Greener Concrete Using Recycled Materials

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Some of the more than 4.5 billion tonnes (5 billion tons) of post-consumer wastes and industrial by-products generated annually in the U.S. are readily recyclable. Within the concrete industry, the most successful examples have been using coal fly ash to make high-quality, durable concrete and recycling old, demolished concrete as aggregate for new concrete. Since the 1990s, other by-products have been successfully used in concrete. These materials include: used foundry sand and cupola slag from metal-casting industries; post-consumer glass; wood ash from pulp mills, sawmills, and wood-product manufacturing industries; sludge from primary clarifiers at pulp and paper mills; and de-inking solids from paper-recycling companies.

USED FOUNDRY SAND AND CUPOLA SLAG

Foundries for the metal-casting industry generate by-products such as used foundry sand, slag, and bag-house dust during core-making and molding operations and produce cupola slag during melting operations. Foundry sand is uniformly sized, high-quality silica sand that is combined with a binder and used to form molds for ferrous (iron and steel) and nonferrous (copper, aluminum, and brass) castings. The automotive industry generates the majority of foundry by-products. U.S. foundries create about 15 million tonnes (17 million tons) of by-products annually.

Commonly, "green sands" are used for mold-making, and they contain sand, clay, additives, and water. Sand usually constitutes 50 to 95% of the total materials in a mold.[1] Clay, in amounts varying between 4 and 10% of the mixture, acts as a binder for the green sand. Organic binders include oil, synthetics, and cereal proteins, while inorganic binders include portland cement, fly ash, and sodium silicate.

Used foundry-sand properties vary due to the type of equipment used for foundry processing, the types of additives, the number of times the sand is reused, and the type and amount of binder.[1] Table 1 shows the typical physical properties of foundry sand.

Cupola slag has also been used as coarse aggregate in concrete. The density (1280 kg/m^3 [80 lb/ft^3]) of cupola slag is between that of normalweight aggregate (1600 kg/m^3 [100 lb/ft^3]) and structural lightweight aggregate (1120 kg/m^3 [70 lb/ft^3]).[2] The absorption for cupola slag was lower than that for the structural lightweight aggregate.

Applications of used foundry sand

Others have replaced up to about 8% by weight of regular sand with used foundry sand in concrete. Extensive investigations by Naik et al.[2] and Naik and Singh[3] revealed that foundry sand can replace regular sand in structural-grade concrete in amounts up to 35% by weight. Test results, however, showed a small loss in concrete strength due to the used foundry sand. Further investigations[4] established that the judicious use of Class C fly ash could compensate for strength loss in concrete containing foundry sand.

Concrete mixtures with a ratio of used foundry sand to regular sand between 20 and 40%, and up to 25% cementitious materials replacement with Class C fly ash, achieved compressive strengths of 42 MPa (6 ksi) at 28 days.[4] The compressive strength, flexural strength, modulus of elasticity, and abrasion resistance of the concrete mixture containing up to 40% replacement of regular sand with foundry sand were compared to the same properties of a control concrete (42 MPa). The 40% foundry sand mixture showed slightly higher strength than the control concrete. The effect of the foundry sand and fly ash on the flexural strength of the concrete mixtures was similar to that observed for the compressive strength, while the modulus of elasticity was not considerably affected. Both concrete mixtures exhibited high abrasion resistance.

In other research to evaluate the performance of foundry by-products in concrete and masonry products, two series of mixtures were made: air-cooled foundry slag was used in concrete as a replacement (50 and 100%) for the coarse aggregate, and foundry sand was used as a partial replacement (up to 35%) of the fine aggregate for masonry blocks and paving stones.[2] Test results indicated that the compressive strength of the concrete proportioned with air-cooled foundry slag as its coarse aggregate decreased slightly. Masonry blocks made with used foundry sand passed ASTM requirements for compressive strength, absorption, and bulk density.

Naik, Singh, and Ramme[5] reported on the use of used foundry sand in controlled low-strength materials (CLSM). Researchers proportioned CLSM mixtures for compressive strength levels of 0.3 to 0.7 MPa (40 to 100 psi) at 28 days. They used two sources of ASTM Class F fly ash and two sources of used foundry sand to replace 30 to 85% of the fly ash. Their results indicated that:

- Excavatable, flowable slurry can be produced with foundry sand as a replacement for up to 85% of the fly ash;
- Water permeability of CLSM mixtures was relatively unaffected by replacing up to 70% of the fly ash with foundry sand; and
- Foundry sand reduced the concentration of certain contaminants. Therefore, including used foundry sand in a CLSM slurry provides favorable environmental performance.

TABLE 1: TYPICAL PHYSICAL PROPERTIES OF FOUNDRY SAND

Property	Results	Test Method
Specific gravity	2.39	ASTM D 854
Bulk relative density, kg/m^3	2590	ASTM C 48/ AASHTO T 84
Absorption, %	0.45	ASTM C 128
Moisture content, %	0.1 to 10.1	ASTM D 2216
Clay lumps and friable particles	1 to 4.4	ASTM C 142/ AASHTO T 112
Coefficient of permeability, cm/s	10^{-3}	AASHTO T 215/ ASTM D 2434

POST-CONSUMER GLASS

The U.S. produces about 10 million tonnes (11 million tons) of post-consumer glass by-product each year, with about 3.4 million tonnes (3.7 million tons) used primarily as cullet.[6] The chemical compositions of three types of glass are presented in Table 2.[6] Most of the glass manufactured in the U.S. is the soda-lime glass. The bulk density of crushed waste glass is about 1120 kg/m^3 (115 lb/ft^3).

Post-consumer glass applications

Mixed, colored, broken glass can be used in flowable concrete.[7] This flowable concrete exhibits decreased permeability, which could prevent future leaching of heavy metals or other undesirable compounds. Due to the strong potential for alkali-silica reaction (ASR) between cement alkalis and reactive silica in glass, using glass as a coarse or fine aggregate also requires the use of Class F fly ash to control ASR.

Naik and Wu[8] studied the feasibility of using crushed, post-consumer glass as a partial replacement of sand in concrete. To minimize ASR, they replaced cement with Class F fly ash at 15, 30, and 45% by weight. For each combination of cement and fly ash, 15, 30, and 45% of the concrete sand was replaced with crushed glass. The compressive strength and splitting tensile strength were determined for each mixture. The occurrence of ASR was also evaluated.

Based on the test results, Naik and Wu concluded that:

- The compressive strength of concrete is slightly reduced when sand is partially replaced by crushed glass;
- Crushed glass is highly reactive with alkalis in the cement. Expansion of mortar bars without fly ash increased almost linearly with an increase in the amount of crushed glass;
- At cement replacement levels up to 30%, fly ash only delays the onset of expansion; long-term expansion is still high; and
- Deleterious expansion can be successfully suppressed by replacing 45% or more of the cement with Class F fly ash, regardless of the amount of crushed glass in the concrete.

Most glass does not contain materials that adversely impact the environment. Lead leachate from lead glass, however, could have a negative environmental impact on ground water quality. The use of glass containing lead in structural-grade concrete may be acceptable due to the encapsulation characteristics of concrete.

WOOD ASH

Wood ash is a waste product created during the combustion of wood products for energy production at pulp and paper mills, sawmills, and wood-product manufacturing facilities. Wood waste is burned with supplementary fuels such as coal, petroleum coke, oil, and gas. Wood ash is composed of both inorganic and organic compounds. The physical and chemical properties of wood ash, which determine its beneficial uses, are influenced by the species of the wood and the combustion methods, which include combustion temperature, efficiency of the boiler, and supplementary fuels used.

Properties of wood ash

Naik[9] determined the physical and chemical properties of wood ashes from over 15 different wood-burning boilers. Scanning electron micrographs indicate that wood ashes are a heterogeneous mixture of varying-sized particles that are often angular in shape. Unburned or partially burned particles that are present in wood fly ash have a cellular structure.

For the wood ashes studied, average moisture-content values were about 13% for fly ash and 22% for bottom ash, but varied from almost zero to 79%. Average values for bulk density (ASTM C 29) were 490 kg/m^3 (31 lb/ft^3) for fly ash and 827 kg/m^3 (52 lb/ft^3) for bottom ash. The average specific gravity (ASTM C 188) for wood fly ash was 2.48. Bottom ash had an average specific gravity of 1.65. The average absorption (ASTM C 128) values were 10.3% for coarse fly ash and 7.5% for bottom ash. The average strength activity index ASTM C 311/C 109 at the age of 28 days for fly ash was about 66%. The average water requirement (ASTM C 311) for wood fly ash was 116%. Autoclave expansion tests (ASTM C 618) for fly ash exhibited a low average expansion value of 0.2%. Overall, the wood fly ash had properties in between Class C coal fly ash and volcanic ash.[9]

Uses of wood ash

Approximately 70% of the wood ash generated in the U.S. is placed in landfills. An additional 20% is applied as a soil supplement. The remaining 10% has been used for miscellaneous applications.[10] Based on its physical, chemical, and morphological properties, Naik and Kraus[11] reported that wood ash has substantial potential for use as a pozzolanic mineral admixture and an activator in cement-based materials. They carried out extensive research on the use of wood ash in the making of concrete and CLSMs. Air-entrained concrete, with up to 35% replacement of cementitious materials with wood ash, achieved compressive strengths of 35 MPa (5 ksi), which is suitable for many structural applications.

Naik et al.[12] produced concrete mixtures incorporating wood fly ash. In these mixtures, wood ash was used to replace about 15, 25, and 35% of the cement. Some mixtures were produced with blends of wood ash and Class C fly ash. Two replacement levels of blended ash (of about 25 and 35%) were used. Fresh concrete properties, compressive strength, and splitting tensile strength were measured. Based on the test results, Naik et al. concluded that:

- Pozzolanic contributions of wood ash were significant;
- Blending wood ash with Class C fly ash significantly improved the performance of the concrete; and
- Structural-grade concrete made using wood ash and/or its blends achieved compressive strengths up to 50 MPa (7 ksi) at 28 days. A construction demonstration was carried out with the production of structural-grade concrete at Rothschild, Wis., in 2001 (Fig. 1 and 2).

PULP AND PAPER MILL RESIDUAL SOLIDS

More than 4 million tonnes (4.4 million tons) of pulp and paper mill residual solids from primary clarifiers are generated in the U.S. Pulp and paper mill sludge (or residual solids, when their water content is reduced) is composed of cellulose fibers (and occasional wood particles), clay, ash-bearing compounds, chemicals, and moisture. Currently, about half of the residuals solids are placed in landfills; one-quarter are incinerated; and the rest are utilized in some other way, such as mine reclamation, farmland soil improvement, or as a bulking agent for composting.[13]

TABLE 2: CHEMICAL COMPOSITION OF GLASS[6]

Constituent	Borosilicate	Soda-Lime	Lead
SiO_2	81%	73%	63%
R_2O_3	2%	1%	1%
Na_2O	4%	17%	7%
K_2O	—	—	7%
B_2O_3	13%	Trace	—
CaO	—	5%	—
MgO	—	3%	—
PbO	—	—	22%

Use of sludge

About 300 kg of sludge is produced for each tonne of paper (600 lb/ton of paper). Soroushian, Shah, and Won[14] used recycled fibers for the production of extruded thin-sheet cement products. Test results showed an improvement in flexural strength and toughness, but reduced stiffness.

Naik[15] studied the use of de-inking and primary-clarifier residual solids in concrete. These solids had a moisture content of about 50% and a specific gravity of about 2. The organic and ash contents were both about 50%. Before mixing, the residual solids were premixed with water and a high-range water-reducing admixture (HRWR) to deflocculate them. Mixtures of concrete were produced with residual-solid contents of 0 to 1.2% by weight of the concrete (0 to 45 lbs/yd^3 [0 to 27 kg/m^3]). At 28 days, the compressive strength, splitting tensile strength, and flexural strength of the concrete containing de-inking residual solids were between 45 and 75% of the corresponding strengths of a control concrete with 0% residual solids.

Fig. 1: Workers ready to place fresh structural-grade wood-ash concrete for a demonstration slab in Rothschild, Wis.

Fig. 2: Finishing the demonstration slab of structural-grade concrete incorporating wood ash, placed in 2001

Naik[13] has examined the use of primary clarifier residual solids from many different sources of pulp and paper mills for use in ready-mixed concrete. He reported that:

- Moisture contents ranged from about 84 to 220%. The average value was about 140%;
- Specific gravities ranged from 0.89 to 1.88. The average value was about 1.6;
- Densities of residual solids ranged between 119 and 343 kg/m^3 (200 and 570 lb/yd^3). The average was about 220 kg/m^3 (370 lb/yd^3); and
- Dominant oxides were CaO (0.6 to 31.5%), SiO_2 (9.3 to 21.8%), Al2O3 (3.4 to 19.1%), MgO (0.2 to 1.7%), and TiO_2 (0.0 to 4.6%). Loss on ignition at 1000 °C (1800 °F) varied between 55.4 and 83.8.

Naik[13] made several concrete mixtures containing residual solids. In calculating the water-cementitious materials ratio (*w/cm*), the water contained in the residual solids and the HRWR was included. The percentage of residual solids was expressed on an as-received basis. For mixtures with a cement content of 364 kg/m^3 (600 lb/yd^3), sand content of 849 kg/m^3 (1420 lb/yd^3), coarse aggregate content of 1026 kg/m^3 (1710 lb/yd^3), and residual solid content between 0.35 to 0.65%, the compressive strengths were determined (Fig. 3). It is possible to get equal strength with various residual solid contents, as shown in Fig. 3. Similar results were obtained for splitting tensile strength, flexural strength, and modulus of elasticity.

Adding residual solids to the concrete reduced chloride-ion penetration.[13] Concrete containing residual solids also showed higher resistance to salt scaling and freezing-and-thawing damage than the control concrete. Pulp and paper mill residuals, as well as de-inking solids from paper-recycling plants, should be properly dispersed in water, preferably hot water, before using such sludges in making structural-grade portland cement concrete.

MANY OPTIONS FOR BY-PRODUCT RECYCLING

This article has shown several innovative ways for recycling industry by-products in concrete. Used foundry sand can replace regular sand in portland cement concrete, cast-concrete products, CLSM, and other cement-based materials. Cupola slag, from steel and iron foundries, can also be successfully used in making semilightweight structural concrete.

Post-consumer glass can be used as a partial replacement of fine aggregate in regular and flowable concrete, as well as in CLSM, with Class F coal fly ash in amounts needed to control ASR expansion.

Wood ashes have significant pozzolanic properties and are typically more reactive than natural pozzolans, but less reactive than ASTM Class C coal fly ash. Structural-grade concrete and cast-concrete products have been manufactured using wood fly ash.

Concrete containing residual solids from pulp and paper mills and paper-recycling plants exhibit improved resistance to chloride-ion penetration and freezing and thawing without loss of strength. The addition of recycled materials can improve the quality of concrete while reducing the amount of waste deposited in landfills.

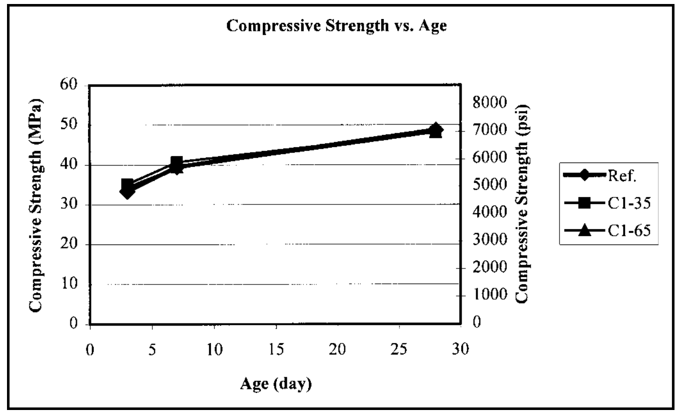

Fig. 3: Compressive strength of concrete mixtures containing two different amounts of residual solids from pulp and paper mills. The C1-35 mixture contained 0.35% residual solids, while C1-65 contained 0.65%

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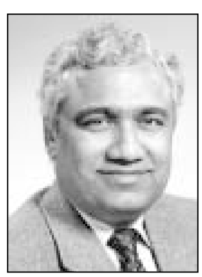

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