PROPERTIES OF GLASS CONCRETE CONTAINING RECYCLED CARPET FIBERS

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Abstract

Carpets are a major component of today's waste streams, totaling an estimated 3.5 - 4 billion pounds in the US in 1996, which corresponds to 1% of all solid waste by weight or 2% by volume. More recent statistics are not likely to be less. In response to federal regulations which require the producers of carpets and carpet fibers to take back old carpets, a number of recycling strategies are now being explored. At Columbia University, a major study to evaluate the feasibility of using post-consumer glass as aggregate in concrete has been expanded to investigate the suitability of large quantities (up to 20% by weight) of recycled carpet fibers in concrete products. The expected benefits were to be threefold: first, the fiber reinforcement was expected to improve the mechanical properties of the concrete. This expectation was fulfilled to some extent, although the effect was less than when virgin fibers were used. Second, it was hoped that large quantities of recycled reportedly hollow carpet fibers would enhance the thermal properties of the concrete by increasing the R-value. Unfortunately, only modest improvements were observed. Finally , the recycling of used carpet fibers is a contribution to sustainable development, as value is added to a material that otherwise would constitute an environmental burden.

1. Introduction

In the light of continuously growing disposal costs today's waste streams are being studied with increasing care for their recycling potential. A straight forward approach to dispose of large quantities of waste is its use as replacement of raw materials in large-volume applications, such as mass concrete or asphalt. A well-known success story is the use of fly ash, a byproduct of coal combustion, as a replacement of Portland cement. Shredded car tires are utilized in the production of asphalt. More recently, waste glass

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was identified as a valuable resource as aggregate in concrete. Likewise, the utilization of waste carpets, which form a substantial part of today's waste streams come to mind. Concrete with waste carpet fibers has been studied in the past, but only as far as the mechanical and durability properties were concerned and involving relatively small percentages of fibers. No efforts have been reported looking at effects carpet fibers could have on other concrete properties. The present study focused not only on mechanical properties, but also tried to identify the recycling potential of carpet fibers in the production of concrete and their effect on the thermal properties of concrete panels, i.e. if carpet fibers could be used to lower heat flux through concrete panels and thereby to increase their thermal insulation properties [1].

2. Carpets

In general carpets have a structure as shown in Figure 1. The backing layers consist typically of two sheets of polypropylene mesh. The face yarn is most commonly made of either nylon or polypropylene, both of which have become increasingly popular in recent decades due to their low production costs. The two backing layers are often held together by latex with $CaCO_3$ as filler. Developed in 1939 by scientists at DuPont, nylon has a much longer tradition than polypropylene. The major differences between nylon and polypropylene of concern to the present research project are summarized in Table 1.

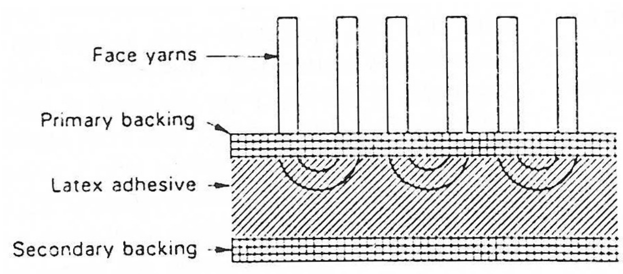

Figure 1: Typical Carpet Structure

Table 1: Properties of Nylon and Polypropylene [3,4]

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 [^{o}C]	265	175
Thermal conductivity [W/m/K]	0.24	0.12

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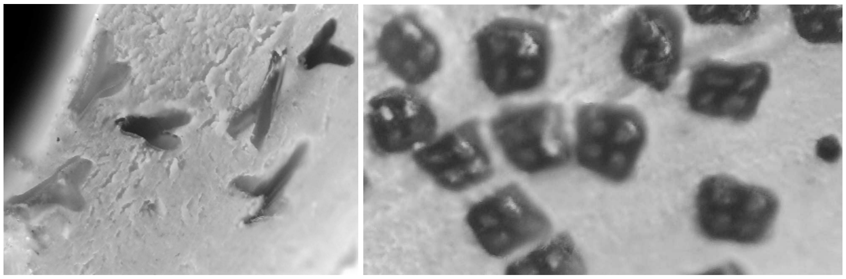
It is important to note that the fibers are industrially drawn into cross sections of various sizes and geometric shapes, not solely circular, but for example Y-shaped or square with four independent hollow tubes, Figure 2.



a) DuPont b) Collins & Aikman

Figure 2: Different Cross Sections of Carpet Fibers

3.Recycling Strategies for Waste Carpets

US demand for carpets and rugs is forecast to rise over two percent per year through 2007 to over 20 billion square feet [16]. The magnitude of the problem of recycling old carpets based on statistical data from 1996 has been described in detail by Malin [5]. The 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"). Such efforts are only partial, as the recycling products are always of lower quality than virgin products. The alternative and ultimate goal of the fiber industry is true closed-loop recycling of fibers, where polymeric fibers are decomposed chemically or by high-temperature treatment and then used to fabricate once more high-quality virgin material. The main challenge in this approach is quality control. Recyclers are receiving material from many different sources, yet to achieve true closed-loop recycling, it is necessary to know the detailed 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" [6]. The typical carpet recycling processes consist of the following steps.

- Sort and organize the carpets by fiber type and construction. Polypropylene-backed 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.

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

4. Fibers Used in this Study

The DuPont Carpet Reclamation Center in Chattanooga, TN, initially provided recycled carpet fibers from different locations in their processing stream for this study. In this "wet" process, the material was first processed in dry form and then further purified in a wet slurry. The two products, which received the most attention were labeled "Mixed Grit" and "Recycled Nylon". Towards the scheduled end of the present research project, however, DuPont decided to switch the reprocessing procedure. The new "dry" process accomplished purity objectives in a dry phase, thereby eliminating the wet slurry part of the process, which resulted in increased efficiency 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 $CaCO_3$ and total inorganic contents. Among various samples from this new process the most promising product was labeled "DFN". In addition virgin nylon fibers from the carpet producer Collins and Aikman were studied for comparison. These fibers are produced by shredding the leftovers on the drums used for the production of carpets.

5. Glass Concrete

A major research project was started at Columbia University in 1995 to investigate the feasibility of utilizing waste glass aggregate in concrete products. Earlier attempts had proven mostly unsuccessful because of the well-known alkali-silica-reaction (ASR). The solution used at Columbia University relies partially on the utilization of metakaolin. Compared with fly ash and silica fume it is a relatively novel pozzolanic material, but with enormous potential, in particular regarding strength development, creep, durability, pore structure, and ASR suppression [12,13,14]. Since 2003 glass concrete is being commercially produced, for example, in the form of terrazzo tiles, non-structural precast elements, and pavers. Besides reducing the amount of solid waste destined for landfill disposal, glass offers a number of advantages if used as aggregate in concrete. Its hardness guarantees high abrasion resistance, and since it does not absorb water, lower water-to-binder ratios are possible. Various methods to produce polished or exposed aggregate surfaces, combined with choice of matrix color, aggregate color, and glass particle size grading give glass concrete a potential for outstanding aesthetic value, and it can be of high strength and excellent durability [2,15].

6. Effect of Carpet Fibers in Glass Concrete

Carpet fiber-reinforced concrete has been studied by several researchers [8,9,10], who used relatively small fiber amounts of up to 4% by volume and were interested mainly in mechanical properties. It is generally agreed that carpet fibers can improve the toughness

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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 have been reported in the literature.

Before proceeding it should be stressed that the results below are to highlight general trends and a path, which can be followed when designing a concrete mix with recycled carpet fibers, rather than a final recipe. The glass concrete system is unique because of its ASR suppressing admixtures, and the mix of carpet fibers will ultimately be different in any follow-up study, or each time the fiber supplier, the waste stream, or the recycling technology changes. This complicates all work involving recycled in place of virgin materials.

6.1 Workability and Compressive Strength

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 some applications, for instance precast residential basement wall panels, fibers may be added to the concrete mix 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. Also, the addition of large amounts of fiber greatly reduces the workability of the mix, making it much more difficult to consolidate it and to achieve a high-quality, low-porosity end result.

During the early phases of this project, involving DuPont's "Mixed Grit" and "Recycled Nylon" fibers, surprisingly large quantities of fibers could be used, Figure 3. 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 also summarizes the strength results for the new DFN fibers, and the shredded virgin fibers obtained from Collins and Aikman (hollow Nylon 66). The strength of samples with 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, 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 $CaCO_3$ 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 (solid symbols in Figure 3) rather than 7-day strengths (hollow symbols), the strengths achieved are likely to be adequate for most applications.

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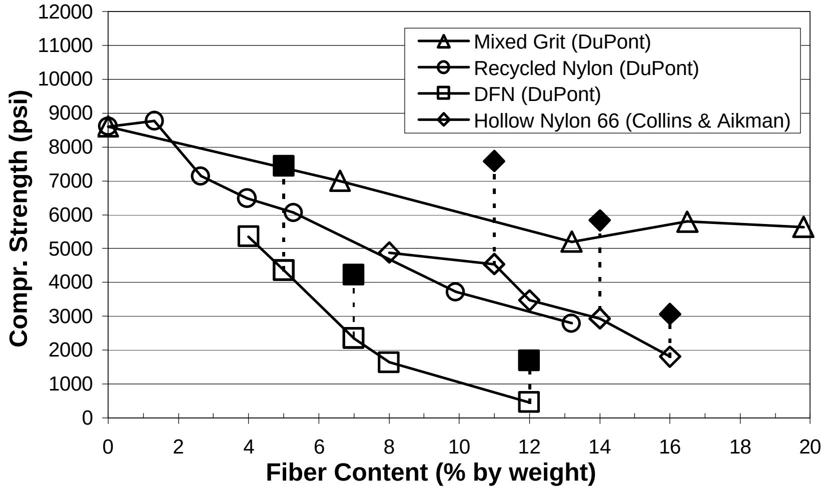

Figure 3: Compressive Strength vs. Amount of Recycled Carpet Fibers
(hollow symbols: 7-day strengths; solid symbols: 28-day strengths)

6.2 Thermal Conductivity of Concrete Panels

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^{o}F temperature difference, e.g. BTU-in/hr-^{o}F-ft2 or W/m-^{o}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. In comparison, a typical concrete mix has an R-value of about 0.2 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 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 differential can serve as a measure of the material’s thermal performance. By plotting the temperature time histories, Figure 5, and integrating the area between the curves for the inside and outside temperature, we obtain a value referred to as “thermal resistivity”.

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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 therefore indirectly on weight density [11]. 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, for example, special hollow-sphere aggregates or foaming agents.

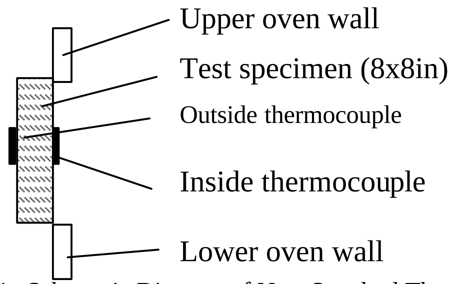

Figure 4: Schematic Diagram of Non-Standard Thermal Test

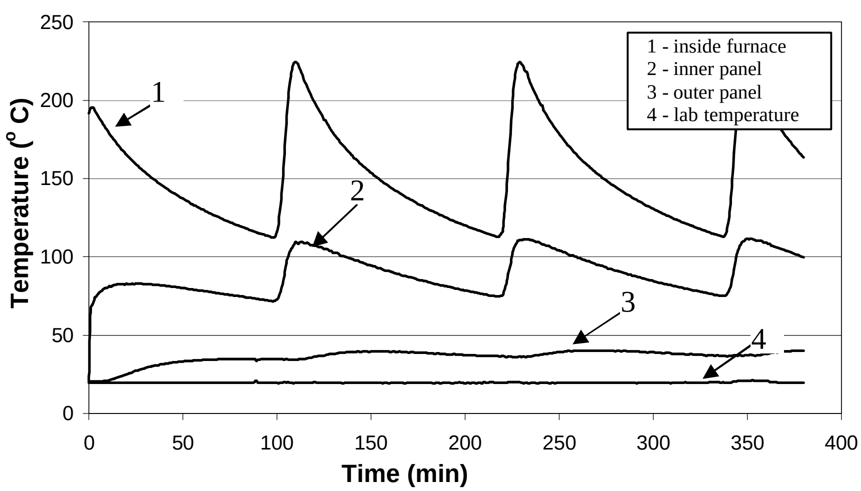

Figure 5 Typical Temperature Time Histories of Non-Standard Test

Relative thermal resistivities and strengths are listed in Table 2, using a mix with neither foaming agent nor fibers as reference. As shown, the approximately 20% improvement

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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.

Table 2: Relative Thermal Resistivity and Strength of Glass Concrete Systems

Sample Mix	Relative Thermal Resistivity	Relative Compressive Strength
0% fiber, 0% foam	100	100
0% fiber, 1.0% foam	120	58
11% C&A, 0% foam	114	48
5% DFN, 0% foam	125	46
5% DNF, 0.3% foam	134	24
5% DFN, 1.0% foam	161	11

6.3 Durability

In addition to the strength and thermal conductivity, the freeze-thaw cycle resistance was determined for concrete systems with carpet fibers according to ASTM C666, which accelerates the service life exposure to natural temperature changes. Specimens were exposed to more than 700 freeze-thaw cycles, without showing substantial scaling or droping of the relative dynamic Youngs modulus. 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 concrete systems containing recycled carpet fibers have excellent durability properties and are likely to be more than adequate for the specific applications.

7. Discussion and Conclusions

It was the original premise of this project to utilize hollow nylon fibers recovered from recycled carpets to increase the R-value of concrete. Contrary to expectation, 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 2a), while virgin nylon fibers received from Collins and Aikman appeared to have hollow cross sections, Figure 2b).

The 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.

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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.

The improvement of the thermal performance of concrete wall panels with recycled carpet fibers is modest at best. There are 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 cost is comparable. The added value derived from beneficial use of a solid waste material alone is not likely to be a sufficient incentive for concrete producers to make the substitution, unless tax advantages are offered for the use of recycled building material content.

9. Acknowledgments

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