Testing of Recycled Glass and Inorganic Binder Paving Tiles

RECYCLING TECHNOLOGY ASSISTANCE PARTNERSHIP
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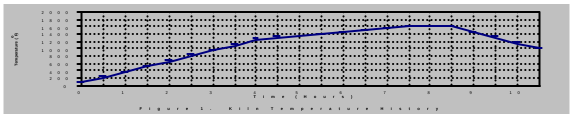

Figure 1. Kiln Temperature History

TESTING OF RECYCLED GLASS AND INORGANIC BINDER PAVING TILES

FINAL REPORT

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CWC is a nonprofit organization providing recycling market development services to both businesses and governments, including tools and technologies to help manufacturers use recycled materials. CWC is an affiliate of the national Manufacturing Extension Partnership (MEP) – a program of the US Commerce Department's National Institute of Standards and Technology. The MEP is a growing nationwide network of extension services to help smaller US manufacturers improve their performance and become more competitive. CWC also acknowledges support from the US Environmental Protection Agency and other organizations.

On this project, the CWC especially acknowledges the work of Steven Resnick and Professor Gregory MacRae for their hard work on this project. The CWC also offers its sincere apologies to those two individuals for the delay in producing this finished work. The report was misplaced during the transition from a state agency to a non-profit and was only recently discovered. Nonetheless, this is important work to have as part of the recycled glass applications literature.

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INTRODUCTION

Post-consumer recycled glass collections have grown faster than the infrastructure that exists to use it. Therefore, the development of alternative uses for post-consumer recycled glass is critical to the economic viability of an increasing number of recycling programs. This project tested glass and inorganic binder paver tiles made from mixed-color recycled glass for strength and absorption in order to assess the tiles' fitness for use.

This report:

- gives some background information on previous research done on recycled glass tiles;
- describes methods used in the production of the recycled glass tiles tested in this study;
- describes the tests performed on the tiles;
- gives the results of the tests; and
- discusses implications of the study for potential production.

1.0 GLASS CHARACTERISTICS

1.1 GLASS

The tensile strength of glass rods or fibers drawn in a vacuum may be as high as 6200MPa (900,000psi), and plate glasses may have strengths as high as 173MPa (25,000psi). The tensile strength of ordinary soda lime glass is usually about 70MPa (10,000psi). However, sand blasted glass, in which many flaws have been created, has a strength of only 14MPa (2000psi). These data demonstrate that highly polished and flawless glass has much higher tensile strength than glass with surface flaws. Fracture mechanics has demonstrated that surface flaws concentrate stress, causing failures at lower tension than would be expected with flawless surfaces. This phenomenon is mentioned because the samples tested during this project have body composition very close to solid glass. It will be demonstrated that the tensile strength of these materials approach that of solid glass which has been sandblasted.

The modulus of elasticity of the glass is in the vicinity of 65,500MPa (10,000ksi), which is approximately one-third that of steel and three times that of normal strength portland cement concrete. (Cordon, 1979 and Felbeck and Atkins, 1984).

1.1.1 Previous work with Recycled Glass

Previous work with recycled glass has involved the development of processes for manufacturing paving or mosaic tiles from sintered recycled glass. Brown and MacKenzie (1982) used powdered glass and up to 10% clay binder to form a composite material. Clay binder was necessary to give a “green” strength for transfer to the kiln before final firing. It was found that green strength was affected by the amount of clay binder, particle size, pressing pressure and amount of water. Fired strength was shown to be considerably greater than that of commercial clay based tiles. Higher stiffness and strength were obtained with smaller particles, less water and binder, and greater pressing pressure. Pressing pressure ranged from 10MPa (1500psi) to 40MPa (5800psi). Binder content ranged from 4% to 20%. Kiln heating rates of between

100º C/hr and 350º C/hr (180º-630º F/hr) gave essentially the same properties, while lower rates resulted in lower strength and stiffness. Slow cooling was important. The strength and stiffness of the samples was greatest when the peak kiln temperature was between 920° C and 950º C (1688º F -1742º F). The maximum modulus of rupture was found to be approximately $4.8x10^6kg/m^2$ (47.1MPa; 6800psi).

The making of mosaic glass from ground waste glass is described by Liu, Li, and Zhang (1991). They used several types of chemical binder to produce mosaic glass of the required texture. The glass was formed into samples and sintered by firing at 640° C - 800º C (1,184° F - 1,472º F) for 30 minutes before slow cooling. The tiles fired at temperatures of 720ºC (1,328º F) had bending strengths which were 1.90-3.22 times stronger than those fired at 640º C (1,184º F), and that strength tended to increase with firing temperature. The maximum bending strength obtained was $10.56kg/cm^2$ (1.04MPa or 150psi). Specimens fired at 640º C (1,184º F) had water absorption of up to 5.25%, while those fired at temperatures at least 720º C (1,328º F) had no appreciable absorption.

In contrast with both of the projects above, this project tested tiles made without pressing. Rather, vibratory compaction was used to obtain adequate density before firing.

2.0 SAMPLE TILE PRODUCTION

Much of the work was accomplished by using a standard mix to make a standard test tile with approximate fired dimensions of 14" x 4" x 1". The approximate fired weight was 1850g.

2.1 STANDARD MIX INGREDIENTS

2.1.1 Glass

The glass component was a combination of coarse and fine particle gradations. In this report, the terms coarse and fine designate particle size with reference to a US#200 sieve. Fine particles pass through a US#200 sieve, whereas coarse particles are retained on this sieve. For the standard mix, only one range of coarse glass particle sizes was used. These particles passed through a US#6 sieve and were retained on a US#16 sieve. The notation “A x B” is used to mean particles passing a US#A sieve and retained on a US#B sieve. The coarse component is therefore described as 6x16. The fines are described as "collector dust," which are a waste resulting from the manufacture of plate or “flat” glass. The coarse component was green, while the fines from the plate glass were clear. All of the glass was of the soda-lime variety.

2.1.2 Binder

The tiles included a small amount of inorganic binder. The amount added was 2.7% by weight of the glass component. The glass component in the standard mix was 1800 grams. Inorganic Binder #1 (IB1) was 2% by weight of glass, or 72g, and the inorganic binder #2 (IB2) was 0.7%, or 13g.

The binder gave the specimens enough green strength after drying to allow handling after being removed from the mold. This enabled the mold to be removed before the kiln firing. Therefore, the mold can be made from any material that can withstand a 200º F drying chamber. Additionally, the refractory nature of the inorganic binder helped the material to maintain its shape during the firing process. Although the glass component gave the material its fired strength, the binder also effects the sintering process. Therefore, the fired strength was influenced by the amount and type of binder. Specifically, the binder can inhibit the sintering process. A balance is required between the amount of binder needed for workability (for green strength and to maintain specimen shape during firing) and the amount that will severely diminish the fired strength.

2.1.3 Water

To achieve the desired consistency of the mixture, a quantity of water was added. The quantity of water added in the standard mix procedure was 250 grams; this equaled 13.9% by weight of the glass.

2.1.4 Salt

The addition of a small amount of a salt helped to reduce the tendency of the water to "pool" on the surface of the material in the mold. The salt acted as a "deflocculant," which inhibited the clumping of the smaller particles, kept them in suspension, and enabled the water to be held within the material as it was leveled in the mold. The result was a better mixture between coarse and fine particles, which increased the particle packing efficiency.

2.2 STANDARD MIXING PROCESS

The production process was designed to be as uncomplicated and reproducible as possible. Much of the process involved readily available and non-specialized tools and equipment.

More closely packed particles reduce shrinkage and produce a stronger fired product. Thus, it was desirable to find the combination of coarse and fine particles that would yield the densest packing of the two gradations. The 3 to 1 ratio of coarse to fine particles was arrived at in the following manner. Maintaining a total mass of 400 g, various combinations of coarse and fine (e.g. 350 coarse, 50 fine; 325 coarse, 75 fine) particles were mixed and placed in a long graduated tube with an internal diameter of 1 inch (25.4 mm). The tube itself was then raised and tapped down 200 times from a height of 2 inches onto a piece of foam-backed carpet. The combination of coarse and fine glass that tapped down the most was found to be the 300g coarse and 100g. Respectively, the particle packing efficiency was then estimated using a specific gravity for glass of 2.5. Knowing the volume occupied by the mixture (from the graduated tube) and the mass (fixed at 400g), a bulk density, ρ_{bulk}, of the mixture was calculated and compared to the density of solid glass, ρ_{glass}. The particle packing efficiency, defined as ρ_{bulk}/ρ_{glass}, for this combination of fines and coarse gradations was 60%.

Initially, the two gradations of glass particles, coarse and fine, were measured in a 3 to 1 ratio; 1350 g of coarse and 450 g fine glass. The powdered binder consisted of 2% by weight or 72g of inorganic binder #1 and 0.7% by weight or 13g of inorganic binder #2.

The three dry ingredients were mixed in a rock tumbler. The water to be added, 13.9 % by weight or 250 g, was then measured. One-quarter teaspoon of a salt was mixed into the water using a standard kitchen blender. The water/salt mixture was then added to the dry ingredients in a bowl and mixed by hand.

After all of the ingredients had been mixed, they were placed in a mold on a shaker table. The mold was lightly lubricated with vegetable shortening to ease "demolding." The table was then activated and the material settled in the mold. The top surface of the specimen was smoothed using a common paint scraper. Brown et al (1982) showed that increasing the pressing pressure on the material from 10MPa (1.450psi) to 40 MPa (5800psi) produced a 14% increase in fired strength. However, the process under consideration required only vibratory compaction under gravity.

2.3 STANDARD FIRING

The mold and material were placed in the kiln and dried at 150° F (66° C) for ten hours. The lid of the kiln was left open during drying. After drying, the specimen had enough strength, referred to as “green strength”, to be handled. After the specimen was removed from the mold, it was returned to the kiln. Firing the tiles involved heating them to a peak temperature of 1600° F (871° C), holding for one hour, and cooling. Figure 1 shows the temperature history. The temperature within the kiln was controlled by using an
electronic controller.

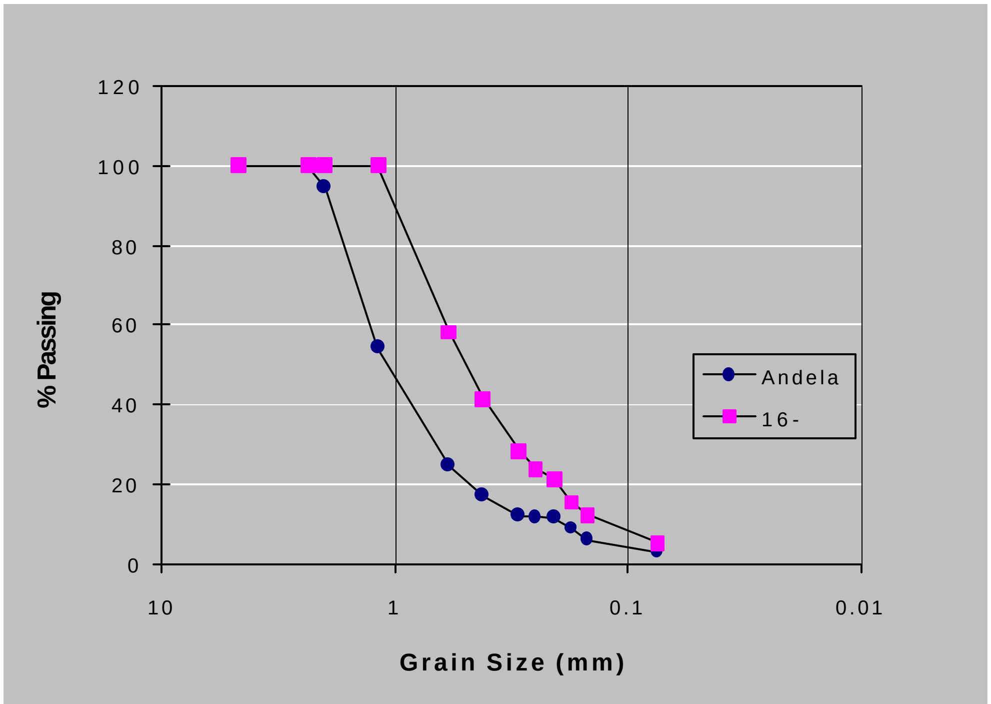


Figure 2. Typical Grain Size Distribution

The firing temperature was chosen to cause the glass particles to fuse by heating and bonding without melting. The goal was to achieve a fired body that would not absorb water and have high strength, a process called sintering. The sintering temperature is several hundred degrees less than the temperature required to fully melt the glass but some softening does occur, as described by Shackelford (1992) below:

“The material...is formed by the densification of a powder. The bonding of powder particles occurs by solid-state diffusion. In the course of this densification stage, the pores between adjacent particles steadily shrink. This overall process is known as sintering. The mechanism of shrinkage is the diffusion of atoms away from the grain boundary (between adjacent particles) to the pore. In effect, the pore is “filled in” by diffusing material.” (Shackelford, p.298).

The kiln used to fire our test samples was oval shaped (plan view) and 27 inches deep. Up to six shelves could be stacked vertically, and each shelf contained a number of specimens.

2.4 MIX VARIATIONS

For a full description of the production parameters for all the test specimens, see Appendix A, Table 1. Note that the parameters which differ from the standard mix are shown in bold face. The last column of the table indicates the variable that was being examined for each batch.

2.4.1 Variation of the Glass Component

As glass was the largest component of the tiles, much of the experimentation involved variation in the color of glass, the coarse/fine ratio and the size-gradation of the coarse particles.

The glass color for the coarse component of each batch is given in the third column of Table 1. The colors used for the coarse component included green, clear, amber and mixed. Mixed color glass in this case is referred to as “Andela” glass. The number of different gradations is given in the fourth column. The fines were generally clear glass, although amber fines were substituted for some batches.

Some important batch differences:

- In the production of Batches 3 and 20, mixed color Andela glass with a gradation of “#8 minus” (all of the particles passed a US#8 sieve) was used as the coarse component. The hole size of the US#8 sieve was 2.36 mm. A typical grain size distribution for Andela glass is shown in Figure 2.6.

- Batch 20 also included a coarser component; this one designated as 3/8 x 1/8 (particles had a grain size of between 3/8 in and 1/8 in).
- Batches 4 and 23 used a higher percentage of fines.
- Batches 6, 18, 23 and 25 used clear glass instead of green for the coarse particles.
- The “pure glass” specimens (Batches 8, 10, 17 nd 27) were made with green glass of gradation “16minus” (all particles passed a US#16 sieve). A typical grain size distribution for the glass component of the "pure glass" specimens is shown in Figure 2.

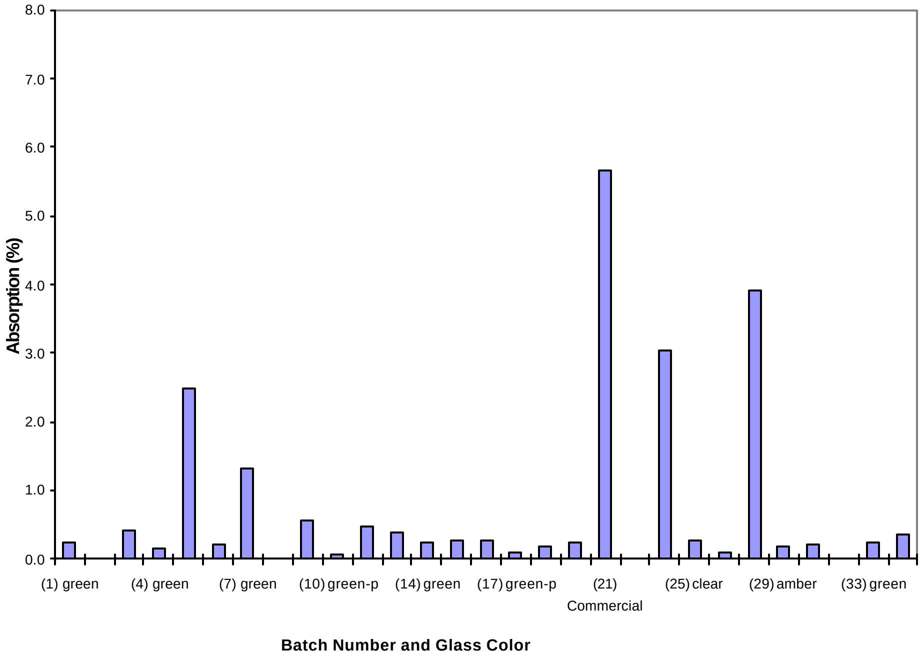


Fig. 12. Average %Absorption for Test Batches

2.4.2 Variation of the Binder Component

- Calcium aluminate cement (“fondu”) was used as the binder in Batches 5, 7, 24 and 28.
- The amount of added fondu ranged from 6.3% for Batch 28 to 10% for Batch 24.

- The binder type and the percent by weight (of the glass component) for each batch can be found in columns 5 and 6 of Table 1.

- In addition, specimens were made that contained no binder (Batches 8, 10, 17 and 27). These batches are referred to as "pure glass" specimens and were fired in a mold. This required a mold that was resistant to kiln temperatures.

2.4.3 Variation of the Water Component

- Generally, the amount of water added equaled 250g.

- However, 260g was used in Batch 4 to obtain the required consistency in the mixture with the finer glass. Because of the greater surface area-to-volume ratio of the finer particles in Batch 4, it was not surprising that more water was needed to achieve the same consistency.

- No water was added to the pure glass specimens.

- For the samples which used fondu as the binder, differing amounts of water were added.

- Batches 5, 7 and 24 used 300 g and Batch 28 contained specimens with 250 g, 275 g and 300 g of added water.

- Table 1, column 7 shows the quantity of water used for each batch.

2.4.4 Variations in Firing Process

- While 1600°F (871° C) was the standard maximum kiln temperature, specimens in Batches 9 and 10, Batches 2 and 8, Batches 18 and 19, and Batches 25-27, were fired at maximum kiln temperatures of 1400°F (760° C), 1500°F (816° C), 1650°F (899° C) and 1700°F (927° C), respectively. When the maximum kiln temperature was altered, the rate of temperature change was also adjusted so that the duration of the peak temperature phase remained constant at one hour.

- The maximum kiln temperature used for a given batch is found in column 8 of Table 1, Appendix A.

- Two different kilns were used to fire the tiles. A common, oval-shaped pottery kiln was used for the majority of the tiles, but a standard rectangular "flat" kiln was used for Batches 29-34.

- The type of kiln used in the production of a given batch is shown in column 9 of Table 1, Appendix A.

2.4.5 Other Variations

- Several batches included certain additives.

- A metal oxide stain was used as a coloring agent to make Batch 33. The amount added was only 0.25% by weight of the glass component.

- In addition to the fondu binder, inorganic Binder #3 (IB3) was added to Batch 28.

3.0 TESTING AND TEST METHODS

3.1 COMPRESSION TESTING

There is no standard or code which describes compression testing of glass paving tiles. However, ASTM C67 (1992) "Standard Test Methods of Sampling and Testing Brick and Structural Clay Tile" provides a method which is applicable to glass.

The test procedure involves capping the specimen (at least 5 inches (127 mm) in diameter) with either gypsum or sulfur-filler. The tile is then placed flat on the test machine, centered below the spherical head mounted block. Compressive force is applied at a uniform rate in order to move from one-half the peak load to the peak load in one to two minutes.

Other test procedures are given for masonry units in ASTM C140, “Standard Methods of Sampling and Testing Concrete Masonry Units”. A sample aspect ratio (height-to-width ratio) of two is specified.

The minimum required compressive strength of a paving brick subjected to light traffic is given in ASTM C902 (1982) “Standard Specification for Pedestrian and Light Traffic Paving Brick." It is 8000psi for an average of five bricks, or 7000psi for an individual brick that will be subject to the most severe environment --- where the brick may be frozen while wet. Average strengths of 3000psi and individual strengths of 2500psi are acceptable in less severe environments.

The paving tiles described in this report were relatively flat, therefore it was difficult to obtain the aspect ratio of 2:1 required by ASTM C140. Therefore, ASTM C67 was more appropriate for testing, however, it was not considered to be fully appropriate for the following reasons:

- the code is material specific (written for brick and clay but not for glass);
- it specifies capping using various methods for brick and clay. These methods are not necessarily appropriate for glass tiles; and
- there is no reference to the required aspect ratio of the specimens. Different aspect ratios would be expected to produce different strengths. For example, confining effects at the center of a tall thin specimen, due to the end plates restraint, will be less than that on a short squat specimen. The shorter specimen would therefore be expected to be stronger.

3.1.1 Procedures

The compression tests were accomplished by using a Baldwin, 300 kip (1335kN) capacity testing machine. The compression testing was performed on disks approximately one inch thick (25.4mm) and having a diameter of about 3.7 inches (94mm). The diameter was measured from each face of the disk using a caliper gauge with a readability of +/- 0.01 in (0.25mm). The area used in calculating the stress was found by averaging the diameter measured on each load bearing face of the specimen according to ASTM C67, 6.4.1.

The upper bearing block of the machine was larger than the specimen itself. If the opposite were true (the upper block smaller than the specimen) it is expected that during the loading, some confining pressure would be exerted by the surrounding material on the material being directly loaded. This would tend to increase the maximum load able to be sustained by the specimen.

In general, the specimens that were tested had some unevenness on the load-bearing faces. The face that was cast face-up was particularly rough. Several methods were attempted to avoid stress concentrations and early failure due to the uneven surface of the compression specimens. The first method involved using a neoprene pad on the roughest surface and nothing on the other face. This technique was discarded because of concern that the neoprene layer, which tended to “bulge-up” around the sides of the specimen, could exert some confining pressure and thus postpone the failure of the specimen. Not enough tests were performed using the pad to assess the validity of this concern.

In order that the load bearing faces are even and parallel, the ASTM standard described techniques for “capping” the specimens. Without any sort of capping scheme, it was expected that the applied load could be unevenly distributed and concentrated on the higher points of the specimen. Therefore, the portion of the total cross-sectional area that was being directly loaded would fail first. Thus, the maximum load and average compressive stress, calculated as the maximum load over the total area, would be less than if the entire specimen were bearing the load evenly.

Strengths obtained showed that there was little difference in compressive behavior between specimens that had been capped and those which had not. Therefore, in order to facilitate testing, no cap was used. By not capping the specimens, the maximum load capacity should be underpredicted.

3.2 FLEXURE TESTING

Using a third-point loading on a beam, which has a depth equal to one-third of the span, is a method of flexural testing and is described in ASTM C78 (1984), “Flexural Strength of Concrete.” In this type of loading, the specimen is supported at the ends and two equal loads are applied, such that the specimen is sectioned into thirds. This produces a constant bending moment over the middle third of the span. “Third-point” loading is depicted in Figure 3.

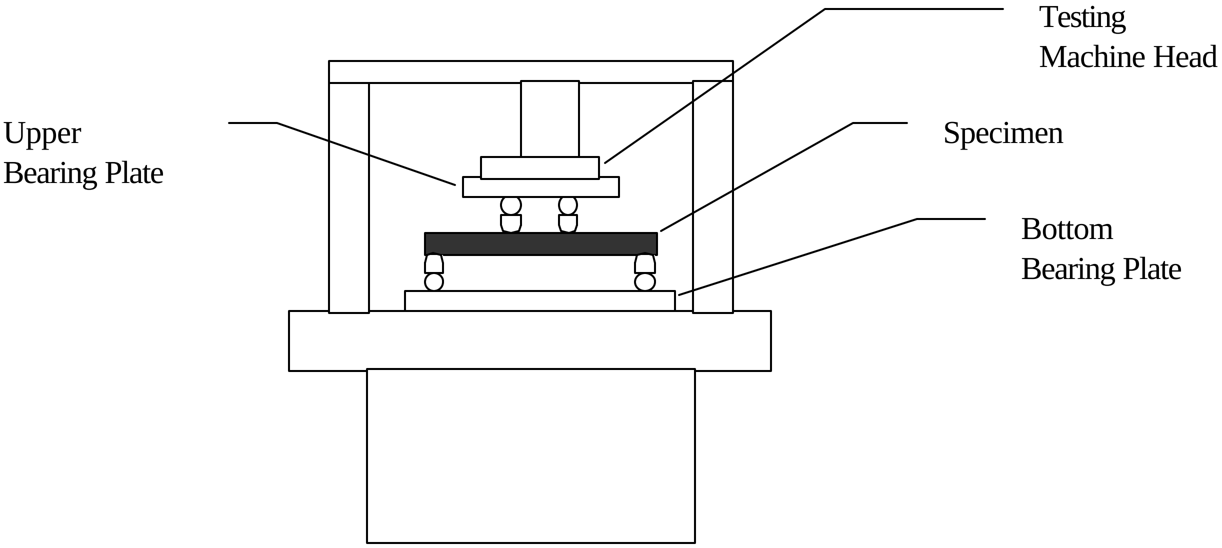
A flexure test for a thinner specimen, such as the ones used in this study, is described in "Sampling and Testing Brick and Structural Clay Tile" (ASTM C67). However, this standard prescribes a centerpoint loading. Here, one load is applied at the center of the span.
There is no specification for the minimum modulus of rupture required for paving tiles.

3.2.1 Procedures

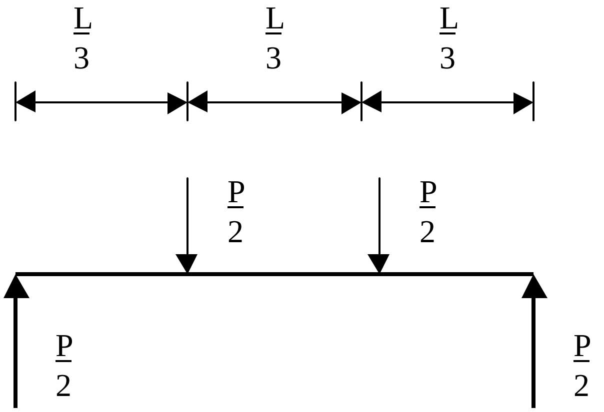
The flexural (bending) tests were carried out using a Baldwin, 60 kip capacity testing machine. Figure 4 shows the testing apparatus. The method used in this study did not rigorously conform to either ASTM procedure because the “third point” method of loading was used and the tiles were much shallower than ASTM C78 concrete beams. The recycled glass specimens tested in this report have a depth of approximately 1/12 the span. However, there is no theoretical difference in the way that flexural tension stress, given by the Modulus of Rupture, was calculated for a “shallow” beam, as compared to a “deep” beam. The depth of a particular specimen used should not matter, as it is accounted for in the Modulus of Rupture formula. The modulus of rupture may be computed in the following ways based on the standard beam elastic formulae.

Figure 3. Third Point Loading Method for Flexural Testing of Samples

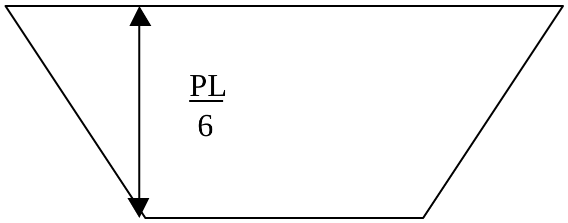
A) Actual Configuration



B) Free Body Diagram (specimen)



C) Bending Moment Diagram



For the third-point loading scheme:

Modulus of Rupture: $$R = \frac{PL}{bd^2}$$

where:
P = maximum load (lb)
L = span length (in)
b = specimen width (in)

For the centerpoint loading scheme:

where: d = specimen depth (in)

Modulus of Rupture: $$R = \frac{3Pa}{bd^2}$$

P = maximum load (lb)
b = specimen width (in)
d = specimen depth (in)
a = average distance from failure plane to end support (in)

The specimens used in this test were relatively flat, rectangular tiles. The length was approximately 14.25 inches (362mm) and the clear span was 12 inches (305mm). The width was approximately 4 inches (102mm) and depth was approximately one inch (2.54 cm). They were tested using a third-point loading technique, which was designed to create an equal maximum bending moment over the entire middle third of the span. Thus, failure was expected to occur in this portion of the specimen. If it occurs too far outside of the middle span, the test result is probably affected by a weakness in the region of lower moment. Failures within 5% of the total span length outside the middle third are permitted by the ASTM. For the 12 inch (305mm) span used, this equals almost 5/8 in (15.9mm). All specimens tested failed in the region of maximum moment.

The following is the test procedure used. The specimen is first labeled and marked (using a ruler) at 4 inch (102mm) centers to show division into thirds. Next, the specimen is positioned on the support bars, such that the end marks lie over the steel bars, with the inch or so protrusion extending past the contact point of the bars. These supports form a 12 inch (305mm) span. The upper bearing plate has spherically seated bars 4 inches (102mm) apart. It is positioned over the two center marks and the entire setup is centered under the testing machine head. The load is applied at the prescribed rate of less than

Figure 4 -- Specimen Under Load

a) Testing Machine

b) Specimen Under Load

2000 lb/min (8918 N/min), according to ASTM C 67, until failure occurs. The maximum load registered by the testing machine is recorded.

After failure, the measurements of the width and depth of the specimen cross-section are made at the two ends and along the edge of failure . The width measurement is made at mid-height of the cross sections and the height is taken along the centerline of the specimen. In the case where there are two failure planes, one is arbitrarily chosen at which to measure. From these values, an average width and height are calculated. These average values are used to calculate the modulus of rupture.

The specimens used had a slight taper of approximately 5° around the edges of the upper surface, sometimes more noticeable along one edge of the specimen than the other. This taper was ignored in the measurement of the dimensions. Thus, the calculated value of the Modulus of Rupture was slightly conservative.

Because of the taper, the contact area of the specimen with the upper bars may have been less than it would have been if the upper surface was perfectly flat. This resulted in the applied load not being as evenly distributed and thus higher stress concentrations in certain regions of the specimen during loading. This effect was considered small and was ignored.

Another aspect of the test method was the weight of the upper bearing plate, which was positioned over the specimen and transferred the load from the testing machine. The weight of the entire apparatus (one plate, two bars and two balls) equaled 30.2 lb (134.7 N). For a specimen to be able to bear a substantially greater load, such as a deeper beam, the effect of this weight on the modulus of rupture calculation would be negligible. However, for the shallow specimens used, this amounted to about 4% of the maximum load registered by the machine. The weight of the apparatus was considered in the calculation of the Modulus of Rupture of the specimens.

Furthermore, the weight of the specimen itself (about 4 pounds) creates a distributed load over the length of the specimen and contributes to the theoretical maximum bending moment. This weight is ignored in the calculation. Including it would add approximately 10psi, or 0.4% of the peak strength, to the modulus of rupture values. Ignoring it, as we have chosen to do, makes the obtained result more conservative.

3.3 ABSORPTION TESTING

Absorption testing was carried out instead of specific freeze thaw testing according to ASTM C67, section 7.3.2.1.

According to ASTM C67, the pieces were first dried in an oven at a temperature of about 230°F (110°C) for a 24 hour period. They were allowed to cool to room temperature and weighed. This weight was recorded as the dry weight *W(d)* . Next, they were immersed in a tank of water at approximately room temperature and left to soak for a 24 hour period. They were removed from the water and blotted dry to remove surface water until they were no longer "shiny," and weighed again to get the saturated weight, *W(s)*. The weight of water absorbed divided by the dry weight equals the percent absorption:

$$\%\textbf{absorption} = \frac{W(s) - W(d)}{W(d)}$$

where:
$W(s)$ = saturated weight
$W(d)$ = dry weight

For this test, pieces of tiles that had previously been broken in the flexure tests were used. This is in accordance with ASTM C 67: "The specimens for the absorption test shall consist of ... tile or ... representative pieces from each of these..."

However, the ASTM standard made no specific mention of what size pieces were to be used. As specimens of a constant thickness get smaller, the specific surface (the ratio of surface area-to-volume) gets larger. Theoretically, this could influence the amount of absorption, as greater specific surfaces have greater portions of the material directly exposed to the immersion bath. In order to facilitate testing, there was some experimentation with modifying the ASTM C67 procedure. It was found that generally, the weight “as is” (prior to any oven drying), was almost exactly the same as the weight after oven drying. Thus, some initial tests were carried out using no drying phase at all. However, because of concerns with potential questions about the testing methods used and to assure validity of the results, it was resolved to strictly adhere to the prescribed guidelines.

The absorption limit for paving brick in the most severe environment is 8%, according to ASTM C902 (1992).

4.0 SAMPLE STRENGTH AND ABSORPTION PROPERTIES

Testing was performed on a variety of specimens to investigate the relationship between performance and production parameters. A summary of the results of all the specimens tested is given in Appendix B, Table 2 and referenced by batch number.

4.1 EFFECT OF POSITION IN KILN

An early concern in the project was that the kiln temperature might vary throughout the depth of the kiln, causing the fired properties of the tiles to be affected by their position. This was investigated in the “stacking test” (Batches 11-16). In this test, specimens prepared with the same specifications were fired in a kiln having vertically stacked shelves. There were six shelves stacked in the kiln, each with three specimens. After the testing of all the fired specimens was complete, an average strength was calculated for each shelf. **No relationship was discovered between the position in the kiln and the fired strength.** Average strength versus kiln position is shown for Batches 11-16 in Figure 5.

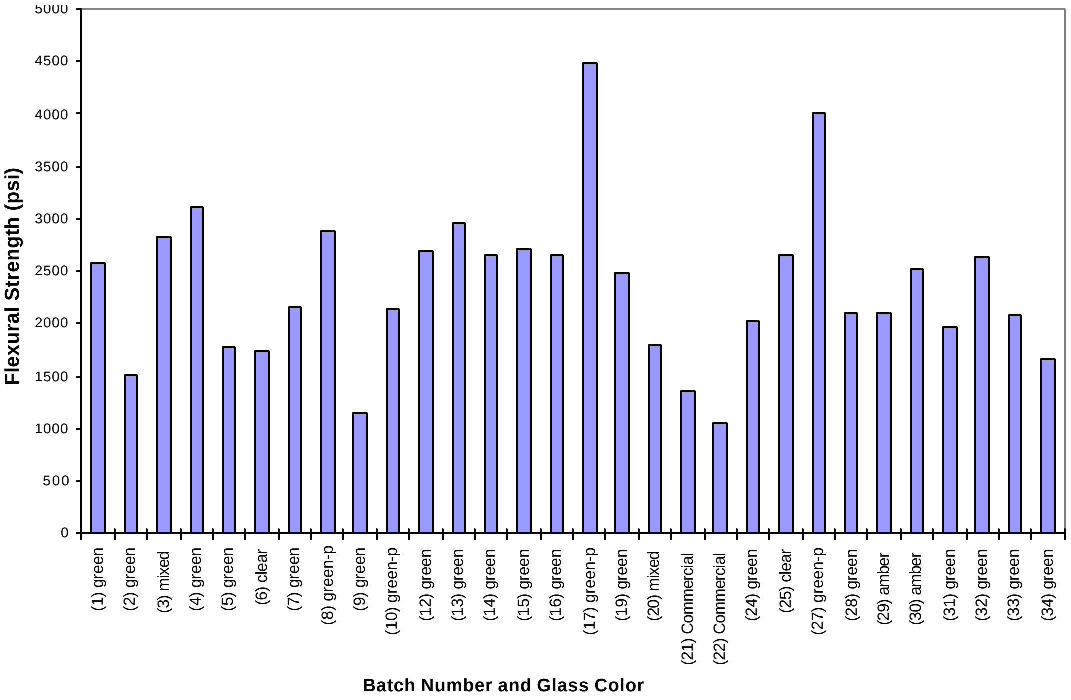


Fig. 11. Average Flexural Strength for Test Batches

Similar results were found for specimens in Batch 20. These specimens were fired in a kiln with three vertically stacked shelves, each shelf having three specimens. An average strength was calculated for each shelf. Again, no dependency on kiln position was discovered, as shown in Figure 6.

4.2 EFFECT OF KILN FIRING TEMPERATURE

The maximum kiln firing temperature ranged from 1400°F (760°C) to 1700°F (927°C). The maximum temperature used to fire each batch can be found in Appendix A, Table 1, column 8.

For the standard mix specimens, Batches 1, 2, 9, 11-16, 19 and 26, and the pure glass specimens, Batches 8, 10, 17 and 27, the fired strength initially increased as the maximum kiln temperature increased, as shown in Figure 7. However, the strength for both peaked at 1600°F (871°C) and then started to decline as maximum kiln temperature continued to

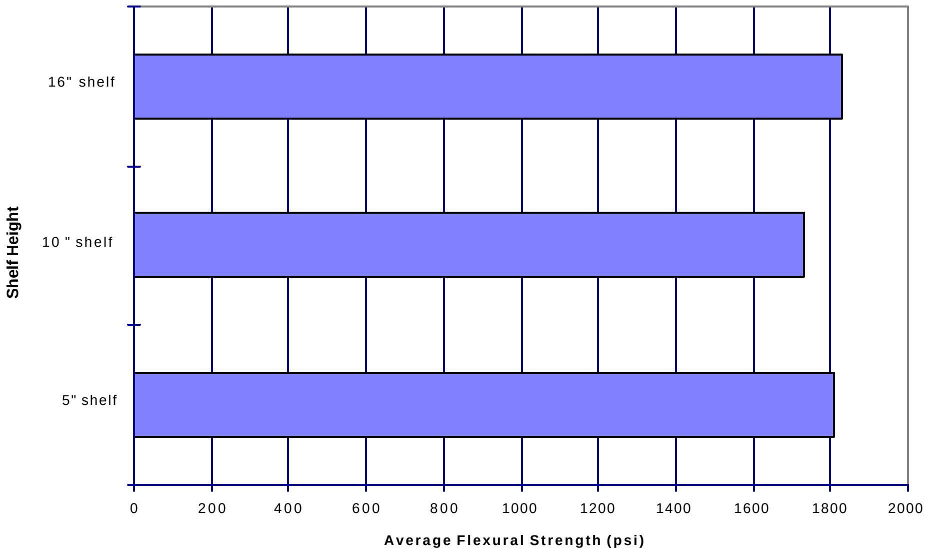


Fig. 6. Stacking Test (Batch 20)

increase. In Figure 7 the standard mix results at 1600°F are based on the average results of Batches 1 and 11-16.

For the standard mix, the absorption properties also exhibited temperature dependency. Initially, the absorption decreased as the maximum temperature increased. This was followed by a slight increase in absorption as the temperature continued to increase past 1650° F (899° C), as shown in Figure 8.

It appears that at a critical temperature, in the range of 1600°F-1650°F (871°C-899°C), optimal particle sintering occurs for the standard mix and pure glass specimens. This gives the fired material greater density (fewer voids), which improves the strength and decreases the amount of absorption. This behavior was also observed by Brown et al. (1982). The specimens fired at 1500°F (760°C) tended to shatter into several pieces in the flexure test, whereas, the 1600°F (871°C) specimens exhibited a “cleaner” failure with a unique failure plane and little debris.

The physical appearance of the pure glass specimens changed with temperature. Batch 17, fired at 1600°F (871°C), actually looked less glassy (more matte) than Batch 10, which was fired at 1400°F (760°C). This is possibly due to devitrification occurring at

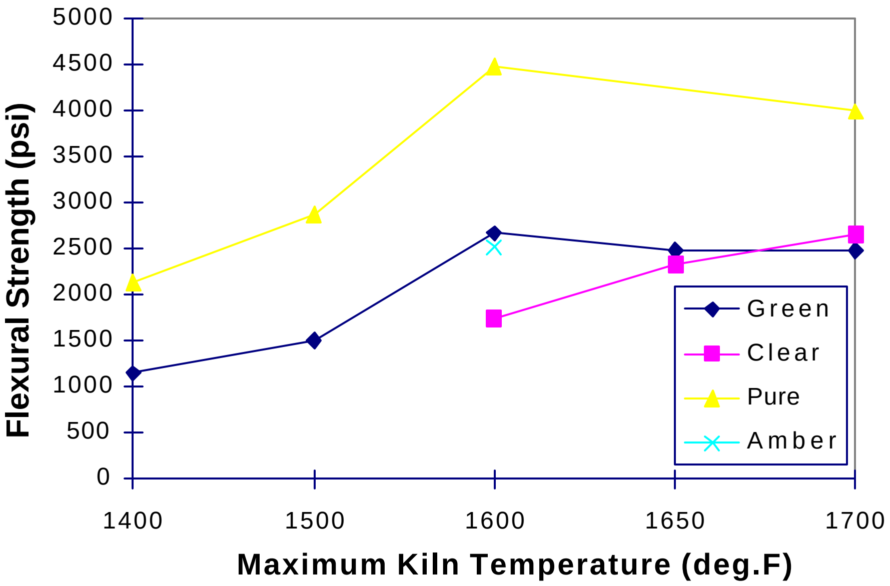


Figure 7. Strength vs. Maximum Kiln Temperature

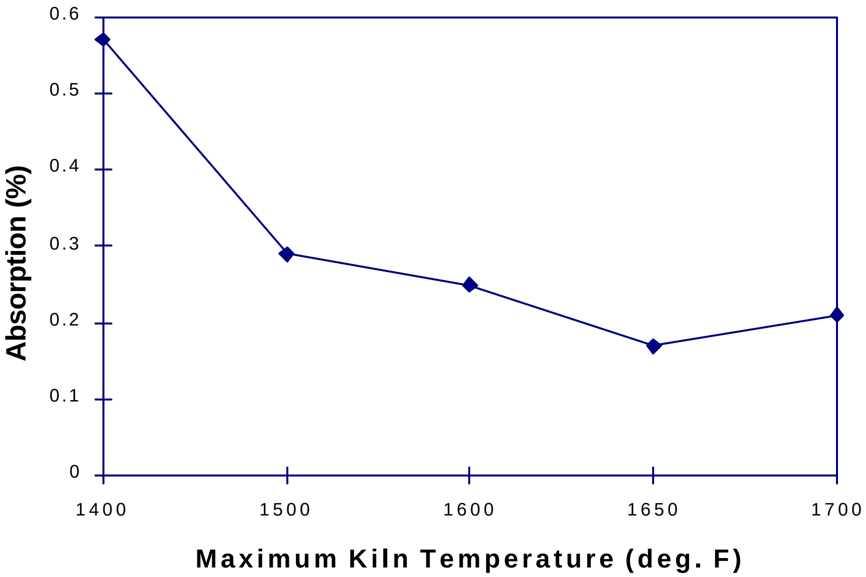


Figure 8. Average Absorption vs. Maximum Kiln Temperature for Standard Mix

the higher temperature. The large increase in fired strength between the 1500°F (816°C) and 1600°F (871°C) pure glass specimens indicates that a critical sintering temperature exists in this range.

The absorption of the pure glass specimens (Batch 17) fired at 1400°F (760°C) was less than for the 1600°F (871°C) batch (Batch 10). This behavior was opposite to trends seen in the standard mix, showing higher absorption at lower firing temperatures. This can be attributed to the fact that the absorption in either case is less than 0.1 %, and within this very small range, the data may not be entirely reliable. It was found during the testing that the absorption of the pure glass specimens could be reduced to almost zero through extra surface drying.

The strength of the clear glass, Batches 6, 18 and 25, tended to increase with firing temperature as shown in Figure 7.

4.3 EFFECT OF KILN TYPE

The majority of the specimens tested were fired in the aforementioned “oval” kiln. Another type of kiln, a “flat” kiln, was also used in making some of the tiles. In order to determine the influence of kiln type on fired behavior, samples made with the standard mix were fired at the usual temperature in the flat kiln (Batch 32). The performance of these specimens were found to be 1.4% less than that of the standard-mix specimens fired in the oval kiln, as shown in Appendix B, Table 2. As this difference was small, it seems reasonable to discount any effects the flat kiln may have had on the fired properties.

4.4 EFFECT OF PARTICLE SIZE GRADATION

A comparison was made between specimens prepared using glass with only coarse particles and those which had both coarse and fine particles. Batch 5 was made with 1300 g of coarse glass. Batch 7 was made with 1150 g of coarse glass and 150 g of fine glass. The total mass was the same for both. The specimens in Batch 7 were made with two particle size gradations; these were expected to have higher packing and fewer voids.

Strength was 21% greater and the absorption was 47% less for the batch that used a mix of two different particle sizes (Batch 7), rather than a single gradation (Batch 5). These results are shown in Figures 9 and 10. **A mixture of both coarse and fine particles resulted in a denser and stronger fired specimen.**

For the two Andela batches, strengths from Batch 20 with 2 gradations, were less than those from Batch 3 with 3 gradations. However, this may have resulted from an unfavorable mixing ratio of the gradations involved -- an insufficient number of medium-sized particles may have lessened the surface contact and sintering with the largest particles. Visually, the specimens in Batch 20 were “blobby” and did not appear to have packed and bonded well.

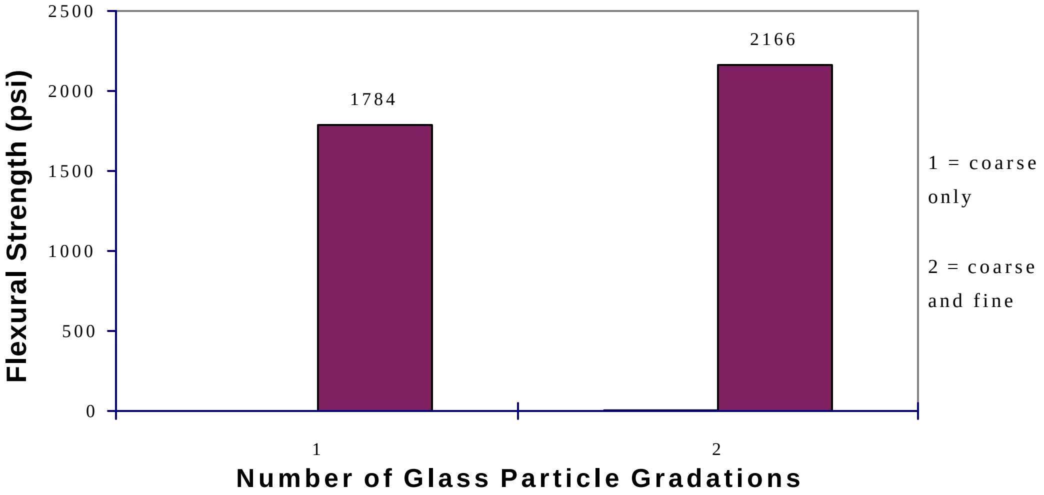


Figure 9. Average Strength vs. Number of Particle Gradations for Fondu

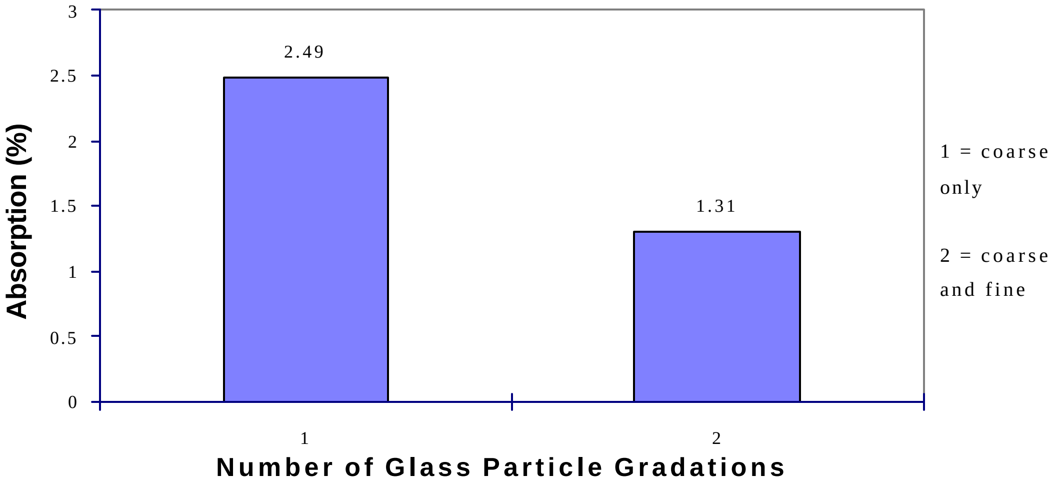


Figure 10. Average Absorption vs. Number of Particle Gradations for Fondu

4.5 EFFECT OF GLASS COLOR

The results for the different glass colors are shown in Figure 7. At 1600°F (871°C), specimens made using green glass for the coarse particles were 53% stronger than those using clear glass. The maximum strength for clear glass occurred at a kiln temperature of equal or greater than 1700°F (927°C), while that for green glass occurred at a temperature of 1600°F (871°C). Clear glass contains less coloring agents than green or amber glass. Coloring agents or additives tend to decrease the softening temperature of the glass. Therefore, at low kiln temperatures, less sintering of the clear glass takes place so it is weaker than colored glass. Because of kiln limitation, no testing was performed on clear glass specimens fired at temperatures higher than 1700°F, so it was not possible to state whether or not the strength versus temperature curve for clear glass would peak at some critical temperature. The strongest Andela tiles, Batch 3, were 6% stronger than the average for the standard mix batches.

4.6 OTHER TYPES OF TILE

An assessment was made of the properties of some commercially available brick and tile. Batch 21, made of clay, and Batch 22, made of concrete, were subjected to flexural and absorption testing. The dimensions of these samples were smaller than could be accommodated by the third-point test method, so they were tested under centerpoint loading. The modulus of rupture was about one-half that of the standard mix. The absorption of the commercial tiles was between 4% and 6%, which was worse than the 0.25% for the standard mix.

4.7 EFFECT OF COLORING AGENT

An eventual production goal is to produce recycled glass tiles in a variety of colors. In order to test the effect of a coloring agent on performance, Batch 33 was prepared using the standard mix with a small amount (5g, which is 0.28% of the glass weight) of metal oxide stain. It was found that this reduced the fired strength of the tiles to 19% below that of the standard mix. The absorption did not change significantly

4.8 EFECT OF WATER CONTENT

There was variation of the water content within Batch 28. There were three specimens made with 250g of water, one specimen with 275g and one with 300g. The results did not reveal a performance trend. The 275g specimen was weaker than both the 250g specimens and the 300g specimen (see results for Batch 28, Appendix A, Table 1). Additionally, the numbers of samples were too small to draw any statistical conclusions; more investigation is needed in this area.

4.9 GREEN STRENGTH

The modulus of rupture of the pre-fired green material was not able to be computed accurately, as the tiles broke under the weight of the loading apparatus. This caused a modulus of rupture of approximately 100psi. However, the green strength was sufficient for production in all cases, as the green specimens could be removed from the mold and handled without breaking.

4.10 COMPRESSIVE STRENGTHS

Average compressive strengths obtained for samples with a firing temperature of 1600°F (871°C) were in the 24.5 to 27 ksi (169 to 186 MPa) range. This is much higher than typical strengths of concrete cylinders, with a height-to-diameter ratio of 2:1, which range from 3ksi to 8ksi (20.7MPa to 55.2MPa). It is also higher than the 8ksi (55.2MPa) required for tiles by ASTM C 902. Test samples used in this study were “flat” -- they had a height to diameter ratio of about 0.25. Specimens with lower height-to-diameter ratios generally have higher strength than those with greater height-to-diameter ratios, as a result of end confinement. This may be one reason for the high strengths. However, ASTM C 902 does not specify required height-to-diameter ratios for the tests. As obtained strengths clearly surpassed 8000psi (55.2MPa), the glass tiles satisfy this code requirement. Compressive strength of Batch 9, fired at 1400°F (760°C) was about half that of the specimens fired at 1600°F (871°C).

4.11 FLEXURAL VS. COMPRESSIVE TESTING

Although a compression test is specified in the minimum standard requirements for pavers and minimum compressive strength cited, it seems that compressive strength may not be as valuable a performance parameter as flexural strength. This is acknowledged by ASTM: “It is the consensus...that compressive strength does not truly express a significant property of a paving unit. Rather, a flexural property...will be more meaningful.“ (ASTM C 936). ASTM further states that a specification value for a tensile strength test has not yet been determined.

The validity of compression testing for the flatish tiles is called into question as the specimens “failure” was not registered by the testing machine until well after serious cracking and crushing of the specimen occurred.

Failure is most likely to occur if a paver is insufficiently supported. The loading creates a situation much like the one emulated by the flexure test. Failure would be expected to occur in flexure before compression failure occurred. For this reason, more tension tests than compression tests were carried out.

While a standard for the performance of a flexural strength test for brick and structural clay tile does exist in ASTM C 67, no mention is made of a minimum required flexural strength. ASTM C 902 states only that “Minimum modulus of rupture values should be considered by the purchaser for uses of brick where support or loading may be severe.”

4.12 FLEXURAL STRENGTH-COMPRESSIVE STRENGTH RELATIONSHIP

An often-used rule of thumb is that the modulus of rupture of concrete is approximately 10% of the compressive strength (Derucher, p.107). For the glass tiles tested, the ratio of the tensile strength to the compressive strength was also approximately 1:10. The results of all the flexure tests are summarized in Figure 11. The strengths of the commercial tiles, Batches 21 and 22, and also Batch 9, which was made by firing at 1400°F (760°C), were about one-half that of the other batches. Batches 17 and 27, made from pure glass with no binder, were significantly stronger than the others.

Most tiles had modulii of rupture ranging from 1500psi to 3000psi. There is no minimum value of modulus of rupture given in the standards. However, if the relationship between compressive strength and modulus of rupture of 10:1 is used, then a modulus of rupture of 800psi (5.5MPa) would relate to a compressive strength of 8000psi (55.2MPa). All of the samples tested have modulii of rupture greater than 800psi (5.5MPa), so they should be satisfactory for use as paving tiles.

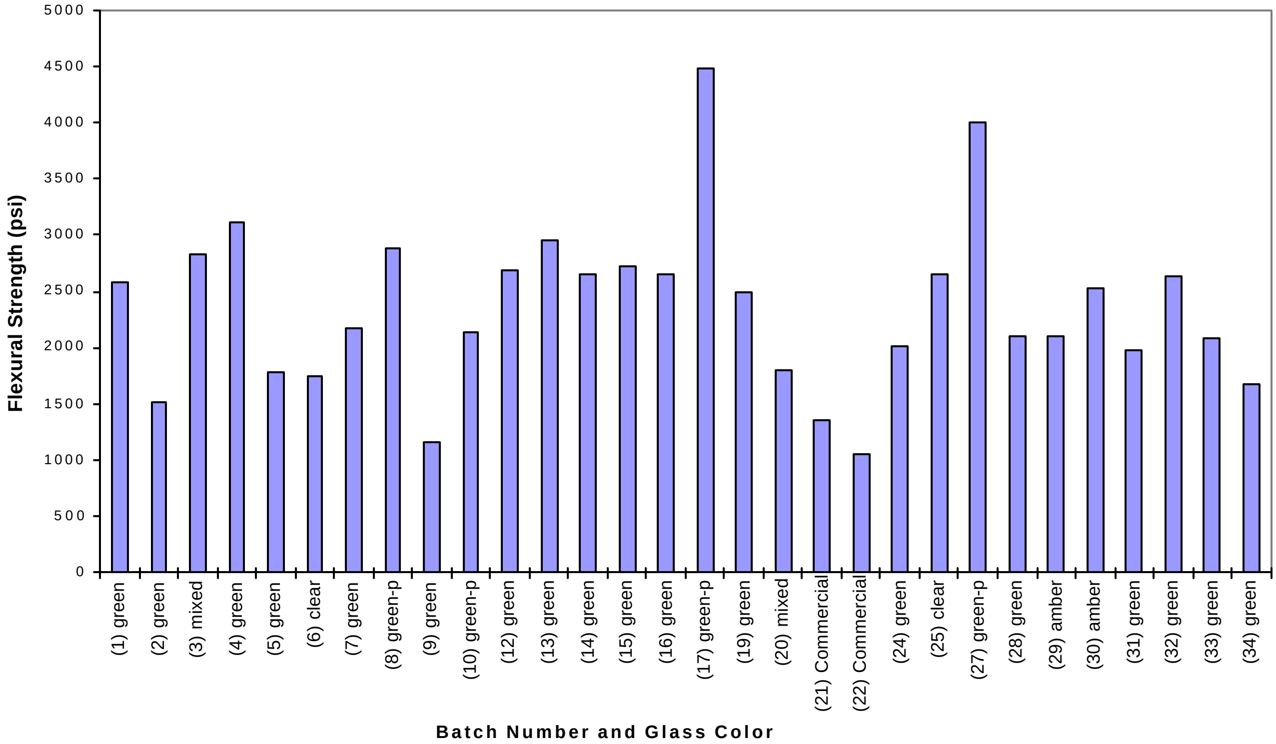


Fig. 11. Average Flexural Strength for Test Batches

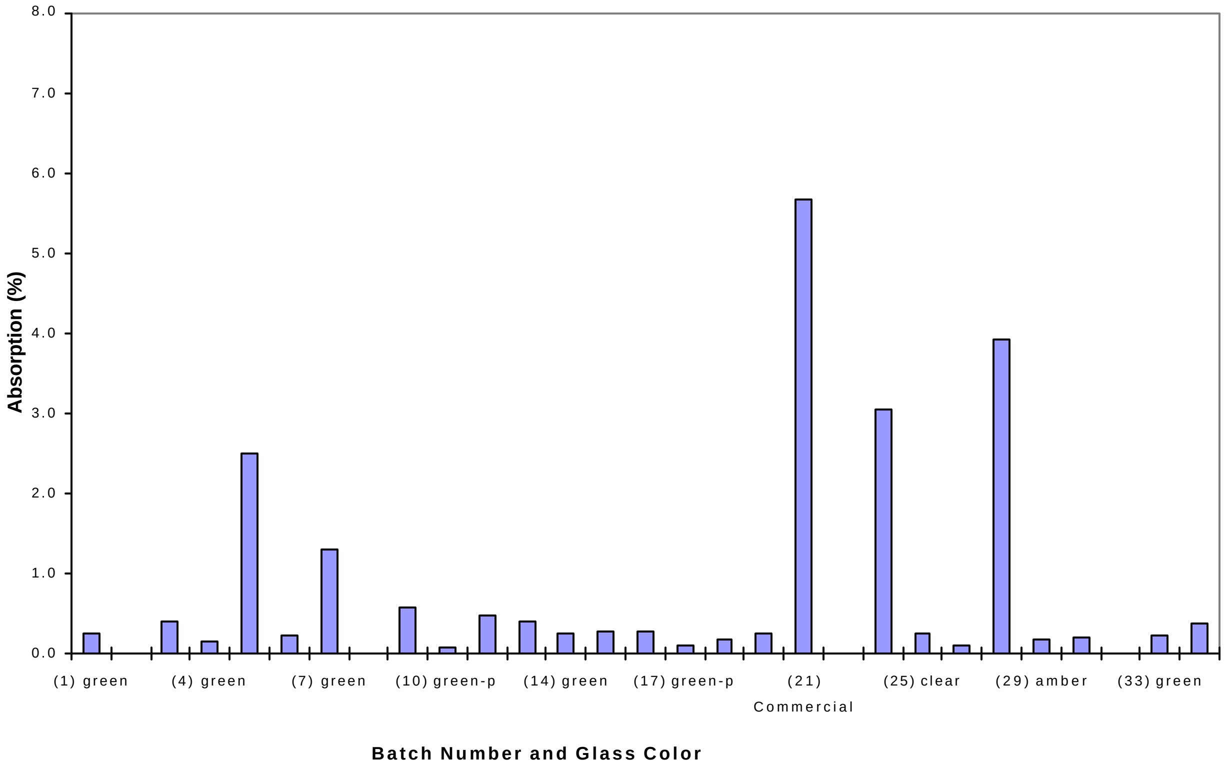


Fig. 12. Average %Absorption for Test Batches

4.13 EFFECT OF ADDITION OF INORGANIC BINDER #3

Batches 24 and 28 show the effect of the addition of inorganic binder #3 (IB3). Batch 28, which contained 100 g of inorganic binder #3 (5.6% of glass weight) had an absorption of 3.9%, while Batch 24, which contained no inorganic binder #3, had an absorption of 3.0%. The strength was not diminished; in fact, it was slightly higher (4.2%) for the batch containing inorganic binder #3.

4.14 EFFECT OF MIX AND AMOUNT OF BINDER MATERIAL

In the standard mix, the binder was 2% inorganic binder #1 and 0.7% inorganic binder #2. A comparison of the results of Batch 29, where the binder is inorganic binder #1 only, with those from Batch 30 containing inorganic binders #1 and #2, show that this small amount of inorganic binder #2 is important. Batch 29 made with 2% inorganic binder #1 as binder had lower strength than Batch 30 specimens, which used 2% inorganic binder #1 and 0.7% inorganic binder #2.

Increasing the amount of binder had very noticeable effects. Batch 31 was made with the standard mix, except that the amount of binder was raised to 3.7% (3% inorganic binder #1 and 0.7% inorganic binder #2), instead of the usual 2.7%. The strength of this batch was 26% less than the average for all the standard-mix specimens. Increasing the binder level to 4.7% resulted in an even larger reduction in strength of 32%, relative to the standard-mix average. The strength of the strongest fondu tiles, Batch 7, was 81% of the standard mix average.

The specimens made with no binder had the highest fired strength and lowest absorption of all of the tiles tested. Figure 13 shows how strength varied with percentage binder for the standard mix specimens.

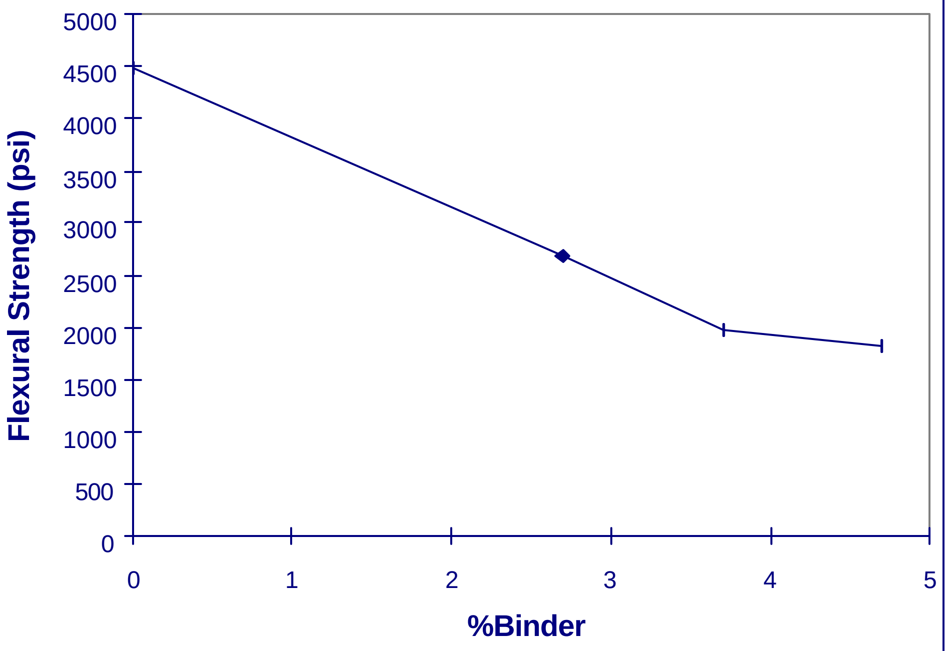


Fig. 13. Average Strength vs. %Binder

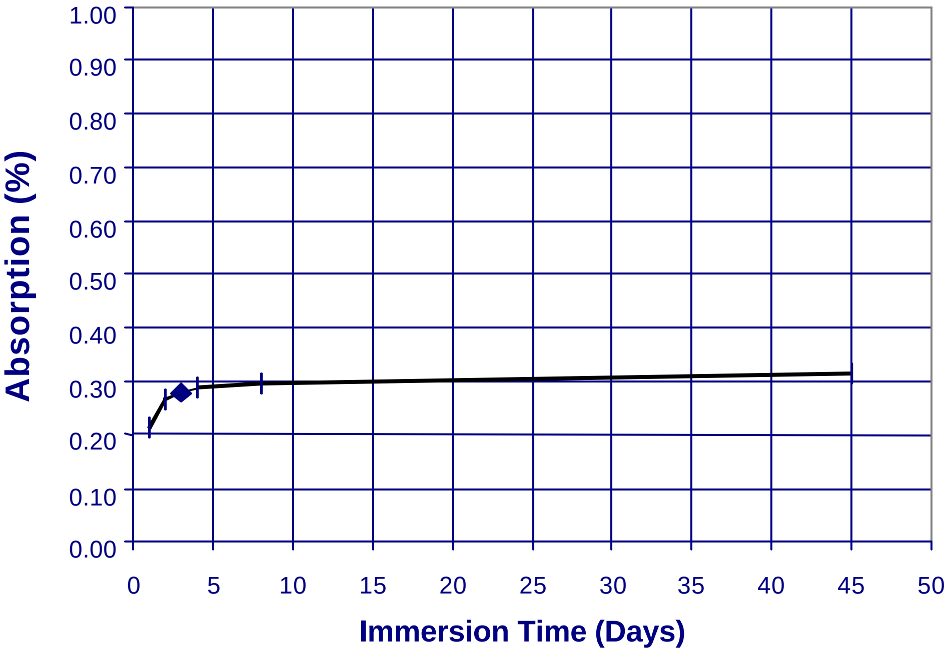


Figure 14. Absorption Over Time

4.15 ABSORPTION

The results from the absorption tests show that the material made from recycled glass had low absorption. Figure 12 summarizes the absorption test results. The values obtained were all quite low, generally less than 1% (or approaching zero absorption). These were well below the most severe allowable values of 8% for brick given in ASTM C902, "Standard Specification for Pedestrian and Light Traffic Paving Brick." High absorption was obtained from the commercial bricks (Batches 21 and 22), as well as by those tiles made with the fondu binder (Batches 5, 7, 24 and 28). The addition of inorganic binder #3 increased the absorption of the tiles, as shown by comparing Batches 24 and 28. It would be expected that tiles with high absorption would be the most susceptible to freeze-thaw damage.

The absorption test requires immersion over a 24 hour period. When carried out over a prolonged duration, the measured percentage of absorption did not show a marked increase. Figure 14 shows these results.

4.16 STATISTICAL VARIATION OF STRENGTH AND ABSORPTION

The standard deviations of the strengths were generally low, as given in Appendix B, Table 2. For example, for the Batch 1 flexural tests, the standard deviation was 155psi (1.07MPa), which was 6% of the average strength of 2573psi (17.7MPa). For other batches, the standard deviation was generally less than 10% of the average value. This scatter was low considering that recycled glass is a brittle material in which fracture may be initiated by any small imperfection. The scatter for absorption was generally significantly greater. For example, the standard deviation was 20% of the average value for Batch 1. It is thought that scatter was high because the absorptions were low and were difficult to measure accurately, as explained previously.

5.0 IMPLICATIONS OF TILE PERFORMANCE FOR APPLICATION

The previous chapter has shown that the strength and absorption properties of well made recycled glass tiles is as good as, and often much better than, ASTM requirements for similar types of material. The significance of the difference in strength between concrete and glass tiles is described below.

In the testing which was undertaken, the modulus of rupture of the glass tiles was often more than two times that of the commercial clay and brick tiles. While there is likely to be a wide variation in strength of commercial clay and brick tiles made by different manufacturers and different methods, it is assumed in this discussion that the ratio of modulus of rupture of glass tiles to that of concrete tiles is about two.

It was shown in Section 3 that the modulus of rupture of a material is related to the thickness of the tile squared. Therefore, the required thickness of glass tiles is $1/\sqrt{2}$ (or 0.71) times that of concrete tiles, in order for them to carry the same load. For example, if it were desired to produce a glass tile with a bending resistance equivalent to that of a one inch (25.4mm) thick concrete tile, then a 0.71in (18mm) thick glass paving tile would be required. Also, a concrete tile having the same bending resistance as a one inch (25.4mm) thick glass tile would have to be 1.41in (35.9mm) thick.

6.0 CONCLUSIONS

A number of recycled glass paving tile test samples were manufactured using low technology procedures. Proportions of raw material and production process parameters were altered. The performance of the tiles was assessed in terms of their flexural strength, compressive strength and absorption capacity. It was found that:

Compressive strength: Average compressive strengths ranged from 14 - 27 ksi (96MPa - 186Mpa). This is much greater than the most severe ASTM requirement of 8ksi (55MPa). Generally the specimens were not capped.

Flexure vs. Compression: Modulus of rupture rather than compressive strength was shown to be a better parameter to estimate tile performance.

Flexural Strength: Flexural tests gave modulii of rupture ranging from 1156psi (7.97MPa) to 4483psi (30.9MPa). Average modulus of rupture was 6% to 11% of the compressive strength. The required compressive strength of 8,000psi (ASTM C 902) conservatively relates to a modulus of rupture of 800psi. All tiles tested were therefore satisfactory.

Effect of Binder on Strength: Strengths of samples increased with lower amounts of binder. Addition of small amounts of inorganic binder #3 increased the absorption, but had little effect on the strength. Tiles made with fondu binder were weaker than those made with the standard mix.

Effect of Particle Gradation on Strength: Strength generally increased with a wider difference between the particle gradations.

Effect of Glass Color on Strength: Clear glass had a higher sintering temperature than green or amber glass. This caused the strength of clear glass to be lower than colored glass at kiln temperatures less than about 1675 °F (913 °C), and greater at higher temperatures. Green and amber glass behaved similarly, however only one batch of amber tiles was tested.

Effect of Kiln Temperature on Strength: Strengths of “standard samples” made with green glass increased with increasing kiln temperature up to a temperature of 1600 °F (871 °C); thereafter, strength declined.

Effect of Kiln Type and Position: Behavior of the tiles was not affected by the position of the tiles in the kiln, or the type of kiln used.

Behavior of Commercial Brick and Concrete Tiles: Average modulus of rupture of the commercial brick and concrete tiles tested were 1356psi (9.35MPa) and 1053psi (7.26MPa), respectively. This is significantly less than the modulus of rupture of the standard glass tile of 2677psi (18.46MPa).

Design of Glass Tiles: As recycled glass tiles have a greater modulus of rupture than concrete tiles, the same bending resistance may be obtained with a thinner tile.

Absorption: Absorption of water in glass tiles was generally less than 1%. Clay and concrete tiles showed an absorption of 4-5%, and tiles made with a fondu (calcium aluminate cement) as binder had absorptions from 1- 4%. The lowest absorptions occurred in tiles fired at 1650 °F (899°C). Lower absorptions were obtained from mixes made from a wider range of particle gradation than those with a narrow range of gradation.

Overall Performance: The recycled glass tiles showed very good strength and absorption properties without being overly sensitive to any of the mix or production parameters. It is believed that there is a lot of promise for the further production and use of these tiles.

7.0 REFERENCES

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APPENDICES

APPENDIX A: TABLE 1   GLASS TILE BATCH CHARACTERISTICS.

APPENDIX B: TABLE 2   SUMMARY RESULTS OF ALL SAMPLES.

APPENDIX A: TABLE 1 GLASS TILE BATCH CHARACTERISTICS

Batch	No. Specimens	Glass Color	No. Gradations	Binder Type	% Binder	Water (g)	Max Temp (°F)	Kiln Type	Parameters Investigated
1	10	green	2	IB#1, #2	2.7	250	1600	oval	standard mix
2	5	green	2	IB#1, #2	2.7	250	1500	oval	standard @1500
3	4	mixed	2	IB#1, #2	2.7	250	1600	oval	andela glass
4	4	green	2	IB#1, #2	2.7	260	1600	oval	finer glass
5	2	green	1	fondu	6.7	300	1600	oval	fondu as binder
6	4	clear	2	IB#1, #2	2.7	250	1600	oval	ckear glass
7	2	green	2	fondu	6.7	300	1600	oval	fondu w/2 gradat.
8	2	green	1	none	0	0	1500	oval	Pure glass @1500
9	4	green	2	IB#1, #2	2.7	250	1400	oval	standard @ 1400
10	3	green	1	none	0	0	1400	oval	pure glass @ 1400
11	3	green	2	IB#1, #2	2.7	250	1600	oval	temp. strat.
12	3	green	2	IB#1, #2	2.7	250	1600	oval	temp. strat.
13	3	green	2	IB#1, #2	2.7	250	1600	oval	temp. strat.
14	3	green	2	IB#1, #2	2.7	250	1600	oval	temp. strat.
15	3	green	2	IB#1, #2	2.7	250	1600	oval	temp. strat
16	3	green	2	IB#1, #2	2.7	250	1600	oval	temp. strat.
17	3	green	1	none	0	0	1600	oval	pure glass @1600
18	4	clear	2	IB#1, #2	2.7	250	1650	oval	clear glass @1650
19	4	green	2	IB#1, #2	2.7	250	1650	oval	standard @ 1650
20	9	mixed	3	IB#1, #2	2.7,3.7,4.7	250	1600	oval	coarse;binder; temp strat; andela
21	4	Commercial Clay							commerc. strength
22	4	Commercial Concrete							commerc. strength
23	3	clear	2	IB#1, #2	4.7	300	1600	oval	More fines; more binder
24	3	green	2	fondu	10	300	1600	oval	
25	3	clear	2	IB#1, #2	2.7	250	1700	oval	clear glass @1700
26	3	green	2	IB#1, #2	2.7	250	1700	oval	standard @ 1700
27	3	green	1	none	0	0	1600	oval	pure glass @ 1700
28	5	green	3	fondu	6.3	250,275,300	1600	oval	fondu w/IB#3; vary H20
29	9	amber	2	IB#1	2	250	1600	flat	w/o IB#2
30	4	amber	2	IB#1, #2	2.7	250	1600	flat	amber glass
31	3	green	2	IB#1, #2	3.7	250	1600	flat	more binder
32	4	green	2	IB#1, #2	2.7	250	1600	flat	flat kiln
33	4	green	2	IB#1, #2	2.7	250	1600	flat	coloring agent
34	4	green	2	IB#1, #2	4.7	250	1600	flat	4.7% binder

APPENDIX B: TABLE 2 SUMMARY RESULTS OF ALL SAMPLES

Batch	Code	Modulus of Rupture (psi)	Compression (ksi)	Absorption	Characteristics	Max Temp °F
1	7-01-96.1	2573	24.5	0.25	standard	1600
2	7-07-96.1	1510	NA	0.29	1500^{o}F	1500
3	7-05-96.2	2834	25.3	0.41	Andela 1/8	1600
4	7-07-96.2	3105	NA	0.16	bend fines	1600
5	7-02-96.2	1784	NA	**2.49**	**fondu** binder,1 gradation	1600
6	7-02-96.1	1749	27.0	0.22	clear glass	1600
7	7-02-96.3	2166	NA	**1.31**	**fondu** binder,2 gradations	1600
8	7-07-96.3	2879	NA	0.10	fused glass 1500^{o}F	1500
9	7-10-96.1	1156	14.0	0.57	1400^o F	1400
10	7-10-96.2	2139	NA	**0.07**	pure glass @1400^{o}F	1400
11	7-15-96.1	2740	NA	0.21	stacking test	1600
12	7-15-96.2	2689	NA	**0.48**	stacking test	1600
13	7-15-96.3	2952	NA	**0.40**	stacking test	1600
14	7-15-96.4	2648	NA	0.24	stacking test	1600
15	7-15-96.5	2720	NA	0.28	stacking test	1600
16	7-15-96.6	2656	NA	0.27	stacking test	1600
17	7-15-96.7	**4483**	NA	**0.09**	pure glass @ 1600^{o}F	1600
18	7-23-96.1	2334	NA	0.29	**clear** at 1650^{o}F	1650
19	7-23-96.1	2490	NA	0.17	green at 1650^{o}F	1650
20	7-28-96.1-9	1790	NA	0.24	coarse glass - vary binder	1600
21	7-28-96.10	**1356**	NA	**5.67**	**commercial (clay)**	N/A
22	7-28-96.11	**1053**	NA	**4.23**	**commercial (concrete)**	N/A
23	7-30-96.1	2837	NA	0.18	finer glass/more binder	1600
24	7-30-96.2	2021	NA	3.04	**fondu**	1600
25	8-01-96.1	2658	NA	0.26	clear 1700^{o}F	1700
26	8-01-96.2	2482	NA	0.21	green 1700^{o}F	1700
27	8-01-96.3	3999	NA	0.10	fused 1700^{o}F	1700
28	8-04-96.1-3	2105	NA	**3.92**	**fondu/clay**, varying w.c.	1600
29	-12-96.2-4%	2097	NA	0.19	2% - 4%binder/flat kiln	1600
30	8-18-96.1	2523	NA	0.21	amber glass/flat kiln	1600
31	8-27-96.1	1973	NA	0.24	3.7% binder	1600
32	9-1-96.1	2640	NA	0.25	flat kiln	1600
33	8-27-96.2	2086	NA	0.23	metal oxide coloring agent	1600
34	8-27-96.3	1824	NA	0.37	4.7% binder	1600
					Total Flexure tests:	**134**
					Total Compression tests:	**20**
					Total Absorption tests:	**133**