2021

Development of a High Strength Composite Material Using Large Scale 3d Printing Applications Using Waste Plastic and Steel

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DEVELOPMENT OF A HIGH STRENGTH COMPOSITE MATERIAL USING LARGE SCALE 3D PRINTING APPLICATIONS USING WASTE PLASTIC AND STEEL

BY

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A thesis submitted in partial fulfillment of the requirements for the

Master of Science

Major in Mechanical Engineering

South Dakota State University

2021

THESIS ACCEPTANCE PAGE

NAGA SRI MADHAVAREDDY

This thesis is approved as a creditable and independent investigation by a candidate for the master's degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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This dissertation is dedicated to my family.

ACKNOWLEDGEMENTS

I would like to express my gratitude to my thesis advisor, Professor Todd Letcher, for his supervision, advice, mentor, and guidance and professional assistance through my course of study. Dr. Todd Letcher has been always inspiration and a great motivator for me and his contribution significantly through my thesis work and my academic career development.

I would like to thank my friends providing me with the support with amenable friendship and kinship that I needed.

I would like to thank all the faculty and staff of Mechanical Engineering Department for their consistence support.

Most of all, I would like to thank my family, my father Janardhan Reddy Madhavareddy, my mother Hema Latha Madhavareddy and my brother Raja Shekar Reddy Madhava for their endless love, encouragement, support, and resolute confidence in me throughout my life. Without their motivation, I could not have finished this thesis.

I would like to thank the Materials Evaluation and Testing Lab (METLAB) and the Mechanical Engineering Department at South Dakota State University for the use of testing equipment and the SD Space Grant Consortium for providing materials for the samples.

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ABBREVIATIONS

mm	millimeter
sd	standard deviation
se	standard error
MPa	Megapascal
GPa	Gigapascal
conc	concentration

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ABSTRACT

DEVELOPMENT OF A HIGH STRENGTH COMPOSITE MATERIAL FOR LARGE SCALE 3D PRINTING APPLICATIONS

NAGA SRI MADHAVAREDDY

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This project focuses on developing a high strength composite material for large-scale 3D printing applications using recycled materials like High-Density Polyethylene (HDPE) and Steel 430. This material has applications for in-space manufacturing (the Moon or Mars) as well as large-scale manufacturing on earth. In addition to creating a strong useful material, materials that are easily recycled, but are often not recycled, are used. Recycling plastic and metal reduces pollution, saves resources, reduces waste going to landfills, and prevents the destruction of habitats from the polymerization of new plastic and similarly mining new ore. The percentage of HDPE generated from recycled waste is less than 21% annually. In the same way, steel makes up the largest category of metals in the municipal solid waste and industrial waste streams. Although the usage of steel in construction sites is very common, the challenges of 3D printing with recycled steel reinforcements are extreme, because of the size and scale of most waste steel products. In this work, material samples are manufactured using a vacuum oven molding process and varying ratios of steel pins to HDPE polymer pellets. Mechanical properties including elastic moduli, ultimate strength, flexural strength, % elongation at break, and surface hardness were evaluated, and the results were compared to other

proportions. Samples were also manufactured using a large-scale 3d printer to determine differences between molding the material and 3d printing the material.

CHAPTER 1 - GENERAL INTRODUCTION

The overall subject matter of this thesis is the development of high strength composite material for large scale 3d printing with a focus of using recyclable materials. Lightweight strong and stiff material is of strong interest for both off-earth and on-earth applications, especially when able to use otherwise “waste” materials, such as plastic and metal scrap materials. On earth it is possible to recycle many of these materials, but off-earth, it will be very difficult to process these materials into more useful versions of the material. Large scale 3d printing, could potentially allow us to skip many of the recycling processing steps and go straight towards reuse of the material as it is.

For this project, we will specifically be adding steel scrap to thermoplastic scrap, hopefully leading to increases in the stiffness and strength of the composite material as compared to the pure polymer alternative. There are only two ways to control the plastic in the environment, either using recycled process or decreasing the production of plastic. As plastics have become commonly used in almost every industry, stopping plastic production seems to be out of the question. Many of these plastic components end up in landfills or loose in the environment because they are not recycled properly. Hence, indirectly this project will help to reduce the plastic pollution going to landfills and it stops effecting marine creatures in the oceans and other waterways.

Finally, using large-scale 3D printing plays an important role in this project, because 3D printers that use recycled products will consume less energy overall as they require less new material and can reuse other materials destined for the landfill. The materials chosen for this study are materials that are commonly recycled but are energy intensive processes. To use the same recyclable materials in this process, very little processing will be required to ensure success in 3d printing the composite material. The product formed will be lighter in weight with more strength than other traditional process.

The next two chapters are two completely separate studies related to High Density Polyethylene, reinforced by steel scrap. This composite material will be examined as a possible material to be used for large scale 3d printing. In Chapter 2, material characterization samples of HDPE with steel pins (commonly used in large-scale construction concrete application as a strengthener) are manufactured in a large oven to determine if this concept is remotely feasible. In Chapter 3, a similar composite material is 3d printed using a large 3d printer. Large blocks are printed, and smaller material testing samples are cut from these large blocks. In both chapters, a variety of plastic to steel ratios are tested to determine effectiveness of the addition of steel.

After reading this thesis, it should become more obvious using large scale 3d printing to reuse commonly scrapped materials is a viable option for some large-scale construction projects. Because 3d printing large polymer structures will most likely mean that the building conditions will vary throughout the construction process, resulting in variation of mechanical properties, more research will likely

be necessary to completely understand how these materials will perform. However, this study provides an excellent overview into the potential of this concept.

CHAPTER 2

MANUFACTURING PROCESS (VACCUM OVEN)

2.1 ABSTRACT

This project focuses on developing a high strength composite material using only highly recyclable materials with the intention of using it for large-scale 3D printing applications in the future. In addition to being useful on earth, this material has applications for in-space manufacturing (such as on the surface of the Moon or Mars). The materials used in this study, high density polyethylene and steel scraps, are materials that are easily recycled, but are often not recycled. Recycling plastic and metal reduces pollution, saves resources, reduces waste going to landfills, and prevents the destruction of habitats from the polymerization of new plastic and similarly mining new ore. Steel is one of the most common metals in the municipal solid waste (MSW) and industrial waste streams. In this paper, a composite material made from raw HDPE pellets and steel pins usually used in concrete, are used to manufacture material samples using a large vacuum oven and varying ratios of steel pins to HDPE polymer pellets. The samples created are tested to determine mechanical properties including elastic moduli, ultimate strength, flexural strength, and % elongation at break. Results are tabulated and compared to determine the feasibility of using steel and HDPE together and the effectiveness of this composite material at varying ratios of steel to polymer.

Tensile, flexural and compression tests were made using five different proportions (0%,15%, 25%, 50% and 75%). The 75% steel tensile sample shows the highest ultimate tensile strength 22.91MPa and highest modulus of elasticity 3.47 GPA.

Flex 15% Steel provides the ultimate strength of 40.9MPa with 0.98 modulus of elasticity and for compression test at 75% sample provides the best results, 39.06MPa ultimate strength with Max. elongation% of 19.23 and max. strain at 0.29.

KEYWORDS:

Additive Manufacturing, Construction materials, High Density Polyethylene (HDPE), Steel 430, composite material, strength.

2.2 INTRODUCTION

There are two components of the composite material being studied in this paper: HDPE and steel. HDPE, the matrix material, is the most common plastic used in the world and accounts for over 34% of the global plastic market, but it is rarely used in additive manufacturing due to several complicating. According to the [1-5] HDPE is a thermoplastic polymer and is made from petroleum products. As one of the most versatile plastic materials around, HDPE is used in a wide variety of applications, ranging from food storage to automobile components. This material is one of the easier polymers to be fully recyclable and has excellent mechanical properties according to the previous research [6] about (wear, fatigue, and creep). HDPE has a high-impact resistance and melting point when compared to some other plastics. HDPE polymer can be used to develop components with high strength and modulus properties and is able to achieve this with a lower density than other materials with similar mechanical properties [7-8]. Therefore, even considering the name “high density” polyethylene, HDPE can still be considered as

a lower density material with high strength characteristics because of the different versions of polyethylene available. Some of the lower density versions of polyethylene are called LDPE and have different material properties and therefore different applications. HDPE is also becoming a special interest material for space projects, which are always looking to reduce weight without sacrificing structural integrity. HDPE is also a very good material for shielding radiation, another crucial property for in-space applications.

HDPE (High Density Polyethylene) is a hydrocarbon polymer that can be prepared from ethylene via a catalytic process. HDPE is a polymer made up of a huge number of repeating units [9] known as monomers, and its chemical formula (Figure 1) can be generalized as $(C_2H_4)_n$.

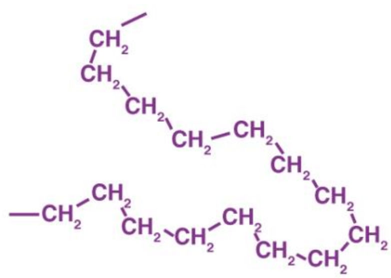

Figure 1: HDPE Chemical Formula C2H4n

Besides being used for food applications [10-11], it can be found in places including wood plastic composites, plastic surgeries and in 3-D printing filaments.

The other material used a reinforcing “fiber” in this composite material is steel 430. This material was chosen because it is commonly used (in pin form) to reinforce concrete and steel is one of the most common waste materials in the major construction. The goal of adding steel to the plastic is to improve the structural strength and stiffness of the material [13]. Table 1 shows the common material

properties of Steel 430, leading us to believe this to be a suitable strengthening material for the composite material.

Table 1: Material Properties for Steel 430[14]

Temperature Range	1500-1900°F
Tensile Strength	450MPA
%Elongation	22% (50.8mm)
Hardness Rockwell	89HRBW (Max)
Density	0.28lb/in^3
Modulus of elasticity	200×10^3 MPA
Electrical Resistivity	23.68µ ohm.in
Thermal Conductivity	26.1 w/m-k

2.3 EXPERIMENTAL METHODS.

2.3.1 Sample Manufacturing Process:

Samples were manufactured in open aluminum molds using a vacuum oven held at 230°C and a pressure of 25-27 psi vacuum. Molds were sized according to the testing standards that govern the types of tests to be conducted [ASTM 1, ASTM 2, and ASTM 3]. Plastic pallets and steel pins were mixed as they were placed into the molds. As the pellets melted into the mold and took up less space in the mold, additional plastic, and steel (mixed at appropriate ratios) were added to the mold. This process continued until the mold was full and the plastic was fully melted. Vacuum pressure was used in the oven to remove air bubbles from the polymer as the pellets melted together.

The molds were filled with 0, 15%, 25%, 50%, and 75% steel to HDPE ratios to test the effectiveness of the steel reinforcements. Six samples were prepared for each ratio and for each type of testing sample (tensile, compression and flexural). Each type of sample required a different heating/melting time, ranging from 1.5 hours for the smaller compression samples to 3 hours for the larger flexural and tensile samples.

After the melting process was complete, molds were removed from the vacuum oven and allowed to cool for 24hrs in an insulated box to prevent the samples from cooling too quickly, forming cracks or other defects. Next, the samples were carefully removed from the molds, ensuring that no cracks or

scratches were created. Samples that cracked during the removal process from the mold were discarded and new samples were made. Milling machine was used to flatten all the samples before test.

2.3.2 Mechanical Testing Procedures:

For each sample, appropriate measurements of the test section were made using a digital caliper at several locations throughout the test section. According to the ASTM testing standard for flexural testing [15], the smallest cross-sectional area at the center of the beam for flexural testing was used to determine appropriate stress values.

MTS universal testing machines were used to conduct the tensile, flex and compression testing [16]. Testing of the samples were conducted on an MTS Landmark load frame with a 100kN load cell, while an MTS extensometer (Model

634.31F-24) with a gauge length of 20mm was used to measure strain for the tensile testing of the sample.

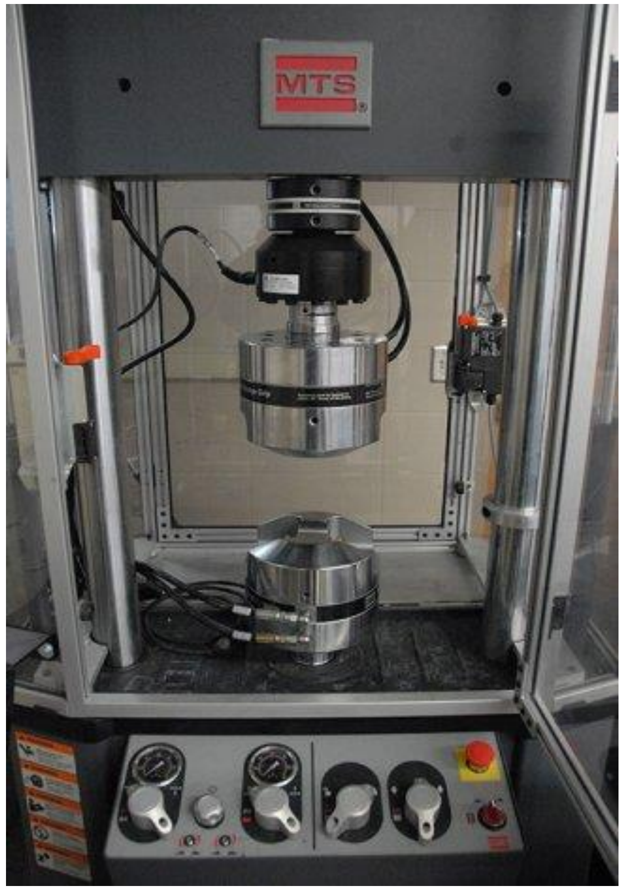

Figure 2: MTS universal loading machine

Samples were tested according to ASTM D638[12-13] Standard Test Methods for Tensile Properties of Plastics [18]. Six samples were tested for each steel to HDPE ratio in this study. The MTS machine was displaced at a rate of 5 mm/min with data (force, grip displacement and strain) collected at 100 Hz. Engineering stress was calculated by dividing the force by the cross-sectional area. Engineering strain was calculated by dividing the extensometer value by the original length of the extensometer.

Flex samples were tested according to ASTM D790 - Standard test method for flexural properties of unreinforced and reinforced plastics and electrical insulating materials [19]. An MTS 3-point flexure test fixture was used. A support span of 10 cm and 15 cm was used, depending on the thickness of the sample. The bending fixture was displaced at a rate of 1.3 mm/min to cause the flexural stress. Bending stress/strain equations for a rectangular beam were used to determine the stress based on the amount of deflection caused by the flexural apparatus and the force values measured.

Compression testing was performed in accordance with ASTM D790 – Standard test method [20]. A constant displacement rate of 1.30 mm/min was used to compress the specimen. Standard engineering stress/strain equations were used to calculate stress and strain for both test types, with the strain being measured by the change in length of the entire sample as measured by grip head displacement (no extensometer used).

In all tests, yield stress calculations were made using the standard 0.2% offset method. The ultimate stress was determined by the maximum stress encountered during the test. Finally, failure was determined to be the point when the sample suddenly fractured.

2.4 RESULTS

2.4.1 Tensile Testing**:**

Sample name	Width(mm)	Thickness(mm)	Ultimate Tensile Strength (MPa)	Modulus of Elasticity (GPA)	Max Elongation (%)
100percent_01	19.16	12.2	17.24	1.43	2.09
100percent_02	19.2	13.29	15.37	1.59	1.49
100percent_03	19.05	13.57	22.57	1.58	3.82
100percent_04	19.27	13.14	21.36	1.55	3.23
100percent_05	19.04	12.21	16.9	1.67	1.67
Average			**19.07±2.98**	**1.56±0.07**	**2.46 ± 0.91**

Table 2: Tensile test results 100% HDPE

Sample name	Width (mm)	Thickness (mm)	Ultimate Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Max Elongation (%)
15percent_01	19.25	13.27	20.58	1.29	3.29
15percent_03	19.02	13.95	15.71	1.35	1.70
15percent_04	19.02	13.96	19.77	1.49	2.52
15percent_05	19.07	11.73	20.02	1.53	2.38
15percent_06	19.12	14.68	19.86	1.33	2.72
Average			**19.18 ± 1.76**	**1.39 ± 0.09**	**2.52 ± 0.51**

Table 3:Tensile test results 15% STEEL

Sample name	Width (mm)	Thickness (mm)	Ultimate Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Max Elongation (%)
25percent_01	19.35	13.03	21.66	1.42	2.98
25percent_02	18.97	13.74	20.80	1.21	2.86
25percent_03	18.62	13.01	15.67	1.11	2.01
25percent_04	18.75	12.02	11.39	1.24	1.02
25percent_06	19.25	9.82	13.55	1.22	1.34
Average value			**16.61±4.01**	**1.24±0.10**	**2.04±0.78**

Table 4:Tensile test results 25% STEEL

	Width (mm)	Thickness (mm)	Ultimate Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Max Elongation (%)
50percent_01	18.85	12.81	22.75	2.48	1.89
50percent_02	19.3	15.22	19.13	2.48	1.38
50percent_03	18.92	13.81	19.71	2.22	1.75
50percent_04	19.23	13.65	21.76	2.02	2.36
50percent_08	19.13	12.33	20.12	1.87	1.81
Average value			**20.69±1.34**	**2.21±0.24**	**1.83±0.31**

Table 5: Tensile test results 50% STEEL

Sample name	Width (mm)	Thickness (mm)	Ultimate Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Max Elongation (%)
75percent_01	19.27	13.62	24.43	3.91	1.75
75percent_02	19	13.16	22.63	2.60	1.77
75percent_03	19.26	14.36	20.21	2.88	1.35
75percent_04	19.01	11.65	24.55	4.61	2.29
75percent_05	19.03	12.54	24.23	3.10	1.95
75percent_06	19.04	12.26	21.43	3.75	1.12
Average value			**22.91±1.64**	**3.47±0.68**	**1.70±0.38**

Table 6: Tensile test results 75% STEEL

Sample name	Ultimate Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Max Elongation (%)
100% HDPE	**19.07± 2.98**	**1.56 ± 0.07**	**2.46 ± 0.91**
15% STEEL	**19.18 ± 1.76**	**1.39 ± 0.09**	**2.52 ± 0.51**
25% STEEL	**16.61±4.01**	**1.24±0.10**	**2.04±0.78**
50% STEEL	**20.69±1.34**	**2.21±0.24**	**1.83±0.31**
75% STEEL	**22.91±1.64**	**3.47±0.68**	**1.70±0.38**

Table 7: Average values of all the proportions

27 tensile samples were tested using five different steels to plastic ratios. The full results of the tensile testing are summarized in Table7. Change in proportion showed different results at different fracture styles. The average 75% ratio samples showed the highest ultimate tensile strength 22.91 MPa, highest modulus of elasticity 3.47 GPa and showed the Max. elongation point at 1.7%.

Figure 3: Tensile Sample 100% HDPE after test

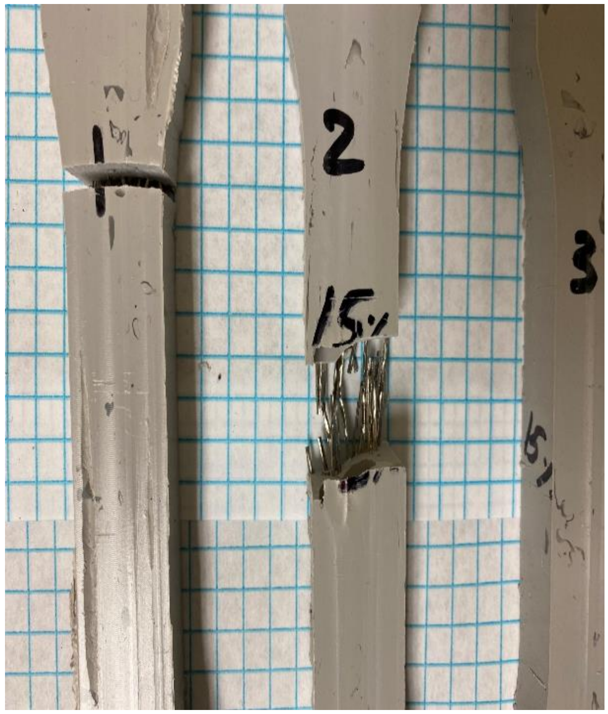

Figure 5: 15% samples after tensile test fracture

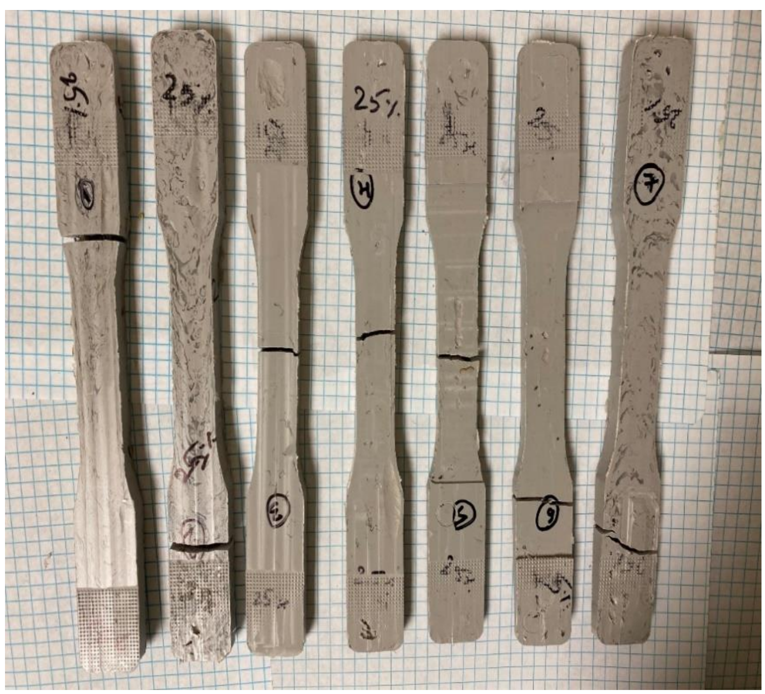

Figure 4: Tensile Sample 25% HDPE after test

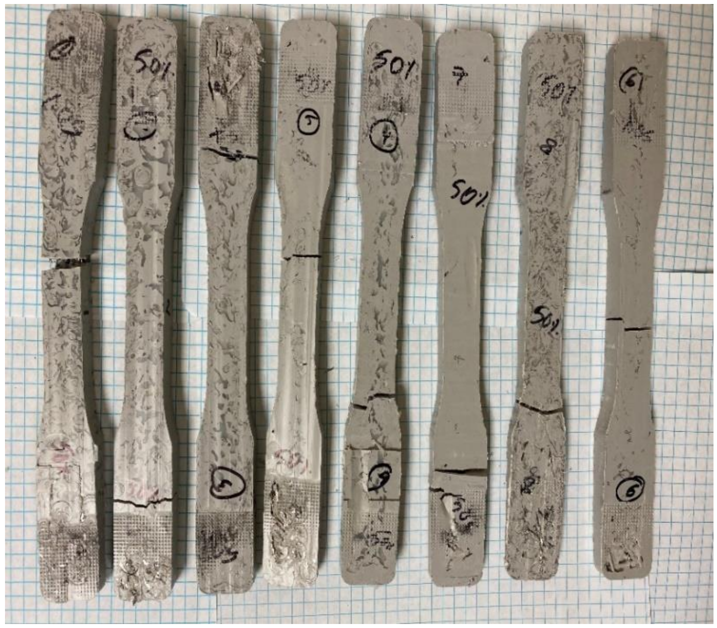

Figure 6: Tensile Sample 50% Steel

Figure 6: Tensile sample 75% steel

2.4.2 Flexural Testing

3-point bending tests were performed to obtain the flexural properties of the samples at varying ratios of steel to plastic. Six samples were tested for each ratio. For this testing, failure was considered if a small crack occurs in the specimen, therefore reducing the load the sample could carry. However, some specimens did not fully break. Some samples were flexible enough to continue flexing until the sample touched the bending fixture. The test was considered over at the point of contact. The results are summarized in the table below.

Filename	**Width (mm)**	**Thickness (mm)**	**Ultimate Flexural Strength (MPa)**	**Modulus of Elasticity (GPa)**	**Yield Strength (MPa)**	**Max Elongation (%)**
100percent_01	25.7	30.33	26.53	0.16	15.99	20
100percent_02	25.82	32.56	19.18	0.12	9.48	24.29
100percent_03	26.37	34.47	25.17	0.07	20.92	45.67
100percent_04	26.18	33.75	12.78	0.12	12.78	8.47
100percent_05	25.83	34.18	32.07	0.12	12.64	55.66
Average value			**23.14±6.60**	**0.11±0.02**	**14.36±3.87**	**30.81±17.30**

Table 8:Flexure test results 100% HDPE

Filename	**Width (mm)**	**Thickness (mm)**	**Ultimate Flexural Strength (MPa)**	**Modulus of Elasticity (GPa)**	**Yield Strength (MPa)**	**Max Elongation (%)**
15percent_02	25.58	13.32	46.36	0.98	26.84	8.43
15percent_03	25.97	14.22	39.31	0.92	22.34	7.57
15percent_04	26.06	15.62	38.05	1.02	21.39	5.84
15percent_05	25.61	13.86	39.88	1.00	17.66	6.94
Average Value			**40.9±3.22**	**0.98±0.03**	**22.05±3.26**	**7.19±0.94**

Table 9: Flexure test results 15% STEEL

Filename	Width (mm)	Thickness (mm)	Ultimate Flexural Strength (MPa)	Modulus of Elasticity (GPa)	Yield Strength (MPa)	Max Elongation (%)
25percent_01	26.12	24.93	36.48	0.37	8.76	19.17
25percent_03	25.74	15.01	40.44	0.66	28.84	7.61
25percent_04	25.84	13.48	33.98	0.96	28.73	4.09
25percent_05	25.72	15.42	40.52	0.75	30.62	6.95
Average value			**37.85±2.76**	**0.68±0.21**	**24.23±8.96**	**9.45±5.76**

Table 10: Flexure test results 25% STEEL

Filename	Width (mm)	Thickness (mm)	Ultimate Flexural Strength (MPa)	Modulus of Elasticity (GPa)	Yield Strength (MPa)	Max Elongation (%)
50percent_01	25.49	36.24	17.03	0.10	3.90	31.96
50percent_04	25.44	35.97	15.99	0.12	8.41	20.54
50percent_05	24.86	36.28	20.67	0.16	6.73	21.10
50percent_06	24.89	35.7	25.54	0.12	25.54	21.10
Average value			**19.80±3.73**	**0.12±0.02**	**11.14±8.46**	**23.67±4.78**

Table 11: Flexure test results 50% STEEL

Filename	Width (mm)	Thickness (mm)	Ultimate Flexural Strength (MPa)	Modulus of Elasticity (GPa)	Yield Strength (MPa)	Max Elongation (%)
75percent_01	26.08	32.24	23.26	0.19	6.07	22.69
75percent_02	25.28	28.77	33.65	0.12	30.75	29.37
75percent_04	25.79	19.2	35.51	0.42	16.02	11.93
75percent_05	26.55	15.94	22.33	0.34	22.33	5.50
75percent_06	26.44	17.54	32.36	0.28	24.76	13.41
Average value			**29.42±5.51**	**0.27±0.10**	**19.98±8.40**	**16.58±8.43**

Table 12: Flexure test results 75% STEEL

Sample name	Ultimate Flex Strength (MPa)	Modulus of Elasticity (GPa)	Yield Strength (MPa)	Max Elongation (%)
100%HDPE	**23.14±6.60**	**0.11±0.02**	**14.36±3.87**	**30.81±17.30**
15% STEEL	**40.9±3.22**	**0.98±0.03**	**22.05±3.26**	**7.19±0.94**
25% STEEL	**37.85±2.76**	**0.68±0.21**	**24.23±8.96**	**9.45±5.76**
50% STEEL	**19.80±3.73**	**0.12±0.02**	**11.14±8.46**	**23.67±4.78**
75% STEEL	**29.42±5.51**	**0.27±0.10**	**19.98±8.40**	**16.58±8.43**

Table 13: Average Values of all the proportions

While the 15% samples showed the average of highest ultimate flexural strength 40.9 MPa with the modulus of elasticity 0.98 GPa and with the yield strength at 22.05MPa.

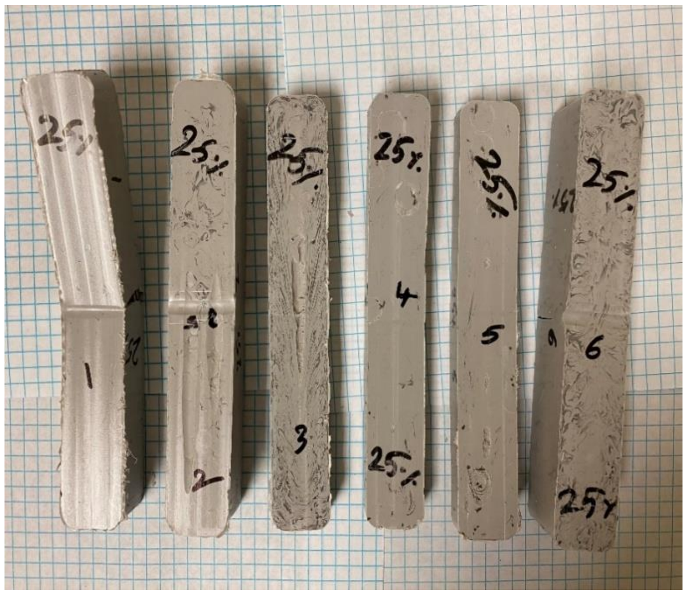

Figure 7:Flex sample 25% after test

Figure 9: Steel fibers in 50% after test

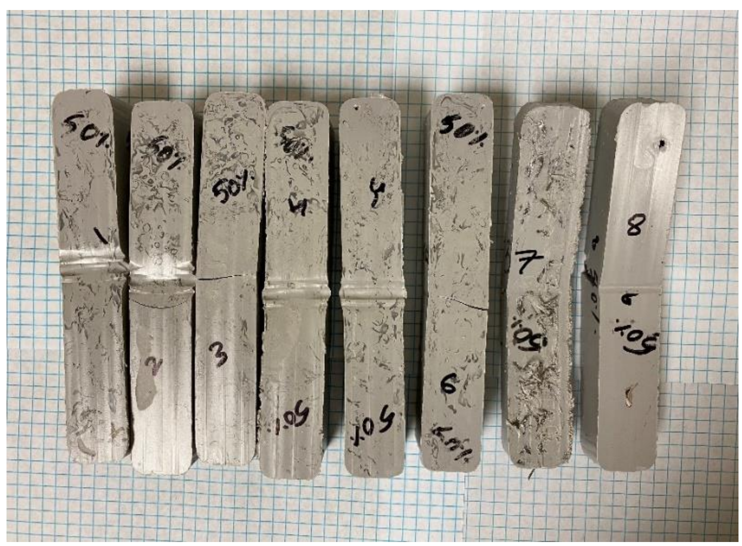

Figure 8: Flex sample 50% after test

2.4.3 Compression Testing:

Filename	Width (mm)	Thickness (mm)	Ultimate Strength (MPa)	Modulus of Elasticity (GPa)	Yield Stress (MPa)	Max. strain
100PERCENT_01	24.86	43.4	32.80	0.57	21.16	0.25
100PERCENT_02	24.85	42.81	27.49	0.54	19.33	0.27
Average value			**30.14±2.65**	**0.55±0.01**	**20.24±0.91**	**0.26±0.01**

Table 14: Compression test results 100% HDPE

Filename	Width (mm)	Thickness (mm)	Ultimate Strength (MPa)	Modulus of Elasticity (GPa)	Yield Stress (MPa)	Max. strain
15PERCENT_01	24.78	48.18	31.02	0.57	17.91	0.27
15PERCENT_02	25.04	44.34	31.76	0.70	13.42	0.30
Average value			**31.39±0.37**	**0.64±0.06**	**15.67±2.24**	**0.28±0.01**

Table 15:Compression test results 15% STEEL

Filename	Width (mm)	Thickness (mm)	Ultimate Strength (MPA)	Modulus of Elasticity (GPa)	Yield Stress (MPa)	Max. strain
25PERCENT_01	24.71	46.51	24.06	0.61	14.75	0.15
25PERCENT_02	25.1	49.5	23.54	0.59	8.73	0.21
25PERCENT_03	25.24	47.83	27.25	0.52	14.22	0.23
			24.95±1.64	**0.57±0.03**	**12.57±2.72**	**0.20±0.03**

Table 16:Compression test results 25% STEEL

Filename	Width (mm)	Thickness (mm)	Ultimate Strength (MPa)	Modulus of Elasticity (GPa)	Yield Stress (MPa)	Max. strain
50PERCENT_01	25	49.58	23.80	0.49	13.87	0.20
50PERCENT_02	24.9	49.13	30.48	0.37	19.29	0.24
50PERCENT_03	25.34	49.89	22.61	0.47	16.24	0.14
50PERCENT_04	25.06	49.02	27.71	0.50	13.83	0.24
50PERCENT_05	25	47.66	31.74	0.45	16.39	0.22
50PERCENT_06	24.74	44.44	35.32	0.49	16.36	0.26
Average value			**28.61±4.43**	**0.46±0.04**	**15.99±1.84**	**0.21±0.03**

Table 17: Compression test results 50% STEEL

Sample name	Width (mm)	Thickness (mm)	Ultimate Strength (MPa)	Modulus of Elasticity (GPa)	Yield stress (MPa)	Max. Strain
75PERCENT_01	25.02	43.74	37.25	0.49	16.86	0.26
75PERCENT_02	24.9	46.54	34.95	0.57	15.37	0.25
75PERCENT_03	25.16	38.61	41.76	0.42	25.05	0.31
75PERCENT_04	25.12	48.42	37.68	0.26	18.28	0.32
75PERCENT_05	24.86	45.74	43.69	0.47	20.62	0.31
Average value			**39.06±3.18**	**0.44±0.10**	**19.23±3.38**	**0.29±0.02**

Table 18:Compression test results 75% STEEL

Sample name	Ultimate Flex Strength (MPa)	Modulus of Elasticity (GPa)	Yield Strength (MPa)	Max. Strain
100% HDPE	**30.14±2.65**	**0.55±0.01**	**20.24±0.91**	**0.26±0.01**
15% STEEL	**31.39±0.37**	**0.64±0.06**	**15.67±2.24**	**0.28±0.01**
25% STEEL	**24.95±1.64**	**0.57±0.03**	**12.57±2.72**	**0.20±0.03**
50% STEEL	**28.61±4.43**	**0.46±0.04**	**15.99±1.84**	**0.21±0.03**
75% STEEL	**39.06±3.18**	**0.44±0.10**	**19.23±3.38**	**0.29±0.02**

Table 19:Average values of all the proportions

18 samples were tested. The 75% ratio samples showed the highest ultimate strength of 39.06 MPa, Modulus of Elasticity of the sample was 0.44 GPa, yield strength 19.23MPa and Maximum strain at 0.29.

Figure 10: Compression sample 75% after test

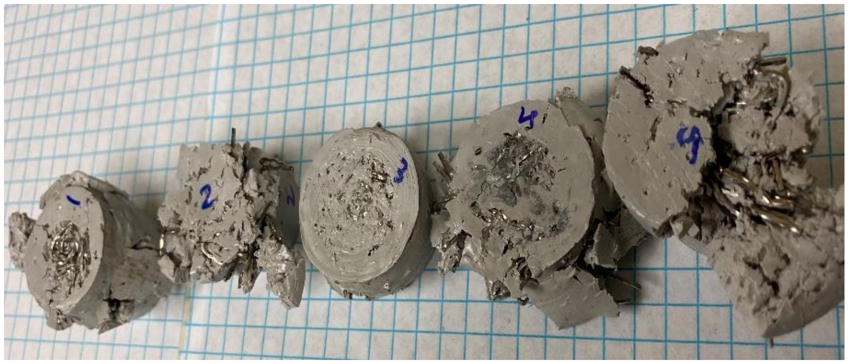

Figure 11: Compression sample 50% after test

2.5 DISCUSSION

Properties	Concrete	Steel
Strength in tension	poor	Good
Strength in compression	Good	Good, but slender bars will buckle
Strength in shear	Fair	Good
Durability	Good	Corrodes if unprotected
Fire resistance	Good	Poor-suffers rapid loss of strength at high temperatures

Table 20: Mechanical properties of concrete and steel

In comparison with steel to concrete, we observe concrete, and steel have some similar mechanical properties as mentioned in the Table [20]. The mechanical properties of steel have high strength qualities than concrete in some areas. Therefore, strength in tension, compression, and shear are good in steel. Concrete

is normally used in large scale 3d printing, major construction projects and it is used in many traditional ways from decades. So having similar properties, is one of the major reasons for considering and developing an idea of using steel fibers in 3D printers and this research also proves that steel is a suitable material for large scale 3D printing.

2.6 CONCLUSIONS

The goal of this paper was to determine if it is possible to develop a composite material for large scale 3d printing that uses common recyclable materials. In this paper, it has been shown that a combination of steel and HDPE polymer can be made into a material that rivals other materials currently used in large scale additive manufacturing. Material testing samples were made using a very simple oven molding process to quickly determine if this composite material functions well. Tensile, flexural, and compression samples were made to determine baseline material properties for HDPE/steel composite materials with varying ratios of steel to polymer.

Test	Sample name	Ultimate Strength (MPa)	Modulus of Elasticity (GPa)	Max. Elongation%	Yield Strength (MPa)	Max. Strain
Tensile	75% STEEL	22.91±1.80	3.47±0.75	1.70±0.41	-	-
Flex	15% STEEL	40.9±3.71	0.98±0.04	7.19±1.09	22.05±3.77	-
Compression	75% STEEL	39.06±3.18	0.44±0.10	19.23±3.38	-	0.29±0.02

Table 21: Average conclusion values of all the proportions

Tensile, flexural and compression tests were made using five different proportions (0%, 15%, 25%, 50% and 75%). The 75% steel tensile sample shows the highest ultimate tensile strength 22.91MPa and highest modulus of elasticity 3.47 GPA. Flex 15% Steel provides the ultimate strength of 40.9MPa with 0.98 modulus of elasticity and for compression test at 75% sample provides the best results, 39.06MPa ultimate strength with Max. elongation% of 19.23 and max. strain at 0.29

Therefore, we believe the next step is to use a large scale 3d printer to test the material using a real additive manufacturing process. When moving to additive manufacturing, other factors may need to be considered, such as cooling time in between layers, nozzle size, layer heights, extrusion rates, extrusion temperatures, and raster orientations.

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CHAPTER-3

LARGE SCALE 3D PRINTING APPLICATIONS

3.1 ABSTRACT

This research work deals primarily with the term Additive Manufacturing or 3D printing techniques. It also explains about the 3D printing modern techniques in various fields. The secondary work shows, the various applications along with the two consecutive type materials HDPE (High density polyethylene) and Steel 430 and their advantages including high strength, high flexibility ratio, low cost, and less weight. Methodology of the work, its advantages and difficulties were discussed. A composite material was manufactured using bigger 3D printers with different proportions 15%, 25%, 50% and 75%. Flexural and compression tests were done to the printed material samples. Mechanical properties including ultimate flexural and compression strength, % elongation at break, maximum strain, elastic modulus, and yield strength were evaluated, and results were compared. This research project helped us to develop the new techniques and to encounter the problems caused by using different materials.

KEYWORDS

Additive Manufacturing, 3D printers, Consecutive material, High Density Polyethylene (HDPE), Steel 430, Material properties.

3.2 INTRODUCTION

3D Printer is becoming the world's fastest machine, it can manufacture a different plastic structure as large as a person in a few hours [1]. 3D printer is not only becoming faster but also producing larger products. 3D-Printers can provide the faster rate of production. Many scientists are coming with more innovations to print and developing high strength, stronger and lightweight material, with mixing multiple materials and making it as a composite material [2]. 3D printer parts are stronger as well as lighter as compared to the parts manufactured by the traditional method. Many aerospace and aviation manufactures are trying to use the advantage of 3D printing techniques. Earlier 3D printers were used for making small and low-grade prototype parts, but now with more advanced techniques 3D printers are also used in medical sciences to repair tissue cells and to replicate the body organs. Kidney, ears, and Heart vessels have already been made and in future it might be possible to print a real 3D printed heart working on its own [3-4]. 3D printer produces very less waste than any alternate method. To prepare one special part, using 3D printer, reduced the manufacturing cost from $10,000 - $600, and the weight of the object by 70-90% [5]. 3D-printers called as Additive manufacturing works on eight different technologies, which are Fused Deposition Modelling (FDM), Stereolithography, Selective Laser Sintering, Selective Laser Melting, binder jetting, laminated objective manufacturing, direct energy deposition and direct write technologies. Additive manufacturing was developed as a novel manufacturing solution to several long-standing logistic drawbacks [6-7].

3.3 EXTRUDING PROCESS

In this process, High Density Polyethylene (HDPE) and Steel 430 are used as a constituent material to develop a high strength composite material. This composite material is introduced as a constructional material using additive manufacturing process. The combination of two different materials HDPE and Steel 430 has several advantages including high strength, high flexibility ratio, low cost, and less weight [8-10]. The secondary aim of this work is also to develop a complete waste material into useful material. Plastics can also be used as a constructional material [11-12]. This research project helped us to develop the new techniques and to encounter the problems caused by using different materials. The other report has shown the easy ways of disposing waste plastics and in the construction of roads were introduced in a research [13]. They have reported that the waste plastics may be used in block making modified light roofing, mastic flooring and polymer reinforced concrete. The blocks can take 350 tons of load and prevents water penetration. They can also be used in lining of canals [14-15]. Hence, plastic is used as constructional material in making blocks in the present work by using additive manufacturing techniques. The Primary focus of this work is on the most frequent technology called Fused deposition modeling (FDM) which comes under the extrusion-based systems. In this process, HDPE pallets and steel pins are fed from the loading carries in the material bay up to the extrusion head. Here, the material is mixed in four different proportions 15%,25%,50% and 75%. Design software used for 3D printer is Repetier - Host V2.16 with providing the directions using G-codes to the extruder 1:25. Six thermocouples were fixed, to heat the extrusion path

and the temperature will be set in an increasing order from top to bottom to all the thermocouples and it ranges between 115°C-230°C. The temperature of the

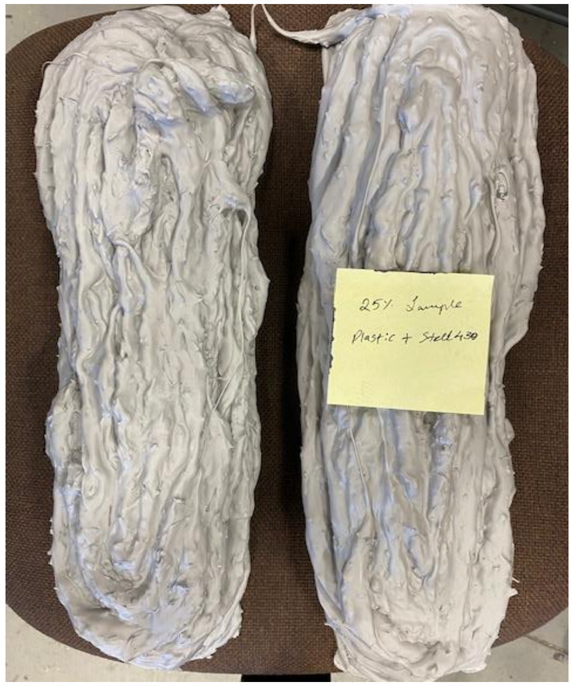

Figure 12: 25% 3D Printed Block

thermocouple will be like (115°C,125°C,150°C,180°C,200°C and 230°C) and the temperature of the thermocouples were checked using infrared thermometer gun. A medium sized nozzle with 0.5 diameter is used in this process. The mixed material forced through the extrusion tips through a heated nozzle, in a semi-liquid state, and precisely deposited onto the modeling in extremely fine layers on top of one another will result in a 3D printed block as shown in Fig 1. The print head moves in x-y direction and the modeling base moves in the z-axis (center line). Two blocks of each proportion were printed using FDM process. FDM is the only technique through which a common person can create things of his own choice which a common person can create things of his own choice which are not available in the stores [16-17].

Eight blocks were printed using all the different proportions and allowed them to cool down at room temperature. Hitachi CB 6Y machine was used to cut the blocks. For each different proportion four rectangular shape samples of minimum 6inch×1inch×1inch were collected for flexural test and for the compression test six rectangular shape samples of minimum 2inch×1inch×1inch were made. Tools available at South Dakota State University's METLAB (Materials Evaluation and Testing Laboratory) [18] were used to assess the mechanical properties of the materials.

3.4 MECHANICAL TESTING

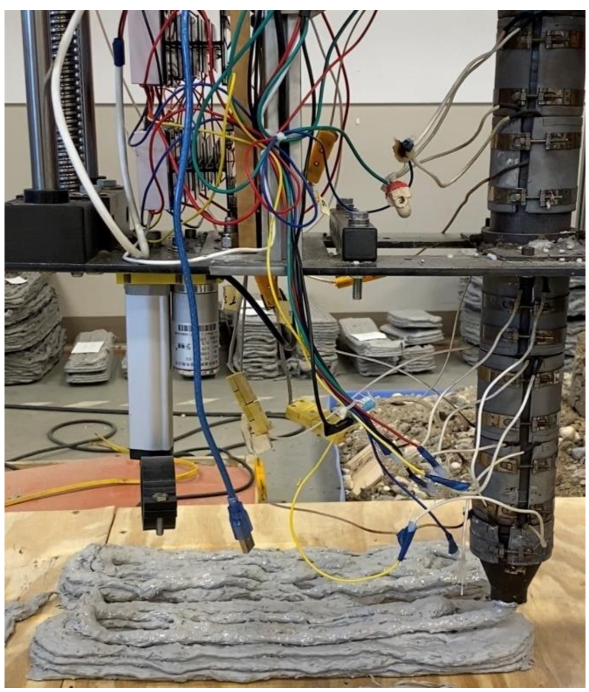

Figure 13: Printer while extruding the material

Flexural test samples were tested according to ASTM D790 - Standard test method with a 5-kN load cell at room temperature for flexural properties of unreinforced

and reinforced plastics and electrical insulating materials [19]. An MTS 3-point flexure test fixture was used. A support span of 10 cm and 15 cm was used depends on the length of the material. The grips were displaced at a rate of 10 mm/min to cause the flexure.

Compression testing was performed in accordance with ASTM D790 [20] using the same MTS 370 Landmark machine, however, strain was calculated. A constant displacement rate of 1.30 mm/min was used to compress the specimen. Standard engineering stress/strain equations were used to calculate stress and strain for both test types. Yield stress calculations were made using the standard 0.2% offset method. The failure load was noted. In each ratio category four samples were tested, and their average value is calculated.

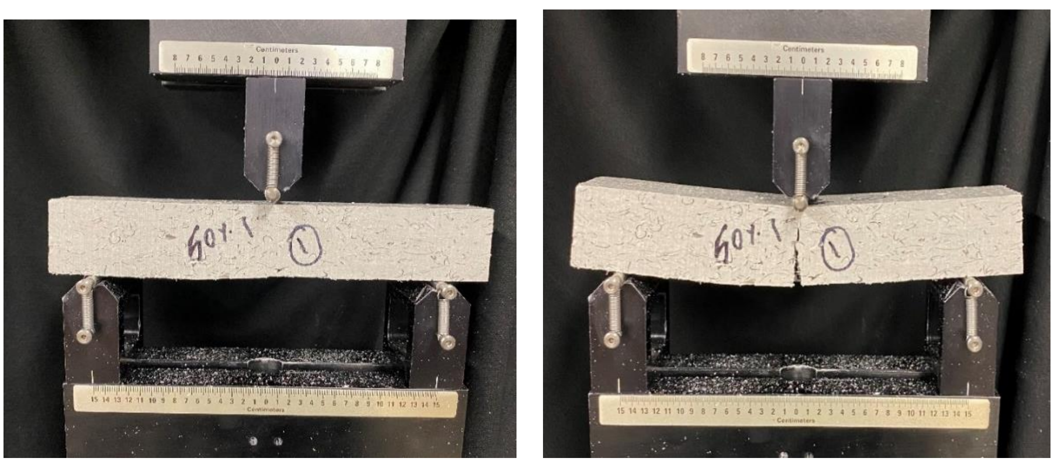

Figure 14: Flex sample before and after test

Figure 16: Compression sample before test

Figure15: Compression sample after test

Mechanical properties that are reported include ultimate strength, elastic modulus, and maximum elongation. These properties were extracted from raw data using an in-house MATLAB code. Mechanical properties including ultimate flexural and compression strength, % elongation at break, maximum strain, elastic modulus, and yield strength were evaluated, and results were compared.

3.5 RESULTS

3.5.1 Flexural Test Results

Filename	Width (mm)	Thickness (mm)	Ultimate Flex Strength (MPa)	Modulus of Flexure (GPa)	Yield Strength (MPa)	Max Elongation (%)
Flex15%_01	41.40	24.38	27.73	0.86	17.63	4.41
Flex15%_02	45.21	26.41	28.09	0.77	18.90	4.74
Flex15%_03	37.33	26.16	22.24	0.71	15.22	3.93
Flex15%_04	41.65	24.13	22.79	0.86	16.17	3.45
Average value			**25.21±2.70**	**0.80±0.06**	**16.98±1.40**	**4.13±0.48**

Table 21: Flexural test results 15%

Filename	Width (mm)	Thickness (mm)	Ultimate Flex Strength (MPa)	Modulus of Flexure (GPa)	Yield Strength (MPa)	Max Elongation (%)
Flex25%_02	38.60	39.37	15.13	0.72	10.62	2.77
Flex25%_03	37.59	32.25	18.76	0.60	15.48	3.57
Flex25%_04	39.37	33.52	15.28	0.77	13.89	2.31
Average value			**16.39±1.67**	**0.69±0.07**	**13.33±2.02**	**2.88±0.52**

Table 22: Flexural test results 25%

Filename	Width (mm)	Thickness (mm)	Ultimate Flex Strength (MPa)	Modulus of Flexure (GPa)	Yield Strength (MPa)	Max Elongation (%)
Flex_50%_01	40.38	34.29	12.72	0.57	10.44	2.56
Flex_50%_02	42.16	33.52	15.97	0.56	12.61	3.23
Flex_50%_03	42.41	37.84	15.53	0.43	7.58	4.65
Flex_50%_04	36.57	37.33	17.11	0.57	10.96	3.92
Average value			**15.33±1.61**	**0.53±0.05**	**10.39±1.81**	**3.59±0.77**

Table 24: Flexural test results 50%

Filename	Width (mm)	Thickness (mm)	Ultimate Flex Strength (MPa)	Modulus of Flexure (GPa)	Yield Strength (MPa)	Max Elongation (%)
Flex_75%_01	44.70	30.22	10.06	0.44	9.52	2.61
Flex_75%_02	36.06	28.44	15.41	0.58	11.77	3.33
Flex_75%_03	36.06	26.41	13.40	0.75	13.00	2.06
Average value			**12.95±2.20**	**0.59±0.12**	**11.43±1.44**	**2.66±0.52**

Table 23: Flexural test results 75%

Sample name	Ultimate Flex Strength (MPa)	Modulus of Flexure (GPa)	Yield Strength (MPa)	Max Elongation (%)
15% STEEL	**25.21±2.70**	**0.80±0.06**	**16.98±1.40**	**4.13±0.48**
25% STEEL	**16.39±1.67**	**0.69±0.07**	**13.33±2.02**	**2.88±0.52**
50% STEEL	**15.33±1.61**	**0.53±0.05**	**10.39±1.81**	**3.59±0.77**
75% STEEL	**12.95±2.20**	**0.59±0.12**	**11.43±1.44**	**2.66±0.52**

Table 25: Average values of all the proportions

Here, the average of 15% samples showed the highest ultimate flexural strength 25.21 MPa and a yield strength 16.98 GPA, with the modulus of flexural 0.80 GPA. Fourteen, flexural samples were tested at each proportion. For this testing, failure was considered if a small crack occurs in the specimen. Here, the observation is made, some specimens were often did not fully break, some were cracked, while the rest of the specimen were flexible enough to break. Eventually the test was stopped before the specimen was touching the fixture. Table above shows the results and the average of each proportion.

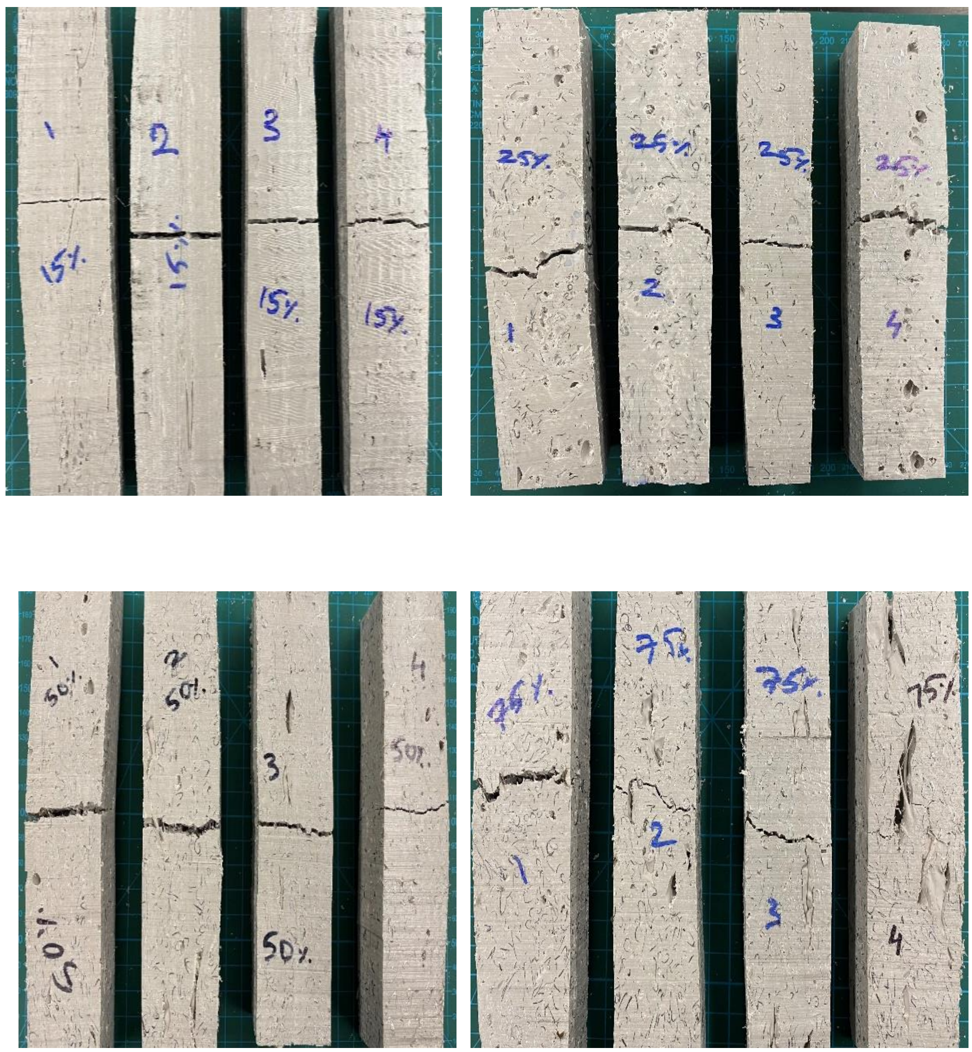

Figure 17: Flex sample after test 15%, 25%, 50% & 75%

3.5.2 Compression Test Results

Filename	Diameter (mm)	Thickness (mm)	Length (mm)	Ultimate Compressive Strength (MPa)	Modulus of Elasticity (GPa)	Yield stress (MPa)	Max. Compression (%)
COMPRESSION15%_01	32.51	31.24	48.26	28.43	0.44	9.54	28.16
COMPRESSION 15%_02	35.56	28.95	51.30	34.14	0.23	6.01	28.19
COMPRESSION15%_06	26.92	23.36	36.06	39.69	0.40	16.39	39.43
Average value				**34.08±4.59**	**0.35±0.09**	**10.64±4.0**	**31.92±5.30**

Table 26: Compression test results 15%

Filename	Diameter (mm)	Thickness (mm)	Length (mm)	Ultimate Compressive Strength (MPa)	Modulus of Elasticity (GPa)	Yield stress (MPa)	Max. Compression (%)
COMPRESSION_25%_01	29.71	31.24	43.94	29.49	0.31	15.47	30.41
COMPRESSION_25%_02	32.25	27.68	36.06	33.87	0.27	20.73	33.05
COMPRESSION_25%_03	25.90	26.41	38.86	38.23	0.30	26.65	28.32
COMPRESSION_25%_04	34.29	26.16	38.1	34.45	0.35	20.96	26.44
COMPRESSION_25%_05	30.48	27.94	42.16	29.02	0.38	11.93	17.69
COMPRESSION_25%_06	23.36	31.49	36.06	31.86	0.26	11.13	29.38
COMPRESSION_25%_07	26.67	23.36	38.35	30.12	0.31	19.36	26.07
Average value				**32.43±3.06**	**0.31±0.03**	**18.03±5.11**	**27.34±4.11**

Table 27: Compression Test results 25%

Filename	Diameter (mm)	Thickness (mm)	Length (mm)	Ultimate Compressive Strength (MPa)	Modulus of Elasticity (GPa)	Yield stress (MPa)	Max. Compression (%)
COMPRESSION_50%_02	24.33	23.87	43.05	33.56	0.38	22.87	25.49
COMPRESSION_50%_03	28.95	27.27	39.11	25.32	0.31	14.26	27.34
COMPRESSION_50%_04	29.08	25.65	42.01	30.11	0.56	11.49	27.67
COMPRESSION_50%_05	26.67	28.32	39.85	29.82	0.46	13.97	19.57
COMPRESSION_50%_06	31.11	24.73	43.86	26.89	0.34	12.83	26.96
				29.14±2.84	**0.41±0.09**	**15.08±4.01**	**25.40±3.01**

Table29: Compression Test results 50%

Filename	Diameter (inches)	Thickness (inches)	Length (inches)	Ultimate Compressive Strength (MPa)	Modulus of Elasticity (GPa)	Yield stress (MPa)	Max. Compression (%)
COMPRESSION_75%_01	26.16	27.17	44.45	32.27	0.30	21.38	29.15
COMPRESSION_75%_02	28.95	24.63	42.41	34.21	0.43	13.77	33.25
COMPRESSION_75%_03	24.13	20.82	42.92	22.06	0.32	15.69	23.60
COMPRESSION_75%_04	23.87	24.89	33.27	31.06	0.34	12.30	33.01
COMPRESSION_75%_05	28.19	34.54	33.02	28.48	0.31	18.31	33.31
COMPRESSION_75%_06	29.46	32.00	37.08	25.87	0.25	17.20	29.77
COMPRESSION_75%_07	25.90	32.51	35.30	37.15	0.39	13.57	42.63
AVERAGE VALUE				**30.16±4.74**	**0.34±0.05**	**16.03±2.93**	**32.10±5.35**

Table 29: Compression Test results 75%

Sample name	Ultimate compression Strength (MPa)	Modulus of Elasticity (GPa)	Yield Strength (MPa)	Max. Compression
15% STEEL	34.08±4.59	0.35±0.09	10.64±4.30	31.92±5.30
25% STEEL	32.43±3.06	0.31±0.03	18.03±5.11	27.34±4.11
50% STEEL	29.14±2.84	0.41±0.09	15.08±4.01	25.40±3.01
75%STEEL	30.16±4.74	0.34±0.05	16.03±2.93	32.10±5.35

Table 30: Average values of all the proportions

A total of 21 samples were tested. The 15% samples showed the highest ultimate compressive strength at 34.08 MPa with the highest yield stress of 10.64 MPa, modulus of elasticity of the sample was 0.35GPa with maximum compression ratio at 31.92%.

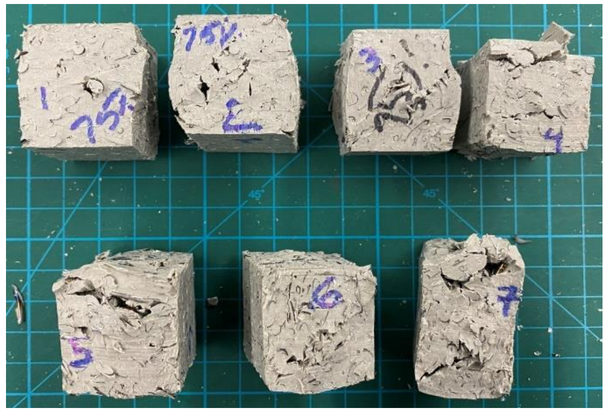

Figure 18: Compression sample after test 75%

3.6 CONCLUSION FOR 3D PRINTED SAMPLES

Test	Sample name	Ultimate Strength (MPa)	Modulus of Elasticity (GPa)	Yield Strength (MPa)	Max. Elongation%	Max. compression
Flex	15% STEEL	25.21	0.80	16.98	4.13	-
Compression	15% STEEL	34.08	0.35	10.64	-	31.92

Table 31: Average values of all the tests

For 3D printed samples 15% shows the best result than other proportions. Flex 15% Steel provides the ultimate strength of 25.21MPa with 0.80 modulus of elasticity and for compression test, 15% sample provides the best results, 34.08MPa ultimate strength with Max. compression at 31.92 and modulus of elasticity is 0.35GPa. In printed samples, increase amounts of steel reinforcements decreased the strength of the material. It can be concluded that, adding little amount of steel to HDPE can strengthen the mechanical properties of the composite material when mixed through the 3d printing extrusion process.

3.7 CHALLENGES WITH 3D PRINTING STEEL REINFORCEMENTS

Steel 430 needles had a wide variety of difficulties while extruding, such as methods for automatically loading, and most importantly nozzle/extrusion tube clogging. The length and diameter of the reinforcement needles must be limited to small lengths to avoid clogging the nozzle. Many trials were made with different size of steel needles (scrap) and finding perfect size steel seems impossible. Due to the sharpness of the steel needles, there might be the chances of puncturing air hoses that typically load materials in the material loading bins.

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CHAPTER 4

Conclusions

- Large-scale 3D printers that use recycled products will consume less energy overall as they require less new material and can reuse other materials destined for the landfill.

- The materials chosen for this study are materials that are commonly recycled but are energy intensive processes. To use the same recyclable materials in this process, very little processing will be required to ensure success in 3d printing the composite material.

- The product formed is lighter in weight with more strength than other traditional large scale manufacturing materials (such as concrete).

- This study shows that plastics have potential to be used in the constructional field and to manufacture a high strength composite material using additive manufacturing techniques.

- Additionally, these composite materials could also someday be used for off-earth habitats/structural components by using recycled materials from cargo missions to off-earth locations.