Feasibility Study of Using Recyclable Polyethylene (PET) Materials as Coarse Aggregate for Concrete Mixtures

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The feasibility of using recyclable household plastics, specifically those made of polyethylene, commonly used in water and soda bottles, as a replacement for concrete coarse aggregate, was assessed. A method was developed for cutting polyethylene materials into fibrous strips. These strips were then used as a replacement for the rock coarse aggregate in batches of concrete. Standard 6" x 12" test cylinders were made using the concrete mixture and subject to destructive compressive testing in order to yield the compressive strength of the concrete mix 7, 14, 21, and 28 days after pouring. Three mixtures were tested, one control with no plastics, and two in which 10% of the coarse aggregate volume was replaced with varying levels of plastics. The results of the tests indicated that there was an overall loss of compressive strength in the concrete when the plastic was added. Observations on the mode of failure were also taken, and additional factors affecting the use of plastics in concrete were discussed, including workability and appearance.

Key words: Concrete, Plastics, Polyethylene, Compressive Strength, Materials, Testing

Introduction

The purpose of this paper is to evaluate the potential use of alternative materials, plastic in particular, as a replacement or supplement for traditional rock and sand as aggregate materials. The existing pool of literature is deep, and the methodology for testing concretes material properties is well established through ASTM and similar engineering standards. The feasibility of such a test should be well within the scope of this research project.

The primary relationship investigated in this report is between the use of post-consumer recycled polyethylene (PET) fibers as a partial replacement for rock coarse aggregate in concrete mixtures, and their resultant compressive strength. As the complexity of construction projects and materials increases, our role as builders will shift to understanding how new construction materials relate to the construction projects on a holistic level, with efficacy and materiality being prime considerations. The compressive strength will be used as the primary bar of efficacy in regard whether concrete mixtures have potential use in industry application. With regard to materiality, the appearance, workability, and mode of breakage for the concrete were also recorded and analyzed. Evaluating these characteristics in addition to the compressive strength gives us another lens by which to determine where concrete with plastic aggregate can be adopted in the construction process.

The fundamental reason for the addition of polyethylene fibers is sustainability. As the use of plastics increases, further methods for diverting plastics in the municipal waste stream from ending up in landfills or the ocean will need to be developed. This project represents an attempt to turn what would normally be considered waste into a usable consumer product.

Variables:

The weight of polyethylene fibers used as replacement for coarse aggregate is the independent variable of the experiment. This was measured through one *control group* (Mix 1) containing 0% plastics, and two *experimental groups*. The first experimental group (Mix 2) reduced the volume of course rock by 10%, and replaced it with a calculated equivalent of plastic. The next experimental group (Mix 3) also reduced the volume of rock by 10%, but added twice the amount of plastic as Mix 2.

A second independent variable was time. The compressive strength was tested 7, 14, 21, and 28 days after pouring for the control and experimental groups. This was done to see the development of compressive strength over the course of the hydration process, with the 28 strength being the measure of the design strength of concrete.

Compressive strength is the primary dependent variable of the experiment, measured as the axial stress required to cause structural failure in a standard 6 x 12 concrete testing cylinder. The maximum axial force required for failure was recorded, and the axial stress required for compressive failure was calculated using the following equation:

$$f = \sigma = \frac{P}{A} = \frac{axial\ force}{perpindicular\ resisting\ area}$$

Figure 1: general equation for axial stress. (Onouye, 2012, pg. 254)

Axial force (P) was measured in pounds (lbs), and the resulting axial stress (f) was measured in pounds per square inch (PSI). These measurements provide a basis for comparing the compressive strength of our concrete mixtures both to one another and to industry standards. This variable is a directly quantitative variable, as the result of the experiment will produce a numerical value that can be measured against typically expected concrete strengths.

The mode of failure for the concrete cylinders is a second dependent variable. The general breakage of the concrete cylinder after structural failure typically conforms to a number of known configurations: Each configuration gives us an insight at the reason the concrete failed. This variable would be classified as a qualitative variable, as it is reliant upon physical observation and a non-numeric classification system.

The slump was the third dependent variable measured in the project. The slump was measure in secondary experiment was conducted to test the workability of concrete. Workability is, "defined as the ease with concrete can be mixed, transported, placed and finished easily without segregation." (Siddique, 2008, pg. 1842) Slump is also quantitative, being measure in inches (in).

Inexperience on the part of the operators may have acted as a confounding variable in the experiment, as neither operator has extensive experience mixing concrete. Another confounding variable occurred in the testing of the 14 day strength of Mix 3. Due to a scheduling error, the cylinder was crushed on the 15th as opposed to the 14th day, as intended. This error may have resulted in a slightly higher compressive strength for that test, though it was still below both the other experimental and control groups.

Hypotheses:

The introduction of polyethylene (PET) fibers will reduce the compressive strength of the concrete cylinders linearly, with greater quantities of plastic resulting in weaker overall compressive strength. The overall strength of the concrete, however, will be within an acceptable threshold for use general commercial application.

The mode of failure within the control and the experimental groups will be the same, as the plastic will bind the cement and sand particles through the concrete matrix in a relationship fundamentally similar to that of the traditional rock coarse aggregate.

The slump of the concrete will increase with the addition of more plastic, as the plastic is thinner and more flexible than the rock.

Literature Review:

Existing academic literature can offer us three things in the valuation of this problem. First, it allows us to define the persistence of the problem, by looking at the existing post-consumer waste streams for plastic. Second, it gives us the tools to formulate a plan of action for addressing the problem, and testing our solution in a manner consistent with existing methods. Finally, it gives us a pool of other data with which to compare our results to.

Recycling and Recovery Routes of Plastic Solid Waste (PSW): A Review, by S.M. Al-Salem, P. Lettieri,and J. Baeyens offers a holistic look at the existing types and quantities of plastics used, and their general post-consumer disposal routes. According to their review of USEPA data, plastics have increased from 11% of the solid waste stream in 2002 to 12.1% of the solid waste stream in 2007, and, "containers and packaging plastics bags, sacks, and wraps, other packaging, other containers, and soft drink, milk, and water containers represent the highest tonnage." (Al-Salem, 2007, pg. 2626) Multiple methods for addressing PSW are reviewed, in the paper. The most applicable for our purposes is mechanical recycling, in which the plastic is broken down mechanically in order to be incorporated into a new product, like concrete. Use of Plastic in Concrete, A Review, also has some insight into the depth of the problem, "According to a 2003 Environment Agency report, 80% of post-consumer plastic waste is sent to landfill, 8% is incinerated and only 7% is recycled." (Siddique, 2008, pg. 1836). When you take into account the quantity of plastic thrown away in the united states, approximately 11 million tons, (Siddique, 2008, 1836) the enormity of this problem comes into clear focus.

The sources which provide a general scholastic understanding of concrete design parameters three-fold. First, Statics and Strength of Materials for Architecture and Building Construction (Onouye, 2012) provides the general equation for axial stress, which is the relation of force to an area, and is shown in figure 1. The second is Design and Control of Concrete Mixtures, which provides general concrete knowledge and a basic understanding of how concretes characteristics are changed through the addition of synthetic fibers. "Depending on fabrication method, random orientation of fibers may be either two-dimensional (2-D) or three-dimensional (3-D)." (Kosmatka, 2008, 121) In our case, the concrete was mixed by hand, orienting the fibers in a three-dimensional fashion. Physical properties vary depending upon the type of fiber used. Generally, however, "…reinforcing with fibers is not a highly efficient method of obtaining composite strength." (Kosmatka, 2008, 121) One of the noted problems with synthetic fibers is, "inconclusive performance testing for low fiber-volume usage with polypropylene, polyethylene, polyester and nylon," (Kosmatka, 2008, 125) which offers our experiment the opportunity to expand upon the limited bank of performance tests done for polyethylene fibers. The final that gives us insight into how to test this problem are the American Standards for Testing and Materials (ASTM) For this particular experiment, ASTM standards C 39, C 192, and C 143 were used to construct the parameters of the tests.

Evaluation of the literature provided a few existing studies from which to compare data. Use of Plastic in Concrete: A Review, (Siddique, 2008) is the most compressive, aggregating data from multiple individual studies. The studies showed mixed results. One, by Bayasi and Zeng showed an increased compressive strength for concluded that, "…19 mm fibrillated polypropylene fibers enhanced the energy absorption and toughness characteristics of concrete under compression." (Siddique, 2008, pg. 1844) Another study reviewed in the same article showed that, "Compressive strength decreased with increase in aggregates content." (Al-Salem, 2009, 1844) A third using polyethylene fibers also indicated, "It can be seen that: (i) compressive strength of concrete mixtures decreased with the increase in PET aggregates." (Siddique, 2008, pg. 1845) An individual study by Ochi T, Okubo similarly indicated that negligable reduction of compressive strength occurred when plastics were used as fiber reinforcement (2007), and another study which ground the plastic down into sand like particles found a negligible loss in strength

(Frigione, 2010) The literature seems to be heterogeneously mixed with studies that indicated a very low loss of strength or a substantial loss of strength for any concretes incorporating plastic at a given W/C ratio. The constant seems to be that the strength is typically lowered. The quantity it lowers by is largely dependent on the quantity of plastic included and the shape of the plastic materials added.

Methods

The concrete test cylinders measured 12” in height and had a diameter of 6”. The samples were poured in Jatco inc. orange plastic molds with a white plastic lid. Overall thirteen concrete test cylinders were poured for the experiment, four for the control group (Mix1), five for Mix 2, and four for Mix 3. The concrete mix designs are shown in table 1:

Mix 1 (Control Group)					
Cement	Water	Coarse Aggregate	Fine Aggregate	Plastic Fiber	Total
40 lbs	20 lbs	90 lbs	70 lbs	0 lbs	220 lbs
18.18%	9.09%	40.91%	31.82%	0.00%	100%
Mix 2					
Cement	Water	Coarse Aggregate	Fine Aggregate	Plastic Fiber	Total
40 lbs	20 lbs	81 lbs	70 lbs	1.27 lbs	212.27 lbs
18.84%	9.42%	38.16%	32.98%	0.60%	100.00%
Mix 3					
Cement	Water	Coarse Aggregate	Fine Aggregate	Plastic Fiber	Total
40 lbs	20 lbs	81 lbs	70 lbs	2.55 lbs	213.55 lbs
18.73%	9.37%	37.93%	32.78%	1.19%	100.00%

Table 1: Specified mix designs of concrete.

The measurements by weight served as a basis for the concrete pours, which were adjusted in the field by the quantity of concrete needed in each pour. The precision of the scale used to measure materials for the concrete pours was limited to 0.2 lbs, which introduces rounding error into the experiment. This instrument rounding error resulting limits the internal validity of the experiment.

Cement used for the experiment is Cal Portland Type II. The water cement ratio was 0.5 for all concrete mixtures. A sieve analysis of the rock and sand was done in a previous lab course, and is referenced in the appendix for a general understanding of the aggregate used in the experiment. Plastic fibers for the experiment were cut mechanically with scissors from waste plastic. The most common plastics used were High Density Polyethylene (HDPE) milk jugs and polyethylene terephthalate soda and water bottles. The length and width of individual fibers varied, but a basis of 4 inches long and 3.8inches wide was considered optimal.

Instrumentation

The following tools were prepared for the concrete pouring procedure:

- Five gallon plastic pails for the preparation of materials
- Shovels to put materials in the five gallon buckets
- A digital scale with a precision of 0.2 lb
- Metal scoops and trowels to transfer concrete into the plastic molds
- 5/8in tapered steel rods for the consolidation of concrete cylinders
- A wheel barrel for mixing the concrete

- Hoes to mix the concrete material in the barrel
- Pans were laid out for the collection of miscellaneous cement from filling the molds
- The 6 x 12 plastic molds with lids

A narrative description of the pouring procedure is as follows. The mixture materials were shoveled into the plastic buckets and weighed by the proportions labeled in table 1. The dry non-cementitious material (rock, sand, and plastic) was poured into the wheel-barrel and mixed with the hoes. The cement was then poured in and mixed with the other materials. The wheel barrel full of material and water were then taken outside the lab. One group member would gradually pour in the water while the others continued to mix the material with the hoes. Once the water was poured into the concrete mixture, two people continued to mix until all the materials were mixed together, a process taking about five minutes. The concrete was then scooped from the wheel barrel directly into the 6 x 12 plastic molds using the metal scoops. For each third of the mold filled with concrete, the material was rodded 25 times with the tapered steel rods in order to consolidate the concrete. When the molds were filled, excess material was struck off with the trowels. The plastic lids were then placed on the molds, which were labeled by mix number and the day-strength they would be tested for, and stored in a wet-room in the concrete lab until they were to be tested. The tools were then washed with a hose, and residual hardened cementitious material was struck off with the trowels. This pouring process was repeated until there were at least four cylinders for the control and each experimental group. One notable exception is that for the control group, the concrete was mixed in a mechanical concrete mixer as opposed to by hand with hoes.

Cylinders were then crushed 7, 14, 21, and 28 days after pouring for each group. Due to operator error, the 14 day cylinder for Mix 3 was crushed on the 15^{th} day. This is reflected in the results below. The testing machine used to carry out the tests was a Forney Testing Equipment model no. QC-50-106.

The following tools were prepared for the crushing procedure:

- A rubber mallet
- A metal cylinder splitter
- Two cylindrical metal bearing blocks with rubber cushions
- Safety glasses
- A brush and dustpan

A narrative of the crushing is as follows. The cylinder to be tested was removed from the wet room and the lid was struck off using the rubber mallet and cylinder splitter. The side of the cylindrical casing was split using the mallet and the splitter, and the concrete cylinder was removed. The concrete cylinder was then placed on the bottom metal bearing block in the QC-50-106 machine and the top bearing block was placed on the cylinder. The cylinder was centered within the machine and the plastic door to the machine was closed. The machine operator then put on safety glasses and turned on the machine. Compressive force was then applied to the cylinder using the machine. The cylinders would reach maximum compressive strength and structural failure would occur, at which point the load being applied would decrease below the maximum load applied steadily. The maximum compressive load was recorded in pounds and later used to calculate the maximum axial stress for the cylinder. The mode of failure for the cylinder was observed photographs were taken of the destroyed cylinder. The destroyed cylinder and concrete fragments were removed using the brush and dustpan. This process was repeated for each cylinder.

The following additional tools for the slump test were used, in addition to those from the pouring procedure:

- A standard metal slump cone, with a four inch top and eight inch bottom
- A flat metal pan, to place the slump cone on
- A tape measure

The narrative of the slump procedure is similar to that of the pouring process, however, the concrete was placed and rodded within the slump cone instead of the plastic cylinders. When the cone was full and excess concrete struck off, the cone was raised vertically, and the difference in height between the remaining concrete and the metal slump cone was recorded.

Results

Mix 1(Control Mix)				
Day	**Maximum Load (lbs)**	**Cylinder Surface Area (SI)**	**Maximum Axial Stress (PSI)**	**Mode of Failure**
7	77,000	28.27	2,723	Shear
14	81,000	28.27	2,865	Cone and Shear
21	72,500	28.27	2,564	Shear
28	98,500	28.27	3,466	Shear
Mix 2				
Day	**Maximum Load (lbs)**	**Cylinder Surface Area (SI)**	**Maximum Axial Stress (PSI)**	**Mode of Failure**
7	56,500	28.27	1,998	Columnar
14	61,000	28.27	2,157	Columnar
21	64,500	28.27	2,281	Shear/Columnar
28a	61,000	28.27	2,157	Columnar
28b	77,000	28.27	2,723	Shear/Columnar
Mix 3				
Day	**Maximum Load (lbs)**	**Cylinder Surface Area (SI)**	**Maximum Axial Stress (PSI)**	**Mode of Failure**
7	41,500	28.27	1,468	Columnar
15	59,500	28.27	2,104	Columnar
21	60,500	28.27	2,140	Columnar
28	79,000	28.27	2,794	Shear

Table 2: Compressive Strength and Mode of Failure for cylinders.

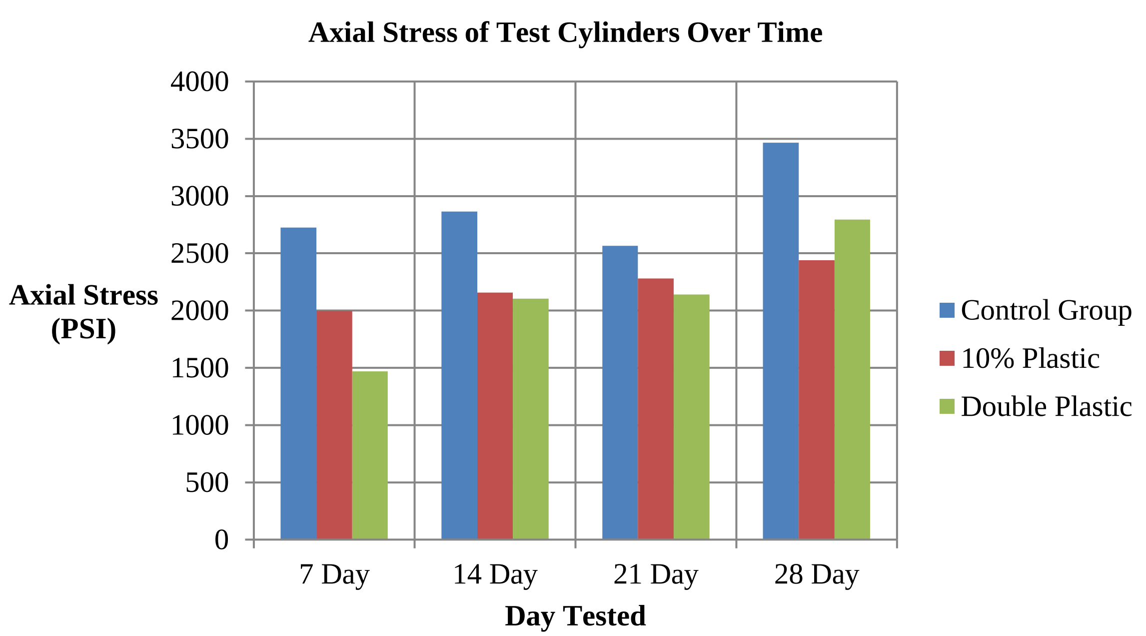

Figure 2: Compressive strength of mixtures, note 10% Plastic 28 day averages 28a and 28b.

The following Photos illustrate the appearance of the test cylinders before and after destructive testing:

<table>
<tr><th></th><th colspan="2">Mix 1</th><th colspan="2">Mix 2</th><th colspan="2">Mix 3</th></tr>
<tr><td>Day 7</td><td>
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<tr><td>Day 14</td><td>
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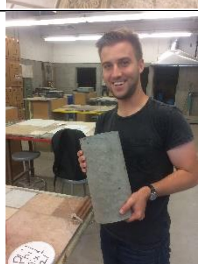
<tr><td>Day 21</td><td></td><td></td><td>
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<tr><td>Day 28</td><td>
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Table 3: Selected before and after cylinder images.

Slump (in)		
Mix 1	Mix 2	Mix 3
2	3/8	0

Table 4: Recorded concrete slumps.

Discussion

The data indicates that there is a strong negative correlation between the replacement of coarse rock aggregate with plastic fibers and the compressive strength of the resulting concrete. For all cylinders in both experimental mix groups, the compressive strength was lower than the control group. This manifested itself in both experimental groups, with a decrease in compressive strength of 19.39% between f_c of the 28 day control mix and the 28 day Mix 3. The mix of design 2 had a slightly larger decrease of 21.43% for 28-2. Both of the plastic groups had cylinders with a higher strength than the minimum standard of 2500 PSI laid out in ASTM C39 (pg. 6). This greater strength loss for Mix 2 is surprising as my initial hypothesis was that the compressive strength of the concrete would consistently decrease as more plastic was added. The fact that three out of the four other Mix 3 cylinders (75%) were weaker than their Mix 2 counterparts leads me to believe that the flipped result of the final plastic group was a result of individual difference in the concrete cylinders. If more tests were run the average of mix 2 would possibly be of slightly greater strength then the average strength of mix 3. The fact that first 28 day cylinder for mix one was weaker may also be a result of the individual differences in concrete strength. The difference between 28a and 28b is 26.23%, much larger than the 6.6% variation in strength between two cylinders permitted in ASTM C39 (pg. 6) The uneven surface of the 28a cylinder may be to blame, resulting in a premature fracture. The fact that the compressive strengths of plastic concrete mixes were so close in the 14 and 21 experimental groups, despite the fact that the weight of plastic doubled, is another unexpected result. This indicates that the primary loss of strength occurred because of the reduction in rock, which was the same in both groups, and the cracking caused by the addition of plastic, which is discussed with the mode of failure.

Visually, the cylinders look much like a traditional concrete mixture. However, there was protrusion of plastic fibers above the surface of the cylinder in both experimental groups. This did not affect the structural performance of the concrete, but it may limit the market for the material, as it affects the aesthetic appeal of the concrete, an important factor for both the architect and the owner of any project.

The mode of failure analysis on the concrete cylinders indicated that the plastic cylinders were much more likely to fail due to columnar cracking, while the control group failed through shear and shear and cone. Visual inspection of the cylinders showed that much of this cracking took place along the plane of the plastic fibers. This indicates that there was low adherence of the plastic to the rest of the concrete matrix, and the plastic served as a conduit for cracks to move through the test cylinders. More testing could be done to determine whether this cracking was the primary factor in the reduction of the concretes strength, or if it was the reduction in aggregate. If I were to run this experiment a second time, I would include a fourth group that had the reduced quantity of aggregate without the addition of plastic, in order to establish a more direct causal connection between the addition of plastic and the compressive strength.

The slump test was also surprising; with results showing that the plastic actually significantly decreased the slump. Possibly the plastic wove throughout the matrix of the concrete, making it more rigid overall. This would be consistent with operator observation that mix three was far more difficult to rod than the other mixes, which caused the consolidation issue seen in Mix 3's 7 day cylinder, as seen in table 3.

The resulting loss in compressive strength is generally consistent with the other studies regarding the incorporation polyethylene fibers. None of the studies I reviewed included a visual inspection of the concrete, so comparing those values directly isn't possible. The low slump did conflict with previous results, which indicated that PET fiber concrete's most attractive feature is its workability, "As evident from this result, the primary characteristic of the PET-fiber-reinforced concrete is that it is easy to handle." (Ochi, 2007, pg. 455 pg. 455) Adjusting the length and width of the fibers may have produced a more desirable result for my concrete cylinders, which is another area in which further tests could be done.

Directly addressing the individual hypotheses, this study concluded that the overall compressive strength was reduced in a manner predicted, with both experimental groups being above the 2500 PSI threshold established in ASTM C39. However, results for the mode of failure and the slump were opposite of what was expected, with the mode of failure for the cylinders indicating that the cylinders failed primarily due to columnar cracking, and the slump was reduced to a near zero value. Given the unexpected qualitative results in this individual study, it is not feasible for recycled polyethylene fiber to be used for general purpose concrete in the manner proposed.

There still are promising studies indicating alternative use of plastic aggregate in concrete for specific industrial applications, however. In, Development of Recycled PET Fiber and its Application as Concrete-reinforcing Fiber, concludes with a few of the it's uses, "PET fiber is used in Japan for spraying and lining tunnels, including expressway tunnels, and future use is expected to increase. Future applications include not only general tunnel support, but also underground structures that are located in harsh environments, such as near the coast or under the sea. In addition, its use as pavement on narrow, winding, and steep roads can be considered." (Ochi, 2007, pg. 455)

References

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Appendix

Sieve Analysis:

	Density		Specific Gravity		Moisture Content		Fineness Modulus
	Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine
Group 1	102	88.9	3.46	1.3	0.6	0.8	2.86
Group 2	97.04	85.41	2.67	1.35	4.35	6.39	2.837
Group 3	62.97	149.62	2.54	2.4	4.34	1.35	2.659
Group 4	64.5	150.27	2.48	1.36	1.56	2.13	2.78
Average	**81.6275**	**118.55**	**2.79**	**1.6**	**2.71**	**2.67**	**2.784**

Table 6: Breakdown of material properties of aggregates taken in the Calpoly CM 114 Fall, 2015 class.

Density Calculations

In order to relate the volume of rock to that of aggregate, the materials were weighed in a plastic 6 x 12 cylinder, filled with water. The following tables show the calculation process used to find the apparent density of materials and generate the quantity of plastic used in the experiment.

Material	Weight (lbs)	Weight Plus Water (lbs)	Water of Water (lbs)	Weight of Material (lbs)
Tare	0.6	11.4	10.8	0
Plastic	1.2	11.4	10.2	0.6
Course Agg.	17.2	21.4	4.2	16.6

Table 7: Weight of measured materials

Material	Cylinder Volume (ft^3)	Density of Water (lb/fit^3)	Volume of Water (ft^3)	Volume of Material (ft^3)	Density of Material (lb/ft^3)
Tare	0.20	62.428	0.173	0.023	0
Plastic	0.20	62.428	0.163	0.033	18.2
Course Agg.	0.20	62.428	0.067	0.129	128.6

Table 8: Density calculations of materials.

Material	Design weight of mat. (lbs)	Density of Mat. (lbs/ft^3)	Volume of mat. (ft^3)
Course Agg.	90	128.6	0.700
Plastic	1.27	18.2	0.070

Table 9: Table used to calculate weight of plastic for Mix 2. As seen in the table, the volume of the plastic is 10% of that for the coarse aggregate. The plastic quantity was doubled for Mix 3, due to the low apparent density of plastic.

Plastic Selection and Cutting Notes

Initial research into the make-up of consumer plastic showed both polyethylene and polypropylene as potential plastics for inclusion in the design mixture. Neighbors contributed from their recycle bins. Using this method, many materials were collected that could be mechanically ground into polyethylene fibers, while there simply was not enough polypropylene material to make concrete.