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An Investigation of the Performance of Paving Units Made from Recycled Glass with a Mineral Additive

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The Chelsea Center for Recycling and Economic Development, a part of the University of Massachusetts' Center for Environmentally Appropriate Materials, was created by the Commonwealth of Massachusetts in 1995 to create jobs, support recycling efforts, and help the economy and the environment by increasing the use of recyclables by manufacturers. The mission of the Chelsea Center is to develop an infrastructure for a sustainable materials economy in Massachusetts, where businesses will thrive that rely on locally discarded goods as their feedstock and that minimize pressure on the environment by reducing waste, pollution, dependence on virgin materials, and dependence on disposal facilities. Further information can be obtained by writing the Chelsea Center for Recycling and Economic Development, 80 Everett Avenue, Suite 221, Chelsea, MA 02150.

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1.0 ABSTRACT

A project was conducted to test the effect of adding an industrial mineral additive to glass during the fusing process of making glass paving units. The additive had been seen to keep soda lime glass "glassy" rather than becoming hazy and dull in the kiln. Both analytical and empirical approaches were taken to confirm the effect and to discover its cause. The identity of the additive is being maintained as a trade secret at this time.

Analysis yielded the finding that a eutectic exists between the additive and soda lime glass. This is the cause of the smoother surfaces seen when the additive is present. In addition, it was found that commonly held ideas about devitrification characteristics of soda lime glass during fusing processes are incorrect. In fact, the haze generally called "devit" is predominantly caused by the volatilization of some component of the glass, assumed to be oxides of sodium.

The ultimate goal of the project was to make and test glass unitary paving products made from glass. In comparisons of flexure strength, it was found that a thirteen-pound per square foot (1" thick) glass paver was stronger in flexure than a seventeen-pound per square foot (1 5/8" thick) brick paver and twenty-four pound per square foot (2 1/3") concrete paver.

In addition, the glass paving product was made with an input of 14,900 Btu per square foot, compared with published data of 20,100 for clay bricks and the equivalent of 26,750 Btu for the manufacture of concrete pavers in energy and greenhouse gas emissions. The theoretical energy needed to make the glass paving is actually only 6,600 Btu per square foot. Future work with continuous kilns will attempt to approach the theoretical value.

2.0 BACKGROUND

2.1 Background of the Process

Although glass container manufacturing plants operate their furnaces at temperatures exceeding 2400 F, at temperatures as low as 1250 F, through the process of sintering, small particles of glass begin to bond, or fuse, with each other. This sintering process is well-known in the ceramics and powdered metals fabrication industries. Through sintering, products can be produced from properly prepared materials at much lower temperatures than those required for melting. Since the early 1980's, researchers were investigating ways to use sintering processes with recycled glass to produce new products.[1]

Most sintered products manufacturing involves combining powdered materials with binders and creating "compacts" in hydraulic presses at room temperature, which are then dried and fired into final products. However, glass particles have the interesting property of fusing to other glass particles to full density even in the dry form, with no binders or water. In particular, it has been found that using appropriate gradations and the right kiln firing profile, a glass particle as it softens under heat has a greater affinity for other glass particles than it does for the mold that contains it. This means that solid objects can be formed at relatively low temperatures in low-cost molds without special containment vessels or refractories.

Having determined that sintering presents a possible technique for making products from recycled glass, the challenge has been to find ways of making aesthetically pleasing and functional products using recycled glass. This has been challenging because the glass from which containers are made, generically called "soda-lime" glass, is made to melt relatively easily, then stiffen and anneal quickly after being poured in high-speed manufacturing processes. However, when soda-lime glass is re-heated in a sintering process, it is unstable and tends to "devitrify," or return to the crystalline state, resulting in weak products with a dull uneven finish not considered to be attractive[2]. Also, the recycled glass in most plentiful supply is mixed color container glass, which when fused makes a murky dark color.

2.2 Discovery of an Effective Additive

After testing many additives to glass trying to improve the appearance and performance of the fused products, it was noticed that a particular mineral additive significantly lightened the fused product and also appeared to create a more "glassy," and more completely fused appearance. The additive sells in industrial markets for about $1.00 per pound. The specific additive and form used is being maintained as a trade secret at this time. Any party interested in this process as a commercial enterprise should contact Robert Kirby at kirbgood@aol.com.

The additive appeared to:

- strengthen the fusion bonds;
- lighten the color of the glass fines, improving the contrast within the piece; and
- help maintain the glassiness of the glass surfaces.

The purpose of this project was to test the effect of the additive and to test products made using the additive with glass. The application investigated in this project is the use of glass with the additive in unitary paving products. In this report, the term "unitary" means pavers that are made at a factory and transported to the construction site for placement, rather than being poured in place.

2.3 Why Paving Products were Chosen

The idea of re-using glass in paving products was chosen for a number of reasons. First, glass paving is expected to be much stronger than concrete or brick paving of the same weight. Several years ago the Clean Washington Center (CWC) sponsored a project testing the strength of fired products made from glass[3]. The average modulus of rupture of the glass samples tested was 4.25 times greater than the modulus of rupture of typical concrete paving units tested during the same project. The CWC report also demonstrated that the modulus of rupture is proportional to the square of the thickness of the paver. Therefore, according to those test results, a one-inch glass paving unit has the equivalent strength in flexure of over two inches of concrete.

Second, rather than trying to create a perfectly glossy surface, as would be required to make wall or floor tile, the mixed glass will be used to make textured and complex surfaces, which will work with the varying nature of the raw material, rather than trying to overcome it.

Third, outdoor paving applications areas are generally larger than interior tiling applications areas. At 13 to 15 pounds per square foot, in thickness from 1 inch to 1.25 inches, the use of glass in outdoor paving presents the opportunity to use significant quantities of this plentiful raw material.

Fourth, the use of unitary paving is increasing in the United States. In this project, "unitary paving" means paving units that are manufactured in a production plant and transported to a construction site, rather than being poured in place. Increasing concerns about stormwater drainage have resulted in communities encouraging the installation of permeable pavements, which can be constructed much more easily with unitary paving than with poured-in-place pavements.

Finally, manufacturing paving from glass is expected to be more resource-efficient and environmentally benign than either brick or concrete.

2.4 Comparison to Brick and Concrete Manufacturing

As mentioned above, manufacturing paving from glass is expected to be more resource-efficient and environmentally benign than either brick or concrete. The following lists summarize the reasons for this expectation:

2.4.1 Comparison with Concrete:

Glass paving has advantages as a substitute for concrete paving in all of the following areas:

- better strength per unit weight
- less energy use in manufacturing
- zero emissions during manufacturing
- no crystalline silica in the worker environment
- no use of water in manufacturing or fabrication
- no potential impacts to groundwater alkalinity
- less energy use in shipping
- recycled glass supply greatest in population centers that also need paving materials (as opposed to sand, concrete or clay which may or not be found where the demand is)
- contributes to waste diversion
- added value to a waste material
- increased speed of manufacturing (no curing)
- local availability of raw material
- no mining of virgin materials
- local small business potential

While it is neither claimed nor expected that glass paving will compete with the economics of poured-in-place concrete or asphalt paving, glass paving should be less costly to the environment than concrete and competitive with cast unitary concrete paving and good quality stone. R. S. Means'[4] construction cost data book for 2000 estimated the average cost for unitary paving at $4.68 per square foot for exposed aggregate concrete (the closest in appearance to glass pavers) and $4.00 per square foot for 1” thick bluestone unitary pavers. These are contractors' prices for the material only. See section 6 for further cost analysis and comparison.

2.4.2 Comparison with Brick:

- lighter per square foot than brick paving
- no drying phase, hence faster production and less energy
- no size restrictions because there is no drying phase to produce cracking
- fires at a much lower temperature
- requires no phase change, hence faster production and 100% theoretically recoverable energy
- creates no volatiles
- raw material is cheaper than clay - free for mixed glass cullet in most urban areas (but there are costs for processing it to the proper size, see Section 6)
- molding methods are simpler than for brick
- transportation costs are less per square foot
- can be colored to look like brick or stone

Taken together, the above reasons suggest that there should be no operational reason that glass pavers should not be cheaper to make and have improved performance over brick paving. According to Ceramic Industry magazine, in 1997, eight billion bricks were sold in the United States at an average wholesale price of 17¢ per 4”x 4”x 8” clay brick.[5] That translates to a wholesale material price of 77¢ per square foot in paving applications. Therefore, there is no reason to assume that glass pavers should not eventually be able to be produced and sold wholesale on a large scale for less than 77¢ per square foot.

Summarizing the advantages, it is not unreasonable to conclude that glass paving should be

Lighter ***Faster*** ***Stronger*** ***Thinner***

than paving units made from concrete or clay.

Preliminary to performing the work reported here, a number of "rough and ready" tests were run comparing glass to normal paving materials. In one case, 4"x 8" glass "bricks" were fired with increasing weight and then put into a vise with spacers opposite a commercial paving brick. The vise was then tightened until either the glass or the clay brick broke.

Figure 1 shows before and after photos of a 1250 gram glass breaking a 1600 gram clay brick.

Figure 1 - 1600 gram clay brick and 1250 gram glass brick before & after breaking

3.0 ORIGINAL SCOPE OF WORK

The project was planned with the following stages:

3.1 Confirm and Optimize Mineral Addition

- Collect glass processed through the Andela Glass Processing System on Orcas Island Washington. This glass will be used as the “standard” for this project.

- Fire a series of sample sets (4”x 4”) with varying kiln profiles and percentages of mineral addition.

- Test the sample sets for breaking strength and absorption to develop a statistically valid profile of the effects of the mineral addition. Absorption is a measurement of the resistance of the product to freezing/thaw cracking. It also demonstrates complete fusing, since inadequately fused products retain air bubbles.

- Test the mineral addition itself for physical characteristics in order to develop parameters for the addition, e.g. gradation, level of contamination, sources, any other identifiable important physical characteristics.

3.2 Attempt to Characterize the Cause of the Effect

An attempt will be made to figure out why the observed effect of adding the mineral additive occurs, using bibliographic research, phase diagram analysis, microscopic analysis, spectrum analysis, and any other tools deemed appropriate to determine the cause.

3.3 Perform Formal ASTM Paving Tests

- Using the optimal profiles and mixtures developed above, fire samples in standard paving sizes.

- Test the samples against paving standards for flexure strength.

3.4 Create Cost and Operations Models for a Small-scale Producer of Glass Paving

Develop a cost model for capital equipment, operations, labor, amortization, etc., as the financial basis for a small business based on using the glass fusing technology to manufacture glass paving.

3.5 Seek a Partnership with a Potential Producer in Massachusetts

Use the Chelsea Center’s contacts and assistance to seek a potential producer in Massachusetts.

4.0 DESCRIPTION OF WORK COMPLETED

4.1 Moldmaking and Sample Collection

In order to control the production of each tile, a set of 50 new tile molds were made from castable refractory and pre-fired prior to initiating actual test firing. Each mold weighed 320 grams. Each 4"x 4" tile made in a mold weighed 220 grams.

The target material for the project is the output from an Andela Products Ltd. Glass Processing System on Orcas Island, owned by San Juan County, Washington. All of San Juan County's recycled glass is processed by the system and made into two grades. The finer grade, which consists of mixed color crushed container glass U.S. standard mesh size 8 and smaller, was used in this project. The ultimate object of the project is to test and develop manufacturing processes for making viable paving products from post-consumer mixed color recycled container glass, without special cleaning or processing. After the glass was returned to the laboratory, it was passed through a number 8 mesh screen to remove pieces of leaves, wood, insects, and other detritus in the material. Figure 2 is a picture of the community glass processing system on Orcas Island.

Figure 2 - Andela Glass Processor on Orcas Island Washington

The gradation, in U.S. Standard Mesh size, is shown in Table 1.

U. S. Standard Sieve Size	Percent by wt. Retained	Percent by wt. Passing
#8	0%	100%
#16	38%	62%
#30	25%	37%
#50	17%	20%
#100	10%	10%
pan	10%	

Table 1 - Gradation of sample glass

The data in Table 1 should be taken as indicative rather than definitive. As can be seen in Figure 2, the glass was collected from a basic processing system, outdoors. The gradation will vary, especially in the finer sizes, depending on a number of variables, including precipitation, wind, state of wear of the equipment, and operator loading characteristics. The goal of this project was to collect typical glass as it was available from a basic processing system.

4.2 Small Tile Sample Testing

4.2.1 Preliminary Testing

For this stage, breaking strength of sample tiles was chosen as a surrogate for the amount of devitrification present in the fused products. This is an appropriate measure because devitrification is a barrier to complete fusing. Therefore, devitrified tiles have weaker fusion bonds than completely vitreous tiles.

Initial sample production was performed to obtain baseline data on the strength of 4"x4" fused glass tile. The Materials Science Department of San Jose State University maintains fixtures to test tiles against ASTM C648-89, "Standard Test Method for Breaking Strength of Ceramic Tile." For these initial tests on 4"x 4" tiles, that facility was used. Table 2 summarizes the test results:

test no.	quan.	glass type	glass grade	kiln/temp	% additive	Break strength (lbs-ft) average	std. dev.
1	10	clear bottle	16 mesh -	batch/1600	0	597	69
2	10	clear bottle	16 mesh -	batch/1650	0	607	53
3	8	clear bottle	8x16 mesh	batch/1600	0	299	31
4	4	clear bottle	8x16 mesh	batch/1600	0.2%	362	45
5	10	clear bottle	8 mesh -	batch/1600	0	356	64

Table 2 - Results of Breaking Strength Tests on the 4” by 4” Tiles

Although the test sets above are small, an interesting comparison can already be made between test sets 3 and 4. They are both made from the same glass with the same firing schedule, but test set 4 contains 0.2 percent of the additive. Test set 4 demonstrated greater average strength than test set 3 by an amount exceeding the standard deviations of both tests. Although this was too preliminary to begin statistical analysis, the trend was encouraging. The large difference observed between sets 1 and 2 and the rest of the sets has to do with the gradations used. There is a tradeoff between gradation and efficiency in fusing. The samples with glass finer than 16 mesh fused stronger in this first test. However, it is considerably more expensive to process glass to 16 mesh than to 8 mesh. And the equipment to process glass to 8 mesh is available in small to medium scale, while the equipment to process glass to 16 mesh is more generally available only for large-scale operations.

<u>4.2.2 First Belt Kiln Tests</u>

To begin testing for this project, three sets of mixed color samples were made in a small belt kiln. Kilns can be segregated into two categories: batch and continuous. In batch kilns, products are made in batches by opening the kiln, arranging the materials to be fired in the kiln, then firing the entire load at one time. In continuous kilns, the kiln box is heated, then materials to be fired are carried through on a belt, carried through on a "car," or pushed through on a ramp.

Most production processes use continuous kilns for at least four reasons. First, there are some ergonomic advantages to having workers standing in one place performing repetitive movements, compared with placing and removing products from a large area. Second, there are significant energy advantages to continuous kilns because the kiln box is only heated once, then the product is passed through it, instead of heating and cooling the kiln box repeatedly. Third, continuous kilns are generally a more efficient use of floor space, since many products pass through the same space each day. Finally, in continuous kilns it is generally accepted that the fired products are more uniform, since each product passes through exactly the same temperature profile.

The three sets of test tiles made in the belt kiln turned out to be statistically unusable. The strengths varied from 40 pounds to 400 pounds within the same kiln run. This means that the tiles were inadequately annealed[a], resulting in highly variable strengths. To fix this problem, the small belt kiln is being modified with an improved cooling section. After firing, the tiles will pass through a temperature-controlled insulated box. By adjusting the amount of thermal mass inside the box, the aim is to anneal the tiles with no additional heat input. However, the capability for adding some heat to facilitate annealing is also being added.

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[a] Annealing: After molten glass is poured, it stiffens and shrinks as it cools. If it cools too quickly, the outside of the glass piece can stiffen before the inside. Then as the inside cools and tries to shrink, it can create a tremendous amount of tension within the glass piece, even breaking the piece immediately or at some later time, usually when it is least expected. Manufacturers of glass products generally apply an "annealing cycle" to account for this characteristic. The molten glass piece will be put into a controlled temperature chamber at a temperature (about 950-1050 F for soda lime glass) that allows the stresses to equalize before continuing to cool. Annealing is extensively written about in the engineering literature[a]. Historically, optical means were used to test for internal stress in glass. When viewed through a polarized lens, the stress lines in glass could be seen, because the stresses created areas of varying light refraction. The products being tested in this project, however, are opaque. Other means, including sonic, are being investigated for future testing for stress in these products.

4.2.3 Batch Kiln Tests

New sets of test tiles were made in a batch kiln. The results are summarized in Table 3:

percent additive	maximum firing temperature- deg. F	average break strength (lbs.-ft)	standard deviation (lbs-ft)
0.0%	1600	424	53
0.5%	1600	412	66
1.0%	1600	366	68
0.0%	1650	456	47
0.5%	1650	431	56
1.0%	1650	414	54

Table 3 - Results of Breaking Strength Tests from Batch Kiln

Although a statistical analysis based on confidence intervals is inconclusive based on the data above, the additive appears to interfere somewhat with the strength of the tiles, because the average strength decrease slightly as the percentage of additive increases. Nonetheless, there is compelling visual evidence that the effect is there.

4.2.4 Decisions on Next Steps

At this point in the project a decision had to be made regarding the direction testing was to take. The visual evidence that the additive helped in the maintenance of a glassy surface was obvious but was not supported by the initial strength tests. One possibility was to perform additional tests on 4"x 4" tiles, varying the kiln profile and "soak time" at the highest temperature. Soak time is the length of time the glass is held at the maximum temperature. Once maximum temperature is reached, even though glass fusing is a viscosity change rather than a change of state, it still takes some time for the temperature to penetrate the entire tile. It is possible that during the short kiln cycle needed to fire the 3/8" thick 4"x 4" tiles, the additive, although it helped to maintain the glossy surface, did not have time to react with the bulk of the glass, and actually interfered with the fusing process. Longer soak times might demonstrate this.

The other option was to move on to the testing of samples that were the actual size and thickness of potential glass paving products. A decision was made to move on to actual prototype testing, especially since a test fixture had been fabricated and was ready at the University of Washington Materials Science Department.

4.3 Surface Effect Analysis

4.3.1 Probable Causes

In conjunction with strength testing, other approaches were tried to determine the cause and characterization of the glassy surface effect clearly being seen. The possibilities were narrowed down to these:

1) A fluxing effect. A flux is defined as “a substance used to promote the fusing of minerals or metals[7].” Fluxes are generally materials that melt at temperatures lower than the materials to be fused, coating the materials with molten liquid and promoting softening and subsequent fusing. An example is the use of lead oxides with glass frit in glaze. Fluxing, defined in this way, was rejected as a possibility because the additive has an extremely high melting point, well above that of glass.

2) A eutectic effect. A eutectic effect is the phenomenon that combinations of minerals mixed in proper proportions often melt at lower temperatures than the individual minerals themselves. For example, silica has a melting point of 3092 F and sodium bi-silicate has a melting point of 1605 F. However, 76% (mole percent) sodium bi-silicate combined with 24% silica has a melting point of 1452 F. It is possible that there is a eutectic between soda lime glass and the additive.

3) An effect associated with sodium leaching. Some technical articles over the years have suggested that the leaching of sodium ions from the surface of glass contributes to devitrification. Sodium leaches in reaction to water or water vapor coming into contact with the glass[8]. There is speculation that the additive may be affecting this leaching, reducing the stiffening that would result from the loss of sodium from the glass.

4) Something else.

<u>4.3.2 Temperature Range Tests</u>

Several series of samples were fired, with and without the additive, at temperature ranges from 1600 to 1900F. At 1600 the normal fusing process was expected. At temperatures above 1800F full melting of the glass was expected.

If the reaction is a straightforward “phase equilibrium” issue, as described in the comments above about a eutectic effect, then a simple temperature-effect shift would be expected. For example, the glass fired at 1850 F without the additive might look about the same as the glass with the additive fired at 1750 F. That is not what was seen. The glass with the additive was glossier across all temperature ranges. This indicates that there is more than just a temperature shift going on.

<u>4.3.3 Initial Material Analysis</u>

The additive being tested is commercially available in several crystalline forms, which are not always explicitly stated on the packaging. Therefore, it was important to have a good materials characterization of the available source. Also, there was some concern that the effects seen when using the material may be due to some unidentified contaminant.

X-ray diffraction analysis was performed to determine the form and content of the material. It turned out to be a quite pure form of a common mineral in a well-known crystalline state.

4.3.4 Differential Thermal Analysis

Thermal analyses are a group of methods by which the physical and chemical properties of a substance or mixture are determined as a function of temperature or time while the sample is subjected to a controlled temperature program. Any process that involves heat can be so analyzed. The test may involve heating or cooling the system (dynamic), or holding the temperature constant (isothermal), or any combination of these. Differential thermal analysis (DTA) measures and analyzes the changes in energy (heat) with respect to temperature. The data is depicted as the difference in heat flow (y-axis) to or from a sample as a function of temperature (x-axis) or time while the sample is subjected to a controlled temperature program. Changes in the substance or mixture such as combustion, solidification, and condensation are detected as peaks in the curve while melting and boiling are detected as valleys.

In an attempt to see whether the additive significantly affected the way glass reacts to kiln heat, a DTA of heat vs. temperature data was performed and evaluated by Hanson Fong (a Ph.D. student in the Materials Science Department of the University of Washington) while ramping up the temperature. At the glass transition point, the slope should become more negative while the temperature increases, the reason being is that the glass softens rapidly in the transition zone, absorbing the heat needed to speed up the molecules.

The output from the DTA that was performed is a large data file. The results of the DTA of glass both with and without the additive are shown as graphical figures in Appendix B. The goal of the DTA was to heat a sample of the material and very carefully measure the energy needed to accomplish the temperature change. In temperature regions where organic materials are burning off, the material may actually be a net supplier of energy. If the additive is lowering the viscosity of the glass, it may be possible to observe the glass absorbing more heat at lower temperatures as it softens faster than the glass without the additive.

To see the effect of the additive, temperatures greater than 650 C were of most interest since that is the onset of glass transition for soda lime glass and the eutectic reaction. The vertical lines in the figure of Appendix B represent the zone within which any difference should be most pronounced. As shown by the graphs, no measurable difference with or without the additive was detected.

TGA (thermal gravimetric analysis) data was also collected and graphed on the figure of Appendix B. It basically measures the weight change with respect to temperature on a very sensitive scale. Hence, any organic matter burning off shows up on the curves. It was less than 0.5% change in both cases. It appeared that the mass loss due to organic matter burn off the TGA curves lagged behind the DTA curves. That is probably because some time is required for the materials to burn off and vaporize out. The lag could have been reduced by decreasing the rate of temperature increase.

The reason that the DTA results within the combustion range do not show peaks and why there are large negative slopes at the beginning of the runs is that the curves were not calibrated. If they were, the curve would be horizontal in regions other than the combustion and glass transition range. Other observations and explanations include:

- The change of slope in the TG curves (top curve) in the 550 C to 610 C represents weight lost due to combustion.

- The change in slope change in the DTA curves (bottom curve) in the 470 C to 530 C range represents the exothermic combustion process of organic matter in the glass.

- The change in slope in the DTA curves in the 650 C to 710 C curve represents the glass transition, which is typical of soda lime glass in this temperature range. There is no measurable difference between the samples with and without the additive.

The DTA demonstrates that the additive has an undetectable, and therefore, marginal effect on the energy characteristics of the bulk glass during heating. The conclusion drawn from the DTA is that if the additive does indeed form a eutectic with glass, then the effect is only on a very thin layer of surface of the glass.

4.3.5 Eutectic

Eutectics are derived from phase diagrams, which show how raw materials act when combined and heated. The reaction between two materials is easy to show on an x-y plot, where the x axis shows percentages of each material, and the y axis shows temperature. In the graph, areas of liquid and vapor are shown to demonstrate how different percentages of each material react differently, depending on the ambient temperature.

Phase diagrams have been developed empirically over the last century, often as the result of graduate theses. Books of phase diagrams are available in technical libraries. For this research, the composition of glass was reduced down to two materials: sodium and silica, present in a ratio of about 3:1. Looking for phase diagrams containing silica, sodium, and the industrial mineral, a eutectic was found with (in mole percentage) 73.6 % silicon dioxide, 24.2 % di-sodium oxide, and 2.2 % of the oxide form of our additive. The eutectic manifests a liquid phase at 1443 F. A scan of the eutectic is shown in Figure 3.

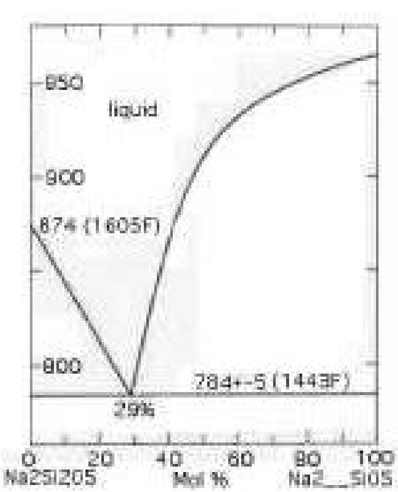

Figure 3 - Two-Way Phase Diagram

(the additive is represented by the __ in "Na_2__SiO_5" on the x-axis of the phase diagram)

It appears that what happens is that the additive, when it is present on the surface of the glass as the temperature is raised above 1443 F, reacts with the percentages of oxides present in the glass to develop a lower viscosity phase. That is why the tiles with the additive are smoother.

The reason the visual effect is being seen at significantly lower percentages of between 0.25 and 1 percent is because the glass is granular and relatively coarse, so the effect is only happening on the surface of the glass particles.

4.3.6 Sodium Loss

The discovery of this eutectic created another dilemma. Recycled soda lime glass has never been a popular material for glass artists performing "kiln casting" because it develops a dull haze on the surface when heated. This haze is generally referred to as "devitrification," because it is assumed to be composed of crystals that form on the surface of the glass. The crystals form because heating the glass lowers the viscosity, allowing the molecules enough mobility to develop crystal structures.

But if the eutectic described above further lowers the viscosity, increased rather than decreased crystal growth would be expected. Furthermore, electron scanning microscopy indicates that the kind of formations seen on the surface appear more as "pits" than as crystals. Figure 4 is an illustration of two samples, with and without the additive and the footnote[b], also by Hanson Fong, describes an interpretation of the photos.

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[b] We have observed that the addition of the additive, as little as 0.75%, results in a drastic increase in the surface glossiness in the tiles. A comparison of magnified optical images of tiles with and without the additive reveals that the former exhibits a smoother surface. For example, as shown in the top figure above, the dominant features of the tile with no additives are pits and ripples (such as those indicated by horizontal arrows). Since these pits and ripples have various contours, they tend to reflect light at different angles. Hence when one looks at the tile surface, it appears dull. On the other hand, as shown in the bottom figure, the addition of the additive significantly reduces the extent of pitting and rippling on the surface. The bottom image shown in Figure 4 shows that the addition of 0.75% of the additive results in more than 85% of the surface being smooth. Since the surface is smoother, back reflection of light is more uniform. Therefore, the appearance of a glossier surface results. This smoothing effect of the additive is observed even at higher temperatures.

The smoothing effect of the additive can be explained by a eutectic formation between the additive and glass. We think that there is a viscosity decrease associated with the eutectic formations. Such viscosity reduction enables the molten glass to evenly cover any surface disparities, resulting in a smoother surface.

Note that the devitrification is observed in all cases. Devitrification is characterized by the presence of acicular features, which are crystals nucleated from the glass matrix. As pointed out by 45^{o} arrows in both figures above, they are present in tiles regardless of the presence of the additive. However it is important to note that the devitrification is not the primary contributing factor to the dull appearance of the glass tiles. Rather the surface pits, which are much greater light scattering sources, are responsible for the surface dullness.

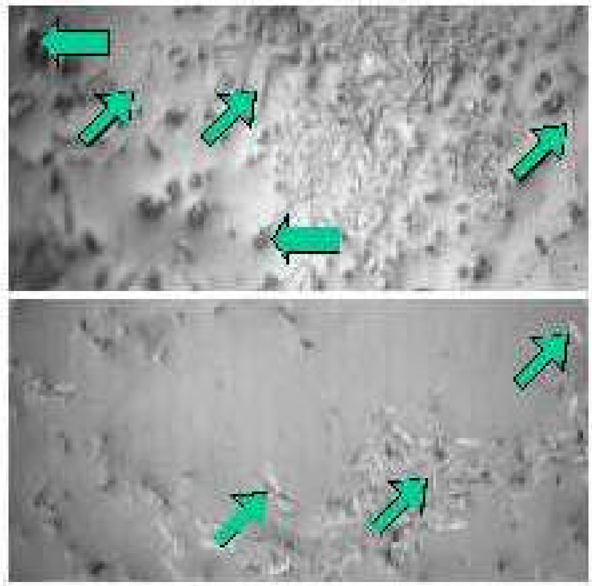


Figure 4 - Photos of Glass Surface

top - without additive bottom - with additive
the horizontal arrows point to pits, the 45 degree arrows point to crystal structures

Artists who melt and pour soda lime glass have said that each time they re-melt glass, they need to add sodium, usually in the form of soda ash, to replace the sodium that volatilizes from the batch during heating. In fact, it is possible that the majority of the haze is due to the loss of sodium rather than crystallization[9]. This is a very important hypothesis.

If the majority of the haze is from the loss of sodium, then different strategies might be considered to reduce or eliminate it.

If loss of sodium is causing the haze, the amount of sodium would not be easily detected from weight loss or sensors in the kiln. However, it may be possible to try to offset the loss and see whether it still occurs.

To test for the sodium loss effect, molds were made with lids. Some of the lids were saturated with a solution of sodium carbonate. Then tests were run with glass in the molds, so there were lidded molds both with and without sodium in the lids. The strategy was to see whether saturating the atmosphere above the glass with volatizing sodium would result in less sodium being lost from the glass, in the same way that water evaporates more slowly in a humid room.

The tiles produced in the molds with the sodium in the lids were both more completely fused and had less surface haze. More tests are being conducted.

4.4 Flexure Tests

4.4.1 ASTM Procedures

There were some problems finding an ASTM procedure appropriate for this project. ASTM C936-96, "Standard Specifications for Solid Concrete Interlocking Paving Units," specifies only a compression test for strength. Similarly, ASTM C902-98, "Standard Specification for Pedestrian and Light Traffic Paving Brick" specifies only a compression test. It is very difficult to test glass pavers in compression because they are too thin. Attempts were made for a CWC project to perform compression tests on glass samples[10]. Testing one-inch samples in compression was impractical because with the thin sample it was very difficult to detect failure. And it is both impractical and not statistically valid to attempt to make two-inch or thicker glass samples.

Civil engineers and materials science specialists have supported the contention that, in fact, most paving fails in flexure rather than compression. Flexure is the deformation of a beam under load, while compression is the reduction in volume of a body under pressure. Typically, a paver that is not placed on a solid sub-base, or one under which the sub-base is eroded will have a heavy load pass over it and fail in flexure. If a paver has a solid sub-base, it is unlikely to fail under pure compression, because the compressive forces required are so large. ASTM C936-82 contained the following note: "It is the consensus of the Task Group that compressive strength does not truly express a significant property of a paving unit. Rather, a flexural property evaluated by means of a tensile splitting test will be more meaningful." That statement was removed from ASTM C936-96, without explanation.

For the reasons stated above, ASTM C78-94, "Standard Test for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)" was chosen as the standard strength test for this project. Third-point rather than center-point loading was chosen because center-point loading concentrates the load at the center point, while the third-point loading spreads the load over the middle third of the test sample.

4.4.2 Flexure Strength Derivation

Calculating the flexure strength modulus is a way of comparing the flexure strength of different materials, especially when the thickness of the test pieces vary as in this case. The formula for calculating the flexure strength modulus for third-point loading is

Modulus of Rupture $$R = \frac{P \times L}{b \times d^2}$$

or $$P = \frac{R \times b \times d^2}{L}$$

where P = maximum load
L = span length
b = specimen width
d = specimen depth.

The higher the value of the Modulus of Rupture, the stronger the material is (for a comparable thickness) and therefore the greater load it can take before breaking. Since L and b are constant for all test samples, the maximum load is proportional to the square of the thickness for a material with a given modulus. The square function means that a small increase in thickness can result insignificant increases in strength.

4.4.3 Test Fixture

A test fixture was fabricated at the University of Washington Materials Science Department. The fixture is shown in Figure 5. Testing was performed on an Instron test instrument, also shown below.

4.4.4 Paver Flexure Test Results

To establish a baseline for comparison, commercial clay and concrete paving bricks were purchased and tested. Then glass with 0 percent, 1 percent, and 2 percent of the additive were fired. All of the samples were fired in an electronically controlled batch kiln, according to the profile shown in Figure 6. The only difference between the firings was the maximum temperature. Maximums of 1600 F and 1650 F were tried.

Figure 5 - Flexure Testing Fixture and Test Instrument

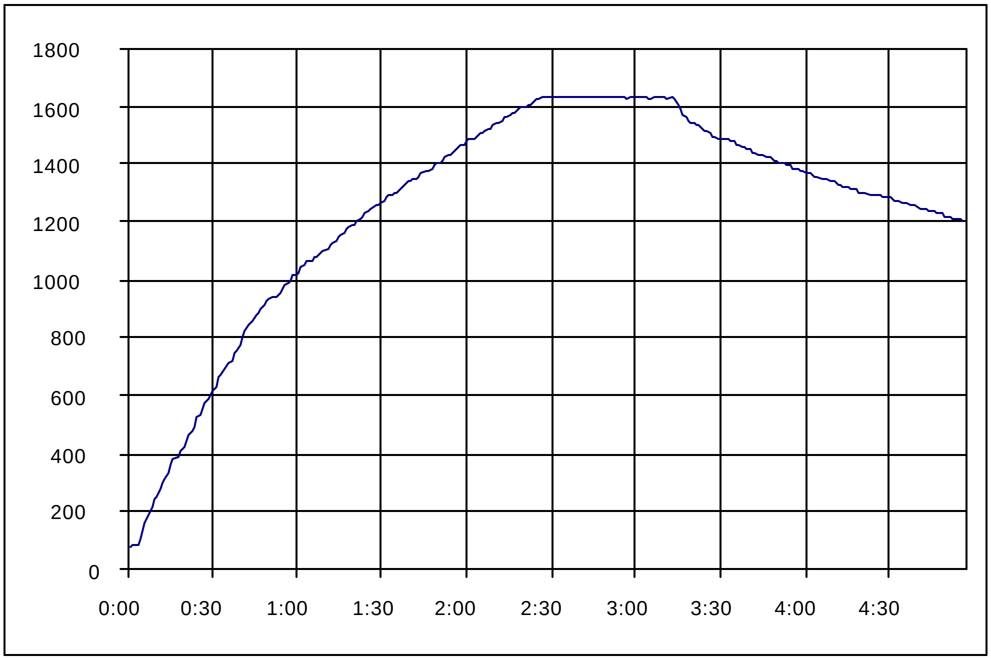


Figure 6 - Temperature Profile for Firings.
(y-axis is temperature in F, x-axis is Time)

Complete data for the firings is in Appendix A. Summary statistics for the firings are shown in Figure 7.

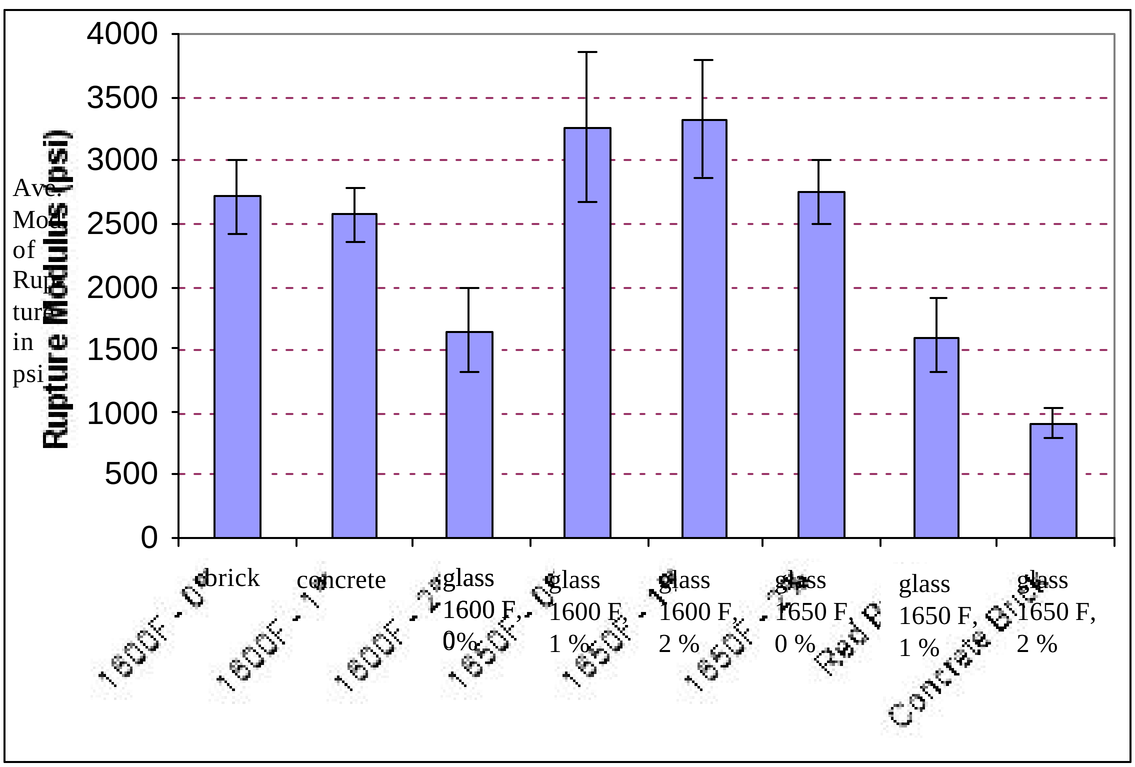


Figure 7 - Visual Summary of Flexure Tests

A data table summary of the flexure test results (Modulus of Rupture R) is shown in Table 4 below:

Sample	Average R (psi)	Std Dev R (psi)
1600F - 0%	2717	296
1600F - 1%	2571	215
1600F - 2%	1651	332
1650F - 0%	3264	603
1650F - 1%	3331	462
1650F - 2%	2756	259
Red Brick	1607	296
Concrete Brick	918	121

Table 4 - Flexure Test Summary Data
(7/8” glass paver, clay brick and concrete)

It is apparent from the data above that the glass pavers have a significantly higher Modulus of Rupture R than clay or concrete pavers. However, the glass pavers tested in this round weighed about 1000 grams and was about 7/8” thick. The goal is to derive the thickness of glass paver that will exceed the strength of actual 2 1/3” commercial concrete pavers in absolute terms. The glass paver with 1 percent additive fired at 1650 F had the highest flexure strength(higher amounts of the additive appear to weaken the glass), so that paver make-up was chosen as the standard for the next round of testing.

As shown above, the maximum load is proportional to the square of the thickness of the piece. So with the length and width constant, the maximum load is also proportional to the square of the weight of the piece. This is important because the dimensions of the clay, concrete, and glass pavers are not exactly the same. The important derivation to make here is the weight per square foot of glass that will be the equivalent of commercial concrete and brick pavers.

The average strength of the concrete pavers was 12.7 kiloNewton (kN). In English units, 1 kN = 225 lbs-f., so the average strength of the 4” x 8” concrete pavers was:

225 x 12.7 = 2858 lbs-f.

The average strength of the glass pavers weighing 995 grams with 1% additive fired at 1650 F was 6.75 kN = 1518 lbs-f. Since the strength varies as the square of the thickness, the weight of glass expected to be equivalent to the strength of the concrete paver is:

Sq.Rt. (2858/1518) x 995 grams = 1365 grams per 4"x 8" brick size.

That translates to:

(1365 grams/paver x 144 sq.in./sq.ft)/(32 sq.in./paver) / 455 gm/lb. = 13.5 lbs/square foot

Since the density of glass is 160 lbs./cubic foot, the thickness of the glass paver that should have an equivalent strength of a concrete paver is:

13.5 lbs/sq.ft. / 160 lbs/cubic ft x 12 in/ft. = 1.0 inches.

To summarize:

A One Inch thick Glass Paver should be as strong in flexure as a 21/3 inch concrete paver.

4.4.5 Tests on Thicker Glass Pavers

After the official end of this project, a number of tests were run on glass pavers with a greater thickness to verify the conclusions derived in section 4.4.4.

The strength results were better than expected. The following chart summarizes the results and compares them to the flexure strength results for 4" x 8" concrete, brick, and clay pavers:

SAMPLE	Thickness	Mean Flexure strength (lb.f.)	Standard Deviation	Sample Weight
red brick	1 5/8”	2370	420	1675
concrete brick	2 1/3”	2790	370	2415
glass 0% additive	1”	2802	318	1225
glass 0.25% additive	1”	2882	175	1250

Table 5 - Flexure Strength Summary Data (1” glass paver)

The results in Table 5 above were expressed in pounds per square inch in order to derive the equivalent thickness of glass that would be as strong as the concrete paver. The results in this table are expressed in pounds force to demonstrate that 1250 gram glass pavers exceeded the strength of the commercial pavers.

The results above demonstrate that glass pavers have been made less than one inch thick that exceed the flexure strength of thicker commercial pavers. It appears that the weight of the glass pavers can be 12.5 pounds per square foot, compared with concrete pavers exceeding 24 pounds per square foot, or twice as much.

4.5 Energy Usage

4.5.1 Energy in Glass, Brick and Concrete Making

One of the most interesting aspects of considering the use of glass as a paving material, from an environmental standpoint, is the potential energy and emissions savings compared to clay or concrete products. An attempt will be made in this section to both explain the energy issues and to interpret the data developed during this project.

Only electric kilns were used during this project. The reasons for using electric kilns were cost and control. Small-scale gas-fired kilns with the level of control needed during this project are not available commercially. Informal experiments have been made firing glass in manually controlled gas kilns, and it has worked well. In fact, the assumption is that at full-scale, only gas kilns would be used to manufacture the glass pavers, in order to take advantage of the efficiencies of the direct use of fuel.

Although it looks simple, the firing of clay into bricks is a complex process from a materials standpoint. One of the useful properties of clay, which was discovered over 4000 years ago, is that moist clay, as it comes out of the ground, can be formed into objects and fired in kilns to make durable products. During the firing, organic materials burn off and chemical changes take place between the inorganic materials, forming a combination of crystalline and vitreous phases that contribute to the attributes of the final product[11]. This process involves phase changes and chemical reactions that consume both time and energy. Although brick manufacturers have endeavored to reduce both the time and energy needed to make bricks, these processes are limiting factors.[12]

In Portland cement manufacturing, raw materials are loaded into kilns and fired at temperatures exceeding 3000 F to form "clinker," which is then ground to powder and mixed with aggregates to make concrete. As with brick manufacturing, a complex chemical process takes place during the manufacture of Portland cement. One of primary reactions that takes place is the calcining of calcium carbonate, the largest single ingredient in Portland cement. Again, the calcining and chemical reactions take a certain amount of time and significant energy to achieve.

In contrast, the process for sintering glass particles is simply a viscosity change. Glass is, by definition, an amorphous, or non-crystalline, material. It has been called an "infinitely viscous liquid." No phase change is required to turn it from having the properties of a solid to that of a liquid. As heat is applied, it simply reduces the viscosity of the glass, making it softer, then runny. If no crystals form, the reaction is completely reversible and the heat is theoretically completely recoverable. The technical challenge is in finding ways to get the heat to penetrate the particles more quickly. In the longer term, this may be accomplished with microwaves. There is no material barrier to be overcome in the form of chemical transformation or phase change.

4.5.2 Energy Calculations for Commercial Products

The average energy consumption for brick manufacturing is estimated to be 20,100 btu per square foot of 1 5/8" thick clay paving brick[13].

The average energy consumption for the manufacture of the Portland cement in one square foot of 2.5" thick concrete (5000 psi) is 10,750 Btu[14]. Aside from energy use during manufacturing, the process of calcining lime in the cement kiln generates significant amounts of CO_2, an important greenhouse gas[15]. The Portland Cement Association estimates the figure at 250 pounds of CO_2 per cubic yard of concrete. That translates to 1.9 pounds of CO_2 per square foot of 2.5" concrete paver. In the northeastern United States, 1.9 pounds of CO_2 is equivalent to the CO_2 generated by the combustion of 16 cubic feet of natural gas, generating 16,000 Btu[16]. Therefore, a case can be made that the manufacture of the Portland cement used to make one square foot of 2.5" paving generates greenhouse gases equivalent to the generation of 26,750 Btu.

In addition, the University of British Columbia has estimated that 360 pounds of total particulates are emitted per ton of cement produced during the manufacturing process[17]. There are also the unquantified casual dust emissions during the handling of cement during mixing and finishing.

4.5.3 Glass Properties

In firing glass pavers, both the mold and the glass need to be heated. Approximate values for specific heat of the major constituents are as follows[18]:

Glass	0.20	Btu/(lb.- F)
Porcelain grog	0.26	Btu/(lb.- F)
Alumina cement	0.27	Btu/(lb.- F)

The approximate ratios of mold and glass, by weight, are:

Glass	74 percent
Porcelain grog	19.5 percent
Alumina cement	6.5 percent

The expected specific heat of the glass/mold combination is therefore

0.74 (0.20) + 0.195 (0.26) + 0.065 (0.27) = 0.22 Btu/(lb.- F)

At 14 pounds per square foot, each glass/mold combination would weigh 18.9 pounds. The heat required to fire that 18.9 pounds from ambient (70 F) to 1650 F would therefore be:

(1650-70) F x0.22 Btu/(lb.- F) x 18.9 lbs. = 6600 Btu per square foot.

Table 6 below summarizes the findings to date on greenhouse gases associated with the production of glass, clay, and concrete pavers:

Clay brick	20,100
Concrete paver	26,750
Glass paver (theoretical)	6,600
Glass paver (best batch experiment to date)	18,400
Glass paver (best belt kiln experiment to date)	14,900

Table 6 - CO_2 emissions in Equivalent Btu per Square Foot

4.5.4 Batch Kiln Experiment

An experiment was run in the batch kiln firing 6 square feet of glass in molds. The total weight of the glass and molds in the kiln was 48,000 grams (106 lbs.). The glass was fired from ambient (60 F) to 1650 F. The kiln draws 52 amps of 240 volt single phase power. The heat capacity of the batch kiln is therefore:

52 amp x 240 volts = 12.5 kw = 42,500 Btu/hour

Firing the kiln with 6 square feet of molds required 2 hours 36 minutes (2.6 hours) of kiln "full on" time. Firing the kiln empty on the same profile required 1 hour and 39 minutes (1.65 hours.) The difference in energy used was therefore:

(2.6-1.65 hours) x 42,500 Btu/hour = 40,375 Btu

The derived specific heat was therefore:

40,375 Btu/[105.5 lbs. x (1650-60) F] = 0.24 Btu/(lb.- F)
which is remarkably close to the derived value of 0.22.

The energy cost per square foot was:

(2.6 hours x 42,500 Btu/hour)/ 6 square feet = 18,400 Btu/square foot.

Therefore, using only a small batch kiln, glass pavers have already been fired using less energy than large brick manufacturers use to make brick and generating less greenhouse gas than Portland cement manufacturers generate in the production of an equivalent amount of Portland cement.

As noted above, the bottleneck in this process is simply the ability to transfer heat into the glass. In order to see how the fusing process was proceeding inside the glass, a thermocouple was placed inside the mold during firing. Figure 8 below shows the temperatures both inside the kiln and inside the mold. The temperature inside the mold lags the kiln ambient temperature throughout the firing. However, as the kiln "soaks" at 1650 F, the mold temperature approaches the kiln temperature. The optimal profile will be one in which the kiln is held at the maximum temperature only long enough to achieve full fusing of the glass. Additional tests are being performed, incrementally decreasing the time held at temperature until the optimal point is found.

Another set of experiments was run to see how energy use in the kiln correlated to the optimal firing schedule. An instrument to record the time the relay on the kiln was energized was attached to the kiln. The kiln "full-on" time was then recorded for a kiln containing six square feet of paving. Then the same kiln profile was run with the kiln empty. Figure 9 shows the temperature profile and the percentage "on-time" for the kiln relay with the kiln empty and full.

Figure 9 is very instructive for understanding the energy consumption of the kiln during firing. The area between the "empty kiln" and "full kiln" curves represents the energy actually going into firing the glass. The area below the "empty kiln" curve is "waste heat," going into heating the kiln box. It is obvious that the process is far less than fifty percent efficient. In addition, looking at the right extreme of the graph, notice how the empty kiln and full kiln lines approach each other. This indicates that the glass inside the molds is approaching the ambient temperature of the kiln, and is therefore "done." A possible kiln strategy would be to cook the glass "like a turkey." That is, have a thermocouple inside one of the molds determine when to shut the kiln off as soon as the glass reaches fusing temperature.

4.5.5 Batch Kiln Simulation

When the empty kiln was running at steady-state at a temperature of 1650 F, the electrical contact was energized, on average, 2 minutes and 12 seconds (2.2 minutes) out of 5 minutes.

Therefore, the energy needed to keep the box hot is:

(2.2/5) x 42,500 Btu/hour = 18,700 Btu/hour

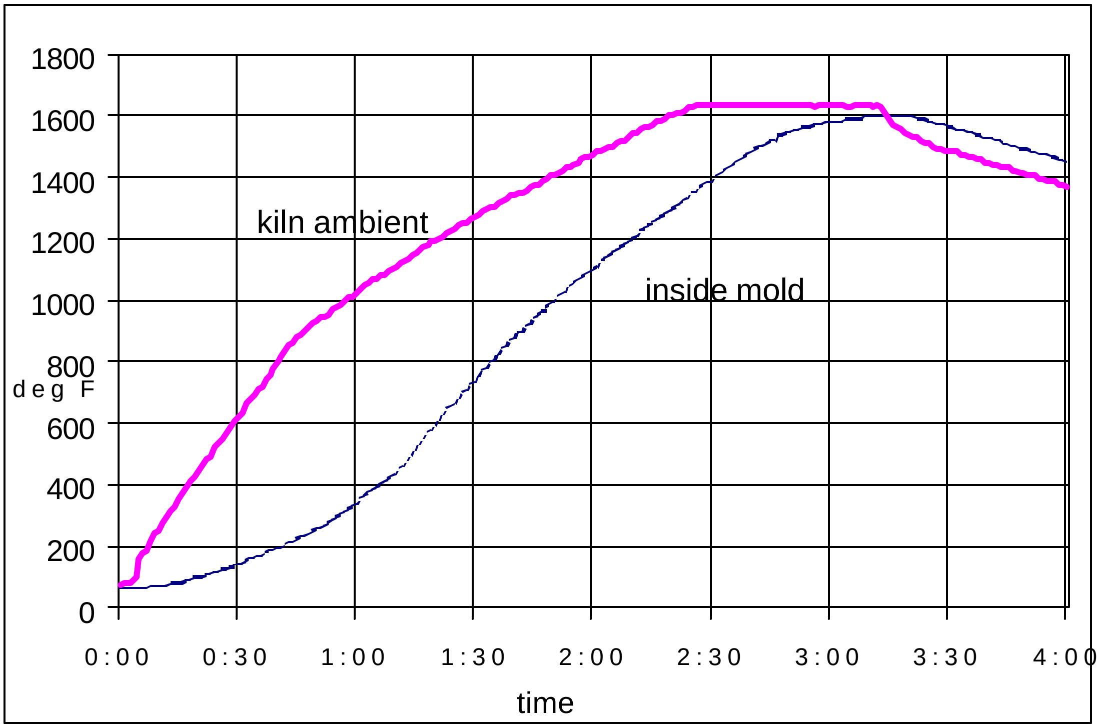


Figure 8 - Temperature Profile Inside Mold and Kiln Ambient

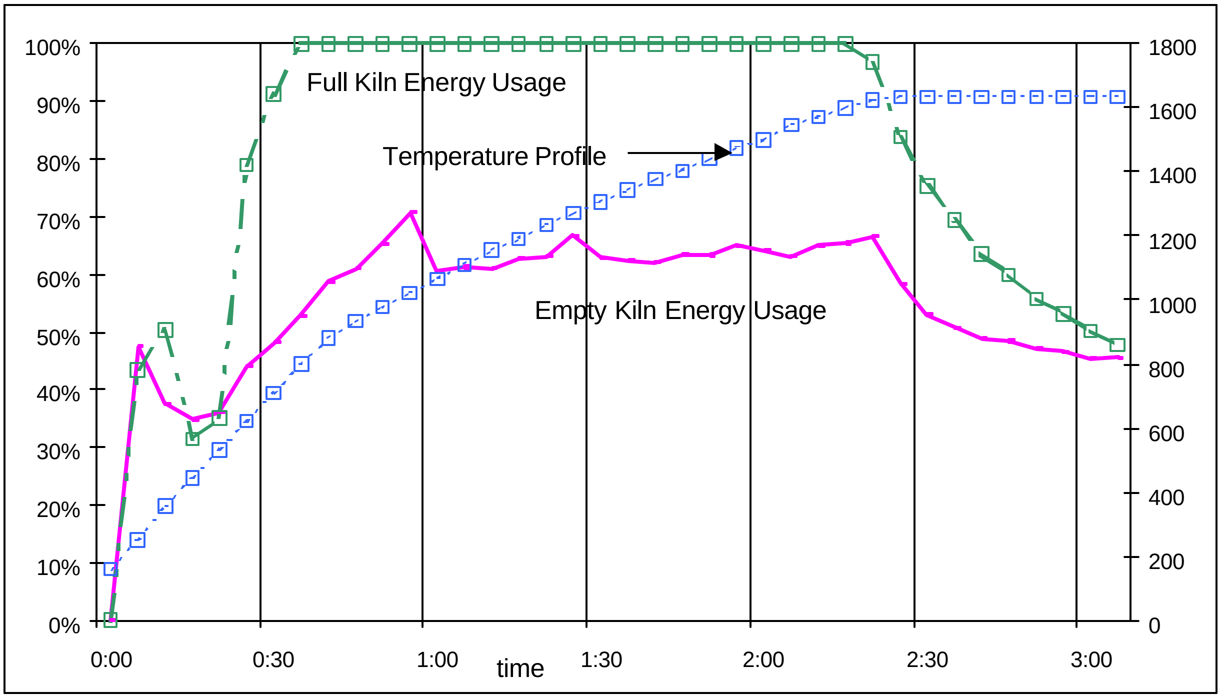


Figure 9 - Energy Use During Empty and Full Firing.

The scale on the left shows percentage "full-on" time in 5 minute increments.
The scale on the right shows kiln temperature (F).

Using the 40,375 Btu figure found in Section 4.5.4 to fire 6 square feet, the time to fire should be:

(40,375 Btu)/(42,500 - 18,700)Btu/hour = 1.7 hours (1 hour 42 minutes)

And the energy used in that time would be:

1.7 hours x 42,500Btu/hour = 72,250 Btu

The energy cost per square foot would then be:

72,250Btu / 6 square feet = 12,000 Btu per square foot.

An experiment was then performed with the batch kiln, using it like an intermittent kiln. The kiln was preheated to 1650 F. Then the top was lifted only far enough to insert two molds full of glass. It was not possible to hold the top open long enough to insert the full kiln load of 6 square feet. Then the kiln was closed and the glass with molds was fired for 90 minutes at 1650 F. The glass bricks were then broken to determine the fused strength. The fused strength was within one standard deviation of expected strength. This supports the derivation above of the potential for using intermittent kilns to save energy.

To reiterate, a batch kiln simulation of a continuous process indicated that the pavers should be able to be made at an energy cost no greater than 12,000 Btu per square foot.

4.5.6 Continuous Kiln Energy Use

Sandhill Industries of Fairbanks, Alaska, owns an electric belt kiln which they use to manufacture glass tile. Sandhill would like to keep as proprietary the details of the construction of that kiln. However, the kiln is typical of belt kilns in that there is an insulated, heated box through which molds containing glass are carried on a belt. One of the advantages of belt kilns is that the insulated box only needs to be heated once. Then the ware to be fired moves through the heated space, saving the energy to bring the box up to temperature for each firing.

The belt kiln is on a separate electrical service, so it was simple to time take readings on the wattmeter while using a stopwatch. The kiln was operated at capacity for two hours to make certain it was stable. Then the kiln was operated at capacity filled with glass and molds for 70 minutes while the wattmeter was monitored. The energy consumption of the kiln was 37.3 kilowatt-hours per hour, which equals 127,268 Btu/hr. The total weight of glass and molds produced weighed 149.9 pounds.

Using the figure of 105.5 pounds of glass and mold to make 6 square feet of finished paver in the batch example above, the 149.9 pounds produced through the belt kiln is the equivalent of 8.5 square feet. The average energy consumption is therefore:

14,900 Btu per Square Foot of Glass Paver

To confirm these results, the kiln was operated empty. The same belt speed and temperature were maintained. The only difference was that no molds or glass were put through. The electricity consumed when the kiln was operated empty was 20.9 kilowatt-hours per hour, which equals 71,326 Btu/hr. It can be assumed that the energy actually put into the glass tile is therefore 127,268 - 71,326 = 55,942 Btu/hr.

It has been found that the pavers can be made in the belt kiln at an operating temperature of 1600 F. As a check to these calculations, the derived specific heat of the glass and mold combination is therefore (55,942 Btu)/((149.9 lbs.)(1600-70 F)) =0.24 Btu/lb.- F. This is remarkably close to the derived value of 0.22 Btu/lb.- F.

The figure of 14,900 Btu per square foot found in this experiment is significantly greater than the 12,000 Btu per square foot developed in the batch kiln simulation in section 4.5.5. The single greatest reason for the disparity may be due to the fact that the batch kiln is insulated with three inches of lightweight insulation, while the belt kiln tested has only two inches of lightweight insulation.

5.0 SUMMARY OF ADDITIVE EFFECTS

Summarizing the findings of this study, an additive was tested which, when added to glass particles that are heated to fusing temperatures, improves the firing characteristics of glass pavers in the following manner:

- Creates a eutectic with soda lime glass
- Maintains lower viscosity over time as well as temperature
- Appears to inhibit volatilization of sodium

In small percentages, the additive results in improved strength of fused products. It also improves the appearance of products made from mixed color glass by lightening the murky color.

In addition, the additive appears to buffer incompatibilities from contamination in the glass. When fused into solid products, the surface of mixed color glass often exhibits small circular cracks, indicating that incompatible particles are present. These may be grains of inorganic material like sand or dirt. Because they have coefficients of thermal expansion dramatically different from glass, they create tension upon cooling and fracture small pieces of glass. With the additive, these cracks are no longer seen. It is possible that the very small grain-size of the additive acts as a buffer between the inorganic incompatibles and the glass.

6.0 ECONOMIC INFORMATION

Two economic models are developed here, one for batch manufacturing and one for continuous manufacturing of glass pavers. The equipment and operations are described, then approximate costs for setting up a shop or plant are developed. These models and costs are based on experience, networking, and phone calls. They should taken as a starting place for further business planning and more detailed cost analysis.

6.1 Description of the Process

Whether the manufacturing is done in a batch or a continuous process, the same steps must be followed:

- mix crushed glass with additives
- fill molds with glass mix, level and compact
- place molds into kiln
- remove molds from kiln
- remove pavers from molds
- renew molds
- inspect and pack finished product
- make new molds as required

It is assumed that processed glass can be purchased, grade #8 mesh and finer, for $50 per ton. This would be the same grade of processing as the glass used for this project.

Experience with tile making in both batch and continuous processes has generated experience with the types of equipment available for each function, and the ergonomics associated with each. The equipment list must include:

- Kiln - batch or continuous
- Blender - double cone blenders work well for these materials
- Shaker table - for leveling molds
- Pallet jack
- Hopper-fed automatic weighing feeder
- Storage shelves
- Storage bins
- Work tables
- Digital scales
- Sinks
- Miscellaneous tools

6.2 Cost Analysis of Batch Manufacturing

The model for batch manufacturing is based on an "incremental worker" concept. Each worker is assumed to operate six 4' x 11' kilns. Each square foot mold is 15"x 15", so each kiln will hold 3 x 8 = 24 square foot molds. The kilns are of the type generally called "top hat" kilns. One manufacturer is Denver Kiln, www.denverglass.com.

Experience has shown that it is not difficult for one worker to perform all of the manufacturing tasks to make 6 x 24 = 144 square feet of pavers per day, in square foot pieces. For this model, no administration or management is included. This is only manufacturing cost. Administration and management needs to be integrated with the number of incremental workers an interested party would project.

INCREMENTAL WORKER MODEL

Fixed costs		
kilns	90000	6-4'x10' flat bed kilns @ $15,000
blender	5000	
feeder	5000	
shaker table	2000	
installation	5000	
other fixtures	5000	
tools	5000	
total	$ 117,000	7 years @ 8%
		$22,472 annual cost of capital
Variable costs		
electric/sq.ft.	0.3	15,000 Btu/3400Btu/Kwh x .07/kwh
glass/sq.ft.	0.375	15# x $50/ton/2000#/ton
mold expense	0.2	$5/mold/25 uses
total	**$ 0.88**	**variable costs**
Annual costs		
labor	39600	1.5*$12/hr x 2200 hours
other utilities	2400	$200/month
rent	14400	2000 s.f. * .40/s.f./mo.
total	**$ 56,400**	**annual expenses**
	$ 78,872	**total annual capital costs plus expenses**

Total manufacturing cost per square foot (assuming 5% reject rate)

percent of capacity	gross sales sq.ft./year	**cost/sq.ft.**	sq.ft./day
20%	7,200	**$ 12.45**	28.8
40%	14,400	**$ 6.69**	57.6
60%	21,600	**$ 4.76**	86.4
80%	28,800	**$ 3.80**	115.2
100%	36,000	**$ 3.23**	144

Table 7 - Incremental Worker Batch Manufacturing Costs per Square Foot

Table 6 shows that using batch kilns, the manufacturing cost for making glass pavers would be about $3.23 per square foot. Adding in management and administrative overhead and profit, downtime considerations, etc., an assumption would be that the wholesale cost would be about $6.00 per square foot. Taking retail mark-ups and transportation into account, the minimum retail price for glass pavers made in batch kiln would probably be:

$10 per square foot retail price.

At this price, glass would need to compete with good quality stone. So far, the aesthetics to compete with good quality stone have not been developed.

Figure 10 shows a possible layout for a two-worker shop. The shop is laid out in a 40' x 100' space. If the operation started out in batch production, it might be possible to convert it later, as markets developed, to a continuous production facility. This shop could only be operated on one shift per day because the nature of batch kiln manufacturing of this type would limit the batches to one per day per kiln.

6.3 Cost Analysis of Continuous Manufacturing

The belt kiln model was somewhat of a surprise. The length of a belt kiln is determined by the desired production rate, the width, and the "dwell time" in each section of the kiln. The belt kiln parameters derived below are quite similar to a kiln purchased by a U.S. tile manufacturer within the last year, so the overall price is known to be fairly accurate. The price includes the gas-fired kiln and a conveyor carrying the empty molds back to the beginning of the kiln.

Some of the parameters (electricity per square foot, cost of natural gas) in the model below were derived from a Department of Energy study at a new gas-fired brick manufacturing plant.[19] One of the parameters that was not used because it could not be justified was the brick plant's estimate of less than one labor hour per ton of bricks produced. At 20 pounds per square foot, that corresponds to:

2000 lbs/ton /20 lbs/sq.ft. = 100 sq.ft. per labor hour

In contrast, in the cost model below, four workers, excluding the foreman, are producing 960 square feet of glass paver in an 8 hour shift, or:

960 sq.ft./(4 workers x 8 hours) = 30 square feet per labor hour

Clearly, there is much to be learned from brick plant operations in streamlining the model presented here (see 6.3.1).

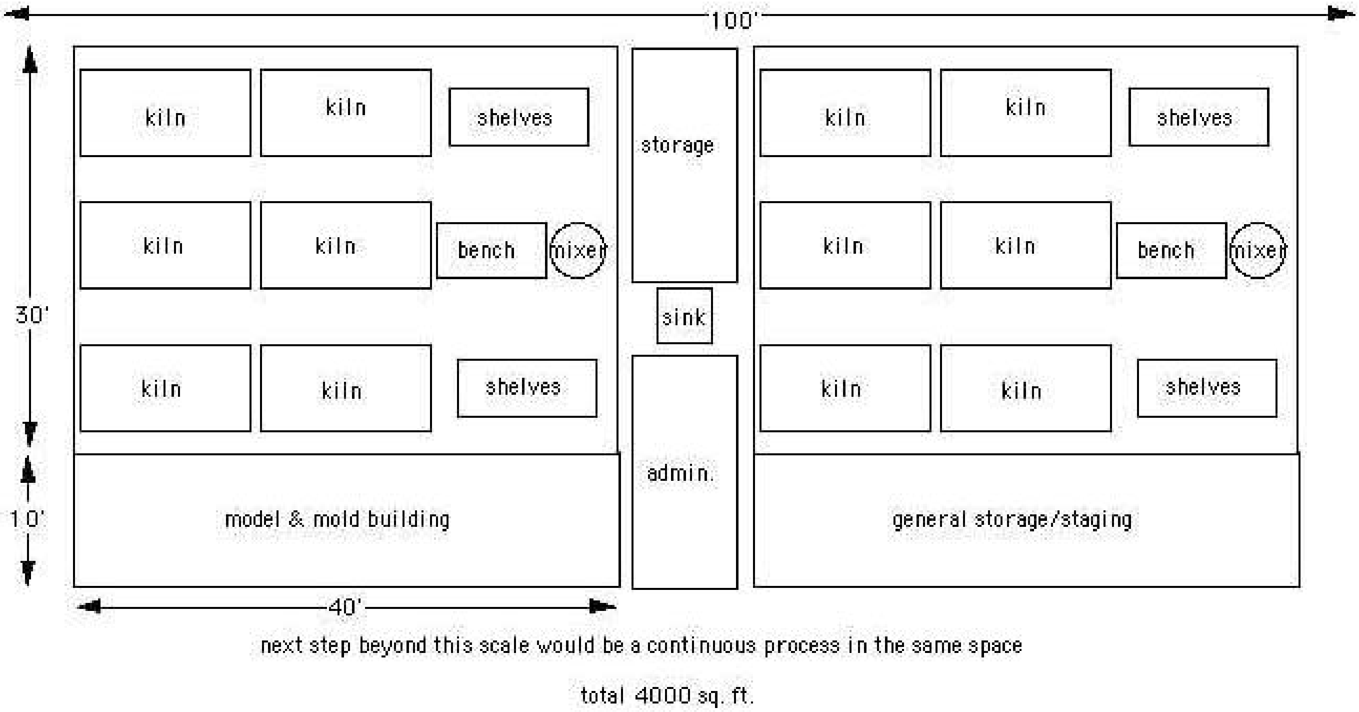


Figure 10 - Possible Kiln Set-Up

Continuous Kiln Cost Model

Belt kiln parameters:

capacity	160 sq.ft. per hour	
belt width	6 feet (4 molds wide)	
time in hot section	60 minutes	
hot section length	50 feet	16"/mold * 40 molds/hr
time in annealing section	60 minutes	
annealing section length	50 feet	
time in cooling section	120 minutes	
cooling section length	100 feet	
overall length	200 feet	
5 workers	1-load	
	1- unload	
	1-mold renewal/misc.	
	1-fill bins/move pallets	
	1- foreman	
effective work shift	6 hours	
production per shift	960 sq.ft.	
facility size	250' x 100'	

Fixed costs			
kilns	$	1,500,000	6 foot belt 200 feet long gas-fired
blender	$	20,000	
feeder	$	50,000	
shaker table	$	10,000	
installation	$	50,000	
other fixtures	$	25,000	
tools	$	25,000	
			7 years @ 8%
total	**$**	**1,680,000**	**$322,682 annual cost of capital**

Variable costs			
gas/sq.ft.		0.06	10,000 Btu/sq.ft. x $6.00/million Btu gas
electric/sq.ft.		0.035	.5 kwh/sq.ft. x .07/kwh
glass/sq.ft.		0.375	15# x $50/ton/2000#/ton
mold expense		0.2	$5/mold/25 uses
total	**$**	**0.67**	**variable costs per sq. ft.**

Annual costs			
labor		158400	4@1.5*$12/hr x 2200 hours
labor		49500	1@1.5*$15/hr x 2200 hours
maintenance		20000	
other utilities		6000	$500/month
rent		90000	25,000 s.f. * .30/s.f./mo.
total	**$**	**323,900**	**annual expenses**
		$646,582	**total annual capital costs plus expenses**

Table 8 – Total manufacturing cost per square foot
(Assuming: one 8-hour shift and a reject rate of 5%)

percent of capacity	gross sales sq.ft./year	**cost/sq.ft.**	sq.ft./shift
20%	48,000	**$ 14.88**	192
40%	96,000	**$ 7.79**	384
60%	144,000	**$ 5.43**	576
80%	192,000	**$ 4.25**	768
100%	240,000	**$ 3.54**	960
tons of glass used/year	1,800		

for 2 shifts: Fixed cost **$ 322,682**
Variable cost **$ 0.67** per square foot
Annual cost **$ 323,900**

percent of capacity	gross sales sq.ft./year	**cost/sq.ft.**	sq.ft./2 shifts
20%	96,000	**$ 7.79**	192
40%	192,000	**$ 4.25**	384
60%	288,000	**$ 3.07**	576
80%	384,000	**$ 2.48**	768
100%	480,000	**$ 2.12**	1920
tons of glass used/year	3,600		

for 3 shifts: Fixed cost **$ 322,682**
Variable cost **$ 0.67** per square foot
Annual cost **$ 323,900**

percent of capacity	gross sales sq.ft./year	**cost/sq.ft.**	sq.ft./3 shifts
20%	96,000	**$ 7.79**	576
40%	192,000	**$ 4.25**	1152
60%	288,000	**$ 3.07**	1728
80%	384,000	**$ 2.48**	2304
100%	720,000	**$ 1.65**	2880
tons of glass used/year	5,400		

It is interesting that, using the kiln for one shift, the cost per square foot is actually somewhat higher than that of batch manufacturing. That is because of the large amount of capital invested in the equipment. So while one of the advantages of the lightweight fiber kilns is that they can be quickly started up and shut down and therefore do not need to be kept heated 24 hours per day, the high capital cost may need three-shift operation.

Because of the higher volume, there would be less administrative cost per square foot for the continuous process. Therefore, operating with three shifts, it may be possible to wholesale the glass pavers at about $3.00 per square foot and have a:

$5 per square foot retail price.

6.3.1 Additional Information on Continuous Manufacturing

Subsequent to the end of this project, a visit was made to a modern brick manufacturing plant. Although all of the production was based on continuous manufacturing, two methods were used to form bricks: extruding and pressing.

In extruding, the clay materials, averaging about twenty percent water by weight, are combined and de-aired in a pug mill, then extruded through a 4 inch by 1 1/2 inch die and cut into standard 8 inch lengths for stacking on kiln cars. In pressing, the drier clay materials, averaging about ten percent water, are fed into a mechanical press and pressed into shape. The bricks made using the pressing method are considered to be of higher quality because less water leads to less shrinkage and the press can form special shapes not possible with the extruder.

According to the plant manager, the press requires about fifty percent more labor per square foot than the extruder, resulting in an average production of 66 square feet per labor hour for pressing compared with 100 square feet per labor hour for extrusion. The process described here for making glass pavers, i.e. pouring a glass mixture into a mold and leveling, would be more like the pressing than the extruding operation. Therefore, the figure of 30 square feet per labor hour used in the continuous production model can probably be safely doubled to 60 square feet per labor hour once the proper automation equipment is installed. In the economic model just presented, this would decrease the estimated cost of production as well as the estimated retail price.

7.0 TRANSFERABILITY OF THIS RESEARCH

Although this project focussed on a specific application of glass with the addition of an additive, much of the information in this report should be of interest to others involved with glass kiln processes.

From an energy perspective, using glass to make durable items has some inherent advantages. One way to look at the process is that in mining the raw materials, transporting them to the glass plant, and making glass from batch (or a combination of batch and recycled glass), the glass container or window manufacturer has done the hard part. That is, the manufacturer has transformed mined crystalline materials into a vitreous state.

Once the material is in a vitreous state, using basic processing and kiln technology, it can be formed and fired into other durable products at only a fraction of the original energy expenditure it took to make it into glass.

Society needs hard, durable materials. Historically, stone was the material of choice for paving and sanitary surfaces. Today, ceramic and concrete surfaces predominate. It seems that hard, durable surfaces are generally made from fired inorganic products. Even stone can be viewed as a product fired in the heat of the planet's natural oven.

Many non-fired materials, especially hydrocarbon products like plastics, have been developed over the century and fill specific applications better than fired products. However, for ultimate hardness and durability, energy inputs are still required in the manufacture of products for some applications. Minimizing the energy inputs to these products will become increasingly important as natural resources become more expensive and as concerns over global warming increase.

8.0 RECOMMENDATIONS FOR FUTURE WORK

8.1 Pilot Plant

The next step is to perform a pilot operation making glass pavers. A pilot plant would answer many of the unknowns in this report, including:

- Can streamlining operations make faster production rates possible?
- Can a properly controlled batch kiln be cycled twice in 24 hours?

Also, market research must be done to determine if there a large enough market at $5 per square foot to support a continuous manufacturing operation?

8.2 Glass Processing Systems

One of the premises of this project was the need to develop uses for mixed color recycled glass containing levels of contamination considered to be typical for post-consumer collections. The processing was performed in basic, inexpensive equipment. With better processing equipment, higher quality and a greater variety of products could be made. Using binders and molds, it may even be possible to make three-dimensional objects like pots.

Better small-scale processing equipment is needed. Ideally, small systems should be available that both size-reduce and clean recycled glass, removing dust and fines and non-glass contamination at a reasonable cost. Additional research to develop this kind of equipment could be useful.

9.0 CONCLUSIONS

This project has confirmed the effect of an additive to glass that improves the properties of glass in fusing processes. The effect had only been observed visually prior to the project. Through this work, it was found that the visual effect is caused by a eutectic involving the oxides of soda line glass and the additive. The eutectic lowers the viscosity of the soda lime glass and helps the glass to maintain its "glassiness" during fusing.

Another discovery made during this project relates more fundamentally to fusing processes and soda lime glass. The surface haze that forms during the fusing of soda lime glass is generally referred to as "devitrification," implying crystal growth enabled by the elevated temperatures used during fusing processes. In fact, it appears that the haze is predominantly caused by the volatilization of some component of the soda lime glass. The volatizing component is assumed to be an oxide of sodium.

Finally, functional paving products were made from glass with the additive. Because of issues of practicality, flexure rather than compression tests were used as the standard for comparison. The result of tests comparing glass with commercial pavers made from bricks and concrete indicated that in flexure 13 pound per square foot glass pavers exceeded the strength of seventeen pound brick pavers and 24 pound concrete pavers. In addition, the glass pavers were made with the investment of 14,900 Btu per square foot, compared with published data of 20,100 for clay bricks and the equivalent of 26,750 Btu for the manufacture of concrete pavers in energy and greenhouse gas emissions.

The following figures contain photos of actual glass pavers made during these tests, how they compare with bricks and concrete pavers and how they can be colored (with metal oxide colorants) and used in forming colorful unitary paving designs.

Figure 11 - Thickness of glass (top), brick (middle) and concrete (bottom) pavers

Figure 12 - Glass (left), brick (middle) and concrete (right) pavers

Figure 13 – Display of 4” x 8” and 12” x 12” colored glass tiles

10.0 APPENDICES

10.1 Appendix A - RESULTS OF FLEXURE TESTS

	Width mm	Thickness mm	Load kN	Fixture Wt Corrected Load (kN)	Test Span mm	Modulus R Mpa	R psi	Weight grams
Red Brick 1	95	40	12.86	12.98	152	13.0	1882	1675
Red Brick 2	95	40	8.97	9.09	152	9.1	1318	
Red Brick 3	95	40	7.00	7.12	152	7.1	1032	
Red Brick 4	95	40	11.11	11.23	152	11.2	1629	
Red Brick 5	95	40	10.18	10.30	152	10.8	1572	
Red Brick 6	95	40	11.78	11.90	152	12.5	1817	
Red Brick 7	95	40	11.88	12.00	152	12.6	1832	
Red Brick 8	95	40	11.48	11.60	152	12.2	1771	
Average	3 ¾”	1 5/8”	10.66	10.78		11.1	1607	
Std Dev			1.89	1.89		2.0	296	

	Width mm	Thickness mm	Load kN	Fixture Wt Corrected Load (kN)	Test Span mm	R Mpa	R psi	Weight grams
Concrete 1	98	60	11.72	11.84	170	5.7	827	2415
Concrete 2	98	59	14.47	14.59	170	7.3	1054	
Concrete 3	98	59	12.75	12.87	170	6.4	930	
Concrete 4	98	59	12.85	12.97	170	6.5	937	
Concrete 5	98	59	10.78	10.90	170	5.4	788	
Concrete 6	98	59	14.87	14.99	170	7.5	1083	
Concrete 7	98	59	10.62	10.74	170	5.4	776	
Concrete 8	no measurement							
Average	3 7/8”	2 1/3”	12.58	12.70		6.3	914	
Std Dev			1.67	1.67		0.9	124	

	Width mm	Thickness mm	Load kN	Fixture Wt Corrected Load (kN)	Test Span mm	R Mpa	R psi	Weight grams
1600F-0%-1	101.5	21	5.07	5.19	160	18.6	2691	988
1600F-0%-2	101.5	21	6.38	6.50	160	23.2	3370	
1600F-0%-3	101.5	21	4.77	4.89	160	17.5	2536	
1600F-0%-4	101.5	21	5.41	5.53	160	19.8	2867	
1600F-0%-5	101.5	21	4.79	4.91	160	17.6	2547	
1600F-0%-6	101.5	21	5.14	5.26	160	18.8	2726	
1600F-0%-7	101.5	21	4.84	4.96	160	17.7	2571	
1600F-0%-8	101.5	21	4.57	4.69	160	16.8	2433	
Average	4”	7/8”	5.12	5.24		18.7	2717	
Std Dev			0.57	0.57		2.0	296	

	Width mm	Thickness mm	Load (kN)	Fixture Wt Corrected Load (kN)	Test Span mm	R Mpa	R psi	Weight grams
1600F- 1%-1	101.5	21	5.05	5.17	170	19.6	2849	995
1600F- 1%-2	101.5	21	4.68	4.80	170	18.2	2644	
1600F- 1%-3	101.5	21	4.48	4.60	170	17.5	2536	
1600F- 1%-4	101.5	21	4.79	4.91	170	18.6	2704	
1600F- 1%-5	101.5	21	4.33	4.45	170	16.9	2452	
1600F- 1%-6	101.5	21	4.96	5.08	170	19.3	2798	
1600F- 1%-7	101.5	21	4.13	4.25	170	16.1	2338	
1600F- 1%-8	101.5	21	3.97	4.09	170	15.5	2250	
Average	4”	7/8”	4.55	4.67		17.7	2571	
Std Dev			0.39	0.39		1.5	215	

	Width mm	Thickness mm	Load kN	Fixture Wt Corrected Load (kN)	Test Span mm	R Mpa	R psi	Weight grams
1600F- 2%-1	101	21	3.90	4.02	160	14.4	2092	969
1600F- 2%-2	101	21	2.76	2.88	160	10.4	1502	
1600F- 2%-3	101	21	2.32	2.44	160	8.8	1273	
1600F- 2%-4	101	21	3.56	3.68	160	13.2	1915	
1600F- 2%-5	101	21	3.93	4.05	160	14.5	2108	
1600F- 2%-6	101	21	2.65	2.77	160	9.9	1441	
1600F- 2%-7	101	21	2.65	2.77	160	10.0	1445	
1600F- 2%-8	101	21	2.63	2.75	160	9.9	1434	
Average	4”	7/8”	3.05	3.17		11.4	1651	
Std Dev			0.64	0.64		2.3	332	

	Width mm	Thickness mm	Load kN	Fixture Wt Corrected Load (kN)	Test Span mm	R Mpa	R psi	Weight grams
1650F-0%-1	101	21	4.99	5.11	170	19.5	2830	979
1650F-0%-2	101	21	6.21	6.33	170	24.1	3502	
1650F-0%-3	101	21	7.74	7.86	170	30.0	4349	
1650F-0%-4	101	21	4.88	5.00	170	19.1	2769	
1650F-0%-5	101	21	4.70	4.82	170	18.4	2668	
1650F-0%-6	101	21	5.49	5.61	170	21.4	3103	
1650F-0%-7	102	21	6.50	6.62	170	25.0	3628	
Average	4”	7/8”	5.79	5.91		22.5	3264	
Std Dev			1.10	1.10		4.2	603	

	Width mm	Thickness mm	Load kN	Fixture Wt Corrected Load (kN)	Test Span mm	R Mpa	R psi	Weight grams
1650F- 1%-1	101	21	7.48	7.60	152	25.9	3759	999
1650F- 1%-2	101	21	6.19	6.31	152	21.5	3124	
1650F- 1%-3	101	21	4.65	4.77	152	16.3	2363	
1650F- 1%-4	101	21	7.09	7.21	152	24.6	3570	
1650F- 1%-5	101	21	6.88	7.00	152	23.9	3464	
1650F- 1%-6	101	21	7.61	7.73	152	26.4	3825	
1650F- 1%-7	102	21	6.43	6.55	152	22.1	3212	
1650F- 1%-8	102	21	6.67	6.79	152	22.9	3327	
Average	4”	7/8”	6.63	6.75		23.0	3331	
Std Dev			0.93	0.93		3.2	462	

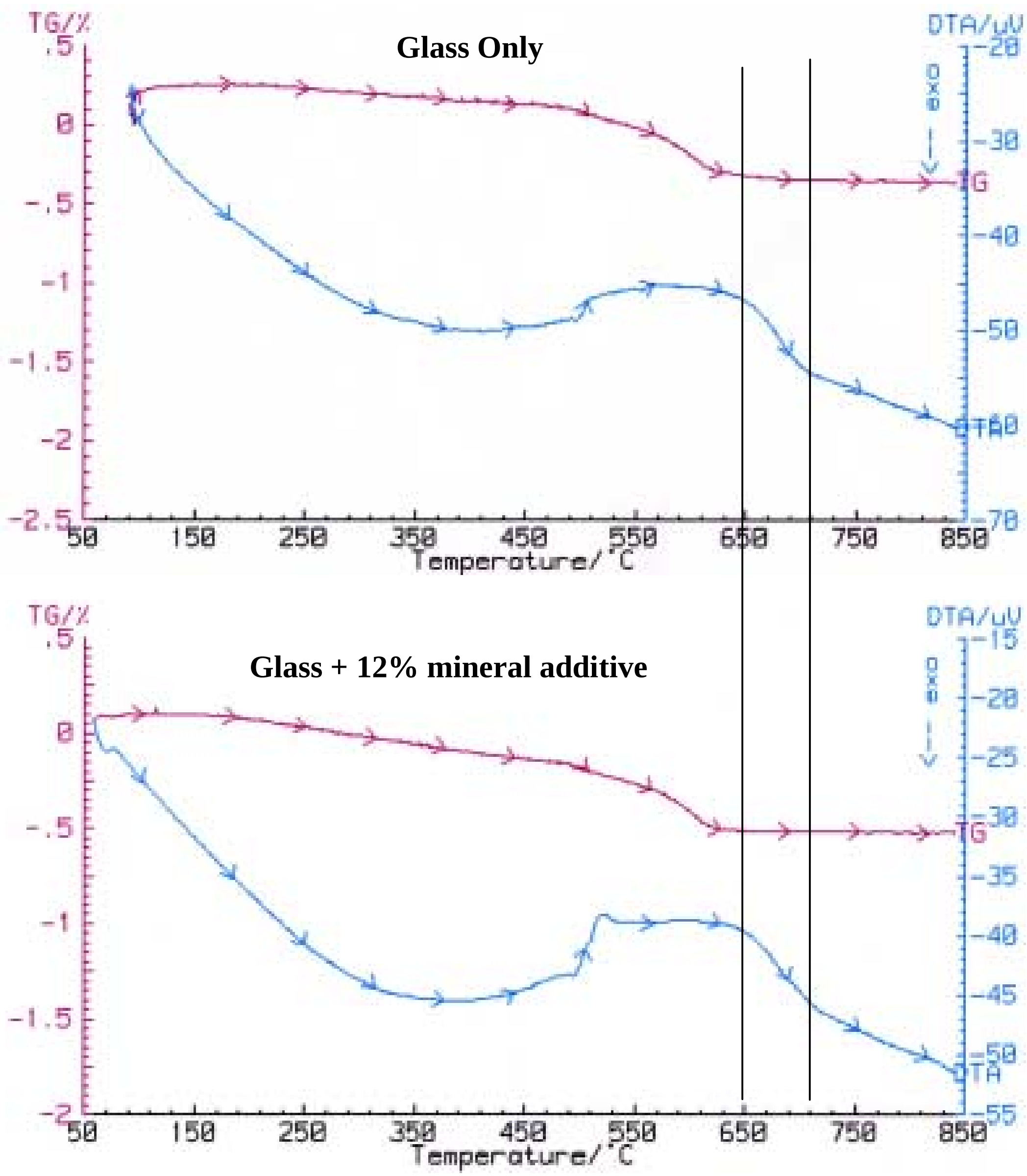
	Width mm	Thickness mm	Load kN	Fixture Wt Corrected Load (kN)	Test Span mm	R Mpa	R psi	Weight grams
1650F- 2% -1	100	21	5.30	5.42	152.4	18.7	2716	989
1650F- 2% -2	100	21	5.89	6.01	152.4	20.8	3011	
1650F- 2% -3	101	21	5.49	5.61	152.4	19.2	2783	
1650F- 2% -4	101	21	4.42	4.54	152.4	15.5	2250	
1650F- 2% -5	101	21	5.13	5.25	152.4	18.0	2605	
1650F- 2% -6	101	21	6.04	6.16	152.4	21.1	3056	
1650F- 2% -7	101	21	5.78	5.90	152.4	20.2	2928	
1650F- 2% -8	101	21	5.32	5.44	152.4	18.6	2701	
Average	4”	7/8”	5.42	5.54		19.0	2756	
Std Dev			0.51	0.51		1.8	259	

			force by top fixture (kN)
Al - top fixture:	9cmx15.5cmx23cm	3208.5	0.120

	Width mm	Thickness mm	Load kN	Fixture Wt Corrected Load (kN)	Load lbs	Test Span mm	R (psi) psi	Weight grams
1650F-0.25%-1	102	26	13.48	13.54	2979	152	4329	1250
1650F-0.25%-2	102	26	11.97	12.03	2647	152	3846	
1650F-0.25%-3	102	26	12.11	12.17	2677	152	3891	
1650F-0.25%-4	102	26	12.75	12.81	2818	152	4122	
1650F-0.25%-5	102	26	13.93	13.99	3078	152	4532	
1650F-0.25%-6	102	26	12.53	12.59	2770	152	4105	
1650F-0.25%-7	102	26	13.77	13.83	3043	152	4538	
1650F-0.25%-8	102	26	13.79	13.85	3047	152	4574	
Average	4”	1”	13.04	13.10	2882		4242	
Std Dev			0.80	0.80	175		293	

	Width mm	Thickness mm	Load kN	Fixture Wt Corrected Load (kN)	Load lbs	Test Span mm	R (psi) psi	Weight grams
1650F-0.0%-1	102	26	11.94	12	2640	152	3837	1225
1650F-0.0%-2	102	26	12.53	12.59	2770	152	4025	
1650F-0.0%-3	102	26	13.01	13.07	2875	152	4179	
1650F-0.0%-4	102	26	14.67	14.73	3241	152	4709	
1650F-0.0%-5	102	26	12.79	12.85	2827	152	4108	
1650F-0.0%-6	102	26	13.95	14.01	3082	152	4479	
1650F-0.0%-7	102	26	12.74	12.8	2816	152	4092	
1650F-0.0%-8	102	26	9.79	9.85	2167	152	3149	
Average	4”	1”	12.68	12.74	2802		4072	
Std Dev			1.45	1.45	318		462	

10.2 Appendix B – Differential Thermal Analysis Graphs



Appendix B:

Differential Thermal Analysis Results

vertical lines depict critical 650 F - 710 F temperature range

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