Concrete with glass aggregate is different from regular concrete in several respects. Mix designs for concrete products that are mass-produced in automated facilities need to be optimized for the particular production equipment used. For example, the zero water absorption of glass improves the mix rheology that influences the mix design, whether a dry or wet process is used. The key to success lies largely in the special admixtures that optimize the flow and consolidation properties without impairing the mechanical and durability properties of the hardened concrete, while being chemically compatible with the cement.

Aside from the ASR problem, glass offers a number of advantages, if used as aggregate in concrete. These can be summarized as follows:

- Primarily because of its basically zero water absorption, glass is one of the most durable materials known to man. With the current emphasis on durability of high-performance concrete, it is only natural to rely on extremely durable ingredients.
- The excellent hardness of glass gives the concrete an abrasion resistance that very few natural stone aggregates can match.
- For a number of reasons, glass aggregate improves the flow properties of fresh concrete so that very high strengths can be obtained even without the use of superplasticizers.
- The esthetic potential of color-sorted post-consumer glass, not to mention specialty glass, has barely been explored at all and offers novel opportunities for design professionals.
- Very finely ground glass has pozzolanic properties and therefore can serve both as partial cement replacement and filler.

PRODUCT DEVELOPMENT

When discussing the economics of glass as concrete aggregate, it is useful to draw a distinction between *commodity products* and *value-added products*. The main purpose of using crushed glass in commodity products is to divert as much glass as possible from the waste stream into beneficial use applications. However, the markets for commodity products, such as paving stones and concrete masonry units are typically very competitive, with low profit margins. Therefore, the economic benefit of substituting glass for fine aggregate or even cement is marginal at best, because it is essential that a dependable source of glass be available that is clean, crushed and graded to specification. Moreover, if the glass is ground sufficiently fine to minimize the potential of ASR damage, it is not possible to see whether products contain such glass or not.

The first commodity product to be developed for commercial production was a concrete masonry block unit, for which a rather modest 10% of fine aggregate was replaced by finely ground glass, or 10% of the cement by glass powder. In view of such small amounts of material substitution, no major effects on strength or other block properties were observed, as expected.

In value-added products, the purpose of the glass substitution is to exploit the special properties of the glass and thereby add value to a material that otherwise would be a waste product. If the glass is sorted by color and this is coordinated with the color of the cement matrix, novel esthetic effects can be achieved, which can be further enhanced with appropriate surface treatments. Surface textures can range from highly polished surfaces, for example, for tiles or tabletop counters, to exposed aggregate surfaces for building façade elements. The economic value of the glass derives to some extent from the material it replaces. For example, terrazzo tiles often contain costly natural aggregate such as imported marble chips. But it is possible to produce with glass visual effects that cannot be achieved with any other material. This would leave the end products basically without competition and, therefore, very attractive for producers and users alike. Glass concrete terrazzo tiles are already being manufactured commercially by Wausau Tile, Inc., of Wausau, WI. Photographs of sample tiles are not shown here, because black-and-white reproductions cannot do justice to their actual appearance.

It should also be mentioned that plain glass concrete is just as brittle as regular concrete. For this reason it may be advantageous to reinforce glass concrete products with either randomly distributed short fibers or, in the case of thin sheets or panels, with fibermesh or textile reinforcement.

One product, which is close to being mass-produced, is a paving stone with up to 100% glass aggregate. Its appeal lies in the novel colors and surface texture effects, such as special light reflections, that cannot be obtained with regular natural aggregate. Other advantages are the greatly reduced water absorption and excellent abrasion resistance due to the high hardness of glass. The paving stone can also be reinforced with fibers to improve its mechanical properties, especially its energy absorption capacity and fracture toughness. A fiber-reinforced paver is just as likely as any other paver to crack under impact, but the fibers will keep such cracks so small as to be basically invisible. Initial tests have shown that the freeze-thaw cycle resistance is excellent, with barely any damage after 600 cycles.

Architects appreciate the many novel surface textures and color effects offered by glass aggregate. This is particularly true for exposed aggregate technologies, which have been known in the architectural concrete community for some time. The added value derives from the fact that both regular concrete and waste glass are inexpensive, but if used in combination, these two component materials can fetch a price that is only marginally controlled by the costs of production. Since most alternative materials are more costly, glass concrete façade elements offer architects and other design professionals considerable flexibility.

The special effects that can be achieved with glass aggregate in the various architectural and decorative fields can be stunning, and the number of potential applications is limited only by one's imagination. To name just a few:

- Building façade elements
- Precast wall panels

- Partitions
- Floor tiles
- Wall tiles and panels
- Elevator paneling
- Table top counters
- Park benches
- Planters
- Trash receptacles

ECONOMICS OF GLASS RECYCLING

The economics of recycled materials is to some extent different from that of virgin materials. Principally, the laws of supply and demand apply to both. On the one side of the economic equation are real costs associated with supplying a commodity, and on the other side is the price that the demand for it generates on the open market. But there are other factors, which complicate an economic analysis of recycled glass.

The largest cost factor is associated with collection, which varies widely among different municipalities. In New York City there are unique reasons why the cost of separate curbside collection of recyclables is unusually high. After a previous recycling program had been discontinued because of escalating costs, the Bloomberg Administration is at present (early 2003) in the process of designing a new recycling program. In the interim period, the glass is simply added to the common solid waste stream, which places a burden on taxpayers, which is unjustifiable, especially during a period of substantial budgetary deficits. The City generates probably more solid waste than any other and at the same time has no nearby landfills to dispose of it. This unique situation is the primary reason for the unusually large negative value of waste glass at the source.

Compared with the cost of curbside collection, the various processing costs are moderate. The glass needs to be cleaned to remove organics, sugars, and other deleterious substances such as bottle caps and labels. Crushing and grading of the cullet to specification is relatively inexpensive and should not cost more than about $1 or $2 per ton. But the cost of transportation can become prohibitive when large distances are involved. The main challenge for a concrete producer is to contractually lock in a secure supply of glass for a guaranteed price.

The value of the glass to the producer or more precisely the amount he is willing to pay for it depends on the material to be replaced. Whereas regular sand and gravel are very inexpensive (typically of the order of $10 to 15 per ton), a producer may be willing to pay hundreds of dollars per ton for specialty aggregates, if the value added to the end product justifies it, i.e., can be passed on to the consumer. By identifying the special properties of crushed glass and exploiting these in the design of concrete products, it is possible to add value to the material, if the result is a product with properties that are superior to those produced with natural aggregates. This added value needs to be emphasized when marketing the product. Moreover, the special esthetic qualities of glass can produce effects that cannot be achieved with natural aggregate. This makes the glass basically without equal for selected applications, so that its value is determined almost entirely by how much the end user is willing to pay.

In addition, there is the possibility of government intervention. If the public at large fails to recognize the need to conserve resources, its elected representatives are expected to act in the public's best interest. In fact, many state and local authorities are already actively intervening in the market economy with incentives and disincentives or prescriptive legislation. Incentives may be offered in the form of tax breaks for developers, who utilize a certain percentage of recycled material content, and special legislation may require certain projects to adhere to principles of "green building" design, for example, certification under the U.S. Green Building Council's LEED program [5]. In exceptional cases, an environmentally concerned developer may decide to pay a premium for environmentally friendly materials, but concrete producers cannot count on this. It is preferable to rely on the superior properties inherent in the glass and the added value of a better product and then let the forces of supply and demand determine the economics.

The creation of a new secondary market for glass cullet can increase the demand for the glass and according to the law of supply and demand lead to an increase in price. From an environmental policy viewpoint such a development would be desirable, and municipalities would end up paying less for the disposal of the glass. The effect on concrete producers would be that only the higher-end products are likely to utilize glass aggregate because of its increased value.

CONCLUSION

Concrete is the world's most important building material, and it is now possible to engineer its properties to satisfy almost any reasonable performance specifications, whether these pertain to mechanical, thermal, chemical, or durability requirements, or relate to unique esthetic demands. By using waste glass as aggregate in concrete, several benefits can be obtained simultaneously. Because of its inherent chemical and physical characteristics, glass can improve the mechanical and other properties of concrete products. Moreover, its esthetic qualities can be exploited to produce decorative effects that are not possible to create with natural aggregates. The glass needs to be cleaned, crushed and graded to specification. Color-sorting adds additional value.

Some glass products such as terrazzo tiles and paving stones are already being mass-produced commercially. The economic success depends on how effectively these products can be marketed. The changing public attitudes towards environmental issues as well as governmental intervention through incentives and disincentives as well as outright prescriptive legislation are indications that such products have a high probability of success. Moreover, the development of concrete with glass aggregate can serve as an example for the industry to reduce its impact on the environment and embrace the principles of sustainable development.

Academic research can lead to new technologies. However, for such technologies to become commercially successful, proper technology transfer is needed as well as adequate funding, that makes the research effort possible in the first place. This requires cooperation between industry and academia. The success story of glass concrete is an illustration that investments in research do not have to be large for the results to be lucrative.

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Properties of Flowable Slurry Containing Wood Ash

by T. R. Naik, R. N. Kraus, Y. Chun, and R. Siddique

Synopsis: Three series of flowable slurry mixtures were made, each series with three different sources of wood ash (W-1, W-2, and W-3). The series of mixtures were: low-strength (0.3 to 0.7 MPa), medium-strength (0.7 to 3.5 MPa), and high-strength (3.5 to 8 MPa) mixtures. Tests were performed for flow, air content, unit weight, bleeding, settlement, compressive strength, and water permeability. Wood ashes W-1 and W-3 caused expansive reactions in CLSM mixtures resulting in little or slight (average 1%) net shrinkage of CLSM. Wood ash W-2 caused either significant net swelling (15% for Mixture 2-L, and 21% for Mixture 2-M) or no shrinkage (Mixture 2-H) of CLSM. The 91-day compressive strength of low-strength, medium-strength, and high-strength slurry mixtures was in the ranges of 0.38 to 0.97 MPa, 1.59 to 5.28 MPa, and 4.00 to 8.62 MPa, respectively. Overall, the slurry mixtures showed an average increase in strength of 150% (range: 25% to 450%) between the ages of 28 days and 91 days. This was attributed to pozzolanic and cementitious reactions of wood ash. In general, water permeability of CLSM mixtures decreased with age.

Keywords: bleed water; cement; compressive strength; controlled low-strength materials (CLSM); flowable slurry; permeability; wood ash

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INTRODUCTION

U.S. pulp and paper mills generate about one million dry tonne of wood ash per year. National Council for Air and Stream Improvement (NCASI) has estimated that of the total wood ash, only about one-third is being utilized (1). The disposal of this large-scale generation of wood ash is a major problem for the industry, mainly pulp mills, saw mills, and energy generating plants that utilize wood and wood residue. The problem concerning the disposal of wood ash in landfills is accentuated by potentially limited landfill space available, strict environmental regulations, and high costs. Co-firing wood residue with coal or other fuels lead to regulatory differentiation between ash from wood residue alone and ash from wood mixed with coal and/or other fuels. Therefore, beneficial utilization options for wood ash is essential for the industry. One of the possible uses of wood ash is in the production of controlled low-strength materials (CLSM), also widely known as flowable slurry. CLSM is a high-fluidity cementitious material that flows like a liquid, self-levels without compacting, and supports as a solid when hardened. The American Concrete Institute (2) describes CLSM as a cementitious material that is in a flowable state at the time of placement and has a specified compressive strength of 8.3 MPa (1200 psi) or less. A number of names including flowable fill, unshrinkable fill, manufactured soil, controlled-density fill, and flowable mortar are being used to describe this material. CLSM is used primarily for non-structural and light-structural applications such as backfills, sound insulating and isolation fills, pavement bases, conduit bedding, erosion control, and void filling (2).

Higher-strength CLSM can be used in applications where future excavation is unlikely, such as structural fill under buildings (2). In deciding mixture proportions of CLSM, factors such as flowability, strength, and excavatability are evaluated. Permeability is, for many uses, an important property of CLSM. Permeability of CLSM depends on mixture proportions, properties of constituent materials, water-cementitious material ratio (*w*/*cm*), and age.

RESEARCH SIGNIFICANCE

The principal objective of this investigation was to evaluate the strength and permeability of flowable slurry incorporating wood ash. In this investigation, three series of slurry mixtures—low-strength (0.3 to 0.7 MPa), medium-strength (0.7 to 3.5 MPa), and high-strength (3.5 to 8 MPa)—were proportioned, each series from three different sources of wood ash (W-1, W-2, and W-3). The results of this investigation will establish mixture proportions and production technology for flowable slurry containing wood ash.

LITERATURE REVIEW

Numerous studies by Naik and his associates (3-9), Ramme et al. (10), Krell (11), Swaffer and Price (12), Larson (13,14), and Fuston et al. (15) have examined and reported on flowable slurry properties such as density, strength, settlement, permeability, shrinkage, and other properties. Lai (16) reported that the compressive strength of flowable mortars containing high-volume coal ash is applicable for backfill or base course construction. It was mentioned that the 28-day compressive strength of about 1 MPa could be achieved with 6% (by mass) cement at excellent flowability. In the 1980s, Naik et al. (9) developed excavatable CLSM mixtures having compressive strength between 0.3 and 0.7 MPa (50 and 100 psi) at 28 days. Naik and Singh (5) have reported on strength and water permeability of slurry materials (0.3 to 0.7 MPa) containing used foundry sand and fly ash as 3×10^{-6} to 74×10^{-6} cm/s. Tikalsky et al. also (17) evaluated the potential of used foundry sand as a constituent of controlled low-strength material (CLSM), and concluded that used foundry sand provides a high-quality material for CLSM. Tikalsky et al. (18) evaluated CLSM containing clay-bonded and chemically-bonded used foundry sand, and showed that used foundry sand can be successfully used in CLSM. Horiguchi et al. (19) evaluated the potential use of high-carbon (12% loss on ignition [LOI]) fly ash plus non-standard bottom ash in CLSM. A total of 20 mixtures were tested for flowability, bleeding, and short-term and long-term compressive strengths. Test results indicated that there is an optimum fly ash to bottom ash ratio for the desirable physical properties of CLSM. CLSM with high-carbon fly ash and non-standard bottom ash showed excellent performance indicating ecological and economical applicability to CLSM. Horiguchi et al. (20) also investigated physical and durability characteristics of CLSM made with used foundry sand and bottom ash as fine aggregates. Based on the test results, they concluded that the one-dimensional frost-heaving rate of CLSM made with used foundry sand and bottom ash ranged from 0.4% to 1.8%. Naik et al. (21) developed two types of CLSM utilizing post-consumer glass aggregate and fly ash. One group of CLSM consisted of cement, fly ash, glass, and water; and, another group of CLSM consisted of cement, sand, glass, and water. They concluded that the flowable slurries containing glass satisfied ACI Committee 229 recommendations (2). Gassman et al. (22) examined the effects of prolonged mixing and re-tempering on the fluid- and hardened-state properties of CLSM. The test results showed that extending the mixing time beyond 30 minutes decreased unconfined compressive strength and delayed the time of setting. Re-tempering did not affect the 28-day strength; however, it did affect the 90-day strength depending upon the mixing time. There are insufficient data available for the permeability of slurry materials. Furthermore, there is a general lack of any information available for use of wood ash in flowable slurry.

EXPERIMENTAL PROGRAM

Materials

Type I portland cement conforming to ASTM C 150 requirements was used in this investigation. The fine aggregate used was natural sand having dry-rodded unit weight of 1770 kg/m^3, specific gravity of 2.67, absorption of 1.3%, and fineness modulus of 2.7. Three different sources of wood ash were used, and these sources are designated as W1, W2, and W3. W1 was obtained from Niagara, Wisconsin; W2 from Biron, Wisconsin; and W3 from Rothschild, Wisconsin. Physical properties and chemical composition of the three sources of wood ash are presented in Tables 1 and 2, respectively. The wood ash used in this project did not meet all the requirements of ASTM C 618 for coal ash (Class C and F) or natural pozzolan (Class N).

Each source of wood ash exhibited different physical properties (Table 1). Fineness of the wood ash (% retained on 45 µm sieve) varied from 23% to 90%. Source W-1 met the ASTM requirement for fineness (34% maximum), while sources W-2 and W-3 exceeded the ASTM limit. Small charcoal pieces were also visible in Source W-2. Source W-3 was very coarse with a particle size distribution similar to coarse sand. The strength activity index of the wood ash is a comparison of the compressive strength development of 50 mm mortar cubes that have 20% (by mass) replacement of cement with wood ash, with compressive strength of standard cement mortar. Wood ashes W-1 and W-3 met the strength activity index requirement of ASTM (75% minimum at either 7 or 28 days), while wood ash W-2 did not meet the requirement. Water requirement of all wood ashes also exceeded the maximum water requirement for coal ash specified by ASTM C 618 (105%); however, Sources W-1 and W-3 satisfied the requirement for natural pozzolan (Class N). The higher water requirement indicated that for concrete and CLSM containing wood ash, more water would be required to produce the same slump or flow as compared with the control mixture. Unit weight values of the wood ashes W-1 and W-2 were 550 and 410 kg/m^3, respectively. These unit weights are significantly less than the unit weight of a typical ASTM Class C or Class F fly ash (approximately 1100 to 1300 kg/m^3). Source W-3 had a unit weight of 1380 kg/m^3. Specific gravity of wood ash Sources W-1, W-2, and W-3 range from 2.26 to 2.60. Specific gravity of wood ash Source W-1 was lower than that of a typical coal fly ash (approximately 2.40 to 2.60). The low unit weight and specific gravity of some wood ashes indicate that adding these wood ashes into CLSM would lower the unit weight of CLSM. This may be useful for obtaining lighter-weight CLSM.

The results of the chemical analysis of the wood ashes are given in Table 2. All wood ashes did not meet all the chemical requirements of ASTM C 618, particularly for the amount of carbon as shown by LOI test results. The LOI obtained for the wood ashes range from 6.7% to 58.1%. These high LOI ashes probably will present some difficulties when developing air-entrained concrete mixtures. The higher carbon content tends to reduce the amount of air entrained in the concrete mixture and thus requires higher dosages of air-entraining admixtures. However, the higher carbon contents of the wood ashes should not affect the performance of these ashes in CLSM. Wood ash W-2 showed a very low value of $SiO_2 + Al_2O_3 + Fe_2O_3$ (23.4%) most likely due to its high LOI. Wood ashes W-2 and W-3 showed high lime contents (13.7% and 19.6%, respectively).

Mixture Proportions

Three series of slurry mixtures were proportioned for the three different sources of wood ash. Each of the three series was developed to obtain a different long-term compressive strength level using the three sources of wood ash. The three target long-term strength levels developed for the project were 0.3 to 0.7 MPa (low-strength), 0.7 to 3.5 MPa (medium-strength), and 3.5 to 8 MPa (high-strength). The low-strength CLSM mixtures (1-L, 2-L, and 3-L) consisted of cement, wood ash, and water. The medium-strength CLSM mixtures (1-M, 2-M, and 3-M) consisted of an increased amount of cement, wood ash, and water. The high-strength CLSM mixtures (1-H, 2-H, and 3-H) consisted of cement, wood ash, sand, and water. These CLSM mixtures were proportioned to maintain a practical value of flow in the range of approximately 250 ± 50 mm. Mixture proportions for low-strength, medium-strength, and high-strength slurry mixtures are presented in Table 3. Cement content of the slurry mixtures was: 53 to 89 kg/m^3 for the low-strength mixtures; 101 to 228 kg/m^3 for the medium-strength mixtures; and, 169 to 205 kg/m^3 for the high-strength mixtures. Within each series, the mixture containing wood ash W-2 was proportioned to have the highest amount of cement and lowest amount of wood ash because of the low strength activity index, high water requirement, and high LOI of wood ash W-2 (Tables 1 and 2).

Manufacturing Technique

The flowable slurry was mixed in a 0.25-m^3 rotating drum mixer. The slurry ingredients were weighed and loaded in the mixer in the following manner. Initially, the required amount of cement and half the amount of wood ash and sand (for high-strength mixtures) was loaded in the mixer and mixed for three minutes. About three quarters of the specified water was then added to the mixer and mixed for an additional three minutes. The remaining wood ash, sand (when used), and water were added to the mixer and mixed for an additional five minutes. Additional water was added in smaller quantities to ensure reaching the required flow consistency of CLSM.

Preparation and Testing of Specimens

The flow/spread, air content, temperature, and unit weight were determined for each mixture before casting test specimens. Fresh slurry was tested for flow/spread in