

Abrasion Resistance of Wet-Cast Paving Stones

The abrasion coefficient measured in this work represents the volume loss of sand blasted area of a paving stone. The values of average abrasion coefficient for WS1, WS2, and WS3 wet-cast paving stones were about 0.53, 0.62, and 0.77 cm³/cm² (0.201, 0.244 and 0.303 in³/in²), respectively. The abrasion coefficients of WS2 and WS3 wet-cast paving stones were about 21% and 51%, respectively, larger than that of WS1 (control) wet-cast paving stones. All the paving stone mixtures met approximately the ASTM C 936 abrasion requirements 0.76 cm³/cm² (0.30 in³/in²).

CONCLUSIONS

Based on the strength and durability results derived in this investigation, the following major conclusions may be drawn.

1. In general, the rate of strength developed all concrete mixtures containing three by-product materials were significant lower compared to control mixture without by-product materials. The difference between the control and by-product materials containing wet-cast products increased with the amount of by-product material and decreased with age.
2. For commercialization of wet-cast bricks or paving stones , rate of strength gain obtained need to be increased through improved mixture proportioning and productions techniques.
3. Mixtures WR2 and WR2 met the ASTM compressive strength requirement for Grade N bricks at the ages of 28 days and 91 days, respectively.
4. All paving stone mixtures with and without by-product materials did not meet the ASTM requirement
5. In warm regions where freezing and thawing is not a concern, all of the wet-cast bricks (WR1, WR2, and WR3) could be used for building both interior and exterior walls within three weeks of moist curing. In cold regions where freezing and thawing is a concern, all of the wet-cast bricks could be used for building interior walls.
6. None of the wet-cast paving stones (WS1, WS2, and WS3) met the minimum compressive strength and the maximum water absorption requirements of ASTM for concrete paving stones.
7. Partial replacement of cement with fly ash, and regular sand with both bottom ash and used foundry sand resulted in considerable reduction in compressive strength, freezing and thawing resistance, and abrasion resistance of wet-cast products.

8. Partial replacement of cement with fly ash, and regular sand with both bottom ash and used foundry sand resulted in considerable increase in drying shrinkage of wet-cast bricks.
9. The individual influence of fly ash, bottom ash, and used foundry sand on the properties of wet-cast products could not be identified because fly ash, bottom ash, and used foundry sand were used simultaneously in the wet-cast concrete mixtures.
10. Partial replacement of regular sand with either bottom ash or used foundry sand resulted in considerable increase in drying shrinkage of dry-cast bricks and blocks.

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Table 1. Properties of Cement and Fly Ash Used

Chemical composition (%)	Cement Type I	ASTM C 150, Type I	Fly Ash	ASTM 618, Class F
Silicon dioxide, SiO ₂	20.8	-	51	-
Aluminum oxide, Al ₂ O ₃	5.2	-	23.3	-
Ferric oxide, Fe ₂ O ₃	2.2	-	7.1	-
Total, SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃	28.2	-	81.3	70.0 min.
Sulfur trioxide, SO ₃	4.0	3.0 max.	0.6	5.0 max.
Calcium oxide, CaO	62.6	-	11.1	-
Magnesium oxide, MgO	2.9	6.0 max.	2.7	
Titanium dioxide, TiO ₂	0.0	-	1.1	-
Potassium oxide, K ₂ O	2.9	-	1.0	-
Sodium oxide, Na ₂ O	0.9	-	1.1	
Moisture content	-	-	0.1	3.0 max.
Loss on ignition	1.1	3.0 max.	1.1	6.0 max.
Physical Properties of Cement				
Air content (%)	9	12 max.	-	-
Fineness (m ² /kg)	386	280 min.	-	-
Autoclave expansion (%)	0.10	0.8 max.	-	-
Specific gravity	3.1	-	-	-
Compressive strength (MPa)			-	-
1-day	14.3		-	-
3-day	23.3	12.3 min.	-	-
7-day	27.5	19.2 min.	-	-
28-day	33.2			
Vicat time of initial Set (min)	125	45 min. 375 max.	-	-
Physical Properties of Fly ashes				
Fineness retained on No. 325 sieve (%)		-	20	34 max.
Pozzolanic activity index with cement, 28-day (% of control)		-	99	75 min.
Water requirement (% of control)		-	96	105 max.
Autoclave expansion (%)		-	0.02	0.8 max.

Specific gravity		-	2.36	-
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Table 2. Physical Properties and Gradation of Regular Sand and Used Foundry Sand

Requirements →	Grading	Deleterious Substances			Soundness
ASTM →	C 136	C 142	C 117	C 40	C 88
Aggregate Tested	Fineness Modulus	Clay Lumps & Friable Particles (%)	Mat'l. Finer than 75- μ m (No. 200) Sieve (%)	Organic Impurities (Organic Plate No.)	Soundness of Agg.* (% Weight Loss)
Concrete Sand	1.82	0	1.4	---	1.0
UFS	1.17	---	9.7	< 3	---
ASTM C 33 Req.	2.30~3.10	3.0 Max.	3.0 Max.**	3 Max.	10.0 Max.

* Tested in sodium sulfate solution.

** For concrete subject to abrasion. For all other concrete, 5% max.

ASTM →	C 566	C 29		C 128			
Aggregate Tested	As Rcv'd Moisture Content (%)	Unit Weight (lb/ft ³)	Void Content (%)	Bulk Specific Gravity, Dry Basis	Bulk Specific Gravity, SSD Basis	Apparent Specific Gravity	SSD Absorp. (%)
Concrete Sand	4.4	108	36	2.71	2.73	2.77	0.8
UFS	1.5	96	28	2.14	2.16	2.2	1.3

Aggregate Tested	Percent Passing						
	9.5 mm (3/8-in.)	4.75 mm (No. 4)	2.36 mm (No. 8)	1.18 mm (No. 16)	600 μ m (No. 30)	300 μ m (No. 50)	150 μ m (No. 100)
Concrete Sand	100	100	100	93	74	42	10
UFS	100	100	100	99	97	77	9
ASTM C 33 Req.	100	95~100	80~100	50~85	25~60	10~30	2~10

Table 3. Chemical, Physical Properties, and Gradation of Bottom Ash

Properties →	Chemical Properties		
ASTM →	C 40	C 641	C 114
Aggregate Tested	Organic Impurities (Organic Plate No.)	Staining Mat'l. (Staining Index)	Loss On Ignition (%)
Bottom Ash	---	---	2.6
ASTM C 331 Req.	3 Max.	< 80	12.0 Max.

Properties→	Physical Properties					
ASTM →	C 142	C 136	C 29	C 151	C 1262	C 157
Aggregate Tested	Clay Lumps & Friable Particles (%)	Fineness Modulus	Unit Weight (lb/ft ³)	Popout Materials of Conc. (No. of popouts)	Freezing & Thawing Resistance of Concrete	Drying Shrinkage of Conc. (%)
Bottom Ash	---	3.15	57	---	Not. Satisf.	---
ASTM C 331 Req.	2.0 Max.	-----	70 Max.	0	Satisfactory	0.10 Max.

Properties →	Physical Properties					
ASTM →	C 566	C 29	C 127 and C 128			
Aggregate Tested	As Rcv'd Moisture Content (%)	Void Content (%)	Bulk Specific Gravity, Dry Basis	Bulk Specific Gravity, SSD Basis	Apparent Specific Gravity	SSD Absorption (%)
Bottom Ash	24.3	52	1.90	2.01	2.13	5.6

Aggregate Tested	Percent Passing						
	9.5 mm (3/8-in.)	4.75 mm (No. 4)	2.36 mm (No. 8)	1.18 mm (No. 16)	600 mm (No. 30)	300 mm (No. 50)	150 mm (No. 100)
Bottom Ash	100	84	70	54	41	27	8
ASTM C 331 Req.	100	85~100	-----	40~80	-----	10~35	5~25

Table 4. Physical Properties of Coarse Aggregates

Requirements →	Grading	Deleterious Substances		Soundness
ASTM →	C 136	C 142	C 117	C 88
Aggregate Tested	Fineness Modulus	Clay Lumps & Friable Particles (%)	Mat'l Finer than 75- μ m (No. 200) Sieve (%)	Soundness of Agg.* (% Weight Loss)
Coarse Agg.	5.34	0	2.9	1.7
ASTM C 33 Req.	-----	2.0 Max.	1.0 Max.	12.0 Max.

* Tested in sodium sulfate solution.

ASTM →	C 566	C 29		C 127			
Aggregate Tested	As Rcv'd Moisture Content (%)	Unit Weight (lb/ft ³)	Void Content (%)	Bulk Specific Gravity, Dry Basis	Bulk Specific Gravity, SSD Basis	Apparent Specific Gravity	SSD Absorption (%)
Coarse Agg.	2.3	110	35	2.74	2.76	2.82	1.0

Gradation

Aggregate Tested	Percent Passing						
	9.5 mm (3/8-in.)	4.75 mm (No. 4)	2.36 mm (No. 8)	1.18 mm (No. 16)	600 μ m (No. 30)	300 μ m (No. 50)	150 μ m (No. 100)
Coarse Agg.	100	38	10	6	4	4	3
ASTM C 33 Req.	85~100	10~30	0~10	0~5	-----	-----	-----

Table 5. Mixture Proportions and Fresh Concrete Data for Wet Cast Bricks

Mix No.	WR-1	WR-2	WR-3
Used Foundry Sand, %	0	26	36
Fly Ash, [A/(C+A)], %	0	30	40
Bottom Ash, [BA/(S+BA)], %	0	26	32
Cement, C, kg/m ³ (lb/yd ³)	329 (555)	225 (380)	187 (315)
Fly Ash, A, kg/m ³ (lb/yd ³)	0	95 (160)	128 (215)
Net Water, W, kg/m ³ (lb/yd ³)	243 (410)	267 (450)	252 (425)
[W/(C+A)]	0.76	0.82	0.79
SSD Fine Aggregate, S, kg/m ³ (lb/yd ³)	1174 (1980)	561 (945)	338 (570)
SSD Used Foundry Sand, kg/m ³ (lb/yd ³)	0	288 (485)	386 (650)
SSD Bottom Ash, kg/m ³ (lb/yd ³)	0	243 (410)	332 (560)
SSD 9.5mm (3/8") Natural Gravel Aggregate kg/m ³ (lb/yd ³)	481 (810)	456 (770)	439 (740)
Slump, mm (in)	85 (2 3/8)	45 (1 3/4)	51 (2)
Air Content, %	5.9	4.0	3.9
Unit Weight, kg/m ³ (lb/yd ³)	2238 (139.7)	2137 (133.4)	2062 (128.7)

Table 6. Mixture Proportions and Fresh Concrete Data for Wet-Cast Paving Stones

Mix No.	WR-1	WR-2	WR-3
Used Foundry Sand, %	0	25	36
Fly Ash, [A/(C+A)], %	0	29	40
Bottom Ash, %	0	23	32
Cement, C, kg/m ³ (lb/yd ³)	377 (635)	255 (430)	211 (355)
Fly Ash, A, kg/m ³ (lb/yd ³)	0	110 (185)	139 (235)
Net Water, W, kg/m ³ (lb/yd ³)	231 (390)	267 (450)	264 (445)
[W/(C+A)]	0.61	0.73	0.74
SSD Fine Aggregate, S, kg/m ³ (lb/yd ³)	1127 (1900)	528 (890)	314 (530)
SSD Used Foundry Sand, kg/m ³ (lb/yd ³)	0	228 (385)	306 (515)
SSD Bottom Ash, kg/m ³ (lb/yd ³)	0	267 (450)	360 (605)
SSD 9.5mm (3/8") Natural Gravel Aggregate kg/m ³ (lb/yd ³)	472 (795)	430 (725)	415 (700)
Air Entraining Admixture (oz/yd ³)	(5)	(30)	(51)
Slump, mm (in.)	92 (3 5/8)	70 (2 3/4)	70 (2 3/4)
Air Content, %	8.1	6.4	6.8
Air Temperature, °C (°F)	22 (71)	19 (67)	19 (67)
Concrete Temperature °C (°F)	24 (76)	25 (77)	26 (78)
Unit Weight, kg/m ³ (lb/yd ³)	2108 (137.8)	2087 (130.3)	2007 (125.3)

Table 7. Compressive Strength and Absorption Requirements of ASTM C 55 for Concrete Bricks

Grade	Compressive Strength*, min., MPa (psi)	Water Absorption*, max., kg/m ³ (lb/ft ³)	Weight Classification	Oven-Dry Density*, kg/m ³ (lb/ft ³)
N**	24 (3500)	160 (10)	Normal	2000 or more (125 or more)
		208 (13)	Medium	1680~2000 (105~125)
S***	17 (2500)	208 (13)	Normal	2000 or more (125 or more)
		240 (15)	Medium	1680~2000 (105~125)

* Average of three units at the time of delivery to the purchaser.

** Grade N—For use where high strength and resistance to moisture penetration and severe frost action are desired.

*** Grade S—For general use where moderate strength and resistance to frost action and moisture are required.

Table 8. Weight Classification and Absorption Grade of Wet-Cast Bricks

Mixture Number	WR1	WR2	WR3
Oven-Dry Density*, kg/m ³ (lb/ft ³)	2163 (135)	2019 (126)	1922 (120)
Weight Classification	Normal	Normal	Medium
Water Absorption Requirement of ASTM C 55 for Grade N Bricks**, max., kg/m ³ (lb/ft ³)	160 (10)	160 (10)	208 (13)
Water Absorption*, kg/m ³ (lb/ft ³)	159 (9.9)	186 (11.6)	203 (12.7)
Absorption Grade	N	S	N

* Average of results from five test ages, three specimens for each test age.

** Refer to Table 7 for water absorption requirement of ASTM C 55 for Grade N and Grade S bricks.

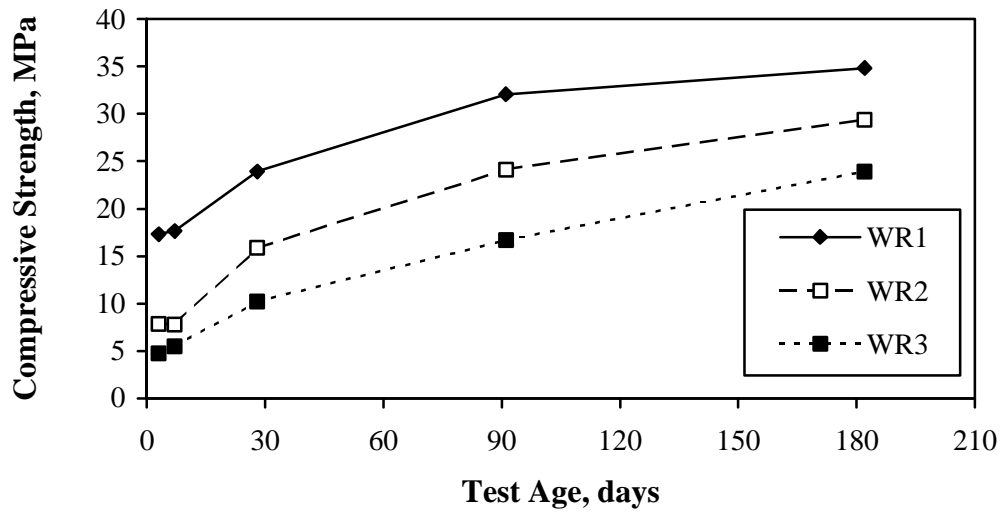


Fig. 1 – Compressive Strength of Wet-Cast Brick Concrete vs. Age

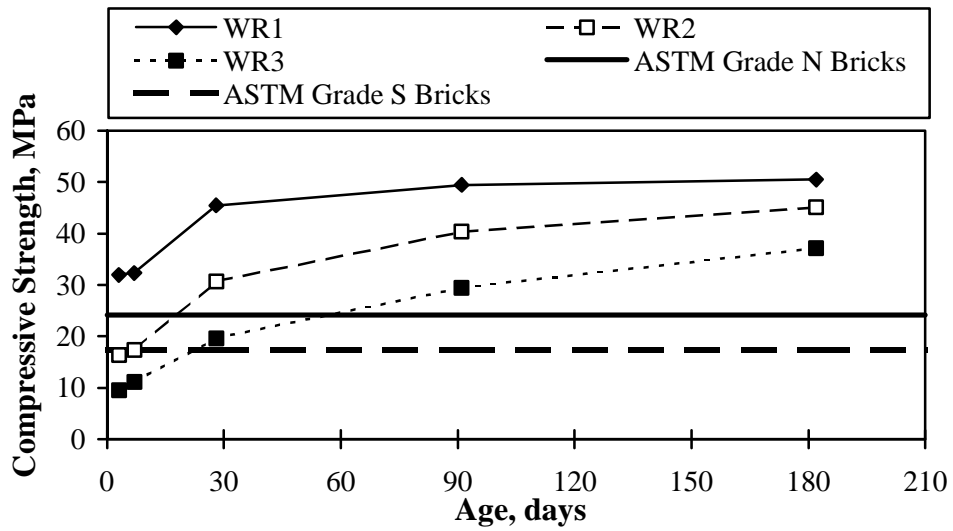


Fig. 2 – Compressive Strength of Wet-Cast Bricks vs. Age

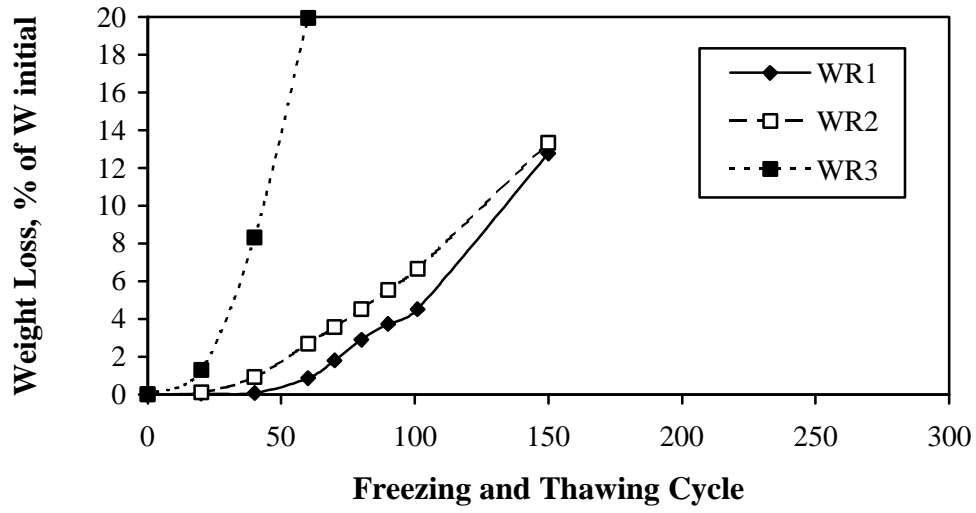


Fig. 3 – Weight Loss of Wet-Cast Bricks vs. Freezing and Thawing Cycle

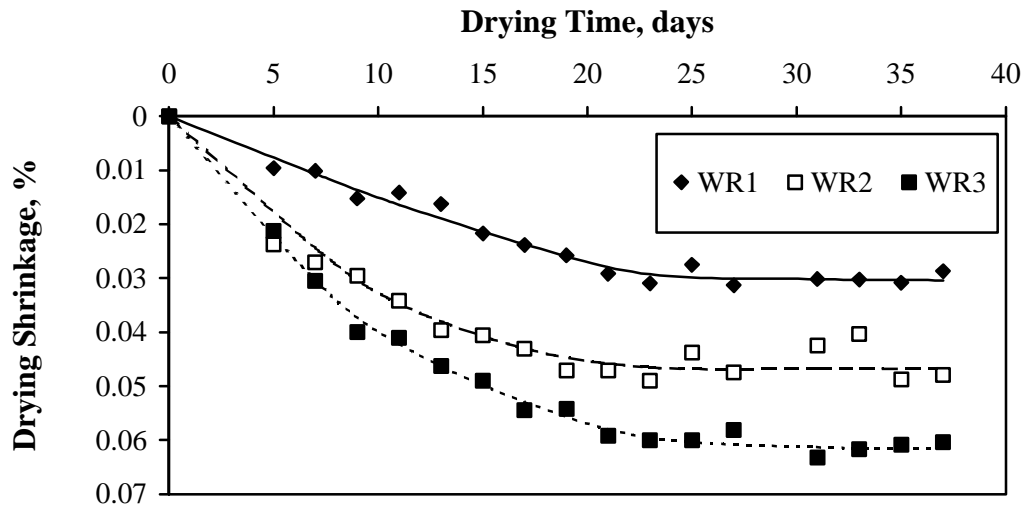


Fig. 4 – Drying Shrinkage of Wet-Cast Bricks vs. Drying Time

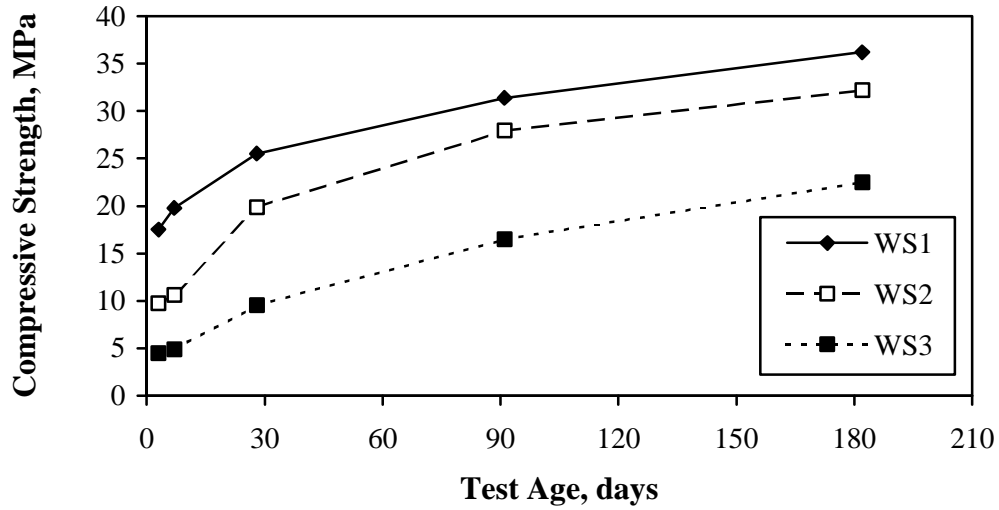


Fig. 5 – Compressive Strength of Wet-Cast Paving Stone Concrete vs. Age

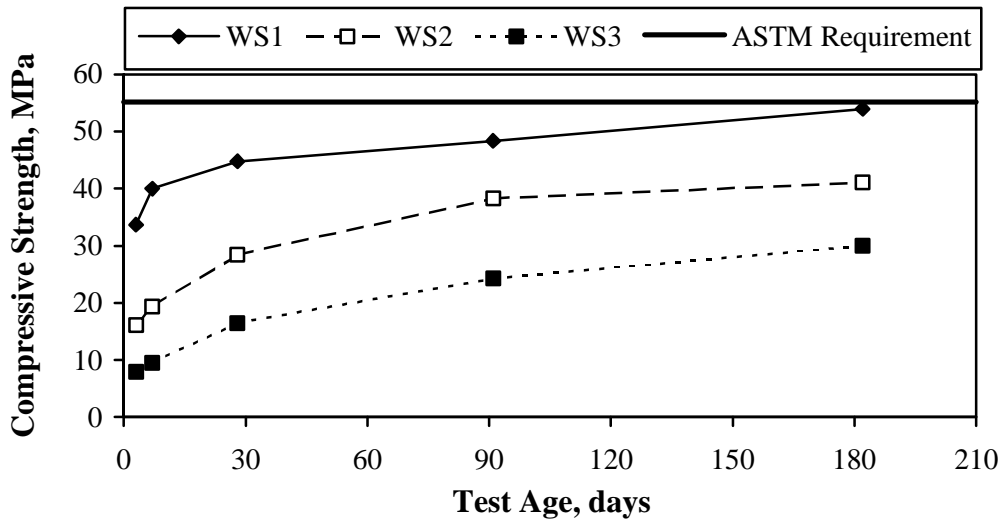


Fig. 6 – Compressive Strength of Wet-Cast Paving Stones vs. Age

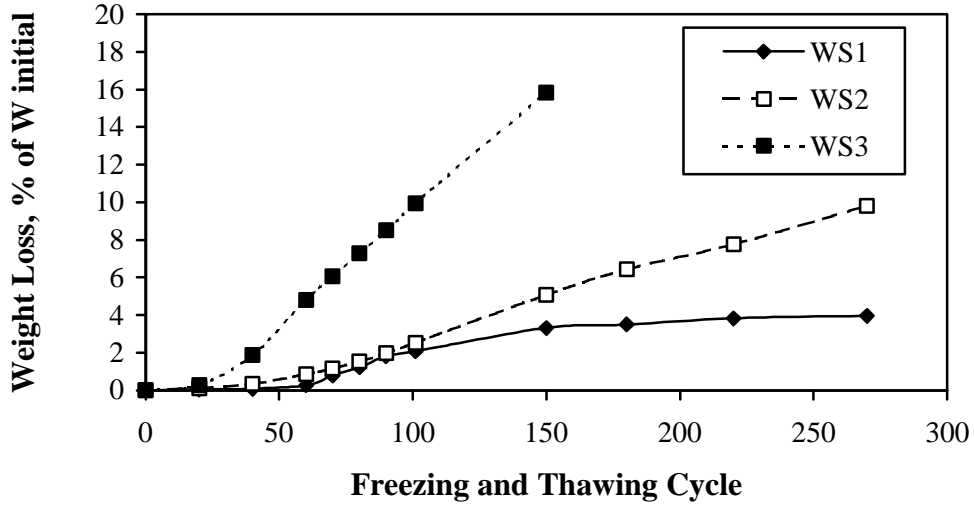


Fig. 7 – Weight Loss of Wet-Cast Paving Stones vs. Freezing and Thawing Cycle

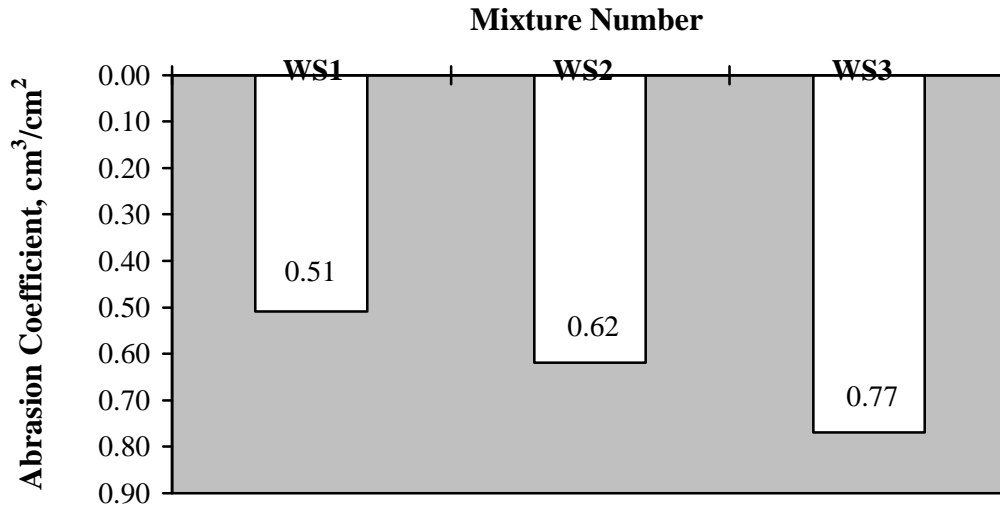


Fig. 8 – Abrasion Coefficient of Wet-Cast Paving Stones