Use of Recycled Plastics to Substitute Aggregates in Concrete

By:

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Acknowledgements

I would like to personally thank the following staff at Humber Institute of Technology for their ongoing support during this research project. Vaska Xoxa, P.Eng, MSc. Joe Marcovic, AScT both were willing to take time out of their busy schedules to coach and mentor me throughout this project. Their enthusiasm and guidance on this subject helped me to not only tackle practical difficulties, but also put complex ideas into simple terms. Humber's Civil Engineering program is extremely lucky to have two professionals on staff with the scientific knowledge and laboratory skills that Professor Xoxa and Professor Marcovic do. I am forever grateful for their assistance and professionalism throughout this research project.

Second, I would like to thank Shazim Dilbar, graduate Civil Technologist, who helped during the trials with measurements, calculations, and running compression tests. Shazim graciously helped with the experiment showing scientific curiosity on this subject and a relentless work ethic. Harjot Saini, currently in 2nd year of Civil Technology, worked together with us at different phases helping to mix concrete and without his efforts my job would have been undoubtedly more difficult.

Bulldog polymers owned by Deanna Fudge, P Eng. and Caroline Davey supplied the recycled plastics for this project and educated me on the technical aspects of HDPE. I wish them both great success in their new venture in the business of recycling.

Furthermore, to Humber College for providing the necessary supplies as well as allowing me to use the civil laboratory during this experiment. Lastly, I would like to acknowledge the entire Civil Technology faculty for their interest in this research project for they have all been very supportive during my time at Humber.

Abstract

Concrete is the most widely used material in construction on the planet and has been for ages. The use of recycled plastics in concrete mix design is a definite possibility in the near future. If the need for mining of sand can be reduced by even 10%, the environmental impact of this would be tremendous. Aggregates currently are responsible for 3.8% of the carbon footprint related to concrete, however, the environmental impacts of extracting these aggregates from nature can be irreversible (MPa, 2014). This study involves integrating recycled plastics into concrete mix designs in the place of fine aggregates using proportions of 10%, 20% and 30%. The goal was to find a composition of these mixes that will withstand the current structural standards that exist for concrete requirements. Each mix design in this study was subjected to a slump test and a compressive strength test. One mix was chosen for a tensile strength test. Each mix design was cast into cylinders and allowed to cure for 7, 14 and 28 days in a distilled water bath before being subjected to the compressive strength testing. Cylinders that were broken were assessed for fractures and points of weakness were determined. It was determined that the concrete did indeed pass all testing and the mix of 20% plastic that was chosen for the tensile strength test was sufficient in all aspects of the concrete design. In fact, the data looks so good that it may be possible to increase the amount of recycled plastics in the concrete mix designs to be even greater. This could lead to further reduction in the need for fine aggregates and yield an acceptable concrete that would be suitable for many needs in construction today.

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1.0 Introduction

This purpose of this report is to investigate the option of replacing fine aggregates with recycled plastics in concrete mix design. Fine aggregates are the main component of concrete, which is the most commonly used material in construction today. In Ontario alone, approximately 14 tonnes of sand, stone and gravel are needed per capita each year, making it the resource that is used the most in the province (OSSGA, 2015). Our increasing need for aggregates in construction comes at a cost to the environment. The expansion of gravel pits leads to the deterioration of local biospheres, and the impact of producing sand and gravel at this rate can lead to irreversible environmental damage. Gravel pit construction removes all natural vegetation that lives on its surface and destroys habitats for wildlife. They also impose the threat to the loss of drinking water from local communities (Toronto Environmental Alliance, 2008). By introducing recycled plastics into concrete mixes as a replacement for fine aggregates, the environmental benefit will be two-fold: reduction of the amount of fine aggregates needed for concrete used in construction, and reduction in the amount of plastics that may otherwise end up in landfills with no chance of biodegradation in our lifetime. Included in this report is a description of the experiments conducted to test the suitability for use in construction of 3 different concrete mix designs. These designs include recycled plastics in place of fine aggregates in amounts of 10%, 20% and 30%. Also included are the results of a control in which concrete was prepared in the regular manner using all fine aggregates and no substitution of plastic. The procedures used in gathering the data for this report are standard methods used to test for the suitability of concrete mixes, including a slump, compressive strength and tensile strength test. The goal of this work is to prove that one of these mixes will have real life applications in the construction world today and be just as suitable for use as regular concrete. Since concrete has such a widespread use in construction, the outcomes of replacing even 10% of the fine aggregates used today would benefit the environment exponentially.

2.0 Methodology:

The overall approach to this research is to construct concrete mixes and test them according to the standards of the American Society for Testing and Materials (ASTM). The following illustrates step-by-step procedures used to collect data on concrete made with recycled plastics.

2.1 Equipment for Testing:

Slump & Air Content Test	**Compression Test**
Concrete mixing pan	Compression Testing Machine
Slump Cone	Retaining Rings -2
Air Content Meter	Compression Pads - 2
Balance 20 kg (± 0.1 g)	Balance 20 kg (± 0.1 g)
Mixing Tools (Scoops, Spoons, Trowels)	Cornstarch
Mixing Trays	Mold Stripping Tool
4 Cylindrical Molds (for compression tests)	Hammer
Beakers	Towels
Graduated Cylinder	
Calipers	Calipers
Measuring Tape	Measuring Tape
Safety Glasses	Safety Glasses
Safety Gloves	

2.2 Mix Designs:

The following mix design criteria were followed in order to obtain the necessary volume of concrete to perform this research project. For accuracy, the plastic to be used in these mix designs needed to be measured through its specific gravity in order for the proper volume to be calculated. This was obtained via Bulldog Polymers to be 0.95

g/cm^3. *Refer to appendix A for full calculations of design mix*. The type of plastic used was High-density polyethylene (HDPE), commonly used in household plastic bottles and food containers (Deana Fudge, P.Eng, Personal Communication, January 14, 2017). The coarse aggregate used in this design was KING 1/2" Gravel ranging in size from 10 mm (3/8") to 14 mm (1/2") and the fine aggregate used was Sakrete multi-purpose sand.

Air Meter Volume					
Diameter	=	215	mm		
Length (L)	=	210	mm		
Volume	=	7624056	mm3	0.00762	m^3
Mold Volume					
Diameter	=	4	inch		
Length (L)	=	8	inch		
Volume	=	1647407	mm^3	0.00165	m^3
			X 5 molds	0.00824	m^3
Required Vol. of Concrete for Trial Mix				0.01	m^3

Table 1- Required Volume of Concrete

Design Criteria								
	» mass per m^3 (kg)	RD (*SSD*)	Volume per m^3	Adjusted Mass	Mass for Trial Mix	+ Mass	- Mass	Mass Used
Cement	340	3.150	0.1079	347.2	3.472			3.472
Water	160	1.000	0.1600	163.4	1.634			1.634
F.A.	680	2.570	0.2646	694.4	6.944			6.944
C.A.	1160	2.699	0.4298	1184.5	11.845			11.845
Air (»1.7%)	1.7%	N/A	0.0170	N/A	N/A			N/A
W/C ratio	0.47	N/A	N/A	0.5	0.47			0.47
Total	2340	N/A	0.9793	2389.4	23.894			23.894

Table 2- Mix Design Criteria

		Mass Sand (g)	Mass of Plastic HDPE (g)
Trial Mix #1	0%	6944	0
Trial Mix #2	10%	6250	251.4
Trial Mix #3	20%	5555.2	502.7
Trial Mix #4	20%	5555.2	502.7
Trial Mix #5	30%	4860.8	754.2
	Total	29165.2	2011

Table 3- Volume of Plastic Needed

2.2.1 Mix Design Procedure:

1) Required volume of concrete was determined for all trial mixes. *See Table 2 above.*

2) Using the design criteria, the quantity of cement, water and aggregates (fine and coarse) was measured out. HDPE volume was calculated using its specific gravity for each trial. *See Appendix A for Calculations.* Water was measured by volume using 1 ml = 1 g.

Figure 1 - Mixing of Concrete

3) 4 concrete compression molds were labelled for each mix with date and sample number.

4) All utensils were dampened to aid in mixing.

5) Half the amount of water, cement, fine aggregate and coarse aggregate was added to the mixing pan. For the purpose of this research, no other add mixtures or additional aggregates were added at this time. The quantities used in these mixes appeared to be satisfactory for workability.
6) HPDE plastics were added to each individual mix according to determined mix design.
7) Trial mix #3 was doubled to allow the casting of a beam (trial mix #4) to test the modulus of rupture using a tensile testing machine which will be explained in tensile testing results.

2.3 Slump Test*:*

A slump test was then performed to check the workability and consistency of the fresh concrete before it is allowed to set. This test measures how much flow the concrete has, its ability to be pumped and the total quality of the finished product.


Figure 2 - Slump Test

2.3.1 Procedure for Slump Test:

1) Slump cone was damped and placed in a separate mixing tray.
2) The cone was filled in three layers with fresh concrete, each layer being compacted with a tamping rod. The rodding strokes were uniformly distributed 25 times per layer of concrete to ensure all gaps are filled. Each layer was rodded through its depth just into the layer below. The top of the sample was levelled off with the tamping rod.

3) The cone was then vertically removed until it was clear of concrete and placed upside down beside the sample. The tamping rod was placed vertically on top of the concrete to measure the distance from the bottom of the rod to the top of the slump cone to determine an average height.
4) Slump distance was recorded to the nearest mm. The test data will be summarized in the results.

2.4 Air Content Test:

This procedure is used to determine the percentage of air in the freshly made concrete and should be done within 15 minutes from the initial mixing. Air will greatly affect the finished product strength and promote early cracking if not great enough.

Figure 3 - Air Content Test

2.4.1 Procedure for Air Content Test:

1) Concrete was first remixed in the mixing tray
2) The base of the air meter was filled with fresh concrete in three even layers. Each layer was tamped with the tamping rod 25 times. The rodding strokes were uniformly distributed with a number near the perimeter to fill all gaps in the concrete. The top surface of the concrete was levelled off to the rim of the base using a straight edge.

3) Care was taken to clean the lip of the base so air does not escape. The cover was then attached and tightened leaving both petcocks open.
4) Using a water bottle, water was then injected through one of two petcocks (release valves) until all air trapped air was expelled through the opposite petcock.
5) The built in air pump was pumped to introduce air into the concrete. Once the gauge was stabilized to zero both petcocks were closed.
6) The thumb lever was pressed down in order to release the air into the base.
7) The gauge was then read to record the percentage of air left in the concrete. Results can be found in table #4.

2.5 Casting Concrete Test Cylinders*:*

Cylinders are used in the compression testing of concrete and are usually taken from grab samples at the construction site to check the durability against stress and overall quality of the product.

Figure 4 - Casting of Molds

2.5.1 Procedure for Casting:

1) Concrete was remixed in the mixing tray.
2) Plastic cylinder molds were obtained and the volume and mass of one empty mold was recorded. This number was used for all volume and mass calculations.
3) The mold was filled in three layers with fresh concrete, rodding each layer 25 times.

4) The mass was determined and recorded to calculate the density of the concrete.
5) These steps were repeated for a total of 5 molds per mix design.
6) Each mold was labelled according to its testing number and left to cure for 20 hours.
7) Once molds had been cured overnight they were striped of the plastic and labelled once again with casting date, mix design number and direction of cylinder casting to allow for proper placement in the compression machine.
8) The cylinders were then placed into a water bath at a temperature of 73°±3°F and left there for the allotted curing times of 7, 14, 28 days.

2.6 Compression Test:

The compression test is used for finding the ultimate force the concrete design can handle. The force is applied in Kilo-Newton's on the cross sectional plain of the cylinder until it ultimately cracks and fails. The stress was measured in Mega-Pascal's (MPa) and compared with the control for strength. Once failure has occurred, the plain in which the cylinder failed will be examined. This will determine the type of shear the concrete endured during failure which helps us understand what is happening internally with the concrete.

Figure 5 - Compression Testing

2.6.1 Procedure for Compression Test:

1) Cylinders were removed from the water bath after a period of 7, 14, 28 days of cuing respectively. Each cylinder was then dried using a towel.
2) Diameter, length and mass of each cylinder was recorded and density was then calculated. *See Appendix A for calculations*
3) Compression pads were obtained to line both top and bottom of the cylinder so concrete did not stick to the rings.
4) The cylinder was then assembled between the two retaining rings, lubricated with cornstarch, centered and placed in the compression testing machine.
5) Care was taken in making sure the cylinder was evenly centered in the machine to allow for even loading.
6) The machine was then powered on and loading was tared to zero.
7) For each cylinder the length, diameter and weight were inputted into the machine.
8) Once all data was inputted, the machines safety glass was secured.
9) The machine was then started. A preload setting allows for the force to gradually be applied ensuring proper uniformed loading.
10) Once the cylinder failed (fractured), the cell was unloaded and examined for points of weakness.

Figure 6 - Failure of Sample

11) These steps were repeated for all design mixes.

12) Data was uploaded from the machines computer, transferred to excel and graphed to visually show each failure. *Refer to Appendix B for graphs.*

2.7 Tensile Test:

Tensile testing on concrete is done to determine the amount of force it takes to crack a specimen. It is important to know how much tensile strength concrete has as it will show its capacity for loading in certain scenario's such as sidewalks, roads, and driveways.

Figure 7 - Tensile Test

The tensile test is measured by its modulus of rupture (MR) in Mega-pascals (MPa). This test was performed with the 20% design mix that was cured for 28 days. The beam was cast in a mold with the dimensions 150mm x 150mm and the span was three times the depth. It was tested in a compression machine under a three point loading system where pressure is applied and stress is measured at the point of rupture. *Refer to Appendix C for illustrations.*

2.7.1 Procedure for Tensile Test:

1) Mix design #3 was doubled and run through slump and air content testing then cast into a beam mold labeled mix #4.
2) The fresh concrete was poured into the mold in three layers. The tamping rod was used to tamp each layer 30 times in order to minimize voids.
3) Once full the mold was levelled off and placed in an ambient temperature room to cure for 20 hours.

4) The following day the concrete beam was unmolded and placed into a water bath at a temperature of 73°±3°F to cure for 28 days.
5) After 28 days of curing, the beam was taken from the water bath and dried with towels. Dimensions and weight were then recorded.
6) The compression machine was setup for tensile testing by installing the three point loading system, in which two plates were installed onto the machine, one on the top and one on the bottom. Each plate has compression points to apply equal pressure across the beam. One directly in the centre of the beam on top, two on the bottom of the beam evenly spaced from the centre. *See Appendix C for Drawings.*
7) All data from the beam was entered into the machines computer and testing was started.
8) Once the beam had failed, it was removed from the machine and failure was recorded.
9) Data was uploaded from the machines computer, transferred to excel and graphed to visually show failure. *Refer to Appendix B for graphs.*

3.0 Results:

3.1 Slump and Air Content

Trial Mix	Slump (mm)	Air Content (%)
1	**35**	**3.8**
2	**55**	**3.5**
3	**46**	**3.8**
4	**46**	**3.8**
5	**55**	**2.9**

Table 4- Results of Slump and Air Content

In the above table note that trial mix #1 (control) has the lowest slump, with the highest being trial mix #2 (10% plastic) and #5 (30% plastic). Air content did not drastically differ between mixes with the exception of trial mix #5 (30% plastic).

3.2 Compression Test Results

Cylinder	***Units***			
Trial Mix #1				
Cure Time	*Days*	7	14	28
Diameter (measured)	*mm*	101.5	101.38	101.43
Length	*mm*	204.8	204.37	203.86
Mass	*g*	3994.9	3984	3977.2
Load	*KN*	270.76	306.47	351.28
Density	*kg/m³*	2411	2415	2414
Strength	*MPa*	33.46	37.97	43.47

Table 5- Compression Test Mix #1

Trial mix #1 was the control and the results were good showing an increase in strength through 28 days to 43.47 MPa. Density stayed in the range of 2414 kg/m^3.

Cylinder	*Units*			
Trial Mix #2				
Cure Time	*Days*	**7**	**14**	**28**
Diameter (measured)	*mm*	**101.9**	**101.49**	**101.53**
Length	*mm*	**205.1**	**202.79**	**203.12**
Mass	*g*	**3898.7**	**3917.2**	**3874.7**
Load	*KN*	**208.57**	**240.18**	**278.91**
Density	*kg/m^3*	**2349**	**2388**	**2356**
Strength	*MPa*	**25.7**	**29.7**	**34.45**

Table 6 - Compression Test Mix #2

Trial mix #2 (10%) showed variance in mass between 7 and 14 days of curing, but strength still increased after each test.

Cylinder	*Units*			
Trial Mix #3				
Cure Time	*Days*	**7**	**14**	**28**
Diameter (measured)	*mm*	**101.8**	**101.48**	**101.49**
Length	*mm*	**203.9**	**207.64**	**204.46**
Mass	*g*	**3841.3**	**3893.3**	**3838.4**
Load	*KN*	**222.21**	**258.45**	**286.77**
Density	*kg/m^3*	**2314**	**2318**	**2322**
Strength	*MPa*	**27.3**	**31.95**	**35.45**

Table 7 - Compression Test Mix #3

Trial mix #3 (same as mix #4 – 20%) resulted in an even higher strength then #2. The mass increased again in this mix design between 7 and 14 days and the strength was overall higher than trial mix #2.

Cylinder	***Units***			
Trial Mix #5				
Cure Time	*Days*	**7**	**14**	**28**
Diameter (measured)	*mm*	**101.6**	**101.44**	**101.59**
Length	*mm*	**203.5**	**204.73**	**205.08**
Mass	*g*	**3771.9**	**3797.8**	**3796.4**
Load	*KN*	**211.23**	**233.69**	**274.0**
Density	*kg/m³*	**2286**	**2295**	**2284**
Strength	*MPa*	**26.1**	**28.9**	**33.8**

Table 8 - Compression Test Mix #5

Trial mix #5 (30%) showed an increase in strength, but is slightly less strong overall as expected. Density and mass were also slightly lower compared to the other mixes. A graph was plotted in excel to visually show a comparison of strength between all trial mixes. *See Appendix B.*

3.3 Tensile Test Results

Beam	***Units***	
Trial Mix #***4***		
Cure Time	*Days*	28
Width	*mm*	150
Depth	*mm*	150
Length	*mm*	535
Mass	*g*	28841
Load	*KN*	32.9
Density	*kg/m³*	2396
Strength (MoR)	*MPa*	4.4

Table 9 - Tensile Test Results

The table above shows the tensile test results and the Modulus of Rupture at 4.4 MPa. Failure was directly in the middle of the beam. This mix was the same design as trial mix #3. *See Appendix B for graph demonstrating modulus of rupture.*

4.0 Analysis of Results and Discussion

4.1 Air Content and Slump Testing:

As shown in the above results, air content testing showed that mix 1 to 4 yielded approximately the same air content. The only mix that differed significantly was mix #5. This shows that the plastic did not significantly affect the ability of the concrete to absorb water and in fact the 10% and 20% plastic mixes showed nearly identical numbers to control mix #1. We can conclude that the plastic in these percentages has no effect on the air content of the concrete. It has been shown that air content in the range of 2.5-3% can perform with satisfactory results in harsh temperatures. However, it is generally recommended to have an air content of 4-6% (Federal Highway Administration, 2006). This concludes that these mixes should be strong enough for use in construction and furthermore withstand temperature changes that promote micro cracking. Ways to slightly increase air content may include using a mechanical mixer instead of hand mixing the concrete.

As for the slump test, it seems that mix 3 and 4 (which are both the 20% plastic mix) had the closest value to the control mix. This is the mix that was chosen for the tensile testing (coincidentally) and it seems to be the best option in that its slump is closest to the trial mix #1 with 0% plastic. For concrete used in applications such as road construction, slabs, retaining walls and mass concrete, the slump is acceptable between 20mm – 50mm (The Constructor - Civil Engineering Home, 2015). This means that the 20% mix will have the appropriate workability for concrete to be poured and should yield a finished product of high quality. Note that the 10% and 30% mixes yielded the same measurements in the slump testing. It is possible that the hand mixing of the concrete affected the reproducibility of the mixes since it introduces human error, as this data seems to be slightly unexpected.

4.2 Compression Testing:

The results of all 3 mixes in the compression testing show that the overall strength for each mix increases as the curing time increases. This is encouraging in that all three mixes are strong enough to be used in construction. It is recommended that for residential construction the concrete pass a compression test with a strength of 17 to 28 MPa for use in commercial building (NRMCA, 2003). All mixes were upwards of 30 MPa after the curing time of 28 days, with the highest being the control mix. The mix containing plastic that preformed the best was mix #3 (20% HPDE) withstanding a total stress of 35.45 MPa. Trial mix #2 contained fewer plastics and resulted in a lower strength and showed a higher slump which demonstrates some inconsistency in either the data or mixing of the product. It would be expected that more sand and less plastic should yield a higher strength even though this was not the case.

Another finding from the compression test was the acceptability of the density of each mix. It should be noted that high density concrete should measure around 2400 kg/m^3 and lightweight concrete at 1842 kg/m^3 (Ari, 2009). The density of each mix containing recycled plastic was found to be just less than 2400 kg/m^3, which would be deemed acceptable for high density concrete. Due to the high density found in these mixes, the finished product should not show any discoloration and allow for polishing of the concrete which adds to the aesthetics of a finished project. In addition, water absorption would not be an issue which can result in cracking due to temperature changes. This is often the case with lightweight, low density concrete (Ari, 2009).

4.3 Tensile Testing:

Concrete is low in flexural strength meaning that it needs reinforcement to help prevent failure from tension. Tensile testing is mostly used in pavement designs giving engineers an insight into the stability of the mix and its need for reinforcement. The results of a tensile beam test should yield between 10-20% of the compressive strength (NRMCA, 2003). Trial mix #4 (20% plastic) gave a Modulus of Rupture of 4.4 MPa. This test concluded that the Modulus of rupture would be deemed acceptable as the beam yielded 13% of its compressive strength. *See Appendix A for calculations.*

4.4 Discrepancies in data

Discrepancies in the data were observed with trial mix #2 in that it had a larger slump and lower strength than mix #3 and #4. This finding seems unlikely as it would be predictable that the trial mix closest to the control mix #1 (containing less plastic and fine aggregate) should perform the best. In addition, another finding that is not intuitive was that mix #2 and mix #5 (the 10% and 30% mix respectively) showed the same results in the slump testing. Again, this is not a result that one would expect, as it would be expected that they would differ in slump and that the 10% plastic mix would perform better than the 30% mix. The likely cause of these discrepancies is that hand mixing was used in the preparation of the concrete, introducing some human error. In addition, the air content may increase by more efficient mixing. Therefore, it would be recommended to repeat this experiment using a mechanical mixer. This would allow for more uniform mixing of the ingredients and produce more accurate, consistent data. The initial hypothesis was that trial mixes #3 and #4 (20% HDPE) would be the strongest and most effective for practical use in the field, while using the most recycled plastic. However, the results show that all mixes pass standard concrete parameters. Thus, it would be recommended to do further testing in which more recycled plastic is used in the mix design, cutting out even more fine aggregate.

In the case of micro cracking in Cementous materials, this experiment did not show any signs of pre-cracking before loading the samples into the compression machine. It may be too early to show these signs of failure, meaning that further testing of these specimens would be recommended to allow for an even longer curing process. This process would have to include higher temperature fluctuations to mimic a freeze thaw cycle in order to see how the different amounts of plastic affect the Cementous material under these conditions. Furthermore, if the cement was to be used in an application where it is expected to be exposed to high levels of salt, continued tests would be needed in order to see if saline solutions affect the quality and strength of the concrete.

5.0 Conclusions

Based on the above discussion and results, the following conclusions can be drawn in regards to the use of recycled plastics in concrete:

- This report has demonstrated that recycled plastics can be used in place of fine aggregates in concrete mix design.
- The mix containing 20% recycled plastic (trial mix #3 and #4) was fully tested including a tensile test, and was deemed acceptable as an alternative for applications involving high density concrete.
- Given the high density of trial mix #3, $2322\frac{kg}{m^3}$, it is possible for it to be used as concrete slab flooring.
- The low slump of all trial mixes with HDPE would be beneficial in agricultural use where livestock waste containers are used.
- Low slump concrete can also be used for cinder block manufacturing allowing for these mixes to be used in foundation work or concrete walls.
- It is possible with further testing that a higher percentage of plastic can be used in place of fine aggregates, making this an even more environmentally friendly option.

6.0 Recommendations:

The following are recommendations that would be required to ensure the accuracy of this study and the success of implementation of this alternative concrete mix:

- Repeating this experiment using a mechanical mixer is imperative to ensure the accuracy and consistency of the data.
- More testing involving a longer curing time to allow for extreme temperature fluctuations to demonstrate the ability of the concrete to refrain from cracking due to freeze thaw conditions.
- Additional testing to determine the ability of the concrete to withstand exposure to saline solutions
- Allowing all concrete to be cured in a 100% humidity room instead of a controlled water bath would allow for more accurate data during the compression and tensile tests.
- Running this experiment again with a finer plastic material could further increase compressive strength by allowing for better adhesion to the aggregates.

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Appendix A: Calculations

Air Meter Volume:

$$\pi * \frac{d^2}{4} * (L) = ((0.7854) * (215^2)) * (210) = 0.00732\ m3$$

Mold Volume:

$$\pi * \frac{d^2}{4} * (L) = ((0.7854) * (4^2)) * (8) = 1005312\ in3 * 25.4mm^3 = 1647407\ mm^3$$

Required Volume of Concrete for Each Trial Mix:

$$0.00165 * 5\ molds = 0.00824\ m3$$

Required Plastic for Each Trial Mix:

$$Mass\ of\ Sand * (-)\% = required\ sand\ for\ each\ trial$$

Sample #3 (20%) = $5555.2g * (-20\%) = 502.7g\ plastic$

$$\rho * 1000 \frac{kg}{m^3} * volume\ of\ sand\ per\ m^3 = \frac{kg}{m^3}\ required\ plastic\ per\ unit\ volume$$

Sample #3 (20%) = $0.95(density\ of\ plastic) * 1000 \frac{kg}{m3} * 0.2646$

Fresh Concrete Density:

$$\frac{Mass\ of\ Fresh\ Concrete}{Volume\ of\ Mold} = \frac{kg}{m3}$$

Sample #3(20%) = $\frac{3790kg}{0.00165m3} = 2297 \frac{kg}{m3}$

Cured Concrete Density:

$$\frac{Mass\ of\ Cured\ Concrete}{Volume\ of\ Cured\ Concrete} = \frac{kg}{m3}$$

Sample #3(20%) after 28 days = $\frac{3838.40}{(\frac{\pi}{4} * 101.49^2 * 204.46)} = 2322 \frac{kg}{m3}$

Stress Calculations:

Sample #3(20%) after 28 days = $\frac{Force}{Area} = \frac{274.07KN}{\pi * 101.49^2} = 35.45\ MPa$

Tensile Test Calculations:

Volume of the Beam Calculation = $L * W * H = m^3$

$$0.535m * 0.150m * 0.150m = 0.0120375m^3$$

Density of Concrete for Beam = $\frac{M}{V} = \frac{kg}{m^3}$

$$\frac{28.841kg}{0.0120375m^3} = 2396\frac{kg}{m^3}$$

Modulus of Rupture (Middle Third Equation) = $\frac{P*L}{b*d^2}$

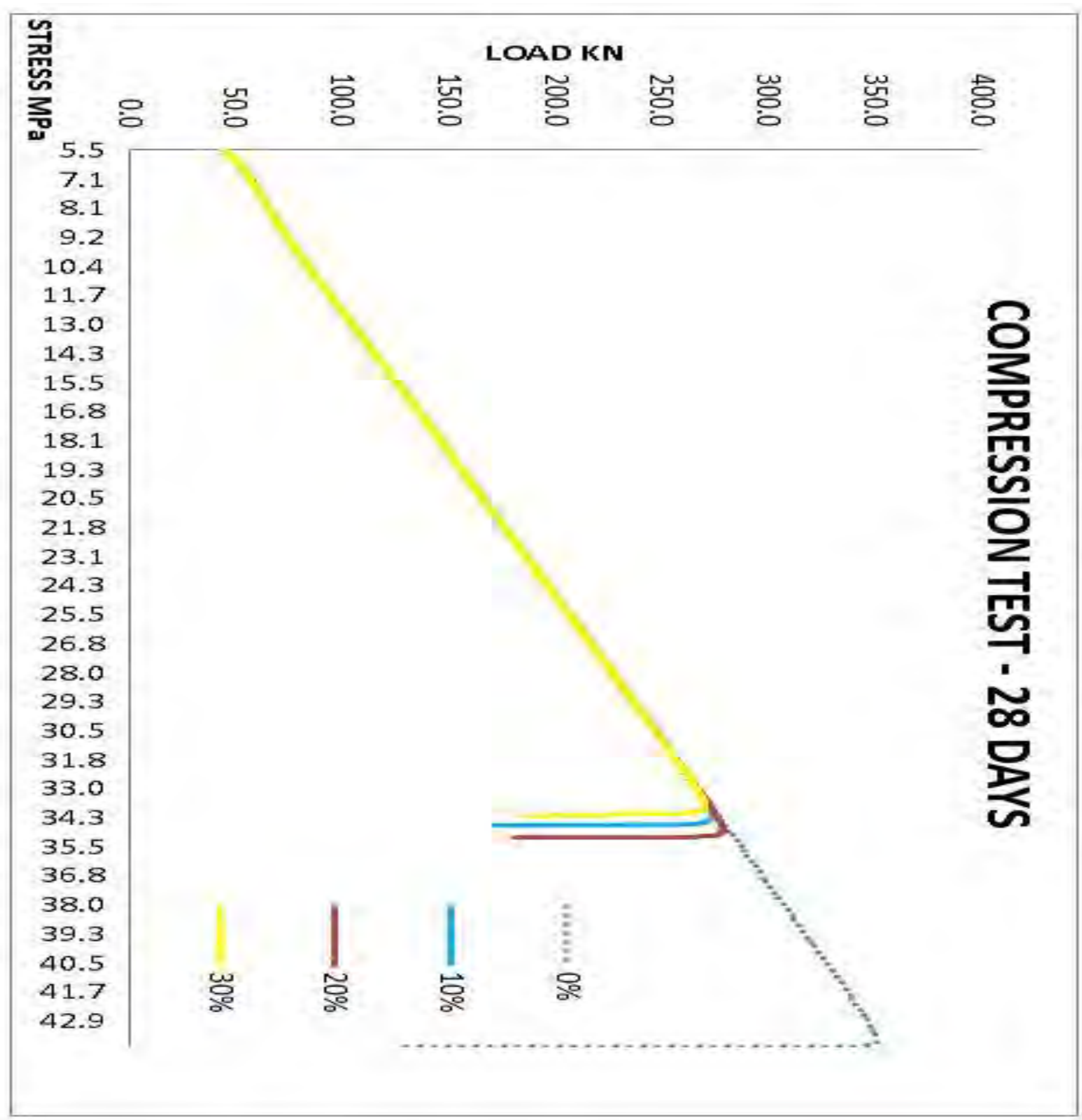
$$P = Load$$
$$L = Span\ of\ Beam$$
$$b = width\ of\ beam$$
$$d = depth\ of\ beam$$

$$\frac{(32.9KN) * (535mm)}{(150mm) * (150mm^2)} = 4.4MPa$$

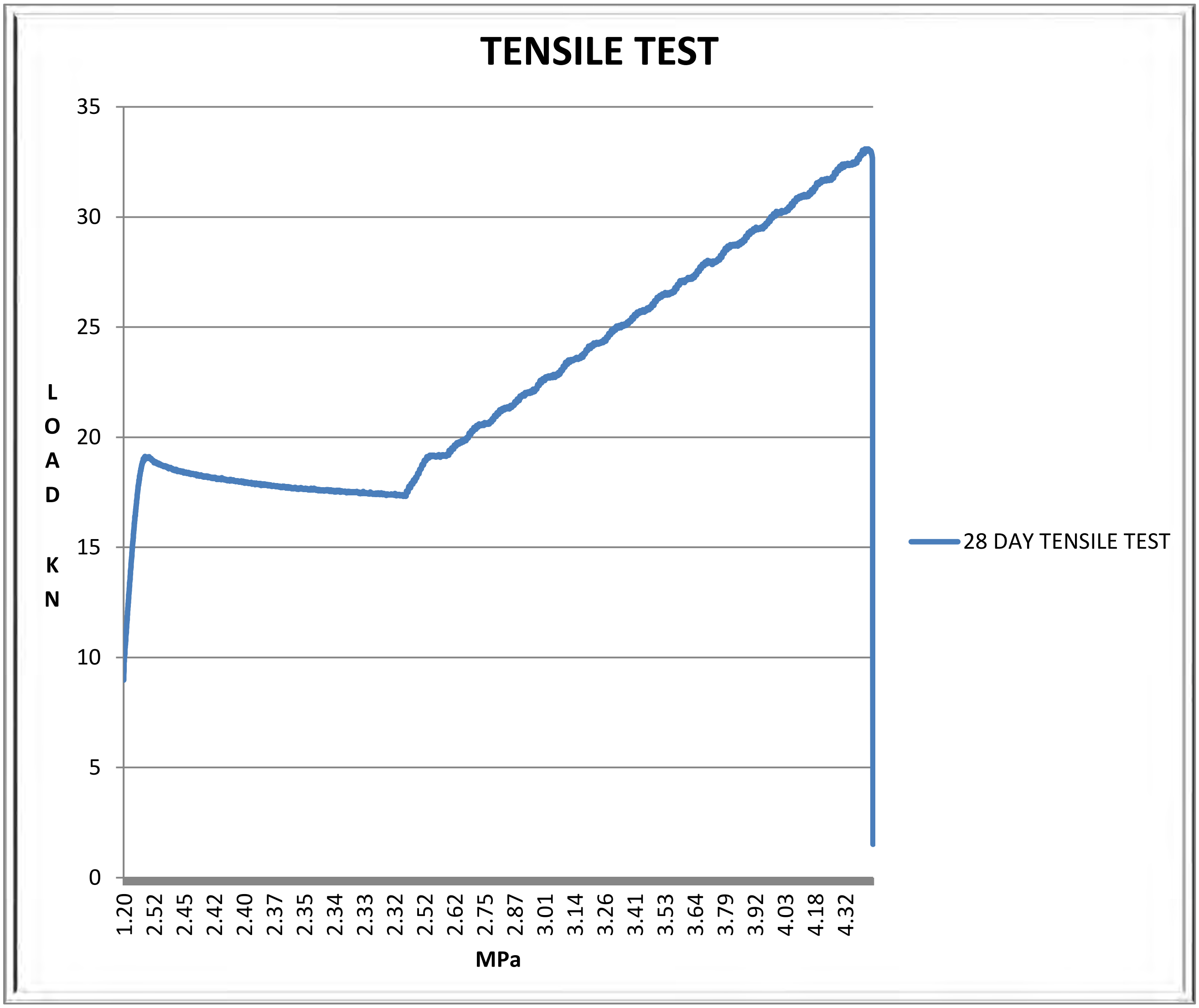
Percentage of tensile strength = $\frac{Modulus\ of\ Rupture}{Compressive\ Strength} * 100 = \frac{4.45}{35.45} * 100 = 12.6\%$

Appendix B: Graphs

Results from Compression Test:



Results from Tensile Test:



Appendix C: Drawings