PRECAST CONCRETE WALL PANELS WITH GLASS CONCRETE

Final Report

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ABSTRACT

A research project was conducted to develop a concrete material that contains recycled waste glass and reprocessed carpet fibers and would be suitable for precast concrete wall panels. Post-consumer glass and used carpets constitute major solid waste components. Therefore their beneficial use will reduce the pressure on scarce landfills and the associated costs to taxpayers. By identifying and utilizing the special properties of these recycled materials, it is also possible to produce concrete elements with improved esthetic and thermal insulation properties. Using recycled waste glass as substitute for natural aggregate in commodity products such as precast basement wall panels brings only modest economic benefits at best, because sand, gravel, and crushed stone are fairly inexpensive. However, if the esthetic properties of the glass are properly exploited, such as in building façade elements with architectural finishes, the resulting concrete panels can compete very effectively with other building materials such as natural stone. As for recycled carpet fibers, the intent of this project was to exploit their thermal properties in order to increase the thermal insulation of concrete wall panels. In this regard, only partial success was achieved, because commercially reprocessed carpet fibers improve the thermal properties of concrete only marginally, as compared with other methods, such as the use of foaming agents. Still, the work reported herein arrived at a design mix of sufficient strength, durability, and thermal resistance that should be of interest to producers of concrete wall panels.

Keywords: architectural concrete; concrete durability; precast concrete; recycled materials; reprocessed carpets; thermal properties; wall panels; waste glass.

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Steven Winter Associates of Norwalk, CT, served as a subcontractor responsible for the thermal aspects of the project, in particular, the thermal analyses. Adrian Tuluca, Principal of that firm, served as main liaison and offered valuable advice on the various thermal response issues. Asher Derman of Green October, New York, NY, and Kean College of New Jersey, Union, NJ, participated in the early phases of the project, also under a subcontract. It was his suggestion originally to use recycled carpet fibers to improve the thermal resistance of concrete wall panels.

Kistner Concrete Products of East Pembroke, NY, a manufacturer of a proprietary precast concrete system for residential basement wall construction, offered valuable assistance to the project. The project focused to a large extent on improving the thermal behavior of Kistner's wall panels. Robert Fox, Principal of Fox and Fowle, Architects, New York City, served as a consultant on architectural concrete panels for buildings and offered valuable advice.

Andy Howell, Robert F. West, and Mark C. Ryan of the DuPont Carpet Reclamation Center, Chattanooga, TN, supplied various kinds of recycled carpet fibers and were very helpful with advice on matters pertaining to recycling of carpets.

Mr. Robert Lange of the New York City Department of Sanitation also provided advice and assistance.

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SUMMARY

The purpose of this research project was to develop a concrete material that contains recycled waste glass and reprocessed carpet fibers and would be suitable for precast concrete wall panels. By identifying and utilizing the special properties of these recycled materials, it was hoped it would be possible to produce concrete elements with improved esthetic and thermal insulation properties and still be economically advantageous.

The economic feasibility of substituting recycled waste glass for natural aggregate depends on the type of concrete product. Commodity products, such as the precast concrete panel for residential basement walls manufactured by Kistner Concrete Products, East Pembroke, NY, were found to bring only modest economic benefits at best, because regular sand, gravel and crushed stone are fairly inexpensive. However, if the esthetic properties of the glass are properly exploited, such as in building façade elements with architectural finishes, value is added to this resource, and the resulting concrete panels can compete very effectively with other building materials such as natural stone. The glass has a number of advantages due to its mechanical, chemical, and esthetic properties, which can create unique visual effects. Because the special aggregates for competing architectural concrete systems are often much more costly than regular coarse aggregate, processed waste glass promises to offer decisive economic advantages.

As for recycled carpet fibers, the intent of this project was to exploit their thermal properties in order to increase the thermal insulation of concrete wall panels. In this regard, only partial success was achieved, because commercially reprocessed carpet fibers improve the thermal properties of concrete only marginally, as compared with other methods, such as the use of foaming agents. Still, the work reported herein arrived at a design mix of sufficient strength, durability, and thermal resistance that should be of interest to producers of concrete wall panels.

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Section 1 INTRODUCTION

GENERAL

This report is on a research project conducted by the New York State Reseach and Development Authority (NYSERDA) and Columbia University to develop a concrete material containing recycled waste glass and carpet fibers for use in precast concrete wall panels.

Since 1994, research has been conducted at Columbia University to find ways of using crushed waste glass as an aggregate for concrete. Prior to the present project, two major projects were funded by NYSERDA, and a third one by the Office of Recycling Market Development, Empire State Development, State of New York. A primary objective of these prior projects was to study and solve the alkali-silica reaction (ASR) problem and to establish a scientific basis for the commercial manufacture of concrete products containing glass aggregate. The present project represents a continuation of these prior efforts.

In 1999, a private start-up company, Echo Environmental, Inc., was incorporated in the State of New York to commercialize the results of the research on concrete with glass aggregate. The company signed licensing agreements with Columbia University for the worldwide rights to the technology and registered the term "glass concrete" as a trademark. It is currently in the process of establishing sublicensing agreements with various manufacturers of concrete products. Any licensing fees and royalty income received by Columbia University from Echo Environmental for glass concrete products will be shared with NYSERDA.

PROJECT OBJECTIVES

The overall objective of the present project was to evaluate the feasibility of using recycled waste glass and carpet fibers in concrete wall panels. Two specific applications were to be investigated. The first was to use recycled carpet fibers to improve the thermal performance of concrete wall panels for residential construction, specifically precast basement wall panels produced by Kistner Concrete Products, East Pembroke, NY. The second application was the development of a concrete mix design comprising both recycled glass and carpet fibers for precast concrete façade elements with architectural finishes.

The specific objectives of this project were:

- To evaluate the feasibility of using recycled waste glass and carpet fibers in the two aforementioned applications;
- To optimize the mechanical, thermal, and durability characteristics of concrete mixes containing recycled glass and carpet fibers;
- To identify the most promising concrete mixes for both types of applications;
- To make prototype panels with the most promising concrete mixes for testing purposes;
- To perform an economic analysis to evaluate the cost advantages of the test panels compared to competing building technologies, including an evaluation of recycled material sources.

APPROACH AND METHODOLOGY

The approach chosen to meet the project objectives was to secure recycled carpet fibers and to develop concrete mixes with improved thermal properties, yet adequate mechanical strength and workability. Prototype panels were to be produced with the most promising mixes and tested for their mechanical, thermal, and durability properties. For the façade elements, the architectural consultant supplied a sample of natural granite with the suggestion to develop an architectural surface finish with similar appearance. This objective was accomplished by developing a technology to produce a wide spectrum of exposed aggregate finishes. Sample panels were produced in the laboratory to be evaluated by the architectural consultant. Before commercial production of façade elements can be started that satisfy all mechanical, thermal, and other requirements as prescribed by the building code as well as the architect, a dedicated research project is needed to finalize an optimized mix design and to develop the proper production technology geared towards the facilities of a specific precast concrete manufacturer. Such a research program was considered beyond the scope of the present project.

Several subcontractors were involved in this work:

- Kistner Concrete Products of East Pembroke, NY, served as a consultant on the residential wall panels and was to produce prototype panels with the final mix designs.
- Steven Winter Associates of Norwalk, CT, served as a consultant on improving the thermal performance of the Kistner wall panels, under a subcontract.
- Dr. Asher Derman of Kean University served as a consultant regarding the various aspects of recycled carpet fibers, under a subcontract.
- Fox and Fowle Architects, P.C. of New York, NY, served as consultant for the architectural aspects of the concrete façade elements.
- Another prospective consultant was to manufacture prototype façade elements with architectural concrete finishes. However, soon after commencement of this project, the company decided to discontinue its production of architectural concrete products.

LIMITATIONS OF CHOSEN APPROACH

The approach and methodology described above was based on the hypothesis that a large percentage of recycled carpet fibers are hollow-fill nylon fibers. It was theorized that the

addition of such fibers, with their small enclosed air pockets, to concrete would slow the flow of heat, thereby increasing the concrete's thermal insulation value (R-value). During the course of this project it was determined that this assumption was unjustified, and the task objective of increasing the R-value of concrete mixes with recycled carpet fiber proved to be more difficult than originally hoped for.

First, only a very small percentage of the recycled fibers turned out to be hollow. Details of physical fiber properties shall be provided later in this report.

A second limitation of the originally proposed approach was inherent in the specific carpet reprocessing technologies. Throughout the duration of this research, we were supplied with fibers from the DuPont Carpet Reclamation Center, Chattanooga, TN. This facility probably reprocesses more used carpets than any other in the United States. It turned out that towards the scheduled completion of this research project, DuPont implemented a major change in its reprocessing procedure. The result was that when the first batch of material supply was exhausted, DuPont was unable to resupply the same kind of fiber. This change in material caused a major delay of the project's completion, because time-consuming mix optimization and numerous tests had to be performed with the fibers produced by the new process.

The final limitation of the proposed approach is common to any technology that utilizes a material with properties subject to considerable variations and uncertainties. The waste stream handled by the reclamation center contained many different kinds of materials from various original manufacturers, and therefore the end product was not as well-controlled as virgin material would have been.

The following sections summarize the findings of this research project in full recognition of the above limitations, which were not as clearly recognized when this work was originally conceived and proposed.

Section 2 DISCUSSION OF TECHNICAL ISSUES

USE OF RECYCLED MATERIALS IN THE BUILDING ENVELOPE

Concern for sustainable development has emerged as one of the major societal issues of the late 20th century. This pertains among others to environmental issues and the conservation of natural resources. The beginnings of this awareness are difficult to pinpoint, but it is clear that it did not originate in the United States, where a public accustomed to an abundance of natural resources was relatively late to realize the limits of these resources and the real costs associated with their wasteful exploitation. But at present, environmental consciousness is being encountered in all walks of life. In the construction industry, increasing attention is being paid to the concept of "green buildings" [1]. New York State has recently passed legislation that provides tax incentives for environmentally friendly construction, such as the incorporation of energy saving features and the use of recycled materials [2]. In New York City, guidelines for green building construction have been issued for Battery Park City [3]. The New York City Department of Sanitation has recently issued a report on an inter-agency task force action plan to encourage the use of recycled-content building materials [4]. It is expected that the construction industry will increasingly be dealing with new technologies that allow owners and developers to reduce the energy consumption of their properties as well as the demand for natural resources for building materials.

The Portland cement industry is a major user of energy and contributor to air pollution. It has been estimated that the production of one ton of cement requires about four million BTUs of heat energy and causes the release of one ton of CO_2 into the atmosphere. The cement industry is responsible for about 7% of total world CO_2 production [5]. Thus, even partial replacement of Portland cement by some other cementitious material has environmental advantages, especially if the substitute material is the byproduct of some industrial or combustion process. For example, fly ash, the residue of coal combustion, is an increasingly popular cement substitute. Its use in concrete is environmentally as well

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as economically far superior to landfilling. The key to the use of recycled materials in the construction industry is to identify components in the solid waste stream that are suitable for partial cement replacement or that offer benefits in addition to the avoidance of landfilling. The use of fly ash concrete in the building envelope may be subject to esthetic constraints. For example, one concrete block manufacturer on Long Island discontinued the trial use of fly ash for concrete masonry blocks because he could not maintain a consistent block color.

Because of generally higher energy costs in Europe, energy consciousness and energyefficient technologies originated there much earlier than in the United States. A classical example is the installation of thermal insulation in residential as well as commercial construction. This practice was widespread in Western Europe long before the energy crisis of the 1970s, which led to increased emphasis on reducing the need for heating and air-conditioning here also. Thermal insulation typically consists of lightweight materials such as synthetic foams or mineral wool. Some of these, such as polyurethane foam, contain hydrochlorofluorocarbons (HCFCs), which have been identified as greenhouse gases that contribute to global warming [6]. Expanded polystyrene does not contain ozone-depleting chemicals and therefore is to be preferred from an environmental standpoint.

The search for "green" or environmentally friendly materials in the building industry involves the development of new materials, but might also lead to the reconsideration of traditional ones. Straw, for instance, is one of the oldest building materials on earth and its comeback may be a matter of time [7].

Another example is the utilization of crushed waste glass as an aggregate in concrete. This option has been researched at Columbia University since 1994, much of this effort having been funded through grants from NYSERDA. A large amount of valuable knowledge was gathered in the process and is well-documented [8-13].

RECYCLING OF CARPET FIBERS

In general carpets have a structure as shown in Figure 2-1. The backings consist most likely of two sheets of polypropylene. The face yarn is most commonly made of either nylon or polypropylene, both of which have become increasingly popular in recent years due to their low production costs. The two backing layers are held together by a lime material, often a latex with $CaCO_3$ as filler.

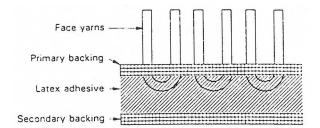


Figure 2-1 Typical Carpet Structure

Developed in 1939 by scientists at DuPont, nylon has a much longer tradition than polypropylene, which was introduced to the carpet industry some years later. The major differences between nylon and polypropylene of concern to this particular research project are summarized in Table 2-1. A more detailed introduction to both polymeric fibers and their use in the carpet industry can be obtained from the literature [14,15].

Property	Nylon	Polypropylene
Unit weight [g/cm3]	1.13 - 1.15	0.9 - 0.91
Reaction with water	Absorbs water	Hydrophobic
Tensile strength [ksi]	11 - 13	4.5 - 6.0
Elongation at break [%]	15 - 300	100 - 600
Melting point [°C]	265	175
Thermal conductivity [W/m/K]	0.24	0.12

Table 2-1 Properties of Nylon and Polypropylene

The magnitude of the problem of recycling old carpets has been described in detail by Malin [16]:

The American carpet industry continues to grow. According to the trade publication Carpet & Rug Industry, 1.6 billion square yards (1.3 billion m²) of carpet were shipped in 1996, enough to cover all five New York boroughs more than one and a half times. To produce that carpet, over 2 billion pounds (900 million kg) of nylon fiber were used, 800 million pounds (360 million kg) of polypropylene, and 230 million pounds (105 million kg) of polyester. Roughly 70% of the new carpet purchased replace existing carpet - for commercial settings the figure is closer to 80%. Estimates of the amount of carpet discarded every year range from 3.5 to 4 billion pounds (1.6 to 1.8 billion kg), accounting for 1% of all solid waste by weight, or 2% by volume.

The Malin study introduces the main players in both the carpet and the fiber industry. It describes partial recycling approaches, such as reuse of carpets after deep cleaning, retexturing and reprinting ("precycling"), and production of plastic products like traffic stops or industrial flooring using PVC backing, which can be separated from the carpet face ("downcycling"). As mentioned above, such efforts are only partial, as the recycling products are always of lower quality than virgin products. There is an alternative, though. Polymeric fibers can be decomposed chemically or by high temperature treatment and then be used to fabricate again high quality virgin material. This would be true closed loop recycling of fibers, an ultimate goal of the fiber industry [16]. The main obstacle towards this goal is quality control. Recyclers are receiving material from many different sources, yet to achieve true closed loop recycling, it is necessary to know exactly the properties of the feedstock material.

All major fiber and carpet producers are posting their recycling strategies and programs on the Internet, e.g. BASF's "6ix Again(R) Program" [17]. The carpet recycling processes consist basically of the following steps.

- Sort and organize the carpets by fiber type and construction. Polypropylenebacked material appears to be most suitable for the present concrete applications.
- Mechanically separate fibers from backing and other materials with a series of shredding, tearing, cutting down size, fiber opening, air separation, screening, sifting, and cleaning devices.

- Pass or reject the material, based on testing for quality standards.
- Bale, label, and store the material for shipping.

As mentioned in the Introduction, the DuPont Carpet Reclamation Center, Chattanooga, TN, decided towards the scheduled end of the present research project to switch its reprocessing procedure. In the old "wet" process, the material was first processed in dry form and then further purified in a wet slurry. The new "dry" process accomplished purity objectives in the dry phase, thereby eliminating the wet slurry part of the process, with resulting efficiencies and associated cost reductions. In addition, the new process can be adjusted, within limits, to satisfy various material performance specifications, such as the degree of fiber purity, length, moisture, and CaCO₃ and total inorganic contents. Section 3 will describe the type of fiber that was determined to be most suitable for our application, among the types that can be obtained using the new dry process. According to DuPont that type of fiber can only be provided in quantity as long as a profitable demand is identified.

CARPET FIBER REINFORCED CONCRETE

Fiber reinforcement of concrete consists of either randomly distributed short fibers or a woven mesh of continuous fibers. Applications involving fiber mesh (or textile) reinforcement are to a large extent still under development. Short random fiber applications, on the other hand, have already a long and successful track record in the concrete industry [18]. The fibers are typically added to minimize shrinkage cracking or to increase the concrete's ductility and fracture toughness, especially in structural components subjected to impact or dynamic loads. The fiber effects on compressive, flexural, and tensile strengths are modest at best. However, the improvement of ductility and fracture toughness can be dramatic [19].

Carpet fiber-reinforced concrete has been studied by several researchers [20-23], who used relatively small fiber amounts of up to 4% by volume and were interested mainly in the mechanical properties mentioned above. It is generally agreed that carpet fibers can

be utilized to improve the toughness of concrete systems. On the other hand, their effect on the thermal conductivity of concrete has not yet been investigated, and no studies of mixes with more than 4% of carpet fibers are reported in the literature.

Although the basic materials of recycled carpet fibers are similar to those of other synthetic fibers that are widely used in the concrete industry, their actual properties may vary considerably, depending on the specific recycling process and the resulting amount of impurities. Dust and dirt accumulating especially around the face yarn and the amount of calcium carbonate derived from the backing material introduce some degree of uncertainty with regard to the mechanical properties of the end product as well as the workability of the mix. In our experience it is nearly impossible to obtain material with the same properties twice. This greatly complicates the research effort and affects the reliability of commercial products that incorporate such material. Among the different types of recycled fiber material originally received, there was one, referred to as "Mixed Grit", of which more than 15% by volume could be added to our special concrete mix without greatly decreasing workability. It was theorized that the kind and amount of impurities present in this particular type of material had a positive effect on the flow properties of the mix.

Section 3 MAJOR FINDINGS

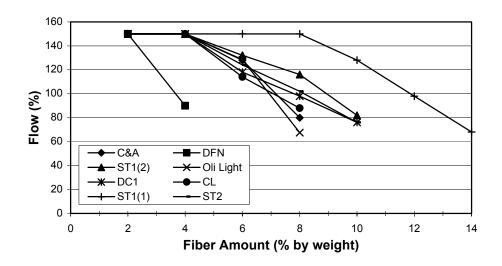
WORKABILITY

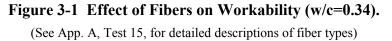
Workability is of extreme significance in concrete production. It determines whether certain performance specifications can be achieved economically. Workability is determined typically by the slump test and if no coarse aggregate is involved a flow table test. In the slump test, a conical metal form is filled with fresh concrete and then lifted vertically. The resulting loss in height of the concrete cone is called "slump", measured in inches. In the flow test, a given volume of fresh material is placed on a flat surface and allowed to spread. The increase of the average diameter of the resulting form, relative to the original diameter, is a measure of the mix "flowability" and directly proportional to workability. For example, a doubling of the original diameter would result in a "100% Flow". A regular glass concrete mix with a water/cement ratio of 0.34 exhibits excellent flowability of about 150% if it contains a superplasticizer together with the ASR-suppressing admixture. Based on reference measurements of the concrete mix design used by Kistner Concrete Products, a value of 90% was considered acceptable in our case.

If randomly distributed short fibers are added to a mix, the workability decreases instantly. An experiment was carried out to determine the maximum amount of fibers that can be added before the workability becomes unacceptable (see Appendix A, Test 16, for details). Keeping the water/cement ratio constant at 0.34, carpet fibers were added in increments of 2% (relative to the weight of cementitious materials) and the flow was measured for each increment. This procedure was repeated until the flow dropped below 90%, as shown in Figure 3-1. It should be noted that 2% of "fiber" is in reality 2% of a mix of various amounts of nylon and polypropylene fibers, dust, and dirt. It is difficult to separate some of the non-polymeric components that are attached to the surface of the fibers. For this reason, it is preferable to specify "fiber" contents in terms of weight rather

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than volume ratios. Also, it is difficult to determine what percentage (by weight or volume) of a given "fiber" sample is actual fiber, and how much of it is calcium carbonate, dust, and dirt. Moreover, it is unknown what influence these non-fiber components have on the mix workability.





A large number of different fiber types and contents were tested, ranging from 0 to 14% (Figure 3-1). These are described in some detail in Appendix A, Test 15. The DFN fiber, which DuPont is able to provide in quantity with their new recycling process, reduced workability more than the other fiber types. However, based on workability, strength, and thermal performance, DFN fibers still proved to offer the best overall performance. The results shown in Figure 3-1 were obtained for mixes with a water-cement ratio of 0.34. If the content of recycled carpet fibers needs to be increased, the w/c ratio has to be increased as well to maintain acceptable workability, and this will reduce strength.

MECHANICAL PROPERTIES

Compressive strength is typically the most important mechanical property of concrete, because it correlates strongly with other properties such as tensile strength and many

durability properties. For precast residential basement wall panels, strength is not nearly as important as for other structural applications. Based on the loads to which such panels are subjected during their service life, nominal strengths suffice. Concrete producers prefer to specify higher strengths for other reasons, such as better resistance to accidental loads during handling, transportation, and installation, as well as improved durability properties.

Fibers may be added to the concrete mixes for basement wall panels for a number of reasons, but an increase in strength is not one of them. Strength is significant only insofar as the addition of fibers should not reduce it below the value specified by the producer. The polymeric fibers used in the carpet industry, although very efficient in increasing the ductility and fracture toughness of an otherwise rather brittle material, are known to reduce the compressive strength of concrete. This can be explained with a basic mechanics principle known as "strain compatibility" of composite materials. If two components of such a composite are forced to undergo the same strains, because they are bonded together, the stress level in each component will be proportional to its Young's modulus or stiffness. Since this modulus is much lower for polypropylene fibers than for the concrete matrix they replace, the stress in the fibers will be lower than that in the surrounding concrete, so that the concrete will be likely to fail sooner than the fibers. More significantly, the addition of large amounts of fiber reduces the flowability or workability of the mix, making it much more difficult to consolidate it and to achieve a high-quality, low-porosity end result. For this reason, it was the purpose of the tests described in Appendix A, Test 16, to compare the rates at which different fibers reduce strength, as their dosages are increased.

During the early phases of this project, when "Mixed Grit" and "Recycled Nylon" fiber were available from DuPont, surprisingly large quantities of fibers could be used (Figure 3-2). In particular, samples with Mixed Grit gave excellent strength results, even for dosages above 10% by weight. A near-constant compressive strength value of just above 5,000 psi can be observed for mixes with fiber weight ratios between 12% and 20%. The fibers obtained with DuPont's modified recycling process gave test results not anywhere near those obtained earlier. Figure 3-3 summarizes the strength results for three different fiber types: the original Mixed Grit (compare Figure 3-2); the new DFN fibers; and a shearing waste product consisting of shredded virgin nylon fiber obtained from Collins and Aikman (another carpet producer and recycler). The strength of samples with

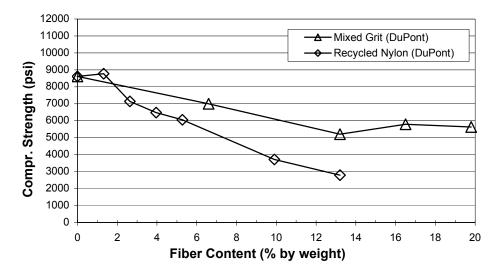


Figure 3-2 7-Day Compressive Strength vs. Amount of Mixed Grit and Recycled Nylon

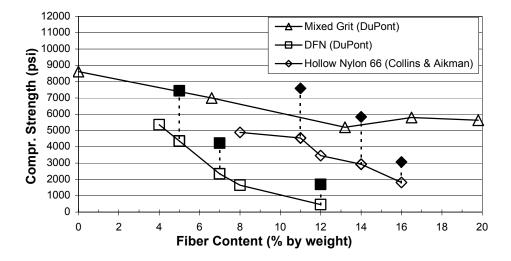


Figure 3-3 Compressive Strength vs. Amount of Recycled Carpet Fibers (white symbols: 7-day strengths; black symbols: 28-day strengths)

DFN fibers decreased at a much greater rate with increasing fiber content than that of the other two. The Collins and Aikman fiber performance was comparable to that of Recycled Nylon (see Figure 3-2), primarily because it was free of dust, dirt, and calcium carbonate. The DFN fiber performance was the worst of the three, presumably because of the large amounts of CaCO₃ and dirt that was counted as "fiber" and disproportionately lowered workability. The large drop in strength for large fiber contents was the result of higher water/cement ratios that were necessary to achieve reasonable workability. Therefore, it is not advisable to add more than 5% of the DFN fiber. When 28-day strengths are considered (black symbols in Figure 3-3) rather than 7-day strengths (white symbols), the strengths achieved were likely still adequate for the specific application.

THERMAL PROPERTIES

An important task of the building envelope is to slow heat flow to reduce heating costs in winter and cooling costs in summer. The property most commonly associated with heat flow is called "thermal conductivity". It measures the rate of heat flow per hour through a unit area of material of unit thickness caused by a 1°F temperature difference, e.g. BTU-in/hr-°F-ft² or W/m-°K. A material with high thermal conductivity is a poor insulator. In the building industry, it is more common to refer to the inverse of conductivity, called "thermal resistance" or "R-value". Thus, a high R-value is indicative of good thermal insulation. For example, the R-value of a fiberglass blanket is 2.9 - 3.8 per inch of thickness.

Tests to measure thermal properties are difficult to perform, if standard ASTM procedures are followed. For this reason, a relatively simple test was developed for this investigation (Figure 3-4). The test procedure utilizes a standard oven with a removable 3 by 4 inch door and automatic temperature control. By replacing the door with a test sample and measuring the temperature on both faces of the sample, the temperature differential between the outside and inside specimen surfaces is obtained. This

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differential can serve as a measure of the material's thermal performance. By plotting the temperature time histories (Figure 3-5) and integrating the area between the curves for the inside and outside temperature, we obtain a value referred to as "thermal resistivity". Although the determination of thermal resistivity is not a standard test procedure, this value permits a rapid determination of thermal performance in relative terms. The thermal performance of a material depends to a large extent on the pore structure, and

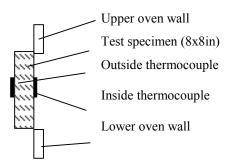


Figure 3-4 Schematic Diagram of Non-Standard Thermal Test

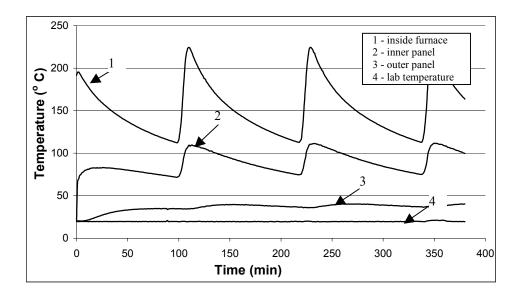


Figure 3-5 Typical Temperature Time Histories of Non-Standard Test

therefore indirectly on weight density. Since weight density is proportional to strength, thermal resistivity and strength correlate inversely. Thus, the best thermal insulators are of very light weight. Lightweight concrete mixes can be designed to have adequate strength. However, ultra-lightweight concretes have generally such low strengths that they are used only for insulation purposes. Such low weight densities can be achieved by using special hollow-sphere aggregates or foaming agents. A considerable body of literature exists on the effect of pore structure on thermal performance (e.g., Reference [24]).

It was the original premise of this project to utilize hollow nylon fibers recovered from recycled carpets to increase the R-value of concrete. Unfortunately, most of the fibers studied during the course of this work turned out to have non-hollow cross sections. The most common cross sections encountered among DuPont's recycled carpet fibers were Y-shaped (Figure 3-6). Virgin nylon fibers received from Collins and Aikman, on the other hand, appeared to have hollow cross sections (Figure 3-7).

The round and hollow virgin fibers from Collins and Aikman were very clean compared with the Y-shaped DFN fibers. It was hypothesized that the dirt and dust particles attached to the DFN fibers create air pockets, thereby increasing indirectly the concrete's thermal resistivity. The Collins and Aikman fibers, because of their smooth surfaces, produced a relatively dense concrete. Although larger quantities could be utilized for comparable workability, their relatively poor thermal performance did not justify their addition in such quantities.

As mentioned above, foaming agents are a common tool to increase the thermal resistivity of concrete. Thermal resistivities and strengths are plotted in Figure 3-8, using a mix with neither foaming agent nor fibers as reference. As shown, the approximately 20% improvement made possible with 1% foaming agent can also be achieved with 5% carpet fiber. If 5% carpet fiber is used together with 1% foaming agent, the improvement

of thermal performance is approximately 60%. For residential construction, such an increase is substantial, but a significant decrease in strength is to be expected in this case.

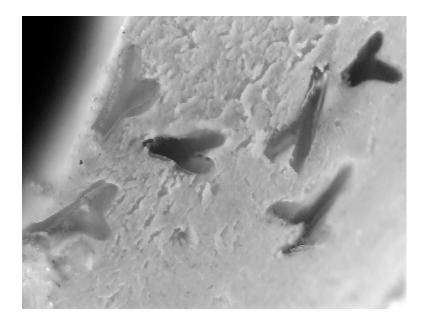


Figure 3-6 DuPont Recycled Carpet Fibers with Typical Y-Shaped Cross Section

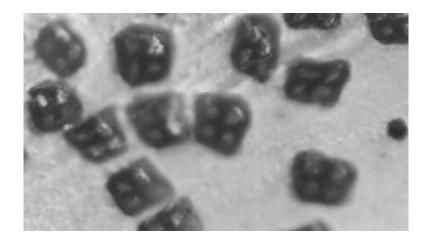


Figure 3-7 Collins and Aikman Carpet Fibers with Typical Hollow Cross Section

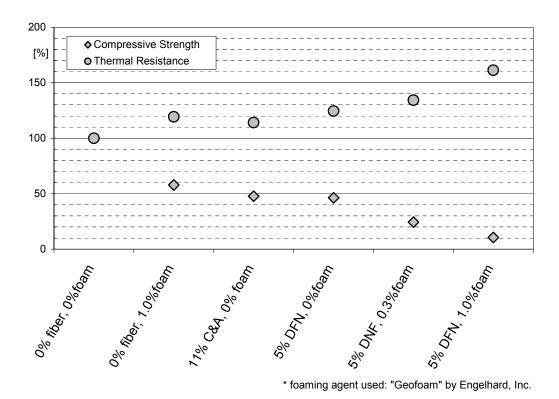


Figure 3-8 Relative Thermal Resistivity and Strength of Glass Concrete Systems

PROPOSED GLASS CONCRETE MIX WITH RECYCLED CARPET FIBERS

Kistner Concrete Products, East Pembroke, NY, manufactures precast concrete panels for residential basement wall systems. One aspect of their system of concern is the thermal performance. At present, the wall panels incorporate a combination of metal hardware and insulating material. One of the objectives of the present study was to investigate the possibility of designing a concrete mix such that the panel's current R-value is maintained or even improved without the added insulation material, thereby reducing cost. It was hypothesized that the inclusion of recycled carpet fibers could improve the thermal resistivity, without compromising strength and workability. In addition, it was proposed to partially replace the aggregate by crushed waste glass. Thus, the primary objective was twofold. First, post-consumer glass and used carpets would be diverted from the solid waste stream and put to beneficial use. Second, the incorporation of these recycled materials would improve the properties of the end product, thereby creating added value.

As described in previous sections, these objectives could not be met to the extent originally hoped for. However, the mix design that resulted from this research project does offer a viable solution with tangible benefits. A glass concrete mix utilizing 5% by weight of recycled carpet fibers is given in Table 3-1, together with the mix design currently used by Kistner Concrete Products. The main proportions of the mix design have not been changed. However, the substitution of crushed waste glass for sand and the addition of 5% carpet fiber necessitate a slightly higher water content and therefore call for different chemical admixtures.

Once a preferred glass concrete mix design was established, a large number of ASTM tests were carried out with the proposed as well as the original Kistner concrete system to determine their respective mechanical, thermal and durability properties. Thus it is possible to directly compare the properties of the final mix design with those of other materials.

	Kistner Concrete		Glass Concrete with DFN Recycled Carpet Fibers	
	Material	Parts	Material	Parts
Coarse Aggregate	3/8" Kistner Stone	223	3/8" Kistner Stone	223
Fine Aggregate	Kistner Sand	172	Crushed Glass	172
Cement	Type III	100	80% Type III, 20% ASR Powder	80 20
Water	Water (fixed)	60	Water (max)	66
Admixtures	MB VR, Pozzolith 400N Pozzolith 322N	0.16 0.75 0.24	MB VR ADVA	0.16 1.25
Fiber	¹ / ₄ in Polypropylen	0.5	Dupont's DFN Fiber	5

Table 3-1 Mix Designs of Kistner Concrete and Glass Concrete with Carpet Fibers.

In order to determine the thermal properties, two concrete slabs of 12 by 12 by 2 inch were cast for both the Kistner and the glass concrete mixes. They were ground to a precise, constant 2-inch thickness and then shipped to the Holometrics Micromet Laboratories, Bedford, MA, where they were tested according to ASTM C177. The results together with the strength test results are presented in Table 3-2. Because of different test specimen geometry (cube versus cylinder) and slightly different water-cement ratios, not all strength test results given in Table 3-2 are directly comparable. But it is clear that the two mix designs have similar strengths. Concerning the thermal properties, the results are directly comparable and show that the thermal conductivity of the glass concrete mix is approximately 31% lower than that of the original Kistner mix. This means that the thermal resistivity, the inverse of conductivity, of our new mix design is about 45% higher.

	Kistner Concrete		Glass Concrete	
	Batch #1 (w/c=0.60)	Batch #2 (w/c=0.60)	Batch #1 (w/c=0.66)	Batch #2 (w/c=0.58)
Compressive Strength (Cubes)	5225 psi	5240 psi	7423 psi	
Compressive Strength (Cylinders)	3270 psi			5465 psi
Modulus of Rupture		721 psi	628 psi	
Tensile Splitting Strength	965 psi			758 psi
Thermal Conductivity (Btu-in / hr-F-ft ²)		7.73	5.34	
Thermal Conductivity (W / m-K)		1.11	0.77	

Table 3-2 Mechanical and Thermal Test Results.

In addition to the strength and thermal conductivity, durability properties were determined for both concrete systems using a freeze-thaw cycle tester according to

ASTM C666, which accelerates the service life exposure to natural temperature changes. In this test, described in more detail in Appendix A, Test 18, specimens are subjected to at least 300 freeze-thaw cycles, with up to 12 cycles applied in one day. Specimens are considered to have passed if, after 300 cycles, they did not experience any substantial weight loss and if the dynamic Young's modulus did not drop below 60% of the initial value. Specimens made with the Kistner and the glass concrete mixes both survived 700 freeze-thaw cycles. In addition, specimens were tested for compressive strength after exposure to 700 freeze-thaw cycles and barely showed a reduction in strength. This result indicates that both concrete systems have excellent durability properties and are more than adequate for the intended application.

THERMAL ANALYSIS OF PRECAST CONCRETE PANELS

One of the objectives of this project was to explore different ways of improving the thermal performance of precast concrete wall panels. Steven Winter Associates, Norwalk, CT, evaluated the thermal performance of different configurations of the specific concrete panel. The firm performed both two- and three-dimensional thermal analyses of the system to characterize the thermal bridging that occurs in the current configuration and to identify methods to reduce heat losses.

A typical horizontal cross section of the panel is shown in Figure 3-9 and clearly identifies the problem. Heat flow has two potential paths, one through the thermal insulation and air space, and one through the stud channel and concrete web. Since the latter one has typically a much lower conductivity, it can be referred to as a "thermal bridge". In the two-dimensional analyses, three parameters were considered – the thickness of the mineral fiber insulation, the concrete conductivity, and the stud channel conductivity. The influence of the first two parameters is illustrated in Figure 3-10. The increased benefit of an 8-inch insulation compared with that of a 2-inch layer is obvious.

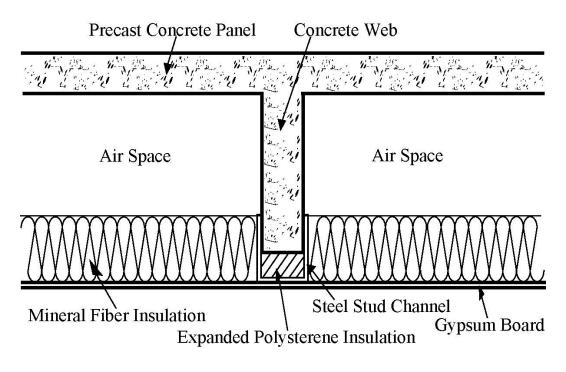


Figure 3-9 Horizontal Cross Section of Precast Concrete Panel

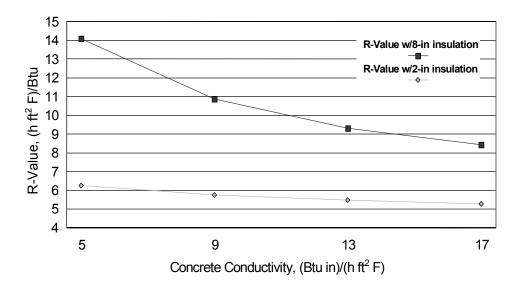


Figure 3-10 Panel R-Value vs. Concrete Conductivity

Also, because of the different gradients of the two curves, the conductivity of the concrete has a greater impact on the overall R-value, when 8 inches of insulation are

used. This holds particularly true for the range of concrete conductivity values determined in this study, namely from 5 to 8 Btu-in/h-ft²-F. Likewise, the conductivity of the stud channel was found to have the most pronounced effect for panels with thicker layers of insulation.

These preliminary studies were followed with extensive three-dimensional thermal analyses, in which the basic panel configuration was varied. Figure 3-11 shows some of the cases that were studied, together with the primary results. A detailed description of these analyses can be found in Appendix B. In the first four configurations, the thickness and position of the insulation was varied. In configuration S-ALT-4, the externally applied insulation was terminated at the grade level, whereas in configuration S-ALT-5, it extended over the entire height of the panel. In the last configuration, the effectiveness of a spray-on plastic coating containing recycled carpet fibers was evaluated. The main conclusions drawn from these studies are briefly summarized as follows.

- The steel stud that covers the edge of the concrete web is responsible for significant thermal bridging. The thermal performance of the system is improved significantly if it is replaced with a plastic or wood stud.
- If an extruded polystyrene insulation strip is added between the steel stud and the gypsum board, the thermal performance of the system is substantially improved. This seems to be an appropriate approach if the steel stud is not replaced by a plastic or wood stud.
- R-5 rigid or semirigid insulation placed continuously on the winter-cold surface of the gypsum board performs better than R-11 insulation placed between the concrete webs.
- Placing the batt insulation against the gypsum board is better than placing it against the concrete wall, if the gypsum board is installed in an airtight manner and if all receptacles have airtight enclosures.
- Exterior insulation significantly reduces the risk of moisture condensation if it fully covers the foundation. Exterior insulation is significantly less effective if it stops at

THERMAL PERFORMANCE OF THERMAL KRETE WITH DIFFERENT INSULATION OPTIONS AND STEEL STUD AT CONCRETE WEB

		TOTAL HEAT FLOW (Btu/h)	EFFECTIVE R-VALUE INCLUDING SOI
BATT INSULATION	S-BASE CASE	68.41	R8.88
BATT INSULATION	S-ALT-1	78.07	R7.78
BATT INSULATION	S-ALT-2 R19	48.79	R12.45
BATT INSULATION	S-ALT-3 R19	56.90	R10.67
RIGID INSULATION	S-ALT-4 R10	96.24	R6.31
RIGID INSULATION	S-ALT-5 R10	40.86	R14.86
SPRAY-ON PLASTIC ATING MADE FROM ECYCLED CARPETS	S-ALT-6	70.00	R8.67

Figure 3-11 Thermal Performance of Panel with Different Configurations (Steel Stud)

grade level (Schemes S-ALT-4 and S-ALT-5), since its thermal performance will be lowered by 50% due to thermal bridging.

- Thermal conductivity of concrete has a relatively small effect on the thermal performance of the concrete foundation system.
- Spray-on or glued insulation on the winter-warm surface of the concrete panel can significantly reduce the risk of moisture condensation, while providing overall Rvalues similar to those of the fibrous insulation (R-5 spray-on or glued compared with R-11 fibrous). The technique may allow the use of recycled carpet fiber as insulation.

ARCHITECTURAL PANELS WITH EXPOSED AGGREGATE

The building envelope has to fulfill a number of separate tasks [25]. First and foremost, it serves as space enclosure to protect the building interior from the elements. A separate but related task is that it should safely carry all applied external loads (e.g., dead load and wind) and transfer these to the building frame. To optimize building maintenance and operating costs, expenditures for heating in winter and cooling in summer need to be minimized, which calls for the envelope to provide effective thermal insulation. In urban areas it is also necessary to protect the building interior from outside noise. Finally, the envelope should lend itself to esthetic treatment, so that the architect can use it as an expressive tool. In the past, all of these requirements could be satisfied simultaneously by using massive walls. In modern engineered structures, a premium is placed on minimizing the amount of materials used and their cost. In that context, most present solutions rely on sandwich construction, in which different layers of the construction are assigned different tasks.

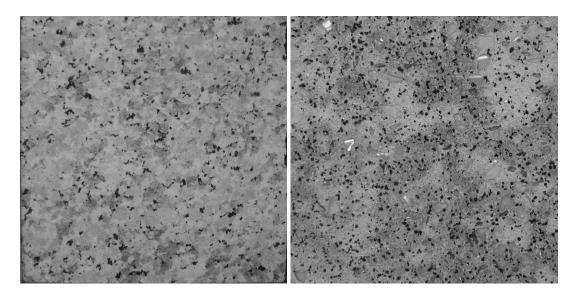
The objective of this part of the current project was to develop a technology to produce architectural finishes of concrete panels with glass aggregate. Such panels can be used as the outer shell of sandwich façade elements in lieu of natural stone sheets. It is also practical to produce single panels with two layers, the larger one consisting of regular concrete, while the "face layer" contains the architectural glass concrete with special surface texture and color treatment. This work builds partially on previous research at Columbia University on concrete with waste glass as aggregate. Since the architectural panels may be very thin (natural stone slabs may be as thin as 1 cm or less), they need to be reinforced. The most appropriate type of reinforcement appears to be one or several layers of continuous fiber mesh, also known as "textile reinforcement" [26,27]. The actual development of such textile-reinforced thin concrete sheets was beyond the scope of this work.

The architectural firm Fox and Fowle of New York City provided a sample of a natural granite with cut but unpolished surface and suggested that we emulate its texture and appearance using glass concrete. The selected approach was to use an exposed aggregate technology, which has been widespread in the architectural concrete industry for several decades. To expose the aggregate, the mould for the concrete product is treated with a so-called "retarder", a chemical agent that slows down or prevents the cement in its immediate vicinity from hardening. After a certain time (typically one day), the product is demolded, and the unhydrated cement slurry is washed off with clean water, thereby exposing the larger aggregate particles. The retarder may be applied in liquid form or as a paper treated with the chemical, and is commercially available in different strengths. By increasing the strength, the amount of concrete material to be washed out is increased, thereby further coarsening the surface texture.

As a first step, a glass concrete mix was developed to emulate the granite sample. Figure 3-12 shows both the natural stone and a glass concrete samples. In order to simulate the black inclusions in the granite (presumably gabbro), so-called "Black Beauty Sand" was added to the glass concrete mix.

It was the wider objective of this task to demonstrate the range of possible surface textures that can be achieved just by varying the retarder strength and the grading of the glass aggregate. All in all, a palette of samples was produced with retarders of three different strengths and 12 different grading curves. The resulting outcomes represent a "catalog" that can be presented to an architect to chose from. A representative set of textures is illustrated in Figure 3-13. The complete set of surface textures can be viewed on the web page:

www.civil.columbia.edu/meyer/retarder/retarder.html.



a) Natural granite

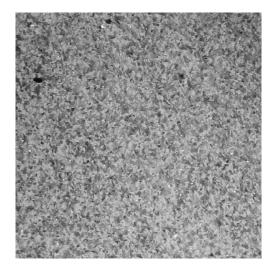
b) Glass concrete

Figure 3-12 Glass Concrete Simulation of Natural Granite

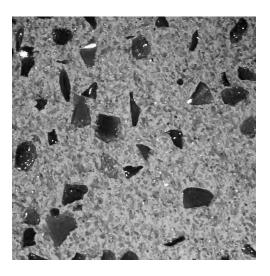
However, it should be noted that color plays a very important role, and even the digitized photographic images displayed on the web page cannot fully characterize the actual appearance of the various samples.

After having presented the office of Fox and Fowle with the catalogue, the architect selected three combinations of retarder strength and aggregate grading. Panels of dimensions 24 by 24 inch were then produced with the appropriate mixes. The panels were 1 inch thick and reinforced with two layers of polypropylene fiber mesh. Since April 2000, these three panels have been exposed to the elements on the roof of 22 West 19th Street in Manhattan, the building in which the offices of Fox and Fowle are located.

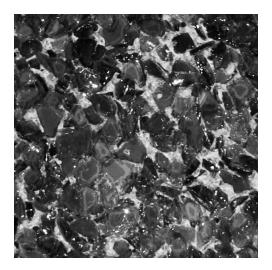
By recent accounts, the panels are weathering nicely. They have been shown to several clients who might be interested in choosing exposed glass concrete façade elements for their buildings.



a) Rough mortar appearance



b) Mosaic or terrazzo look



c) Glass dominated surface

Figure 3-13 Typical Exposed Glass Aggregate Surface Categories

Section 4

COMMERCIALIZATION OF GLASS CONCRETE WALL PANELS

The successful commercialization of building products that contain recycled glass aggregate and recycled carpet fibers depends on several conditions and the completion of a number of separate tasks:

- Assurance that the end product satisfies all performance specifications, such as strength, thermal conductivity, durability, and architectural appearance;
- Development of the technical know-how to mass-produce the products;
- Availability of production facilities capable of mass-producing the product;
- Demonstration that the products are commercially viable and marketable;
- Assurance of a secure supply of raw materials, i.e., recycled glass and carpet fiber.

Some of these tasks were beyond the scope of this project. However, sufficient knowledge has been generated to support the optimistic outlook that commercially viable glass concrete wall panels can be produced. A few comments shall highlight the current status with regard to each one of the above tasks.

As discussed in Section 3 and documented in detail in the Appendices, it has been shown that all performance specifications for the end product such as the Kistner wall panel can be satisfied. Actual mass production will still require the finalization of a mix design, that is dictated by specifications defined jointly by the producer and the end user. Within the context of this project it can be claimed that Task 1 has been completed successfully.

Development of the technical know-how for mass production transcends the scope of this project and logically would be part of a demonstration phase. But since Kistner Concrete Products has the facilities and know-how to produce glass concrete panels, i.e., the next listed task, availability of production facilities, the demonstration phase could be entered at any time, provided an agreement could be reached with the company to conduct

industrial trial runs, which would raise the question of funding of such trial runs. Only following such trial production runs would it be possible to demonstrate the commercial feasibility of the panels.

Finally, assurance of a secure supply of raw materials is a difficult task and subject to numerous uncertainties. The laws of supply and demand for recycled materials are not only subject to the same influence factors as virgin materials but also to additional social and economic factors that are inherent in the recycling processes and therefore very hard to predict. Based on the experience with the market forces affecting recycled glass, there is good reason to believe that the task of securing a supply of recycled carpet fibers will be just as difficult.

The value of post-consumer glass varies greatly from geographic region to region. In major metropolitan areas, it is generally negative, i.e., municipalities are paying recyclers to collect and dispose of the glass. In New York City, this negative cost had been \$45 per ton for a number of years, but has increased substantially after the closing of the Freshkill Landfill. In order for the glass to be suitable as aggregate for concrete basement wall panels, it needs to be washed, crushed, graded, and transported. The cost of this processing should not exceed the difference between the initial negative value and the price fetched by a competing material such as natural sand, which is only on the order of \$10 per ton. For architectural panels, the situation is different because the competing materials are considerably more expensive, while the cost of the glass remains virtually the same, except possibly for the additional effort of color separation. The economies of glass recycling would become even more uncertain following commencement of mass production of wall panels. The quantities of glass involved would be potentially so large (hundreds of tons per week) that they would have an impact on sources of supply and exert upward pressures on cost. How such a situation would play out would depend on other factors, such as local competition between recyclers. However, a principal conclusion drawn from our research project in this regard is that mass production of glass concrete wall panels has the potential of increasing the market value of post-consumer glass and of easing the pressure on taxpayers to subsidize the disposal of a major

4-2

component of solid waste. Echo Environmental, Inc., which has licensed the glass concrete technology from Columbia University, has made major efforts to secure supplies of recycled glass in New York and New Jersey, and therefore should be in a position to enter into contractual agreements with potential users such as Kistner Concrete Products.

In conclusion, it will be very difficult to replace natural aggregate by waste glass in commodity products like the Kistner basement wall panel such that the producer maintains a comparable profit margin. In the case of architectural panels, the situation is different, because of the value added by the glass by virtue of its esthetic and mechanical properties. The potential profit margin is considerably wider for such applications, making it much more attractive for producers.

The question of improving thermal performance with recycled carpet materials is completely different. The original hypothesis of using recycled carpet fibers to increase R-values appears to be difficult to sustain. As the thermal analyses have shown, relatively simple changes of the panel configuration can be much more effective in achieving this goal. The value of using recycled carpet fiber for this application is moderate at best. This does not mean that in other applications the fiber properties cannot be more effectively exploited. According to DuPont, the cost of virgin fibers ranges from \$0.30 to \$0.35/lb. If they need to be colored, the cost may be on the order of \$1.60/lb. The cost of recycled carpet fiber depends strongly on the specifications. DFN fibers with up to 85% purity (the balance being polypropylene, calcium carbonate, etc.) may cost as much as \$0.90/lb. But fibers of the low purity and greater length that were tested in this study may be available for as little as \$0.20/lb. Thus, there is a clear economic advantage for a concrete producer who wishes to substitute recycled carpet fiber for virgin material, as long as the improvement of the material's thermal properties is not the objective.

4-3

Section 5 CONCLUSIONS

This research project had several objectives. The first goal, based on the results of previous studies, was to explore the feasibility of using crushed waste glass as an aggregate in precast concrete wall panels. A second objective was to study whether recycled carpet fibers are suitable to enhance the thermal performance of such precast concrete wall panels.

Regarding the first objective, two different types of wall panels were considered: a precast concrete panel for residential basement walls, such as used in the proprietary system manufactured by Kistner Concrete Products, East Pembroke, New York, and architectural panels with exposed aggregate, such as used for building façade elements. As for the basement wall panels, it was determined that the substitution of crushed waste glass for natural sand and stone is feasible, but does not appear to offer much of an economical advantage. It was shown that it is possible to produce concrete mixes with recycled glass that are equal or superior in terms of mechanical and durability properties compared with mixes that use only natural aggregate. However, the natural materials are very inexpensive, and for recycled glass to be competitive, the processing costs of collecting, washing, crushing, and transporting should not exceed the cost of the natural material plus any subsidy that local municipalities are willing to provide for disposal of the glass. Otherwise, a concrete producer would have no incentive to make that substitution, unless some other economic stimulus were offered. New York State's recent legislation to encourage the use of recycled materials in construction with tax incentives may be the basis for such an incentive.

Regarding architectural façade elements, the economics are quite different, because in this case the glass can produce architectural effects, which are difficult if not impossible to duplicate with natural materials. In this case, the prices producers are willing to pay for the glass are likely to be considerably higher than the processing costs, although in the end, market forces of supply and demand would determine the final price.

As for recycled carpet fiber, the improvement of the thermal performance of concrete wall panels using such material is modest at best. There are much more effective alternatives available to increase the R-value of such panels. The use of such fibers may still be feasible for other reasons. First, the addition of small amounts of synthetic fibers to precast concrete products has almost become routine in the industry, primarily for crack control. Therefore there would be little problem with substituting recycled fibers for virgin fibers, provided the prices were comparable. The added value derived from beneficial use of a solid waste material alone is not likely to be sufficient as an incentive for concrete producers to make the substitution, unless again tax advantages are offered for the use of recycled building material content.

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Appendix A

Test Documentation

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