POLYPROPYLENE AS PARTIAL FINE AGGREGATE SUBSTITUTE IN CONCRETE

ARCE 453 SENIOR DESIGN PROJECT
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ABSTRACT

The objective of this project is to discover a structurally effective method in repurposing recyclable plastic waste through its partial substitution for traditional fine aggregate in concrete.

Results obtained from analysis indicate a 25 percent compressive strength reduction with polypropylene at a 10 percent partial substitution for total sand content. This material successfully performed as an alternative, presenting a ductile mode of failure.

Three material alternatives - polypropylene, polyethylene, and rubber - were substituted for a percentage of sand. These materials underwent concrete cylinder crushing tests to determine their ultimate crushing strength, with the intent of identifying the most effective substitute.

A secondary set of concrete cylinder tests proportioned different percentages of the independent variable (polypropylene) as a substitute. Results obtained from these tests indicate the mix design for concrete cast beams, from which the analysis results are derived. This beam experienced a 10% reduction in flexural capacity compared to a similar beam made of typical concrete. The beam section remained tension-controlled, as required by ACI 318-19 9.3.3.1.

This alternative mix design promotes sustainable building practices and can be utilized as a reduced-strength concrete for beams, slabs, and foundations.

INTRODUCTION

The inspiration toward researching this project stems from the building industries heavy reliance and usage of concrete as a dead weight for overturning anchorage. The intent of documenting this material is to remove recyclable plastic from the waste stream through its implementation and storage within concrete building systems. The definition of sustainability assumed for the project will be creating a solution to better future generations.

Concrete, a heterogeneous material comprised of coarse/fine aggregate, cement, and water, is utilized for its compressional strength, durability, as well as versatility as a building material. Due to extraction and harvesting of raw material components, concrete has significantly impacted building emissions of carbon dioxide. According to Ramsden's [7] publication from the University of Princeton, concrete as a material contributes around 8 percent of total greenhouse emissions of carbon dioxide globally. The U.S. Green Building Council reports that buildings contribute to roughly over 40 percent of emissions of carbon dioxide. Based on these findings, concrete alone represents 20 percent of this figure, emitting more pollution than any other standard building material in industry.

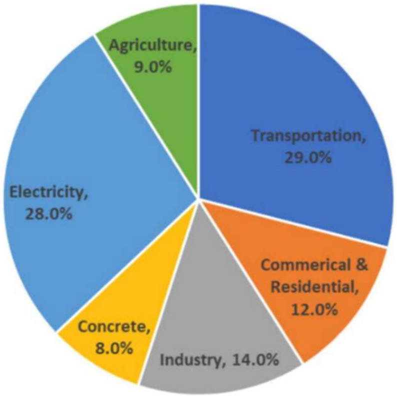

Figure 1- Global Emissions by Category Ramsden [7]

Concrete is the most consumed substance on earth after water (Savary [9]). Its production is expected to grow from 4.4 billion tons to 5.5 billion tons by 2050. In response to these challenges, many research initiatives are looking toward reusing waste. In India 60 million tons of waste is disposed annually (Suram [10]). Most of this waste comes from water bottles (polyethylene) and food containers (polypropylene). In the United States, more than 280 million reusable and waste tires (rubber) are generated annually (FHWA [12]). Incorporating recycled materials, such as industrial by-products or other post-consumer waste products, into concrete mixtures offers a promising solution to reduce environmental impact and promote resource conservation.

BACKGROUND

To understand this interface between material and emissions, it is vital to understand the components of concrete, how they interact, and how they produce emissions as a byproduct.

The primary component of concrete is cement, which acts as a binding agent, effectively joining together concrete as a mixture. Portland cement is favored due to its ability to form a cohesive matrix when mixed with water. Water acts as a catalyst in the hydration process, facilitating the reaction between cement and the aggregate. As hydration occurs, cementitious compounds form, securely binding aggregates together and creating a solid mass (Portland Cement Association [6]). Proper water to cement ratios are necessary for achieving desired structural properties.

Cement is produced through a reaction called calcination, where limestone, clay, and other materials are fired in a kiln. Calcination involves the breaking down of calcium carbonate into calcium oxide and carbon dioxide (the emission byproduct). This process accounts for roughly half of all concrete emissions (Gibbs [2]). Additionally, the energy required to fire the material significantly increases fossil fuel consumption, further exacerbating emissions from concrete production. The remaining CO2 emissions arise from the transportation and harvesting of materials, leading to habitat destruction and resource depletion. Storing recyclable waste products within concrete such as polypropylene, polyethylene, and rubber can effectively work to counter act resource depletion. See material property descriptions below for each alternative implemented in this projects initial phase of cylinder testing:

Polypropylene was first synthesized by Natta and Ziegler in the 1950's, where it was known for its high melting point, lightweight nature, and excellent chemical resistance (American Chemical Society [5]). These attributes combined with polypropylene's low moisture absorption and high fatigue resistance make it the ideal material for a variety of applications, such as food containers, medicine bottles, and packaging.

Polyethylene, which was discovered accidentally by Fawcett and Gibson in the 1930's, is categorized in two types: low-density polyethylene (LDPE) and high-density polyethylene (HDPE). LPDE exhibits a flexible chemical structure which explains its use in grocery bags, films and containers. HPDE is more rigid in nature making it suitable for milk cartons, detergent bottles, and piping systems (Malpass [4]).

Rubber, an elastomer, comes in both natural and synthetic forms. Natural rubber suffers from degradation. Today the most commonly used rubber is synthetic which due to the discovery of vulcanization is made possible (Samsuri [8]). Synthetic rubbers provide characteristics such as improved durability, heat resistance, waterproofing, and vibration absorption. A large contribution of rubber waste stems from recycled car tires. Shredded tires can be repurposed to create astroturf fields, playground or gym surfaces, asphalt mixtures, and even shoe soles.

Plastic pollution harms the environment through landfill and marine overflow, leaching of toxic chemicals, wildlife ingestion, entanglement, and habitat destruction. Through investigation of materials such as polypropylene, polyethylene, and rubber, hybrid concrete and recyclable material solutions can be tested to prevent recyclable waste from entering the waste stream.

LITERATURE REVIEW

The use of recyclable plastic and rubber waste as a substitute for traditional fine aggregate in concrete has gained significant interest in recent years. This literature review explores various studies examining the effectiveness of polypropylene, polyethylene, and rubber as partial replacements for sand in concrete, focusing on their impact on mechanical properties and potential benefits for sustainability.

A study published by Abdelmoti and Mustafa [1] in the University of Khartoum Engineering Journal, titled, *Use of Polypropylene Waste Plastic Pellets as Partial Replacement for Fine Aggregate in Concrete*, investigates the flexural and compression strength of concrete with polypropylene as a fine aggregate substitute. Their research suggests that with 5% and 10% partial replacement of plastic for fine aggregate, the value for slump increases as more plastic was implemented within the mix design. Since plastic is hydrophobic in nature it is reasonable to expect a greater slump as more water is freely available to be absorbed by other remaining components. This assertion highlights aspects of workability. Abdelmoti and Mustafa utilized square blocks crushed in a hydraulic press to obtain values for compressional strength of the material. Results by Abdelmoti and Mustafa show that blocks with 10 percent replacement decreased crushing strength by 12 percent and blocks with 5 percent replacement decreased 15 percent as compared to control variable (no plastic). Flexural strength was tested through cast beams applying a load midspan to measure the ultimate failure load. Results show an increase of 8 percent and 19 percent for 5 and 10 percent replacement respectively as compared to the control.

List of Nomenclature

a	depth of equivalent compression zone at nominal strength, in
b	width of section, in
As	area of steel, in^2
fy	specified yield strength of steel for reinforcement, psi
f'c	specified compressive of concrete, psi
d	distance from extreme compression fiber to centroid of tension reinforcement, in

$$a = \frac{As*Fy}{0.85\, f'c*b}$$

Equation 2

$$Mn = [A_s*F_y\,(d - \frac{a}{2})]$$

Equation 3

It is questionable the reliability of this testing. See Equations 2 & 3 from ACI 318-19. If the crushing strength f'c is smaller in comparison to the control, via equation 2, the depth of the compression block "a" should increase in value. Subsequently, via equation 3, if "a" is increased this should result in a reduced moment capacity.

The study conducted by Abdelmoti and Mustafa reports having a reduction in compressive strength followed by an increase in flexural strength respective to the control. These results appear contradictory, indicating a potential error in the study. However, it is worth noting that this research group commented upon this discrepancy, asserting that the flexural increase is due to the pellets having a higher bending resistance than sand. The report does not indicate whether section is tension controlled.

A study conducted by Suram [11] at Gokaraju Rangaraju Institute of Engineering & Technology (GREIT) titled, *Plastic as a substituent material for fine aggregate in concrete*, investigated the effect of substituting fine aggregate by weight with polyethylene terephthalate (PET) and polypropylene (PP). Results indicate an increase in slump with increased content of polypropylene and a decrease in slump with increased content of polyethylene terephthalate. Regarding crushing strength tests, both polyethylene and polypropylene showed similar reductions in 28-day compression strength showing an approximate 26-28 percent error from the control variable (no plastic). They concluded that as plastic content increases, compressive strength and workability will decrease. They assert that the optimum replacement for PET is 10% while an optimum replacement for PP is 5% for fine aggregate. In comparison to the study published to the University of Khartoum, this group asserts that plastic will decrease workability. However, the data regarding slump published in this study illustrates that polypropylene samples increased in slump with higher percentages of plastic content matching that of the Khartoum study. This correlation of data would point toward Polypropylene increasing total workability.

A study conducted by Shukur [10] with the department of Civil Engineering at the University of Mosul, titled *Mechanical properties of concrete using different types of recycled plastic as an aggregate replacement,* investigated the effects of substituting Polyethylene terephthalate (PET) and polypropylene pipe (PEP) as fine aggregate replacements. Shukur found that the use of recycled plastic reduced the compressive strength, tensile strength, and flexural strength by up to 31%, 22%, and 60%, compared with normal concrete, respectively. Flexural strength was determined through finite element analysis software. This raises concerns regarding unrealistic bounds; confounding variables such as mesh size, element type, boundary conditions, and material property assumptions may lead to inaccurate results of flexural software analysis. Compression and slump properties were tested empirically. Regarding their values for slump testing, as increased amounts of PEP were added slump decreased, comparatively as increased amounts of PET were added slump increased as compared to the control (no plastic). This finding shows results contradicting the results of both previously mentioned studies with PET showing increased workability and PP showing reduced workability.

The consensus between all three studies indicates that slump testing is highly variable. Due to the nature of this test, it is hard to accurately compact and record slump measurements. External factors such as temperature, material qualities, and true water content impose additional variables convoluting and or completely altering results/ recording of slump value. Furthermore, it is observed that as plastic content is increased compressional strength decreases. Based on this observation it is reasonable to assume that the flexural strength shall decrease resultantly as per equations 2 & 3 above.

METHODOLOGY

The replacement aggregate candidates used in the experiment were polypropylene, polyethylene and rubber pellets. The experiment took place in the CAED Concrete Yard (*Figure 2*). When replacing the aggregate in the concrete, the amount of aggregate replaced was determined based on percentage weight. A mixing drum was used to mix the concrete, which was then cast into 4" diameter by 8" tall cylinders. During this process, the slump of the concrete mixes was also measured using a 12" tall slump cone. Once the cylinders had cured, they were compression tested in a hydraulic press. The force required to break the cylinders was recorded and divided by the area of the face of the cylinder to determine the compressive strength of the concrete in accordance with ASTM C39.

The best aggregate of the candidates was then chosen based on the criteria of strength, looks after curing, and overall impact on the environment. The look of the concrete cylinder plays a huge part due to not wanting any gaps for any possible structural problems or having a client not like the look of the finished product. The look of the cured mix was determined through visual inspection. The criteria of overall impact on the environment stems from which fine aggregate replacement would create the biggest impact for society if it were chosen for use in the mix. The impact was determined through research of the aggregates. After choosing the preferred aggregate, the same cylinder test was repeated on multiple percentages of replacement. Then after crushing the multiple cylinders, a single percentage of replacement was chosen to be used in casting for a full beam.

Figure 2 - CAED Concrete Yard

When casting two 46" full beams with a span of 36" (*Figure 3*), the rebar cages were built by hand with (3) #4 bottom rebars, (2) #3 top rebars and #3 stirrups. The mixture was mixed in a mixer, not by hand. A cylinder from each beam's mixture was also cast to test the strength of the concrete at a 28-day cure. Lastly the two beams, after fully cured in 28 days, were placed in a mechanical press to test the failure mode and compare the strength results from the cylinder testing. The results from a previous experiment conducted were also used as a control as a starting point of expectations to compare our final beam results (*Table 3,4,5)*.

Figure 3 - Casting Beams

Table 1 – Control Concrete Mixing Data

Mix	Water (lbs/ft^3)	Cement (lbs/ft^3)	Coarse Aggregate (lbs/ft^3)	Fine Aggregate (lbs/ft^3)	Slump (in)
Standard	19.78	39.36	103.99	63.60	0.0
Extra Water	24.75	39.36	103.99	63.60	1.0

Table 2 – Control Cylinders Crushing Data

Mix	Days after Curing	Crushing Force (lbs)	Average Force (lbs)	Avg. Compressive Strength (psi)
Standard	7 days	53,370	51,035	4,060
		48,700		
	28 days	66,500	66,300	5,280
		66,100		
Extra Water	7 days	25,250	27,915	2,220
		30,580		
	28 days	44,850	42,120	3,350
		39,390		

Table 3 – Control Beam Batch Crushing Data

Mix	Crushing Force after 28 days of curing (lbs)	Average Force (lbs)	Avg. Compressive Strength (psi)
Standard	74,120	73,613	5,860
	72,170		
	74,550		

Table 4 – Control Beam Cracking Data

Mix	Length (in)	Flexural Reinf.	Shear Reinf.	Cracking Load (k)	Predicted Deflection (in)	Actual Deflection (in)
Standard	36	3 - #4	#3 @ 4” o.c.	18.05	0.0226	0.0200

Table 5 – Control Beam Failure Data

Mix	Length (in)	Flexural Reinforcement	Shear Reinforcement	Predicted Failure Load (k)	Actual Failure Load (k)
Standard	36	3 - #4	#3 @ 4” o.c.	36.23	36.08

PROCEDURE

Preliminary Cylinder Batch

To determine which of the replacement aggregates candidates stated in the methodology would be most effective, the first batch of cylinders were cast using three mixtures, with each mixture replacing 10 percent of the fine aggregate weight with an equal replacement aggregate weight. Three cylinders were cast for each mixture using the replacement aggregate. Two cylinders of each mixture would be crushed after seven days of curing, while the final cylinder of each mixture would be crushed at 28 days. The aggregate candidate with the greatest compressive strength would be used for further testing. The volume of a cylinder is 0.05818ft^3.

Table 6 – Replaced Aggregate Concrete Mixing Data

Mix	Replacement %	Water (lbs/ft^3)	Cement (lbs/ft^3)	Coarse Aggregate (lbs/ft^3)	Fine Aggregate (lbs/ft^3)	Replacement Aggregate (lbs/ft^3)
Replacement: Preliminary	10%	19.78	39.36	103.99	57.24	6.36
Replacement: Proportion	5%	24.75	39.36	103.99	60.33	3.27
	10%	24.75	39.36	103.99	57.24	6.36
	15%	24.75	39.36	103.99	53.97	9.63
	20%	24.75	39.36	103.99	50.88	12.72

Figure 4 – Preliminary Batch Measured Concrete Mixes

Figure 4 shows the 3 mixtures separated in buckets by material and by calculated weight (*Table 6*). The mixtures were based on the control mixture (*Table 1)* from previous experiment conducted then expanded on by replacing the fine aggregate by weight.

The mixer in the concrete yard was used to ensure that the mixture would be uniform and done quickly to not lose too much water. The dry materials were put in the mixer first (*Figure 5).*

This is done before adding water to make sure the dry material is uniformly distributed (*Figure 6)*.

Figure 5 – Dry Mix

Figure 6 – Wet Mix

When the mixture was done, the contents of the mixer were dumped into a wheelbarrow. The concrete was then scooped into a 12-inch slump cone to compact and check for slump (*Figure 7*). Then the concrete was compacted into the cylinders to cure for 7 and 28 day crushing tests.

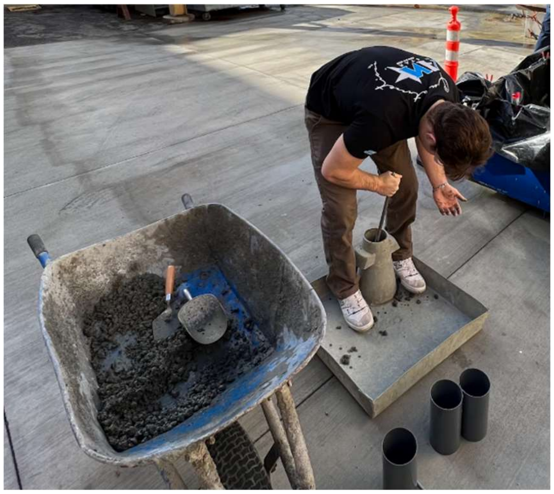

Figure 7 - Cylinder Compaction and Slump Test

Figure 8– Preliminary Batch Cylinders at 7 Day Cure

Figure 9 - Preliminary Batch Cylinders at 28 Day Cure

The pictures above show how the cylinders looked for the 7 day (*Figure 8*) and the 28 day (*Figure 9*) crushing tests. After examining data from the 28-day test performance (*Table 7)*, the polypropylene was chosen for further testing.

Aggregate Replacement Proportion Cylinder Batch

The second batch of cylinders were cast using four mixtures, with each mixture replacing 5-20% of the fine aggregate with a replacement aggregate (*Table 6*). Four cylinders were cast for each mixture using the different replacement aggregate proportions. Two cylinders of each mixture would be crushed after seven days of curing, while the final two cylinders of each mixture would be crushed at 28 days. The aggregate replacement proportion with the greatest compressive strength would be used for further testing.

The same process as the preliminary cylinder batch was done on the 5%, 10%, 15%, and the 20% aggregate replacement batches.

Figure 10- Proportion Batch Placed in Temperature Regulated Subaquatic Curing Chamber

The batches were placed in a temperature regulated subaquatic curing chamber (*Figure 10*) for 7 days and 28 days. Once the curing process was complete, they were tested in the hydraulic press with the same intent to find the best mixture with our previously stated parameters of strength, looks and overall impact on the environment.

Beam Casting

The day of the beam casting was lots of prep work to organize the 2 mixes (*Table 6)* for the two beams so the casting process would run smoothly. The entire mix needed for a single beam was mixed in a single batch to ensure that the concrete was of an even consistency without any loss of water. The fine aggregate replacement ratio chosen for the beam mixes was a 10% replacement ratio (*Figure 11*). The volume of the beams are 2.130ft^3

Figure 11– First and Second Beam Measured Concrete Mixes

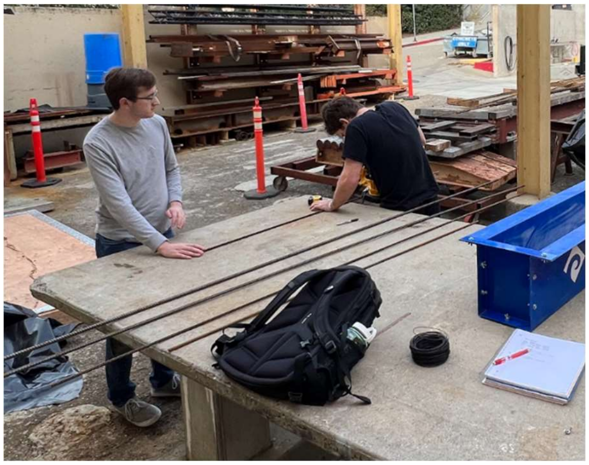

Figure 12- Cutting Rebar to Size

Figure 13 - Bending Rebar to Fit in Formwork

Metal reuseable formwork was used for casting the beams. The bottom bars needed to be longer to be bent upwards at the ends of the beams. When bending the rebar to fit within the formwork a bend radius was accounted for when cutting the length of the rebar (*Figures 12 & 13*). Prefabricated uniform stirrups (*Figure 14*) were used to not have any inconsistencies bending them by hand. The stirrups were evenly and left a space for the strain gages to be attached for testing purposes (*Figure 15 & 16*).

Figure 14 – Prefabricated Uniform Stirrups

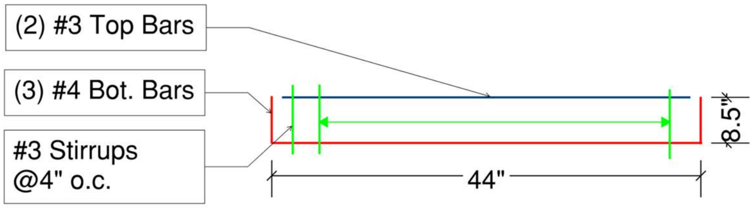

Figure 15 - Rebar Cage Dimensions

Figure 16 - Rebar Cage in Formwork

The same process as the cylinders of starting with the dry mix then adding the water was used when mixing the beam batches (*Figure 5 & 6*). The material was added from largest to smallest. The coarse aggregate, then the fine aggregate, the polypropylene pellets, then lastly the cement mix at the end of the dry materials. Then the water was added last to make a homogenous mix.

The mix was enough to fill a full beam and cast a couple cylinders to test on test day. The mixture was distributed evenly throughout the formwork and rebar by using a handheld vibrator power tool.

Figure 17 - Poured Beams with Removed Caged Supports

Figure 18 – Concrete Beam Dimensions

The large mixes accomplished filling both formworks and having enough extra calculated to fill a few cylinders for future testing. After a few minutes letting the concrete set, the blocks of wood that held the rebar cage from sinking to the bottom of the formwork were removed (*Figure 17*). After a day the formwork was removed to allow the beams to cure outside on their own (*Figure 19*). The day before testing, the beams were painted with watered down paint to allow the paint to flake as the beam is being tested (*Figure 20*). This allows for easy identification of crack locations to mark and document during different steps of loading. Two pieces of #3 and #4 rebar were tested to determine their yield strength.

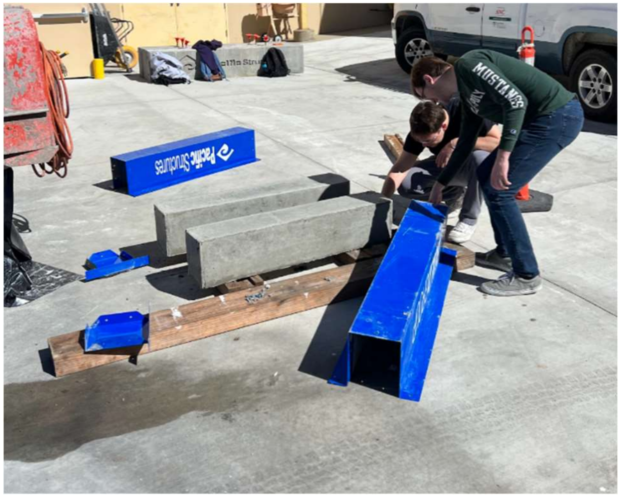

Figure 19– Cured Cast Beams Removed from Formwork

Figure 20 – Painted Beams Prepped for Testing

Beam Mixture Cylinder Batch

The third and final batch of concrete was cast into two concrete beams and three additional cylinders (*Figure 21*). By crushing the additional cylinders and determining the compressive strength of concrete cast from the same mixture as was used in the beams, the compressive strength can be used to calculate the approximate load at which the beam would fail. This predicted load would be used to gauge if the beam would behave as expected when subjected to shear and flexure loads.

Figure 21 - Beam Mixture Cylinders 28 Day Cure

The First Beam Flexure Test

The first beam was placed in the mechanical press with the help of a forklift. The beam needed to be placed evenly on a support on each side of the beam. The mechanical press induced a point load on the center of the beam (*Figure 22*). The load was halted periodically to check the cracking and mark it with a colored marker. The colored marker lines were drawn to show how much damage was occurring at certain loads. Once that data was recorded, the beam was pushed to failure down to the table. After a complete failure occurred, the beam was removed with the same forklift (*Figure 23*). The results are shown in *Tables 15, 16.*

Figure 22 - First Beam in Mechanical Press

Figure 23 - First Beam Failure on Forklift

The Second Beam Flexure Test

The second beam was loaded onto the supports after removing the first beam and cleaning the table (*Figure 24*). The second beam testing was done the same way as the first beam to record more data (*Tables 15, 16)* to compare to the control beam and the first beam flexure test. The second beam test was used to check for consistency within our results.

Figure 24 - Second Beam in Mechanical Press

RESULTS AND ANALYSIS

Preliminary Cylinder Batch

Table 7 - Preliminary Batch Casting and Crushing Data

Replacement Aggregate	Slump (in)	Crushing Force (lbs)			
		Cylinder 1: 7-day strength	Cylinder 2: 7-day strength	Average 7-day strength	Cylinder 3: 28-day strength
Polypropylene	0.25	14,160	16,460	15,310	28,800
Polyethylene	1.00	10,620	12,710	11,665	17,770
Rubber	0.00	21,170	15,220	18,195	26,550

Table 8 - Preliminary Batch Compressive Strength

Replacement Aggregate	Area of Face (in^2)	Compression Strength (psi)			
		Cylinder 1: 7-day strength	Cylinder 2: 7-day strength	Average 7-day strength	Cylinder 3: 28-day strength
Polypropylene	12.566	1,130	1,310	1,220	2,290
Polyethylene	12.566	850	1,010	930	1,410
Rubber	12.566	1,690	1,210	1,450	2,110

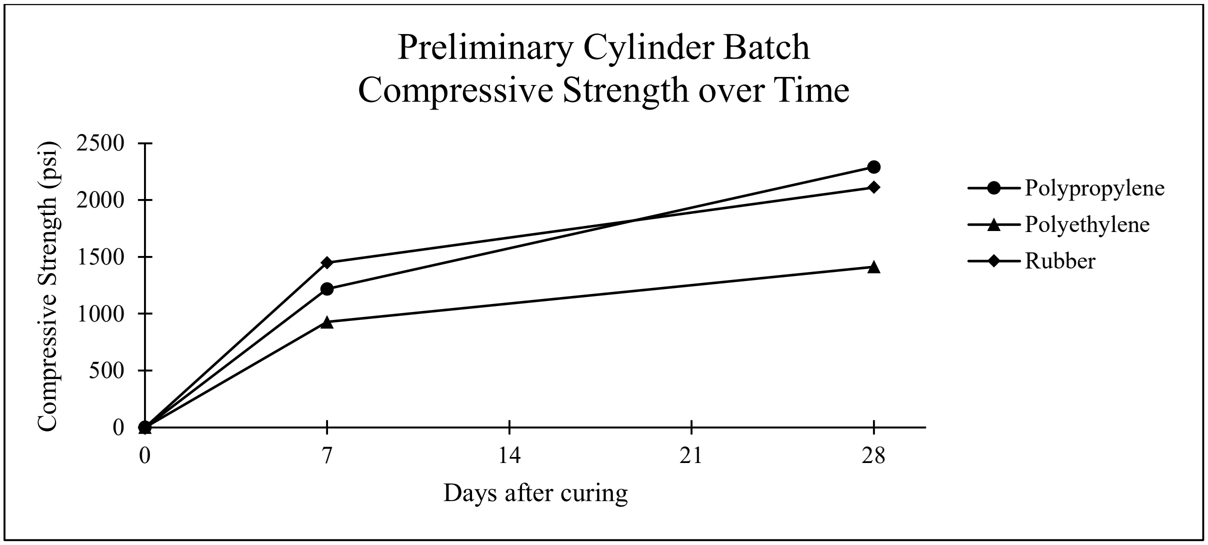

Figure 25

Of the three replacement aggregates tested, polypropylene had the greatest strength after 28 days of curing, as seen in *Figure 25*. It was for this reason that polypropylene was determined as the most suitable aggregate for further testing. Changes were made to the casting procedure based on observations of the cured cylinders. Many of the cylinders had a rough or inconsistent outer surface, which is undesirable for structural concrete. After discussion with professionals experienced with concrete casting process, the amount of water used in the mix was increased for future batches.

Aggregate Replacement Proportion Cylinder Batch

Table 9 - Aggregate Replacement Batch Casting and Crushing Data, 7-days

Replacement Aggregate	Slump (in)	Crushing Force (lbs)		
		Cylinder 1: 7-day strength	Cylinder 2: 7-day strength	Average 7-day strength
5%	1.00	24,670	25,700	25,185
10%	0.75	25,810	24,130	24,970
15%	0.75	8,640	15,170	11,905
20%	0.25	13,020	16,710	14,865

Table 10 - Aggregate Replacement Batch Casting and Crushing Data, 28-days

Replacement Aggregate	Slump (in)	Crushing Force (lbs)		
		Cylinder 3: 28-day strength	Cylinder 4: 28-day strength	Average 28-day strength
5%	1.00	13,120	32,720	22,920
10%	0.75	35,900	33,150	34,525
15%	0.75	25,240	24,980	25,110
20%	0.25	17,210	16,110	16,660

Table 11 - Aggregate Replacement Batch Compressive Strength, 7-days

Replacement Aggregate	Area of Face (in^2)	Compressive Strength (psi)		
		Cylinder 1: 7-day strength	Cylinder 2: 7-day strength	Average 7-day strength
5%	12.566	1,960	2,040	2,000
10%	12.566	2,060	1,920	1,990
15%	12.566	690	1,210	950
20%	12.566	1,030	1,330	1,180

Table 12 - Aggregate Replacement Batch Compressive Strength, 28-days

Replacement Aggregate	Area of Face (in^2)	Compressive Strength (psi)		
		Cylinder 3: 28-day strength	Cylinder 4: 28-day strength	Average 28-day strength
5%	12.566	1,040	2,600	1,820
10%	12.566	2,860	2,640	2,750
15%	12.566	2,010	1,990	2,000
20%	12.566	1,370	1,290	1,330

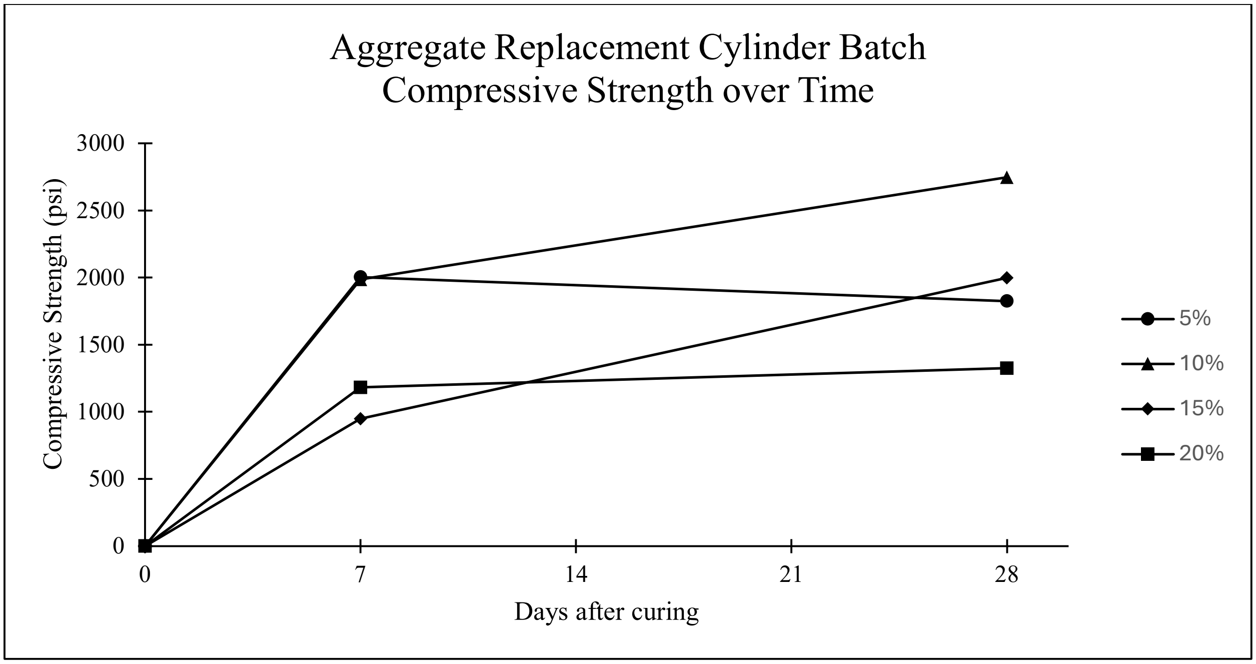

Figure 26

Of the four aggregate replacement proportions tested (*Figure 26*), the 10% replacement had the greatest strength after 28 days of curing, as seen in Figure 25. The 5% replacement had similar strength at 7 days, but a possible outlier in the data resulted in a lower average strength than the 10% replacement. If this outlier was ignored, the 10% replacement would still have a greater average strength than the 5% replacement.

In addition to strength, the amount of recycled material used requires consideration. While the 20% replacement would use the greatest amount of recycled material, it was significantly weaker than the other replacement ratios. Furthermore, cylinders cast using the 15% and 20% replacement mixes had a rough outer surface, which was deemed not suitable for a concrete beam. As such, the 10% replacement mix was chosen for the casting of the concrete beams.

Figure 27 - 5% Cylinder Crush

Figure 28 - 10% Cylinder Crush

Figure 29 - 15% Cylinder Crush

Figure 30 - 20% Cylinder Crush

Figure 27 shows the cylinder compression test result of a 5% fine aggregate replacement. The result ended with large strength but not enough replacement for it to be impactful on the environment. *Figure 28* showed an ideal break in the compression test while replacing 10% fine aggregate and while still looking visually pleasing. *Figure 29* showed the result of 15% fine aggregate replacement. It showed signs of bad bonding after curing. It was not strong nor visually appealing. *Figure 30* with a 20% fine aggregate replacement resulted in low strength and bad bonding very similar to the 15% replacement.

Beam Mixture Cylinder Batch

Table 13 - Beam Mixture Batch Casting and Crushing Data, 28 days

Cylinder No.	Slump (in)	Crushing Force (lbs)
Cylinder 1	1.00	36,480
Cylinder 2		38,800
Cylinder 3		39,955

Table 14 - Beam Mixture Batch Compressive Strength, 28 days

Cylinder No.	Area of Face (in^2)	Compressive Strength (psi)
Cylinder 1	12.566	2,900
Cylinder 2		3,090
Cylinder 3		3,180
AVERAGE		3,057

Table 15 – Yield Strength of Longitudinal Rebar

Rebar	Area (in^2)	Yield Force (lbs)			Yield Strength (psi)
		Bar 1	Bar 2	Average	
#3	0.11	7,025	6,883	6,954	63,218
#4	0.2	9,750	9,482	9,621	48,105

The values of the concrete compressive strength and steel yield strength can be used to calculate the internal tension and compression forces within the beam. To determine the moment capacity of the concrete section, an equilibrium of the beam's cross-section must be achieved. Figure 31 displays the variables used to determine if the cross section is in equilibrium.

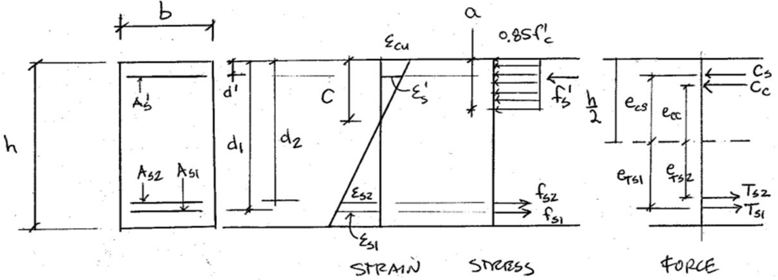

Figure 31 – Equilibrium of a Concrete Cross Section

Using an Excel spreadsheet, the depth of the compression zone, c, was found through an iterative process and used to calculate the moment capacity of the beam section. That moment capacity was then used to determine the applied point that would produce that critical moment in the beam at midspan.

Figure 32 - Beam Mixture Cylinder Strength Tests

The beam mixture cylinders performed very well in the hydraulic press compression test showing good signs of an ideal cracking cases in the form of an ‘x’ or diagonally (*Figure 32*).

First and Second Beam Flexure Test

Figure 33 - First Beam Cracks 28.52 kips

Figure 34 - First Beam Failure at 36.50 kips

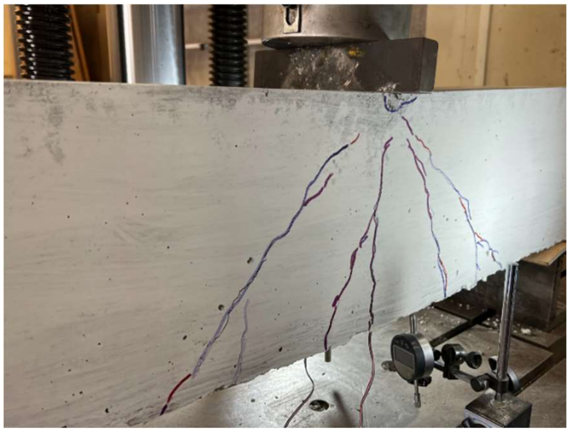

Figure 35 - Second Beam Crack at 24.03 kips

Figure 36 - Second Beam Failure at 30.00 kips

As the beams cracked (*Figures 33, 35*), they behaved similarly to typical concrete and the control concrete beam. The cracking formed in the beams formed in a diagonal pattern from the point load to the supports showing the shear lines crossing the internal stirrups. As predicted, the beam at failure (*Figures 34, 36)* showed the rebar visibly yielding. The beams both failed in shear.

Beam Results

Table 16 – Replacement Aggregate Beam Cracking Load

Beam No.	Length (in)	Flexural Reinf.	Shear Reinf.	Cracking Load (k)	Predicted Deflection (in)	Actual Deflection (in)
1	36	3 - #4	#3 @ 4” o.c.	28.52	0.0358	0.0482
2	36	3 - #4	#3 @ 4” o.c.	24.03	0.0301	0.0430

Table 17 – Replacement Aggregate Beam Failure Load

Beam No.	Length (in)	Flexural Reinf.	Shear Reinf.	Predicted Failure Load (k)	Actual Failure Load (k)
1	36	3 - #4	#3 @ 4” o.c.	33.41	36.50
2	36	3 - #4	#3 @ 4” o.c.	33.41	30.00
AVERAGE					33.25

DISCUSSION AND REVIEW OF RESULTS

Through our testing, a 10% replacement of fine aggregate with polypropylene pellets resulted in concrete with a compressive strength of roughly 3,000 psi. From the control tests conducted previously, the concrete made with the standard mix had an average compressive strength of 5,557 psi. The replacement aggregate resulted in a 45% reduction of the concrete's compressive strength compared to the standard concrete mix. When compared to the extra water concrete mix, which had the same water-cement ratio as the replaced aggregate mix, the replaced aggregate had a compressive strength that was only 8.7% less.

The replaced aggregate beam resisted about 10% less flexure loading than the similar beam made of standard concrete. This reduced compressive strength had minimal impact on the strength of the concrete beam, as the beam remained tension controlled. As such, the only effect that the compressive strength has on the moment capacity of the beam is in determining the depth of the Whitney stress block. However, the replaced aggregate beam experienced roughly 30% greater deflection at midspan than predicted. In comparison, the standard concrete beam experienced 11.5% less deflection at midspan than predicted. This suggests that replaced aggregate concrete is not as stiff as typical concrete. The cracking load values for the replaced aggregate beam do not directly correspond to the cracking load value of the standard concrete beam, as the value was not recorded at the first sign of beam cracking, which was the point at which the control beam's deflections were recorded. A portion of the difference between the predicted and actual deflection values is likely due to this error. While this error makes direct comparison impossible, a comparison of the relative accuracy of the predicted deflections remains valid.

The primary reason that the replaced aggregate concrete did not perform as well as typical concrete is that the replacement aggregate did not serve the same functions as the sand it replaced. Throughout the course of the project, it was noted that differences in aggregate size, texture, and chemical composition likely prevented the polypropylene pellets from bonding with other concrete component materials. Consequently, the replaced aggregate concrete cracked more easily than typical concrete, which significantly impacted its structural performance. To remedy this, several treatments could be used to alter the size and shape of the pellets and improve the cohesion of replaced aggregate concrete. Grinding up some of the pellets into a fine powder, fracturing pellets frozen with liquid nitrogen, and applying an adhesive to the pellets are ideas that were proposed throughout the course of the project to address this issue.

Another issue was found in how the plastic interacted with the mix. When after crushing the beams, it was noted that more plastic pellets were found near the top of the beam than near the bottom. This suggests that the pellets are not as dense as the surrounding cement and, during the mixing or curing process, rose to the top of the concrete. While the effect of this uneven distribution is unknown, it is considered undesirable to have the components distributed in such a way, as this distribution may not be easily replicated. To address this, materials denser than polypropylene should be considered for future testing. This issue may be related to the above-mentioned cohesion issue, such that solving that issue may also solve this issue.

With this initial phase completed, there are opportunities for expanding the scope of this project. It was observed that the replacement aggregates seemed to “leech” at the water in the concrete mix, resulting in cylinders that did not have smooth surfaces. This leeching effect decreased the effect of water in terms of workability and surface smoothness. This was remedied by adding additional water to the mix, with the amount added taken from data collected in the control experiments. A more rigorous study of different water contents in addition to replacement aggregate may reveal a correlation between these two parameters. Additionally, the effects of additives, such as fly ash or super plasticizers, might be able to counteract the drawbacks of the replacement aggregate used, allowing for a higher percentage of aggregate to be replaced.

These initial results show that there is potential for using recycled materials to replace traditional aggregates in concrete without a severe loss in performance. Further studies should be conducted to improve the performance of this concrete, including tests of the possible replacement of coarse aggregate. This study was primarily concerned with the performance of the material and only measured the environmental impact of the use of recycled materials by the amount used in the concrete mix. A long-term analysis of the durability of replaced aggregate concrete would better determine how effective this material is at keeping plastic waste out of the environment.

PROJECT REFLECTION

Throughout the course of the project, our team was able to add to our knowledge of concrete mixing, curing, construction, and testing, which we used to improve on our experimental procedure as the project developed. Our previous experience was only about 30 hours spent in a concrete design course during the last three months of 2023. While we grew familiar with the process of mixing and casting concrete during this time, we did not gain an intuitive understanding of how that process contributed to the material properties of cured concrete. Despite that, this experience prompted our interest in possible sustainable solutions for concrete and pushed us towards undertaking this project.

While we were aware of sustainability efforts focused on reducing emissions of cement production, we wanted to see if there was a way that sustainable practices could be applied to concrete aggregate. Through our research, we discovered several studies that pursued similar goals and used that to form the basis of our experimental procedure. Our initial plan was to simply apply our previous mixing and casting experience to this new aggregate, but we soon discovered that was not possible. Our cylinders had incredibly rough exteriors with large cavities throughout, and they performed much worse than we initially hoped. To remedy this, we consulted with our faculty advisor and a contractor with experience in casting concrete. Both suggested that we increase our water content for future batches, which did address this issue. Encountering this problem with our cylinders led us to engage with those more knowledgeable than us and to learn something about how our new material interacts with the concrete mix.

Reflecting on the project, the team feels much more confident in our ability to mix, cast, and test concrete members. Through observing how our replacement aggregates interacted with the other components of concrete, we gained a greater understanding of the role traditional fine aggregates, namely sand, play in concrete. While loading our beams, we were able to apply our understanding of theoretical beam behavior and then observe how the actual loaded beams confirmed that conceptual knowledge. This project made us more familiar with concrete as a material, in terms of both design calculations and member construction.

APPLICATIONS TO THE REAL WORLD

The project's goal was to find a way to leave the world in a better state than it was found. The team was also tasked to address possible global, economic, political, environmental, and societal considerations. The team was able to tackle these goals and tasks as students from Cal Poly's Architectural Engineering Major, having opportunities to learn how to design and analyze concrete structures and components. The theory learned from research and the mechanics of materials of the mixture is applied by making fully reinforced beams in the CAED concrete yard.

The production of the cement component of concrete produces 1.4 billion tons globally of carbon emissions. To put the quantity of carbon emissions emitted by the production of cement in perspective, it is comparable to the total flight emissions of the world yearly. This creates a massive impact on considerations mentioned.

This research project was tailored toward investigating a fine aggregate substitution instead of direct cement replacement due to its importance as a binding component of the mixture. Altering cement proportions drastically reduces efficacy of concrete as a homogenous mixture. This is what led to the decision to replace a portion of the fine aggregate to attempt to offset the "net emissions" from the final mixture while attempting to keep the strength and visual appeal.

The project's idea was to be able to remove microplastics from the polluted oceans and repurpose it by melting them into pellets suitable to be a proportional substitution within the concrete mixture. About 16.5% of microplastic in the world's oceans comes from specifically polypropylene. This would help the environment globally by removing waste from the oceans. Removing waste from the oceans would not only help humans but also help animals restore their habitats and ecosystems to what they once were. Economically, to set up the production of filtering the oceans and turning the filtered plastic into a suitable mixing material for concrete, would most like likely be a big initial set up cost. That initial set up cost for production would most likely be the biggest hurdle alongside getting governmental approval and support to back it. In the long run that cost would be small in comparison due to most likely having a political agenda backing production. Politicians would have an easy win by supporting something that is good for the world's wellbeing. Another hurdle that would need to be tackled would be getting the building industry's support. The building industry could be incentivized to repurpose the plastic as a "green" component of concrete. With building "green" there could be government incentives to use more sustainable concrete globally. Societally, as the building industry leans more towards building "greener", there are more clients that will pay more to be using the product if successful. Overall, if this product, after more research, is successful it seems to be a win-win situation for all considerations if there is financial and government support.

The project's end resulting 10% substitution being suitable may not seem like a whole lot but when comparing to the amount of concrete weight throughout an entire building, it becomes substantial. For example: with a 10% small aggregate replacement from a small 3 story concrete building, there would be a use of 15,000 lbs. of microplastics and helping with the overall net emissions from a total 450,000 lb. building.

With the resulting ratio, the concrete was able to maintain a reasonable amount of strength. There is potential where the mixture would be able to be used in smaller structures, residential projects, sidewalks, driveways, patios, but not quite ready for large scale commercial structures.

With further research and testing the mixture could find its way taking steps towards leaving the world in a better state than it was found for the next generations to come.

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