Use of industrial by-products in sustainable construction practices

R.N. Kraus, T.R. Naik, & Y.-m. Chun
UWM Center for By-Products Utilization, University of Wisconsin-Milwaukee, Milwaukee, WI, USA

ABSTRACT: In the USA, significant quantities of industrial by-products are generated each year. It is estimated that over 10 million tons of foundry by-products, three million tons of wood ash, and over 110 million tons of coal combustion by-products are produced each year in the USA, with the majority sent to landfills at a considerable cost. Tipping fees and transportation costs average $30 per tonne in the USA and an unknown long-term environmental risk associated with landfilling. These materials are being thrown away, while aggregates continue to be mined, cement manufactured, and energy consumed in the processing of virgin materials. There would be a substantial savings if more by-products were used. The emphasis behind recycling is conserving resources for future generations and preserving the environment. This paper briefly describes the uses of coal ash, wood ash, and used foundry sand in concrete. Test results on concrete are summarized, including mixture proportions and fresh properties of concrete.

1 INTRODUCTION

Concrete is the world's most consumed man-made material. To produce one ton of portland cement, 1.5 tonnes of raw materials are needed. These materials include good quality limestone and clay. Therefore, to manufacture 1.5 billion tonnes of cement annually, at least 2.3 billion tons of raw materials are needed [Naik 2005]. According to the World Commission on Environment and Development [McDonough 1992]: sustainability means "Meeting the needs of the present without compromising the ability of the future generations to meet their own needs." This would mean that use of natural resources associated with cement manufacture and the environmental impact of cement production should be minimized.

Sustainability also has an economic impact. For the US, the US Department of Labor reported that over 2 million jobs are directly related to the cement and concrete industry [Naik 2005]. If the supplies of limestone or other raw materials are exhausted, as it is predicted to happen in some places, then portland cement and concrete could not be produced. Employers and the associated concrete industry would be lost, along with their employees.

Cement production also has an environmental impact. The production of one tonne of portland cement releases approximately one tonne of CO_2 and other greenhouse gases (GHGs) into the atmosphere. For each tonne of portland cement clinker, 1.5 to 10 kg of NOx are released into the atmosphere. [Naik 2005]. Over 5-million BTU of energy is needed to produce one tonne of cement. The large amount of CO_2 generated from the cement manufacturing process also needs to be reduced since increased levels of CO_2 has been directly linked to global climate change. Since industrialized countries account for most of the CO_2 generated (Table 1), these countries need to take a leading role in reducing the amount of CO_2 produced.

Table 1. CO_2 Emissions by Industrialized Countries in 2003 [ORNL 2006].

Country	Percent of world production of CO_2
U.S.A.	22
E.U.	15
Russia	6
Japan	5
China	15
India	5

Reducing cement production through the use of alternate materials such as coal fly ash and wood ash would reduce CO_2 and other GHG emissions. Replacing 15% of cement worldwide by other cementitious materials (e. g. pozzolans) will reduce CO_2 emissions by 250 million tons.

Use of concrete structures and pavements in construction benefits the environment in a number of ways. Thermal mass of concrete contributes to operating energy efficiency and reduced cooling costs, under some climatic conditions. Longer lasting concrete structures reduce energy needs for maintenance and reconstruction. Made-to-order concrete means less construction waste. Concrete is a locally available material; therefore, transportation cost to the project site is reduced. Light colored concrete walls and pavements reduce lighting requirements and therefore, energy consumption. Reduced rolling resistance of tires on concrete versus asphalt also conserves fuel. Concrete also absorbs CO_2 through carbonation reducing the carbon impact of its use. Therefore, considering these energy, and environmental benefits, concrete must keep evolving to satisfy the increasing demands of all its users. Reuse of post-consumer wastes and industrial by-products in concrete is necessary to enhance the sustainability of concrete.

2 FLY ASH USE IN CONCRETE

The American Coal Ash Association [ACAA 2006] has reported that over 110 million tonnes of coal combustion products are generated each year. The overall rate for beneficial reuse is approximately 40%. Therefore, if an overall average of $30 per tonne is assumed for a disposal fee in the USA, two billion dollars are wasted each year on the disposal of coal combustion products.

Fly ash is the most well-known coal-combustion product that forms as very fine particles in the boiler during combustion of pulverized coal. These particles, are typically spherical in shape, ranging in size from less than 1 micron to 150 microns, (Fig. 1). They are collected from flue gases by use of either electrostatic precipitators, or bag-houses. Fly ashes typically possess pozzolanic activity, and some also have cementitious properties, depending on the source of the coal used for combustion. Fly ash contains some calcium aluminosilicate glass [Naik & Singh 1997]. The amorphous silica reacts with calcium hydroxide formed during hydration of cement, to form calcium silicate hydrate (C-S-H). The alumina in the pozzolan may also react to form calcium aluminate hydrate, ettringite, gehlenite, and calcium monosulphoaluminate hydrate.

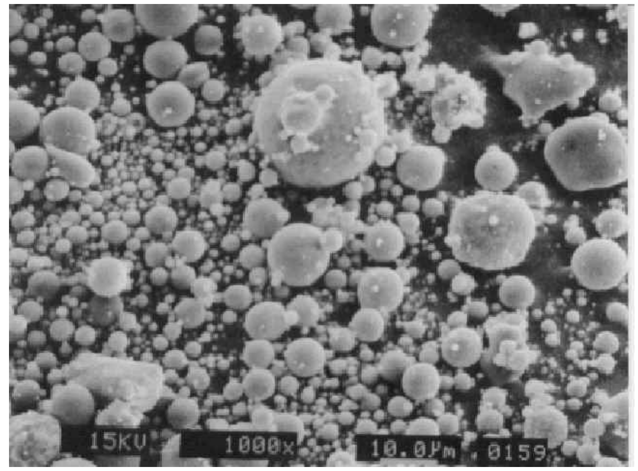

Fig. 1. Scanning electron micrograph of fly ash particles.

2.1 *Fly ash use in concrete*

Fly ash is the most commonly used pozzolan in the manufacture of concrete due to its low-cost and ready availability. Typically, strength development of concrete made with fly ash, especially fly ash meeting ASTM Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete (C 618) Class F requirements, is slower at the early-age than concrete without fly ash. "However, recent advances in concrete technology have solved this problem to a great extent by using appropriate mixture proportions at a low water-cementitious materials ratio, with high-range water-reducing admixtures (HRWRA)" [Naik et al. 2004]. One of the earliest prototype applications reported on the use of high-volume fly ash that met ASTM C 618 Class C requirements in concrete mixtures was by Naik and Ramme [Naik & Ramme 1989]. In the work described in this paper, many concrete mixture proportions were developed with a design 28-day compressive strength of 21 MPa to 35 MPa. Concrete mixtures were tested at 0, 20, 30, 40, 50, and 60% Class C fly ash as a replacement for Type I cement. All concrete mixtures were produced at ready-mixed concrete plants. Some of the results of the compressive strength tests are shown in Figs. 2 and 3. As can be seen from these compressive strength test results, up to the age of seven days, the strength development of concrete having up to 40% Class C fly ash all were equivalent or better than concrete without fly ash. The compressive strength of the mixture containing 50% was slightly lower, but also quite acceptable. All mixtures, including the mixture containing 60% Class C fly ash, met the required design strength at the age of 28 days. This clearly demonstrates that high-volumes of fly ash can be successfully used in structural-concrete; however, the lower compressive strength developed at the earlier ages when incorporating over 50% Class C fly ash should be accounted for when placing the concrete in cold-weather service.

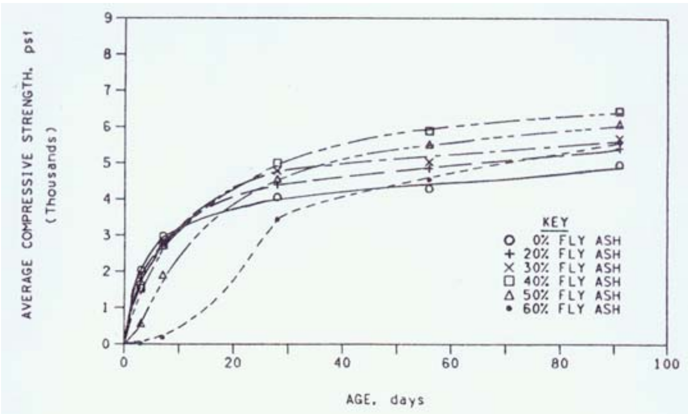

Fig. 2 – Concrete Mixtures Using Class C Fly Ash – 28-day Design Strength of 21 MPa (3,000psi) [Naik & Ramme 1989]

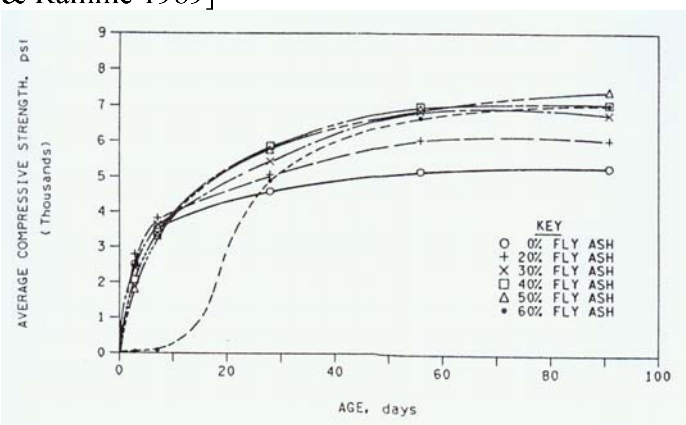

Fig. 3. Concrete Mixtures Using Class C Fly Ash – 28-day Design Strength of 28 MPa (4,000psi) [Naik & Ramme 1989].

The long-term performance of pavements constructed since 1984 using concrete containing high-volumes of Class F and Class C fly ash has also been excellent. Naik [Naik et al. 2004] evaluated concrete pavements constructed with six different mixtures, three mixtures with Class C fly ash replacing up to 70% of cement, and three mixtures with Class F fly ash replacing up to 67% cement. These concrete pavements for roadways were subjects to the severe freezing and thawing environment of Wisconsin, USA, applications of chloride de-icers, and heavy loading from truck traffic. Testing of cores taken from the in-situ concrete pavement included compressive strength, density, and resistance to chloride-ion penetration.

Results of the compressive strength tests are shown in Fig. 4. The rate of early-age strength gain of the Class C fly ash concrete mixtures was higher compared to the Class F fly ash concrete mixtures. This is attributed to greater reactivity of Class C fly ash compared to Class F fly ash. Long-term pozzolanic strength contribution of Class F fly ash is greater than Class C fly ash, resulting in long-term compressive strengths of Class F fly ash concrete mixtures in actual pavements to be higher than the strength obtained from concrete mixtures containing Class C fly ash. "Therefore, the use of Class F fly ash is more desirable from the long-term perspective for the manufacture of high-performance concretes (HPCs) because HPCs are required to possess both long-term high-strength properties and durability." The ratio of compressive strength at seven or eight years to the 28-day of the compressive strength gain of Class C fly ash concrete mixtures remained relatively constant, but the gain for Class F fly ash mixtures increased with the increase in fly ash content (Fig. 5). This is most likely due to a greater formation of pozzolanic C-S-H from Class F fly ash in concretes compared with Class C fly ash.

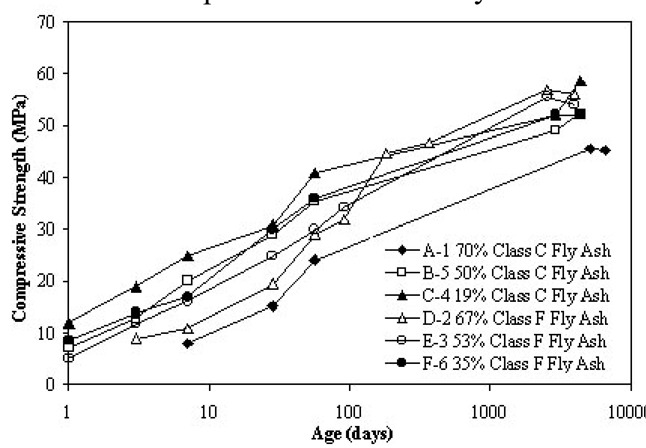

Fig. 4. Compressive Strength of Concrete Pavements (using cores after 365 days) [Naik et al. 2004]

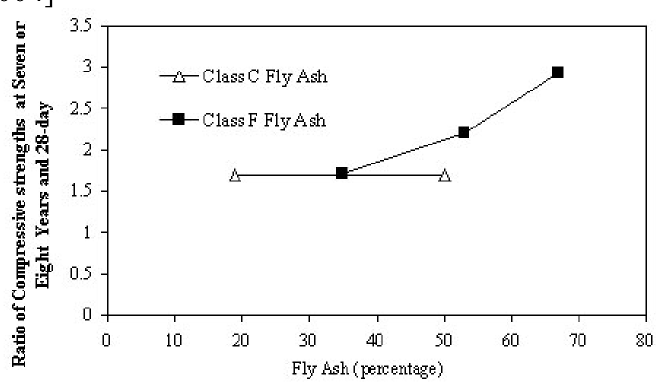

Fig. 5 – Rate of Strength Gain for Concrete Using Class C and Class F Fly Ash [Naik et al. 2004]

Generally, the concrete mixtures containing Class F fly ash exhibited higher resistance to chloride ion penetration relative to mixtures containing Class C fly ash. Within a group of mixtures containing the same class of fly ash, chloride ion penetration resistance increased as replacement rate of cement with fly ash increased. The concrete mixtures were extremely resistant to chloride ion penetration and were rated to have "negligible" chloride or "very low" chloride ion penetrability in accordance with ASTM C 1202.

3 WOOD ASH USE IN CONCRETE

Wood ash is generated as a by-product of combustion of wood from boilers at pulp and paper mills, steam power plants, and other thermal power generating facilities. In some combustion processes, the wood ash is co-fired with another fuel source such as coal. Since wood is a renewable resource for energy and an environmentally friendly material, there is an increased interest in using "waste" wood for energy production. This is expected to increase the amount of wood ash generated in the future. In the USA, approximately 3.6 million tonnes of wood ash is generated each year by the pulp and paper industry alone. The majority, 70% of the wood ash, is landfilled. Disposal of wood ash in landfills costs the pulp and paper industry significant direct cost plus unknown future liabilities due to possible environmental impact related to such materials in landfills.

3.1 *Properties of Wood Ash*

ASTM specifications do not exist for wood ash. Therefore, determining the applicable physical and chemical properties for wood ash for use in concrete is not straightforward. The closest comparison is with ASTM Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, C 618. Therefore, ASTM C 618 was used to give some indication of the potential for wood ash to be used as a mineral admixture in cement-based materials. The physical and chemical properties (Table 2 and 3) were determined for 12 different sources of wood fly ash [Naik & Kraus 2003]. These test results indicated that wood fly ash can be used as a partial replacement of cement and fine aggregates in the manufacture of concrete and other cement-based products. If the source is coarse, the wood ash may be acceptable as a substitute of sand in ready-mixed concrete, or in dry- or wet-cast concrete products.

Table 2. Gradation of wood fly ash [Naik & Kraus 2003]

Sieve Size	% Passing		ASTM C 33
	Average	Range	% Passing
19.1 mm	98.8	91.8-100	100
12.7 mm	97.0	81.5-100	100
9.5-mm	93.2	73.1-100	100
4.75-mm	87.7	60.3-100	95 to 100
2.36 mm	83.1	50.1-100	80 to 100
1.18 mm	75.0	37.3-99.5	50 to 85
600 µm	60.9	19.2-99.2	25 to 60
300 µm	50.5	8.0-97.5	10 to 30
150 µm	41.4	16.0-90.8	2 to 10

3.2 *Mixture proportions of concrete using wood ash*

The UWM Center for By-Products Utilization has completed laboratory and field mixtures that have used wood ash in air entrained and non-air entrained concrete. Based upon the laboratory evaluation, the following conclusions were drawn [Kraus & Naik 2000].

The effects of source of wood ashes on physical and chemical properties, and microstructure are significant. All sources of wood ash must be properly tested before use in construction material.

Most of the wood ashes that were evaluated do not conform to ASTM C 618 requirements for coal fly ash.

Loss on ignition and alkali contents of wood ashes are generally greater than those found in coal ashes.

Based on the properties of wood ash, several potential applications of wood ash exist in low- and medium-strength concrete, structural concrete, and cast-concrete products.

Based on the initial laboratory evaluation, an additional project was conducted on the use of wood ash in structural concrete pavement [Naik & Kraus 2004]. The work associated with this project consisted of a laboratory, pilot-scale field, and construction demonstration of air entrained concrete pavement mixtures. Mixture proportions used for the final construction demonstration are given in Table 4.

Table 3. Chemical composition of wood ash [Naik & Kraus 2003]

Analysis Parameter	Wood Ashes		ASTM 618 requirements		
	Average, %	Range, %	Class C	Class F	Class N
Silicon Dioxide, SiO_2 (%)	26.5	4.0-59.3	--	--	--
Aluminum Oxide, Al_2O_3 (%)	9.0	5.0-17.0	--	--	--
Iron Oxide, Fe_2O_3 (%)	5.4	1.0-16.7	--	--	--
$SiO_2 + Al_2O_3 + Fe_2O_3$ (%)	40.7	10.0-72.2	50 Min.	70 Min.	70 Min.
Calcium Oxide, CaO (%)	16.0	2.2-36.7	--	--	--
Magnesium Oxide, MgO (%)	3.0	0.7-6.5	--	--	--
Titanium Oxide, TiO_2 (%)	0.51	0.0-1.2	--	--	--
Potassium Oxide, K_2O (%)	5.0	0.4-13.7	--	--	--
Sodium Oxide, Na_2O (%)	1.7	0.5-14.3	--	--	--
Sulfite, SO_3 (%)	4.8	0.1-15.3	5 Max.	5 Max.	4 Max.
Loss on Ignition (1000^oC) (%)	23.4	6.7-58.1	6 Max.	6 Max.	10 Max.
Moisture (%)	2.6	0.1-21.5	3 Max.	3 Max.	3 Max.
Available Alkali, Na_2O (%)	3.3	0.4-20.4	1.5 Max.	1.5 Max.	1.5 Max.

Table 4. Mixture proportions for wood ash – concrete mixtures [Naik & Kraus 2004].

Mixture Number	C-1	C-2	C-3	C-4
Wood Ash (%)	0	5	8	12
Cement (kg/m^3), C	302	285	260	263
Class C fly ash (kg/m^3)	30	60	77	80
Wood Ash (kg/m^3), WA	0	20	31	47
Water (kg/m^3), W W/(C+WA)	137	155	144	136
SSD Fine Aggregate (kg/m^3)	835	820	780	805
SSD Coarse Aggregate (kg/m^3)	970	980	950	950
Air Entraining Admixture (L/m^3)	1.3	1.4	1.3	1.3
Slump (mm)	132	119	120	116
Air content (%)	6.6	6.0	6.5	4.9
Fresh Concrete Density (kg/m^3)	2280	2300	2200	2290

3.3 *Compressive Strength*

The compressive strength was evaluated for the concrete mixtures (Series C-1, C-2, C-3, and C-4) from the full-scale manufacturing. The addition of wood ash did not affect the compressive strength of concrete. The compressive strength of mixtures made with wood ash was very much comparable to the mixture containing no wood ash. In fact, at later ages (91, 182, and 365 days) wood ash seemed to have contributed to strength gain due to pozzolanic reaction. All concrete mixtures from full-scale manufacturing achieved approximate strengths of 33 MPa at 28 days and over 42 MPa at 365 days. Therefore, concrete made with wood ash can be used for many structural applications [Naik & Kraus 2004].

3.4 *Resistance to Freezing and Thawing*

Resistance to freezing and thawing of concrete mixtures manufactured for the full-scale mixtures were evaluated by testing in accordance with ASTM Standard test Method for Resistance of Concrete to Rapid Freezing and Thawing, C 666, Procedure A. In addition to testing for relative dynamic modulus and change in length specified by ASTM, changes in pulse velocity was also measured.

There was no significant effect of freezing and thawing cycles (300 cycles) on the relative dynamic modulus of the concrete mixtures. The inclusion of wood ash in concrete mixtures did not make a significant difference in relative dynamic modulus. The relative dynamic modulus after 300 cycles of freezing and thawing was 98% for Control Mixture (C-1) without wood ash, 96 % for Mixture C-2, 98% for Mixture C-3, and 96 % for Mixture C-4. For Control Mixture (C-1), percent change in length was 0% at 32 cycles, and -0.006% at 360 cycles. The percent change in length for Mixture C-2 was –0.003% at 32 cycles and 0.011% at 300 cycles, 0.003% at 32 cycles and 0.009% at 300 cycles for Mixture C-3, -0.0004% at 32 cycles and 0.012% at 213 cycles for Mixture C-4 [Naik & Kraus 2004].

There was no significant effect of inclusion of wood ash on the pulse velocity of concrete mixtures. At 300 cycles, the pulse velocity of concrete was 5,425 m/sec for Mixture C-1, 5,480 m/sec for Mixture C-2, 5,555 m/sec for Mixture C-3, and 5,435 m/sec for Mixture C-4 [Naik & Kraus 2004].

4 USED FOUNDRY SAND IN CONCRETE

Foundries in the USA generates over seven million tonnes of foundry by-products each year [Naik 2005]. Wisconsin alone produces over 500,000 tonnes of foundry by-products. Due to insufficient use, the majority of these by-products find their way to landfills. Disposal of foundry by-products in landfills not only causes loss in resource and energy recovery, but also environmental problems associated with their disposal. Additionally, shrinking landfill space in the country is making disposal more costly and restrictive. As a result foundries are facing serious challenges in waste product management, such as regulatory controls, increasing cost and scarcity of disposal options. Due to environmental regulations, many foundries are forced to re-evaluate their normal disposal. Work conducted by the UWM Center for By-Products Utilization has demonstrated that the use of foundry sand may be used in concrete. The following sections contain some of the details of this work [Naik et al. 1994, Naik et al. 1996, Naik et al. 2001].

4.1 *Materials*

Three types of sand were used for the concrete mixtures, clean (unused) foundry sand, used foundry sand, and typical concrete sand. The clean foundry sand was obtained from a sand mining company and the used foundry sand was obtained from a steel casting company. Fly ash, clean foundry sand, and used foundry sand were tested for their physical and chemical properties. For comparison purposes, some properties of regular concrete sand were also measured.

The sieve analysis data are shown in Fig. 6. The gradation results show that both the clean foundry sand and the used foundry sand are outside the ASTM limits for fine aggregate for concrete. The foundry sands contain predominantly finer particles compared to those of regular concrete sand. Approximately 50 to 60 percent of the clean and used foundry sands passed through the 300-μm (No. 50) sieve, and (95 to 100 percent passed the 600-μm (No. 30) sieve).

Other physical properties data for the three sands are shown in Table 6. The properties of used foundry sand vary greatly due to the type of equipment used, type of additive, the number of times the sand is recycled in the foundry process, and the type and amount of binder used.

. The foundry sand exhibited lower bulk density (due to nearly uniform particle size) and higher water absorption compared to normal concrete sand. The bulk density of the used foundry sand was slightly higher than that of the clean foundry sand. This may be attributed to particles adhering to used foundry sand particles, such as steel particles bonded to the sand during the foundry process. Both the used and clean foundry sands exhibited high absorption values compared to the regular concrete sand. However, the difference between the values for clean and used foundry sand was insignificant.

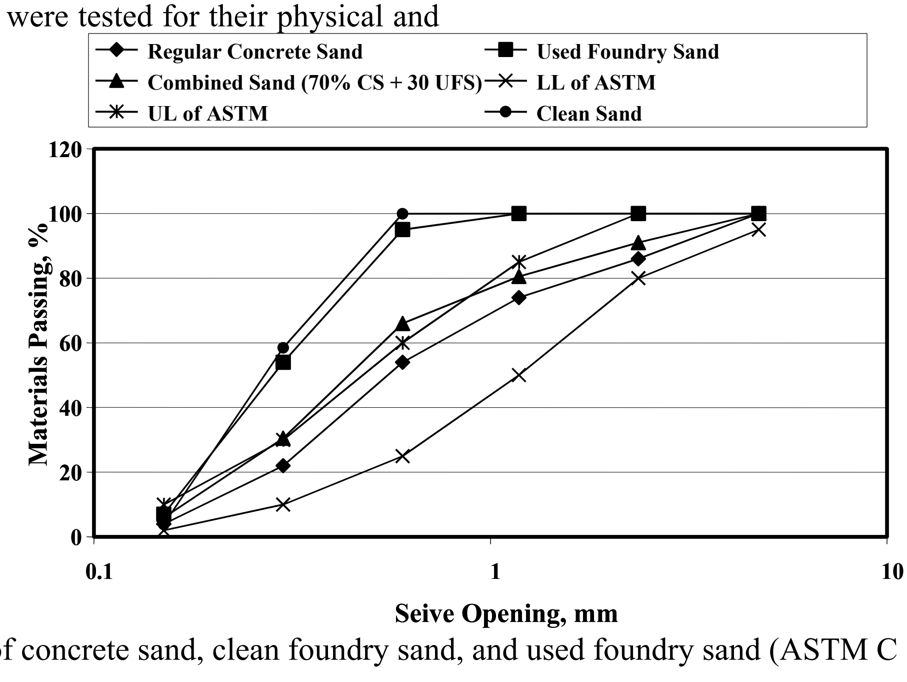

Fig. 6. Gradation of concrete sand, clean foundry sand, and used foundry sand (ASTM C 136) [Naik et al. 2001]

Table 6. Physical properties of aggregates and foundry sands.

	As Received Moisture Content, %	Bulk Density, kg/m^3	Bulk Specific Gravity	Saturated Surface Dry Absorption, %	Voids, %	Fineness Modulus	Clay Lumps & Friable Particles, %	Mass Loss in Soundness Test, %	Material Finer than 75-µm (No. 200) Sieve
ASTM	C566	C29		C128	C29	C136	C136	C88	C117
Concrete Sand	0.39	1840	2.43	1.0	25.0	3.57	0.2	10.0	1.40
Clean Foundry Sand	0.19	1730	2.38	4.9	33.8	2.33	0.1	10.5	0.17
Used Foundry Sand	0.25	1784	2.44	5.0	34.8	2.32	0.4	54.9	1.08

The foundry sand exhibited lower bulk density (due to nearly uniform particle size) and higher water absorption compared to normal concrete sand. The bulk density of the used foundry sand was slightly higher than that of the clean foundry sand. This may be attributed to particles adhering to used foundry sand particles, such as steel particles bonded to the sand during the foundry process. Both the used and clean foundry sands exhibited high absorption values compared to the regular concrete sand. However, the difference between the values for clean and used foundry sand was insignificant.

An ASTM Class C fly ash was used in the concrete mixtures. The fly ash conformed to the ASTM C 618 requirements for Class C fly ash, except that the sodium oxide content was slightly higher than the requirements of ASTM C 618. A Type I cement meeting the ASTM C 150 specification for Type I cement was used throughout this investigation.

4.2 *Concrete mixture proportions using foundry sand*

Eleven concrete mixtures were developed by the UWM-CBU. The mixture proportion data are presented in Table 7 [Naik et al. 2001]. A reference mixture (R0+0) containing no by-product materials was proportioned to attain a compressive strength of 31 MPa (4,500 psi) at the age of 28 days. Four mixtures were proportioned to contain used or clean foundry sand as a replacement of 20 to 40% regular concrete sand. The water to cement ratio (W/C) was kept at about 0.48 + 0.01 for these mixtures. The remaining six mixtures were proportioned with used or clean foundry sand as a replacement of concrete sand, and with Class C fly ash as an additional cementitious material. The water to cementitious materials ratio (W/Cm) for fly ash concrete mixtures was 0.39 + 0.03. These mixtures were air entrained using an air entraining agent meeting ASTM C 260 with a design air content of about 6% + 0.5%. The fresh concrete properties such as slump, air content, temperature, density, and ambient air temperature are given in Table 3. The slump of the concrete mixtures varied between 75 to 160 mm. The actual air content of the mixtures varied between 5.1 and 6.3%. Due to the use of fly ash, concrete mixtures containing fly ash exhibited a lower W/Cm as compared with concrete made without fly ash. The fresh concrete properties were not greatly affected by inclusion of either used or clean foundry sand.

4.3 *Compressive strength of concrete mixtures*

Test data on compressive strength are presented in Fig. 7. The results showed that the compressive strength of concrete was not greatly influenced by inclusion used or clean foundry sand as a replacement of up to 40% concrete sand. However, concrete made with 40% clean sand showed slightly higher compressive than the reference mixture. The compressive strength of the reference mixture ranged from approximately 23.1 MPa at 3 days to 39.5 Mpa at 182 days. The compressive strengths of concrete mixtures containing up to 40% foundry sand without fly ash varied from 21.6 to 25.9 MPa at 3 days to 38.5 to 43.2 MPa at 182 days.

Table 7. Mixture proportions of concrete mixtures using foundry sand [Naik et al. 2001].

Mix Designation*	R0+0	U20+0	U40+0	C20+0	C40+0	U10+17	U20+20	U30+22	U40+25	C20+14	C40+14
Design Strength, MPa	31	31	31	31	31	31	31	31	31	31	31
Cement, kg/m^3	336	336	335	336	340	327	332	207	323	327	329
Fly Ash, kg/m^3	0	0	0	0	0	68	82	94	106	53	54
Water, kg/m^3	163	166	164	163	162	161	160	155	158	157	162
Sand, SSD, kg/m^3	797	635	476	636	487	694	599	538	460	619	460
Foundry Sand, SSD, kg/m^3	0	160	318	159	323	77	158	231	307	155	312
¾” Aggregates SSD, kg/m^3	997	997	993	997	1010	969	983	971	956	970	972
Slump, mm	135	160	150	105	75	125	100	100	100	125	95
W/C Ratio	0.48	0.49	0.49	0.48	0.47	0.49	0.48	0.46	0.49	0.48	0.49
W/Cm Ratio	0.48	0.49	0.49	0.48	0.47	0.41	0.39	0.38	0.36	0.42	0.42
Air Content, %	5.8	6.3	6.3	5.9	5.1	5.5	5.5	5.2	5.4	6.2	6.2
Air Temperature, ºC	22	24	23	22	22	23	24	22	22	22	23
Concrete Temperature, ºC	21	23	24	26	27	26	24	10	25	24	22
Fresh Concrete Density, kg/m^3	2290	2290	2290	2290	2323	2290	2323	2339	2307	2275	2290
Hardened Concrete Density, kg/m^3	2387	2355	2371	2339	2371	--	--	2371	2339	--	2339

* Ri+j, Ui+j, and Ci+j are reference mixture, mixtures containing used foundry sand, and mixtures containing clean foundry sand, respectively. The number i refers to the percent of regular concrete sand replacement with foundry sand, and j refers to the percent of fly ash addition.

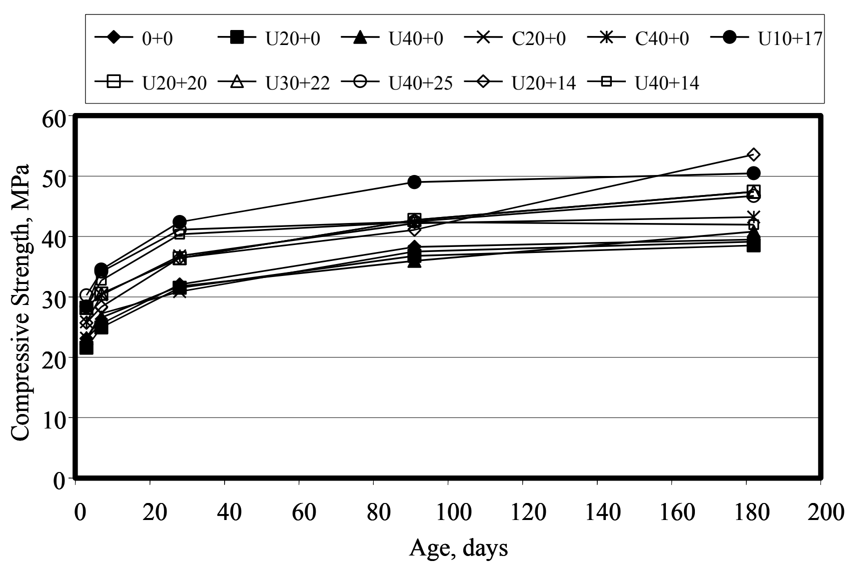

Fig. 7. Compressive strength of concrete mixtures using foundry sand [Naik et al. 2001]

In this study, fly ash was added as an additional cementitious material for some of the concrete mixtures. Using the fly ash improved concrete performance significantly. Fly ash content was varied from 14% to 25% of total cementitious materials used. All concrete mixtures up to 40% foundry sand (clean or used) with fly ash contents up to 25% outperformed the reference concrete. The compressive strengths of mixtures containing up to 40% foundry sands and fly ash up to 25% ranged from 25.7 to 30.3 MPa at 3 days, to 42.0 to 50.5 MPa at 182 days. This was attributed to generation of additional C-S-H crystals resulting from cementitious and pozzolanic reactions of the fly ash. Although the use of large amounts of used foundry sand did not decrease compressive strength in this investigation, previous studies [Naik et al. 1994, Naik et al. 1996, Naik et al. 2001] had recorded a reduction in the strength of concrete when used foundry sand was used to replace more than 20% regular concrete sand. Since variation occurs in the quality of used foundry sand, it would be desirable to add fly ash when proportioning concrete mixtures to compensate for any potential decrease in the concrete strength. The use of fly ash could also result in a better quality structural-grade foundry sand concrete compared to the reference concrete without any by-product material.

4.4 *Abrasion resistance*

The depth of abrasion data of concrete mixtures decreases as the compressive strength increases. No definite trend could be established concerning the effects of age and mixture proportions on concrete resistance to abrasion. Mixtures U20+20 (2.1 mm abrasion depth), U30+22 (2.4 mm abrasion depth), U40+25 (2.3 mm abrasion depth) exceeded 2.0 mm maximum depth of abrasion (specified maximum depth for high resistance to abrasion), while the remaining mixtures attained depth of abrasion less than 2 mm at the age of 28 days. Beyond 28 days, all mixtures made with or without foundry sands of fly ash showed a depth of abrasion values less than 2.0 mm. Thus, all concrete mixtures with or without foundry sand attained high resistance to abrasion.

5 SUMMARY

Based on the work conducted by the UWM Center for By-Products Utilization (UWM-CBU), it has been shown that a number of industrial by-products can successfully be used in ready-mixed concrete. Use of these by-product materials saves energy, conserving resources, and also preserves the environment.

5.1 *Use of fly ash in concrete*

The use of fly ash as a replacement of cement has been accepted in construction, but typically at low replacement rates, up to 30 percent. The UWM-CBU has demonstrated through various projects that high-volume fly ash use of high-volume fly ash mixtures using 50% or more fly ash as a replacement of cement can successfully be used in concrete. When using high-volume fly ash concrete the lower rate of initial strength development should be taken into account. However, long-term compressive strength due to pozzolanic reaction was higher than a comparable mixtures made without fly ash.

Concrete mixtures containing Class F fly ash exhibit higher resistance to chloride ion penetration relative to mixtures containing Class C fly ash. Within a group of mixtures containing the same class of fly ash, chloride ion penetration resistance increased as replacement rate of cement with fly ash increased. The concrete mixtures were extremely resistant to chloride ion penetration and were rated to have "negligible" chloride or "very low" chloride ion penetrability in accordance with ASTM C 1202.

5.2 *Use of wood ash in concrete*

The addition of wood ash did not affect the compressive strength of concrete. The compressive strength of mixtures made with wood ash was very much comparable to the mixture containing no wood ash. In fact, at later ages (91, 182, and 365 days) wood ash seemed to have contributed to strength gain due to pozzolanic reaction. All concrete mixtures from full-scale manufacturing achieved approximate strengths of 35 Mpa (5000 psi) at 28 days and over 41 Mpa (6,000 psi) at 365 days. Therefore, concrete made with wood ash can be used for many structural applications. Splitting tensile strength and flexural strength results also showed a similar pattern of increased strength with age.

Use of wood ash did not affect the freezing and thawing resistance of concrete mixtures. All mixtures had excellent resistance to freezing and thawing.

Based on the work conducted by UWM-CBU, it can be concluded that structural concrete can be produced with the addition of wood ash..

5.3 *Use of used foundry sand in concrete*

Both used and clean foundry sands did not pass all ASTM C 33 requirements for fine aggregate for use in concrete. These foundry sands were much finer than typical concrete sand.

Inclusion of used foundry sand as a replacement of up to 40% a typical concrete sand produced compressive strength equivalent to the reference mixture. The concrete mixture made by replacing 40% of typical concrete sand with clean foundry sand showed slightly higher strength than the reference mixture.

Inclusion of fly ash improved the compressive strength of concrete mixtures. All concrete mixtures with up to 40% foundry sands (used or clean) and up to 25% fly ash outperformed the reference mixture. All concrete mixtures with and without foundry sand exhibited high resistance to abrasion.

All the concrete mixtures proportioned with up to 40% used foundry sand with or without fly ash exhibited strength properties appropriate for most structural applications.

ACKNOWLEDGEMENT

The UWM Center for By-Products Utilization was established in 1988 with 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; We Energies, Milwaukee, WI; Wisconsin Power and Light Company, Madison, WI; and, Wisconsin Public Service Corporation, Green Bay, WI. Their financial support and additional grant and support from Manitowoc Public Utilities, Manitowoc, WI, are gratefully acknowledged.

REFERENCES

ACAA 2006. *2005 Coal combustion product (CCP) production and use*, American Coal Ash Association, Aurora, CO, USA.

Kraus, R.N., & Naik, T.R. 2000. *Use of wood ash for the production of structural concrete and CLSM*, Final Report to the UWS Solid Waste Research Program, Oct. 2000, Report CBU 2000-31, Milwaukee, WI, USA.

McDonough, W. 1992. *The Hannover principles: design for sustainability*, EXPO 2000, The World's Fair, Hannover, Germany, 1992.

Naik T.R. & Ramme B.W. 1989. *High-strength concrete containing large quantities of fly ash*, ACI Materials Journal, Vol. 86, No. 2, Mar.-Apr. 1989.

Naik, T.R., Patel, V.M., Parikh, D.M., & Tharaniyil, M.P. 1994. *Utilization of used foundry sand in concrete*, Journal of Materials in Civil Engineering, Vol. 6, No. 2, May 1994.

Naik T.R., Singh, S.S., Tharaniyil, M.P. & Wendorf R.B. 1996. *Application of foundry by-product materials in manufacture of concrete and masonry products*, ACI Materials Journal, Vol. 93, No. 1, 1996.

Naik, T.R., Singh, S.S. 1997. *Influence of fly ash on setting and hardening characteristics of concrete systems*, ACI Materials Journal, Vol. 94, No. 5, Sept.-Oct. 1997, pp. 355-360.

Naik, T.R., Singh, S.S., Kraus, R.N., Ramme, B.W., & Domann, R.A. 2001, *Enhanced materials for concrete construction using foundry by-products* published at the Third CANMET/ACI International Symposium on Sustainable Development of and Concrete, Supplementary Proceedings, San Francisco, CA, September 2001.

Naik, T.R., Kraus R.N. 2003. *A new source of pozzolanic material*, Concrete International, Vol. 25, No. 12, ACI, pp 55-62.

Naik, T.R., Ramme, B.W., Kraus, R.N. & Siddique, R. 2004. *Long-term performance of high-volume fly ash concrete pavements*, ACI Materials Journal, Vol. 100, No. 2, Mar.-Apr. 2003.

Naik, T.R. & Kraus, R.N. 2004. *Demonstration of manufacturing technology for concrete and CLSM utilizing wood ash from Wisconsin*, Final Report submitted to the Wisconsin Department of Natural Resources, Madison, WI, USA.

Naik, T.R. 2005. *Sustainability of the cement and concrete industries*, presented and published at the Global Construction: Ultimate Concrete Opportunities, Dundee, Scotland.

ORNL 2006. *National CO2 emissions from fossil-fuel burning, cement manufacturing, and gas flaring, 1751-2003*, May 2006, Gregg Marland, Tom Boden, Robert J. Andres, Carbon Dioxide Information Center, Oak Ridge National Laboratory, Oak Ridge, TN, USA.

WU 2000. *Development of high-performance blended cement*, Zichao Wu, PhD thesis, T. R. Naik advisor, College of Engineering and Applied Science, 2000. University of Wisconsin-Milwaukee, WI, USA.