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The Performance of Concrete Containing Recycled Plastic Aggregates

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The Performance of Concrete Containing Recycled Plastic Aggregates

BY

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UNDERGRADUATE THESIS

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The Performance of Concrete Containing Recycled Plastic Aggregates

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Abstract

Currently, our planet faces an issue with plastic waste and even with current recycling methods, there is still a large amount of it found in landfills and bodies of water. The goal of this research is to find a practical solution for the use of recycled plastic. This will be done by adding various amounts of recycled plastic aggregates into concrete mixes. The aggregate will act as a replacement (by volume) for sand and will be added in amounts of 0, 10, 30, 50, and 70 percent. There will be a 28-day compressive strength test, using 3 samples for each mix. These samples will be compared against each other using the mix with no plastic as a reference. The goal of this research is to understand the relationship of plastic in concrete and eventually develop a mix that can sustain similar compression results compared to standard concrete.

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Introduction

Over the past century, plastics have become a dominant part of human life with uses ranging from packaging to construction. As of 2010, cumulative global plastic waste was estimated to be 275 million tons (Our World in Data 2019). Recycling efforts are limited due to cost and inefficiency. There are logistical challenges that make these efforts difficult, such as sorting, contamination, and transportation. According to National Geographic (2018), less than a fifth of all plastic is recycled globally, with Europe having a recycling rate of 30% and the US at 9%. As a result, an estimated 18 billion pounds of waste flow into the world's oceans every year. Waste that is inadequately disposed can find its way into rivers that can eventually lead to the oceans. With a majority of the population living in coastal areas, it is no wonder how easily this waste can end up out in open water. All this waste poses a threat to many different types of marine life. It is estimated that one million seabirds and 100,000 marine mammals are killed each year from plastic (Marine Insight 2017). While in the water, plastic can breakdown into billions of microparticles that get ingested by sea creatures. These microparticles can make their way up the food chain and potentially harm humans as well. The goal of this research is to find a practical solution for the use of recycled plastic particles.

With U.S. cement consumption at an estimated 88.5 million metric tons in 2018 (Statista 2018), plastic can potentially be used as a replacement for sand in concrete. This research will test recycled plastic aggregates (PAG) mixed with concrete to see if it can withstand standard compression and slump tests. This mixed recycled aggregate can be obtained by shredding different types of plastic. The idea behind this is to be able to reuse as many different types of plastic as possible. Some types, such as thermoplastics, can easily be recycled by melting it down and reforming it. Others, such as thermosets, cannot be recycled due to strong molecular bonds. When these are heated, they burn and release harmful chemicals such as carbon dioxide and benzene (BBC 2019). In this case, random amounts of plastic are taken from local dumpsters and shredded. The types of plastic and amount are completely random. Items that were grabbed include milk jugs, water bottles, bottle caps, and packaging items. By adding these particles into concrete, there is potential to minimize waste and open practical discussion on the different use's plastic can serve.

Literature Review

In the past two decades, research has been conducted on the performance of concrete containing plastic aggregates. These studies have sourced their plastic waste from a multitude of locations and have used varying amounts of different types of plastic in the samples. A study by Sorelli et al. (2017) used infrared optical sorting through a recycling stream to harvest PP, PE, PS, and PVC. Their samples contained mixes of all the plastics combined, along with individual types in each. Replacement rates ranged from 5% to 10% to 20%. Among the results, they concluded that a mix with all the plastics at a 20% replacement rate reduced compressive strength by 47%. Unique to this study, they are the first to notice a reduction of strength loss with the addition of air-reducing agents.

A study by de Brito et al. (2011) used collected PET bottles that were processed into 2 larger, irregular types of aggregates and a smaller, smoother aggregate. Using replacement rates of 7.5% and 15%, compressive tests resulted in strength loss across the board. Something noted here was the correlation between the shape of the aggregate and the loss of compressive strength and workability. They found that a smoother, more regular PAG, resulted in a better, more workable mix, along with a reduction in strength loss. From the study, cylindrical, pellet shaped particles (3mm length) performed better than large (10-20mm length) and shredded, flakey particles (2-5mm length). In this case, a less workable mix leads to an increase in the w/c ratio, in order to maintain slump and workability, but causes a loss in strength.

The first signs of positive results come from a study by Orr et al. in 2016. Using various plastics, a 14-day compressive target was set at 53 MPa. Table 1 shows the various mixes with a description of the PAG and figure 1 shows the compressive strength for each mix. It is interesting to note the mix with the most strength loss (PET4) included a chemical treatment of bleach (sodium hypochlorite) and caustic soda (sodium hydroxide). They state the reasoning for a 78% compressive strength loss in PET4 is due to the chemicals forming crystals on the plastic. When added to the concrete mix, these crystals dissolved in the water and decomposed forming oxygen bubbles. These air voids are the direct cause of such a stunning loss of strength. On the other hand, PET1 showed a great comparison to the reference mix using PAG that was graded to match sand. From this research, it can be concluded that using plastic graded fine enough, and at a low replacement rate, PAG can be a viable alternative to sand in certain situations. According to the study though, in all cases, plastic was debonded from the cement paste as shown in figure 2. This poses a problem as the loss in strength can be directly attributed to plastic's inability to bond to the cement paste.

Table 1 - Mix Reference

	Mix code	Base mix design	Mix description
1	Ref	R1	Reference mix
2	PET1	P1	PET fragments graded to match the sand replaced
9	PET2	P1	PET fragments between 0.5 and 2 mm in size
8	PET3	P1	PET fragments between 2 and 4 mm in size
7	PET4	P1	PET fragments between 2 and 4 mm in size and treated with sodium hydroxide and sodium hypochlorite
10	PET5	P1	PET fragments between 2 and 4 mm in size and treated with sodium hydroxide and sodium hypochlorite and washed
3	HDPP1	P1	Smooth spherical polypropylene pellets 3 mm diameter
4	HDPE1	P1	Shredded high-density polyethylene carrier bags passing through a 4 mm sieve
6	PPS1	P1	Virgin polypropylene strips (aspect ratio 6.7)
5	PPF1	P1	Virgin polypropylene fibres (aspect ratio 400)
11	PPF2	P1	0.64% substitution of sand with virgin polypropylene fibres

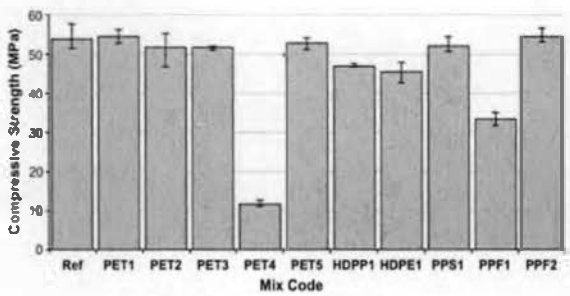


Figure 1 - Compressive Strength Results

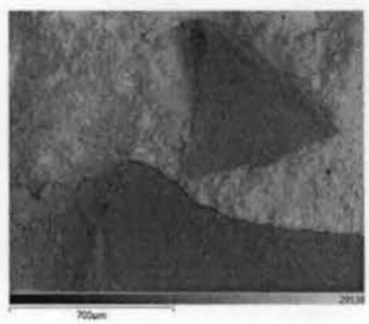


Figure 2 - Microscopic View of PAG in Cement Paste

To reduce the effects of bonding issues, a study by Choi et al. (2003) processed PET bottles in a way that their fine aggregate (granulated blast furnace slag) covered the plastic pellets, sized 5-15mm. Figures 3 and 4 show a diagram of the PAG mix and the PAG itself. In this test they used replacement rates of 0%, 25%, 50%, and 75% and water/cement ratios of 53%, 49%, and 45%. Despite using the regular aggregate/plastic mixture, they still saw a loss of compressive strength with each replacement rate. Tested at 28 days, they saw a 21% loss of compressive strength at a 75% replacement rate with a w/c ratio of 45%. The loss of strength for a 25% replacement and w/c ratio of 53% was only 5.7%. They noted that compressive strength loss decreased with a higher w/c ratio, meaning the PAG performed better with a higher water content.

Figure 3 - Combined aggregate

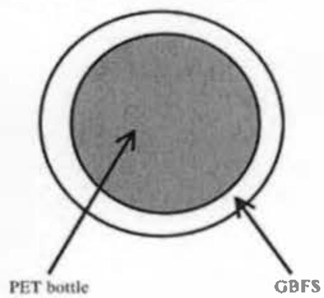
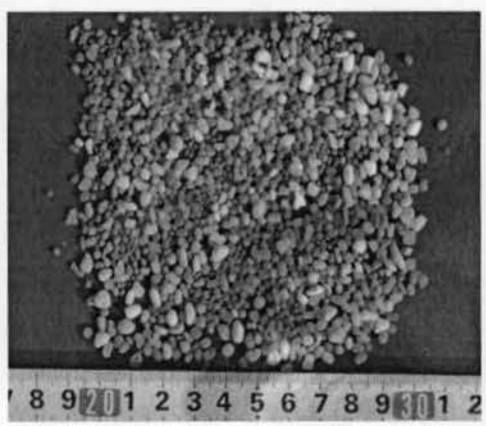


Figure 4 - Plastic aggregate



Despite numerous studies undertaken with many different variables, most results show plastic's negative effects towards the strength and workability in concrete. The issues that arise stem primarily from debonding. Only when these issues are solved can plastic become a viable alternative for sand.

Methodology

Materials

The plastic aggregate will act as a replacement for sand (by volume) at levels of 0, 10, 30, 50, and 70 percent. The plastic was obtained from recycling bins at random amounts of each type. Included are polyethylene terephthalate, high-density polyethylene, polypropylene, and polycarbonates. These plastic bottles, cups, and packaging materials were shredded using a Foremost granulator. Aggregate sizes range from 0.025 in. to 0.262 in. and shapes include flakes, cylindrical pellets, etc. created by the grinder.

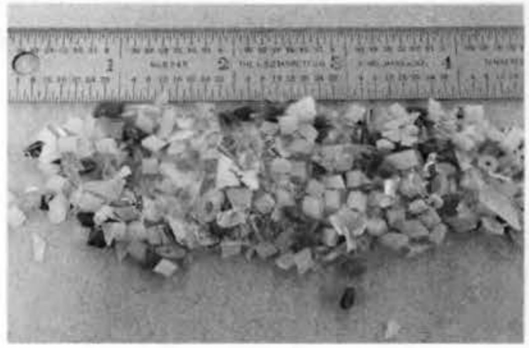


Figure 5 - Plastic Aggregate

Mix Designs

To determine the quantities of materials in the different mixes, the density and specific gravity of each ingredient was found. This was done by first weighing the material, adding water, and figuring the amount of displaced water. From there, volume, density, and specific gravity of the specimen could be obtained through calculations. This density test was done on the plastic aggregate, sand, and gravel. Each mix was then calculated using 0.75 ft^3 as the total volume and had a water/cement ratio of 53%. Tables 2-6 show each mix with weight and volume of the materials.

Table 2 - Mix 0 with 0% PAG

Ingredient	Specific Gravity	Weight (lbs)	Volume (ft^3)
Cement	3.15000	19.00	0.0967
Water	1.00000	10.00	0.1603
Gravel	3.38775	52.00	0.2460
Sand	2.49590	38.50	0.2472
Plastic Aggregate	0.80703	0.00	0.0000
Water/Cement Ratio:	0.526	Total Volume:	0.7501

Table 3 - Mix 1 with 10% PAG

Ingredient	Weight (lbs)	Voume (ft^3)
Cement	19.000	0.0967
Water	10.000	0.1603
Gravel	52.000	0.2460
Sand	34.650	0.2225
Plastic Aggregate	1.245	0.0247
	Total Volume:	0.7501

Table 4 - Mix 2 with 30% PAG

Ingredient	Weight (lbs)	Volume (ft^3)
Cement	19.000	0.0967
Water	10.000	0.1603
Gravel	52.000	0.2460
Sand	26.950	0.1730
Plastic Aggregate	3.735	0.0742
	Total Volume:	0.7501

Table 5 - Mix 3 with 50% PAG

Ingredient	Weight (lbs)	Volume (ft^3)
Cement	19.000	0.0967
Water	10.000	0.1603
Gravel	52.000	0.2460
Sand	19.250	0.1236
Plastic Aggregate	6.224	0.1236
	Total Volume:	0.7501

Table 6 - Mix 4 with 70% PAG

Ingredient	Weight (lbs)	Volume (ft^3)
Cement	19.000	0.0967
Water	10.000	0.1603
Gravel	52.000	0.2460
Sand	11.550	0.0742
Plastic Aggregate	8.714	0.1730
	Total Volume:	0.7501

Workability

When made, each mix will be tested for slump and bulk density. The slump tests measures the workability of the concrete and exposes a mix that has too much or too little water. The water content in concrete is important in determining how strong a mix is, as extra water weakens the concrete. Any mix that shears or completely collapses is considered a failure and needs to be reworked. According to ASTM C 143, any slump within the range of 1.0" to 6.5" is considered acceptable but is completely dependent on the project and use of the concrete. Bulk density can be calculated by dividing the mass of the concrete with the volume of the batch. Typical bulk density of concrete is 150 lbs/ft^3.

Compressive Strength

Each mix will be poured into nine 4"x 8" cylindrical molds. The purpose of this is to have a 28-day compressive strength test with 3 specimens for each mix, with a total of 15 cylindrical samples. Twenty-four hours after the molds are poured, they will be taken out and put in a tub to wet cure. When 28 days has passed the samples will be taken out of the wet chamber and tested on the Test Mark compressive testing machine, which can be seen in figure 6. Each sample will be placed in metal caps with neoprene pads inside to ensure equal pressure distribution. The machine will compress the samples at a rate of 35 ± 7 psi and record pressure at which it broke. The purpose of this test is to determine the amount of compressive strength each sample can withstand. Among that, fracture types, as seen in figure 7, will be recorded and compared amongst the samples.

Figure 6 - Testmork Compression Machine

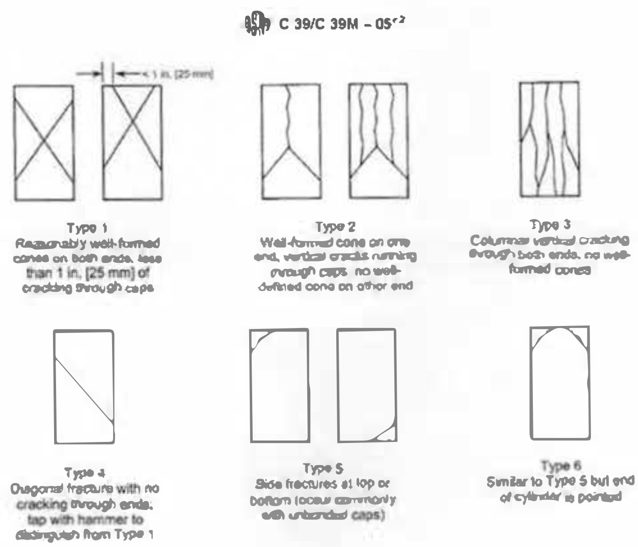


Figure 7 - Typical Fracture Patterns

Results

Table 9 shows the results of the slump test, weight and bulk density of the concrete batch after each pour. It is noted that the slump for mixes three and four (which contained 50% and 70% plastic respectively) completely sheared off and would be considered a failure. Any mix with these results would be denied on site and would have to be reworked. Below, figure 8 shows each of the slump tests.

Table 9 - Slump and Bulk Density

Mix	Slump (in)	Weight (lbs)	Bulk Density (lbs/ft^3)
0	2.25	113.76	151.68
1	2.75	110.67	147.56
2	3.00	103.73	138.31
3	5.50	98.33	131.11
4	6.75	93.91	125.21

Results for the compression test can be seen on table 10 and figure 9. Mix 1, containing 10% PAG, only had a compressive strength loss of 6.5% showing promising results for the use of this concrete in practice. Figure 10 shows percent compressive strength loss for each mix with PAG, compared to the base mix (0).

Figure 8 - Slump Test Results

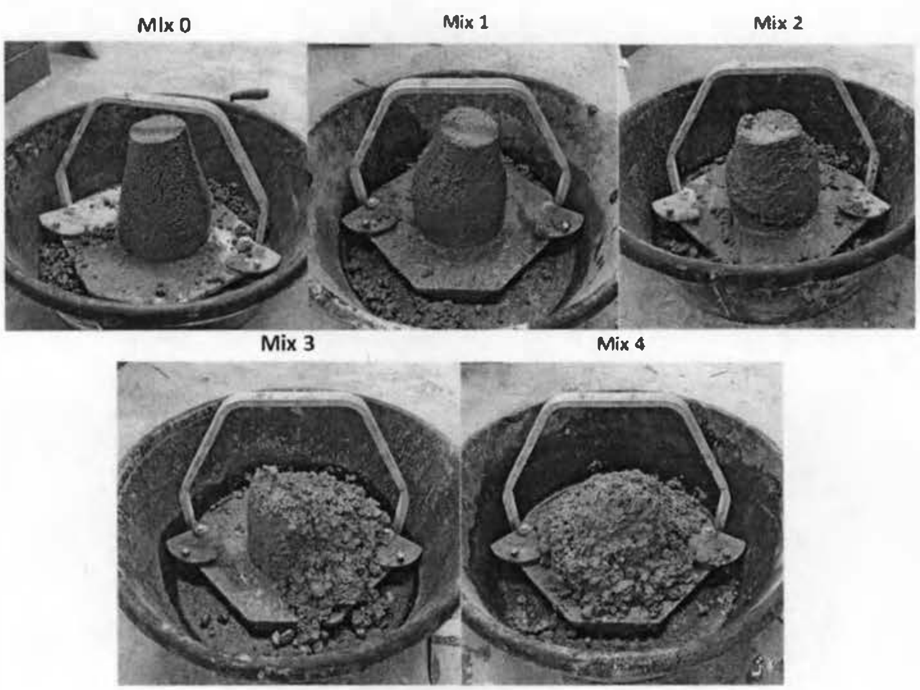


Table 10 - Compression Test Results

Mix #	Compressive Strength (PSI)	AVG Compressive Strength (PSI)	Break Type
0	6263	5967	2
	5490		1
	6148		1
1	5436	5579	2
	5548		2
	5754		2
2	4394	4475	2
	4414		3
	4619		3
3	3247	3179	3
	2997		3
	3292		3
4	2239	2077	3
	2056		3
	1936		3

Figure 9 - 28-day Average Compression Strength

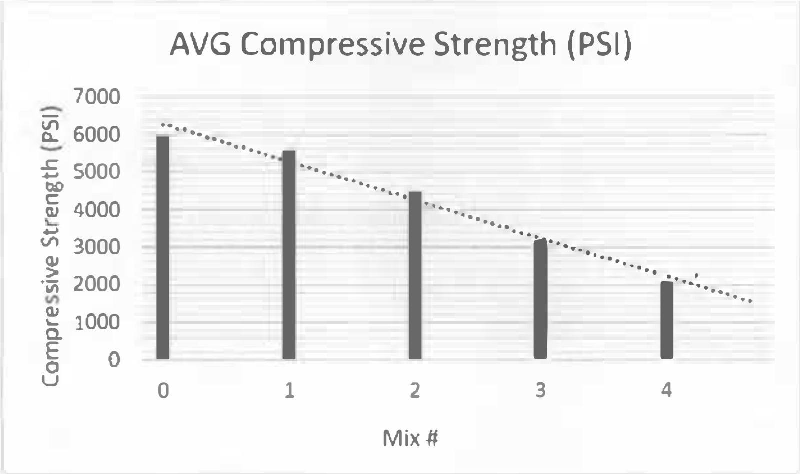
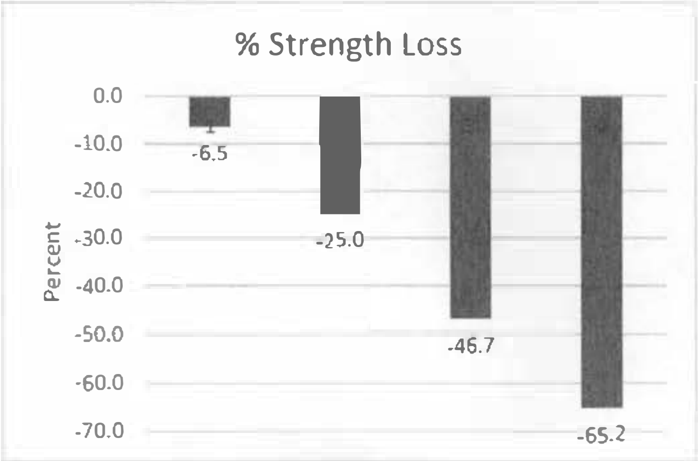


Figure 10 - Compressive Strength Loss Percentages



According to the International Building Code (IBC) and ACI 318 Standard, the minimum compressive strength required for structural concrete is 2500 PSI. This means that mixes 0-3 (up to 50% PAG) meet the minimum strength requirement for structural concrete. Table 11 shows the PSI requirements for various concrete uses (Concrete Manual 2012). Realistically, mix 1 would suffice for reinforced beams, slabs, columns, and walls.

STRENGTH REQUIREMENTS	
TYPE OR LOCATION OF CONCRETE CONSTRUCTION	SPECIFIED COMPRESSIVE STRENGTH, PSI
Concrete fill	Below 2000
Basement and foundation walls and slabs, walks, patios, steps and stairs	2500–3500
Driveways, garage and industrial floor slabs	3000–4000
Reinforced concrete beams, slabs, columns and walls	3000–7000
Precast and prestressed concrete	4000–7000
High-rise buildings (columns)	10,000–15,000

Table 11 - Concrete Strength Requirements

The type of break occurring in each cylinder can also be seen in table 10. While testing, it was noticed that mixes 2, 3, and 4 slowly crumbled with peak compression instead of 'popping' like in mixes 1 and 2. The way these broke indicates the points of failure were the PAG. Because of bonding issues, as seen in previous research, the PAG, spread throughout the sample, created many weak points within the cylinder that caused it to crumble instead of popping. Bonding issues can be seen in figure 11 as the mix 4 cylinder edges crumbled after being taken out of the molds. The inability of the PAG to bind to the cement paste is what causes the reduction in strength.

Figure 11 - Mix 4 Cylinders

Conclusions

The goal of this research was to determine the potential of PAG in concrete. Through literature review and data collection, results point to a variety of uses in certain situations. The most promising data comes from mix 1 (10% PAG) with only a 6.5% loss of compressive strength. The slump test for mixes 1 and 2 also prove with low amounts of PAG, workability is not compromised. For this to be applied in the industry, further research would need to be conducted on tensile strength, water absorption, air content, and others to determine concrete's full potential at certain replacement rates.

There are many different variations of this study future researchers can test. The variables that most impact strength and workability are type of plastic, shape/size of plastic, and replacement rate. If done again, researchers would need to focus their efforts on which type of plastic has the least amount of strength loss, and what shape is most conducive to bonding. The issue with bonding poses a problem for this type of research. From previous studies, the most promising shape is a smaller, rounded PAG, versus an irregular one. When trying to replace sand, it may be advantageous to process the PAG into particles sizes similar to the sand. A PAG powder could possibly produce results similar to reference samples. Another solution to debonding may be chemical treatment of the plastic. But, as seen in the study by Orr et al., certain chemicals actually ruin the integrity of the concrete due to the introduction of air bubbles formed from the composition of the PAG chemical mixture. Further research will need to be conducted to find possible alternative chemicals.

Beyond the problems of the integrity of the concrete with PAG, issues may arise with the logistics of recycling plastic. Not only does an established recycling program need to be in place, but further processing could cause the cost of PAG to be impractical for daily use. If methods from this research were used, costs would include the price of the recycled plastic (if any), transportation, and shredding/milling. Additional costs could come from chemical treatment, cleaning, further processing, and more.

With improvements to recycling methods and PAG types, it is possible to create a usable concrete mixture with PAG. Although slow to change, the concrete and construction industry could become a proponent in recycling efforts that the entire world could benefit from. It is up to us to think outside the box to develop and implement ideas that could have drastic effects on our planet. We are in a time where the decisions we make as a society impact every facet of life for decades to come.

Appendix A: ASTM Standards Used

To ensure proper lab results are obtained, all procedures will be in accordance with ASTM standards. Below are each of the standards used.

Procedure	Standard Used
Compressive Strength	ASTM C39
Slump	ASTM C143
Bulk Density	ASTM C138
Curing Specimens	ASTM C511
Making Specimens	ASTM C192
Capping	ASTM C617

Appendix B: Abbreviations

PAG	Plastic Aggregate(s)
w/c	Water to Cement Ratio
PSI	Pounds per Square Inch
ASTM	American Society for Testing and Materials
PP	Polypropelene
PE	Polyethylene
PS	Polystyrene
PVC	Polyvinyl Chloride
PET	Polyethylene Terephthalate

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