Investigating the Potential Applications of Elastomeric Polymers (such as Polyuria And Polyurethane) for Accelerated Bridge Construction and Retrofit

Quarterly Progress Report

For the period ending December 1, 2021

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Project Abstract

Elastomeric polymers such as polyurea and polyurethane are nonlinear elastic materials with high tensile strength and strain capacity, adhesiveness, and resistance to permeability and environmental conditions. They have been used commercially as waterproofing and anti-blast coating for reinforced concrete components. While the elastomeric polymer is an interesting material with unique characteristics, there has been limited research on its potential structural applications. A number of research studies have shown the remarkable increase in flexural and shear strength of polyurea-coated reinforced concrete beams. However, further research is needed to explore the application of the polyurea coating system as a new structural material in the bridge industry.

This proposal takes the first step of a long-term research vision to examine and investigate the innovative applications of elastomeric polymers and, specifically, polyurea coating in accelerated bridge construction. Our focus is on the application of elastomeric polymer coatings for the design and retrofit of bridge girders. There are three aspects that can be considered for this application: *(i)* enhancing the flexural and shear strength of the beam through the application of a spray coating, *(ii)* enhancing the weather resistivity, which is especially important for side beams, and most importantly, *(iii)* over height vehicle collision impact resistance. This proposal only focuses on the flexural and shear strength of polyurea-coated RC beams. This simple step is taken to start gaining experience and knowledge on this relatively new material and incrementally examine other aspects of the applications and other potential applications through future proposals and other funding opportunities. We plan for an experimental-analytical research effort to develop simple phenomenological material models for the polyurea coating system and to investigate the potential cost vs. benefit of the coating in the design and retrofit of side girders.

Research Plan

1. Statement of Problem

Based on the collective studies in the literature, it can be concluded that polyurea coating system (Figure 1):

- Increases the flexural and shear strength of RC beams and slabs. It also increases the ductility and failure deformation of RC beams and slabs (which adds to the structural safety by providing alarming deformations before failure) (e.g., [1], [2], [3]),
- Provides waterproofing and environmental resistance to RC surfaces and has good resistance to deteriorating environmental conditions (e.g., freeze-thaw and deicing agents),
- Provides a remarkable local energy dissipation capacity, due to the deformation-induced glass transition of the material, which can enhance the impact resistance of members,
- Is easy to apply (spray coating), dries fast, and has a good bond with the concrete surface, which makes it a solution for on-the-ground as well as in-situ construction and retrofit applications.

Based on the outlined conclusions from the literature, the polyurea coating system is an interesting material with remarkable characteristics that can help to improve the multi-hazard design, construction, and retrofit of accelerated bridge components, with minimum impact on the construction time and site. Figure 2 summarizes the potential applications of the polyurea system in accelerated bridge construction. Despite the significant body of related literature, the practical development of design and construction guidelines requires further experimental and analytical research. This is considering the relatively new introduction of polyurea systems in the structural application and especially the bridge industry.

(a) (b) (c)

Figure 1: Application of polyurea coating (a) masonry slab (photo is taken from [4]*), (b) RC beam specimens (photo is taken from* [3]*), and (c) concrete pipe (photo is taken from* [5]*).*

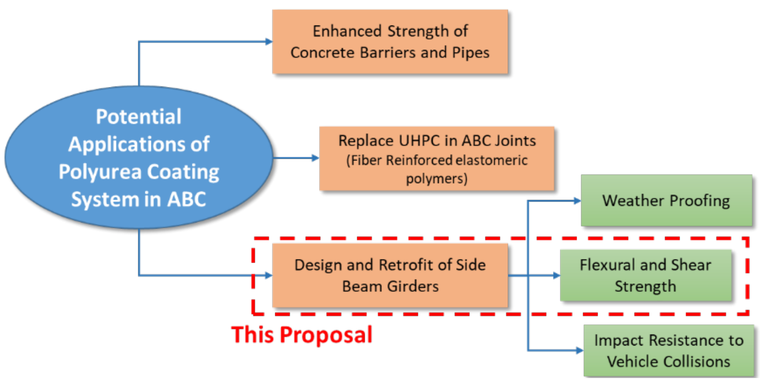


Figure 2: Potential applications of the polyurea system in accelerated bridge construction. This proposal takes the first step of a long-term research vision to examine and investigate the innovative application of the polyurea coating system.

2. Research Approach and Plan

This proposal takes the first step of a long-term research vision to examine and investigate the innovative applications of elastomeric polymers and specifically polyurea coating in accelerated bridge construction. The focus of this proposal is on the application of elastomeric polymer coatings for the design and retrofit of side beams in RC girder bridges. Three aspects can be considered for this application: enhancing the flexural and shear strength of the beam through the application of a spray coating, enhancing the weather resistivity – which is especially important for side beams – and, most importantly, overheight vehicle collision impact resistance. This proposal only focuses on the flexural and shear strength of polyurea-coated RC beams. This simple step is taken to start gaining experience and knowledge on this relatively new material, and incrementally examine other aspects of the applications and other potential applications through a future proposal and other funding opportunities (see Figure 2). The research proposal included 4 tasks as summarized below.

Task 1 – Literature Review

A comprehensive literature review will be performed on the polyurea material and coating system for structural application, including the experimental results, numerical modeling, material models, etc.

Task 2 – Coupon Sample Tests

A series of polyurea coupon samples will be tested under uniaxial cyclic loading scenarios to develop a phenomenological stress-strain and viscosity material model.

Task 3 – Material Model Implementation and FE Numerical Studies

The phenomenological material model will be implemented in a FE simulation platform (e.g., LS DYNA) and will be used to model the response behavior of coated RC beam specimens tested in the literature. The analysis results will be compared with the experimental counterparts provided in the literature to validate the modeling techniques. A model calibration method based on Bayesian inference will be utilized for model calibration and reducing the discrepancies between simulation and experimental results.

Task 4 – Parametric Studies & Economic Analysis

With the calibrated FE model and modeling techniques developed in Task 3, a parametric study will be performed to examine the increase in flexural and shear strength capacity of bridge girder beams due to the polyurea coating. The cost of the polyurea system vs. the increase in strength will be compared with similar solutions (e.g., FRP) to provide an estimate of the economic feasibility of the new material. This step will pave the way to investigate the other potential benefits of polyurea systems for side girder design and retrofit.

The project was planned to be completed in 12 months, starting from August 2020 (Table 1).

Table 1: Proposed project timeline.

Year	2021											
Month	1	2	3	4	5	6	7	8	9	10	11	12
Task												
Task 1: Literature Review												
Task 2: Coupon Sample Tests												
Task 3: FE Studies												
Task 4: Parametric Studies												

Progress Report

<u>COVID19-related delays:</u> Due to the Covid-19 pandemic and the closure of U.S. embassies, we could not admit the targeted student researcher that was supposed to join us from the fall semester of 2020 and work on the project. Therefore, the project progress has been delayed for about 5 months (August-December).

We were able to identify and hire a master's student, Pawan Acharya, who has joined our program since January 2021. The updated project timeline would be as follows.

Task 1 – Literature Review: January 2021 – March 2021 (100% completed)

Task 2 – Coupon Sample Tests: March 2021 – December 2021 (100% completed)

Task 3 – Final Report: January 2022 – May 2022 (Ongoing – 30% completed)

Task 1 – Literature Review (100% completed)

An extensive literature review was done and completed in the earlier part of the research.

Task 2 – Coupon Sample Tests (Ongoing – 100% completed)

Polyurea manufacturer and applicator company "Bridge Preservation" supplied us with different polyurea coating samples used in the market. We acquired the polyurea samples and other required equipment to perform the uniaxial tensile tests on two ASTM standard dies.

We also added two new polyurea materials from the Company named "Nukote Global" for possible strength and mechanical properties. Similar to previous polyurea samples, two new polyureas were tested under monotonic tensile and rate-dependent tests under different loading rates. One of the promising materials was tested for cyclic and fatigue behavior. Test results are included in Appendix A.

We explored the possibilities of getting higher strength with the polyurea by adding fibers to the resin and understanding the behavioral changes. We mixed polyurea and different types of fibers such as polypropylene and polyethylene with different properties and repeated similar behavioral tests to assess the changes in strength and ductility. The polyurea used in this study was Nukote JFHM with a slow reaction time, allowing for mixing fiber to the polyurea by hand mixing. Tensile tests were performed on the different polyurea fiber mix to see preliminary results. Results are added in Appendix B.

Task 3 – Final Report (Ongoing – 30% completed)

We are in the process of summarizing all results from the exclusive comprehensive coupon testing done in this project in a final report.

Overall Progress of tasks in this project is shown in the table below:

Item	% Completed
Percentage of Completion of this project to Date	75%

Appendix A: Polyurea Material Testing

Polyurea Material

We examined two more polyurea materials to the previously tested six types of commercial polyurea materials. Table 2 shows the list of polyurea materials added with the commercial names, assigned material type, and the characteristics according to the manufacturer datasheets [6], [7]. Gel time is the time taken for polyurea to be highly viscous and turn to a solid or semi-solid gel. Tack-free time is the time the polyurea material surface becomes non-sticky.

Table 2: *Properties of polyurea used in the study based on the manufacturers datasheets*

Material type (S#)	Commercial name	Rupture strength MPa [psi]	Elongation at rupture	Gel time	Tack free time
S7	Nukote PP300	55±3 (8000±500)	2±1%	15-20 sec	60-90 sec
S8	Nukote HTD	26±2 (3550±250)	200-300 %	5-15 sec	30-45 sec

Monotonic Tensile Tests

Uniaxial monotonic tension tests were performed for both ASTM D638 [8] die type I and IV polyurea coupons. Loading rates for the coupons were evaluated based on the ASTM recommendation. Four coupons for die size recommended by ASTM D638 based on thickness were tested for each polyurea. As the consistency of polyurea behavior was observed, only two coupons for the other die type were tested. Test matrix and loading rates used for each polyurea material with the average thickness and number of coupons tested are shown in Table 3.

Table 3: Test matrix, loading rates used, polyurea coupon thickness, and number of coupons tested

Material type	Die types	Loading rates used mm/min (in/min)	Average coupon thickness mm (in)	Number of coupons tested	
				Die type I	Die type IV
S7		5.08 (0.2)	2.5 (0.098)	2	4
S8		254 (10)	2 (0.079)	2	4

Results of the monotonic tensile test

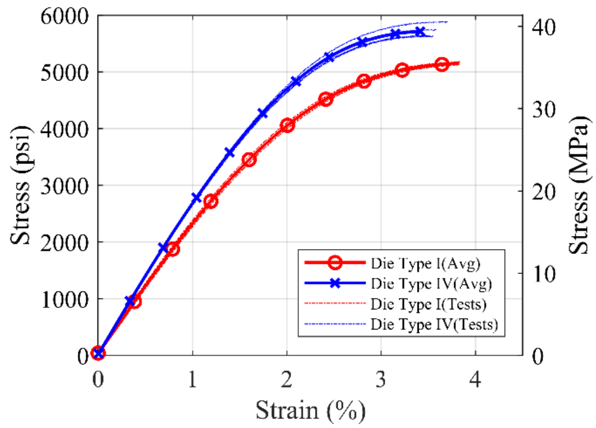


Figure 3: Stress-strain curve of S7 polyurea material for ASTM D638 Die Type I and Die Type IV coupons under monotonic tensile loading

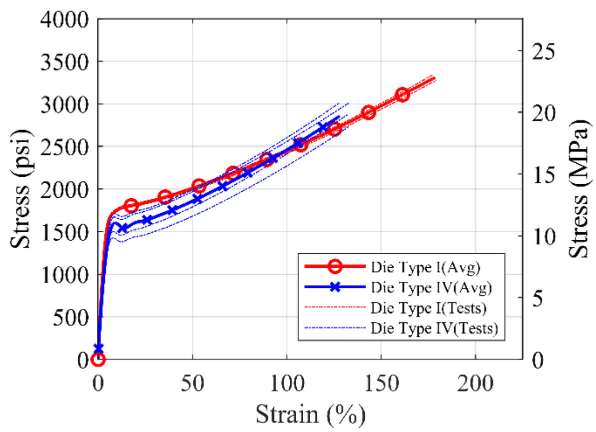


Figure 4: Stress-strain curve of S8 polyurea material for ASTM D638 Die Type I and Die Type IV coupons under monotonic tensile loading

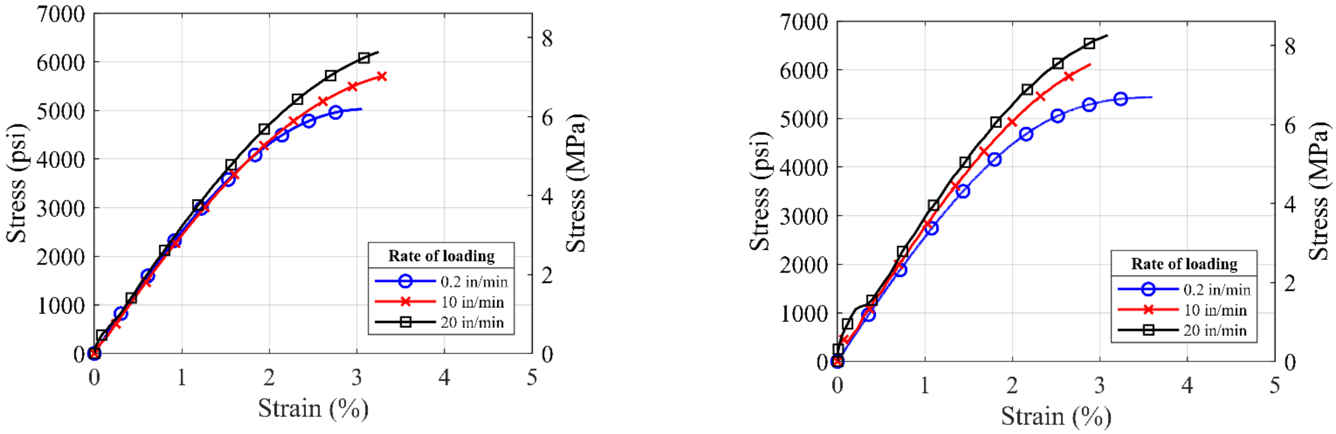
Rate Dependent Tensile Tests

The coupon samples of polyurea were tested under three different loading rates selected to account for vehicular impacts and seismic loading events. Strain rates range of 10^{-4}/s to 10^{-3}/s for vehicular impact [9] and 10^{-3}/s to 10^{-1}/s observed by Li et al. [10] for earthquake ground motions were used to evaluate equivalent loading rates for the test. The coupons used, test setup, and test procedure were similar to the tensile test. Table 3 shows the test matrix for the rate-dependent tensile tests for added polyurea.

Table 4: Test matrix for the rate-dependent test for added polyurea

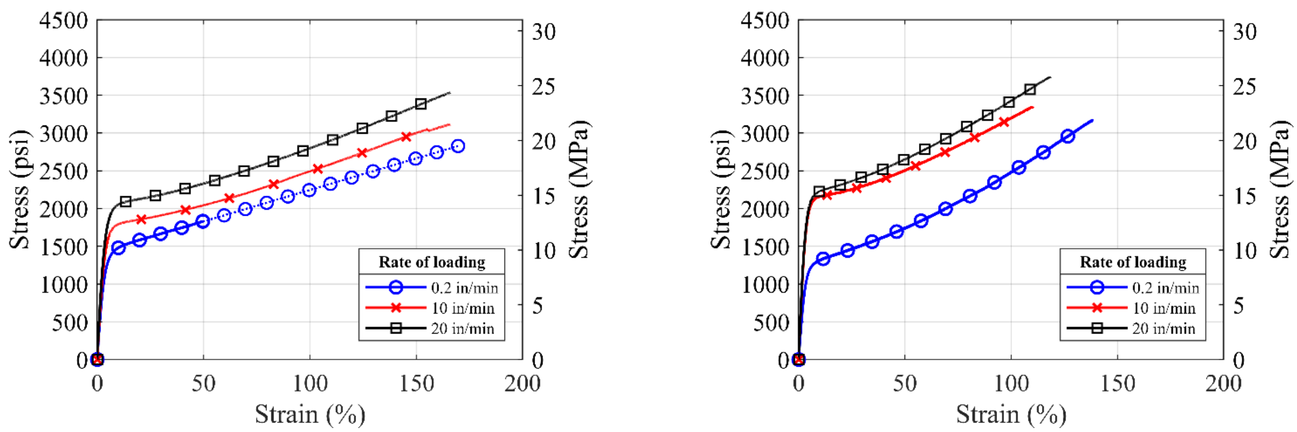
Material type	Die types	Loading rates used mm/min (in/min)	Average coupon thickness mm (in)	Number of coupons tested	
				Die type I	Die type IV
S7	I, IV	5.08 (0.2) 254 (10) 508 (20)	2.5 (0.098)	2	2
S8			2 (0.079)	2	2

Rate Dependent Behavior Of Different Polyurea



(a) *(b)*

Figure 5: Stress-strain curves of S7 material: (a) ASTM die type I, and (b) ASTM die type IV for three loading rates(in/min)



(a) *(b)*

Figure 6: Stress-strain curves of S8 material: (a) ASTM die type I, and (b) ASTM die type IV for three loading rates(in/min)

Figure 5 and Figure 6 show the average stress-strain curves generated from the rate-dependent tests on the remaining commercial polyurea. For loading rate of 0.2 in/min and Die Type I coupons of S8 material, the tests were terminated at 2 inches maximum elongation to avoid grip slippage problems. The dotted lines are the projected estimate for the tests terminated. All the tested polyurea material types show some degree of rate dependency. For all pure polyurea materials, the strength of the polyurea increases as we increase the rate of loading. The S7 material shows a low rate-dependency compared to the S8 polyurea.

Cyclic test

The type I die coupon of S7 polyurea material is tested under cyclic loading. The coupons, test setup, and data acquisition were similar to the tensile test. The loading rate used for the tests is 5.08 mm/min (0.2 in/ min). The coupons were loaded such that the sample is extended twice to different percentage levels of the maximum strain obtained from the tensile test till failure. Three coupons for each polyurea material were tested under cyclic tensile loading with a loading pattern, as shown in Figure 7.

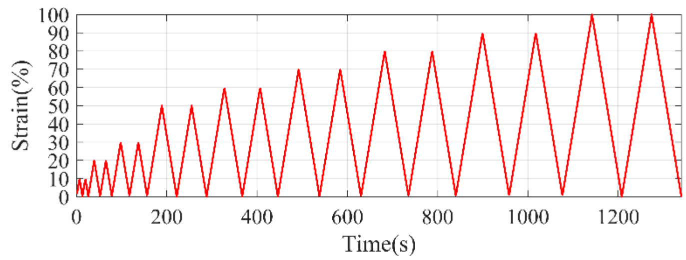


Figure 7: Loading pattern for cyclic test

Cyclic behavior of the selected polyurea

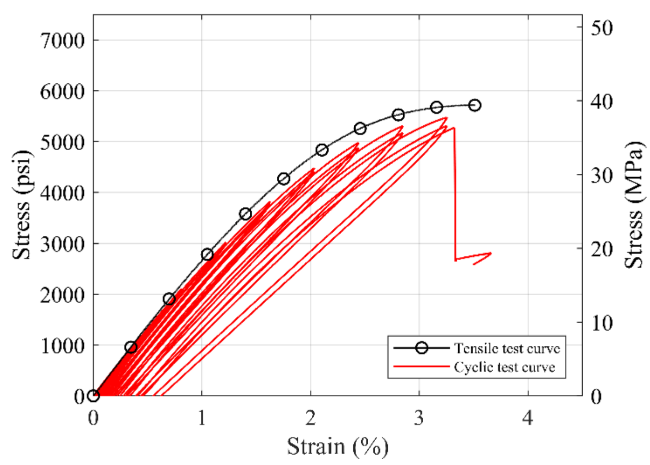


Figure 8: Average stress-strain curve for the cyclic tensile test of S7 material

Figure 8 shows the average stress-strain curve generated from the cyclic tests on the S7 polyurea. It is observed that the unloading curve of polyurea nearly overlaps the reloading curve until the third cycle of loading. There is no distinct softening effect on the tensile capacity of polyurea due to the cyclic loading. After the polyurea coupon yields, the unloading and reloading curves separate and plastic deformation is observed. The unloading stiffness of the S7 material decreases gradually. This indicates the nonlinear behavior of the polyurea material. The average stress-strain curve from the uniaxial tensile test under the monotonic loading is also shown in Figure 8. The backbone curve of the cyclic test is consistent with the tensile test's stress stain curve showing only a slight decrease in strength under the cyclic loading. Even under cyclic loading, the polyurea material reaches a max strength of 5.3 ksi. This adds to its suitable mechanical properties for structural application.

Fatigue test

Die type I coupons of S7 material were also tested for tensile fatigue loading. The fatigue load used in this test is 70% and 90% of the average peak loading from the tensile tests. The samples were loaded either up to 150 cycles or until the failure for each fatigue load case. The test setup was similar to the tensile test setup. The loading rate used was 50.8 mm/min (2 in/min) for all polyurea coupons. The results of the test are discussed below.

Fatigue behavior of the selected polyurea.

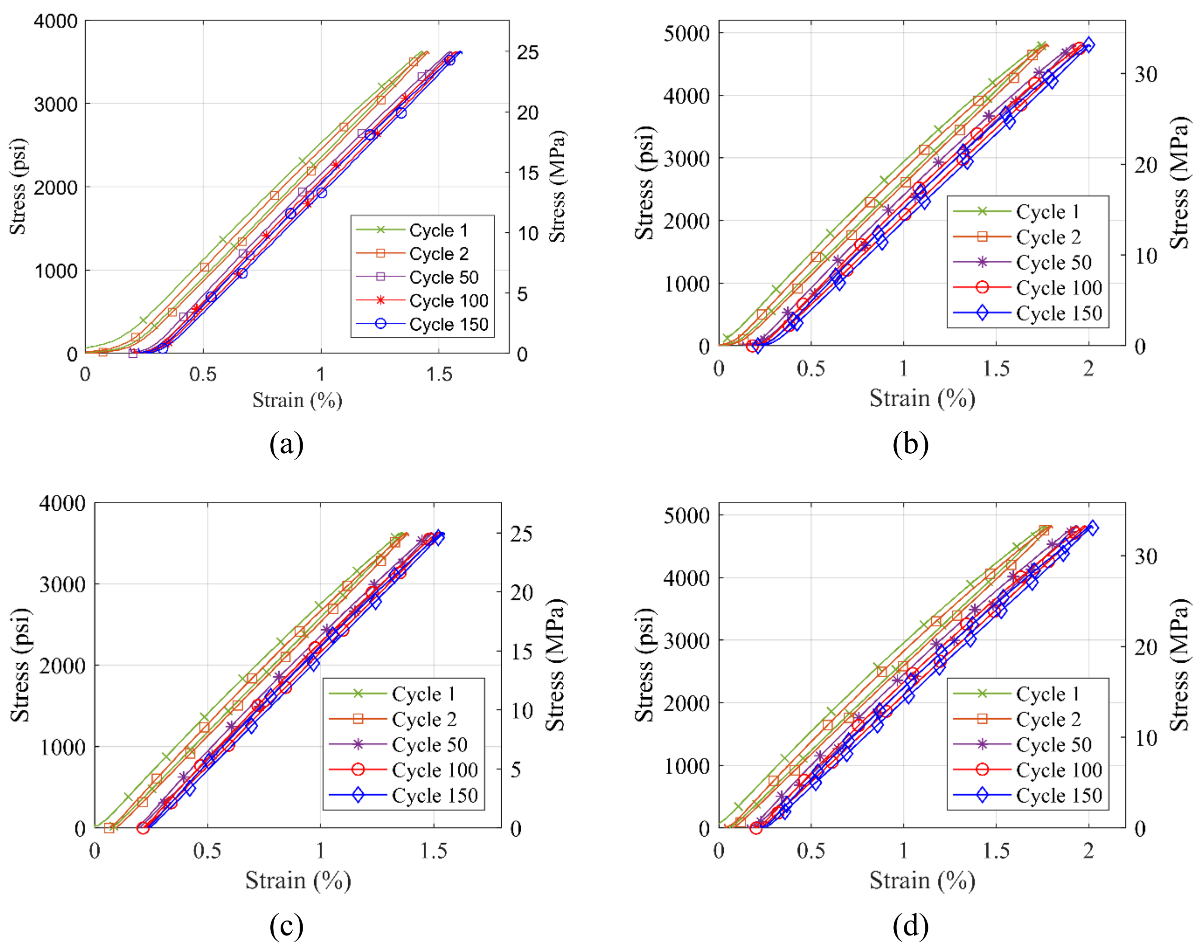


Figure 9: Stress-strain curve for fatigue testing of S7 material with (a) 70% of the max load for sample 1 (b) 90% of the max load for sample 1 (c) 70% of the max load for sample 2 (d) 90% load for sample 2

Both the test coupons completed the full 150 cycles for 70% and 90% of the ultimate loading in the fatigue testing. Figure 9 shows the results for the fatigue testing for both load ratios of the two samples. It is observed that the material is already in the plastic region on 70% of the ultimate load. The slope of the stress-strain curve does not seem to be changing drastically, but a small plastic deformation is observed in each cycle of the fatigue loading that accumulates with every cycle. This result suggests a further in-depth study of the fatigue load behavior for the polyurea material is needed.

Appendix B: Polyurea with Fiber Testing

Polyurea mixed with fibers test

Polyurea is a type of elastic polymer formed by the polymerization reaction of two components: polyamine and diisocyanate, at a suitable ratio of the two components. Only the first five fibers were mixed and tested to check whether any behavioral changes could be observed or not.

Fiber (1% by volume) was mixed into the polyamine component before adding the diisocyanate component to get polyurea. Sheets of polyurea mixed with fibers were prepared by manual mixing inside a chemical fume hood. Table 5 shows the properties of the fiber used. ASTM D638 Type IV Dies were cut out from the sheets using a steel die and a manual arbor press.

Due to the quick reaction time of the polyurea and the highly viscous nature of the raw components, getting a uniform mix of fibers and the polyurea components has become an issue in sample preparation. The research team is trying to figure out the solution to tackle the problem.

Table 5: Properties of fiber used as per manufacturer

SN	Fiber Material	Fiber notation	Length (mm)	Density (gm/cm3)
1	Polypropylene	PPSTD-015NRR	3	0.91
2			6	0.91
3		PPSTD-030NRR	6	0.91
4			12	0.91
5	Polyethylene	PEUHM-020NLH	6.3	0.97
6		PEUHM-020NLH	12.7	0.97
7	Micro steel fibers	WSF01206	6	7.8
8		WSF01210	10	7.8
9	Glass fibers	NYCON-AR-HD	12.7	2.7
10		NYCON-AR-DM	12.7	2.7
11	PVA fibers	NYCON PVA RECS100	12.7	1.3
12		NYCON PVA RECS15	8	1.3

Uniaxial monotonic tension tests were performed for ASTM D638 die type IV polyurea coupons. Loading rates for the coupons were evaluated based on the ASTM recommendation. Figure 10 shows the poured sheets of polyurea with fiber in molds, sheets of the polyurea with fibers and cut out coupons for tensile testing.

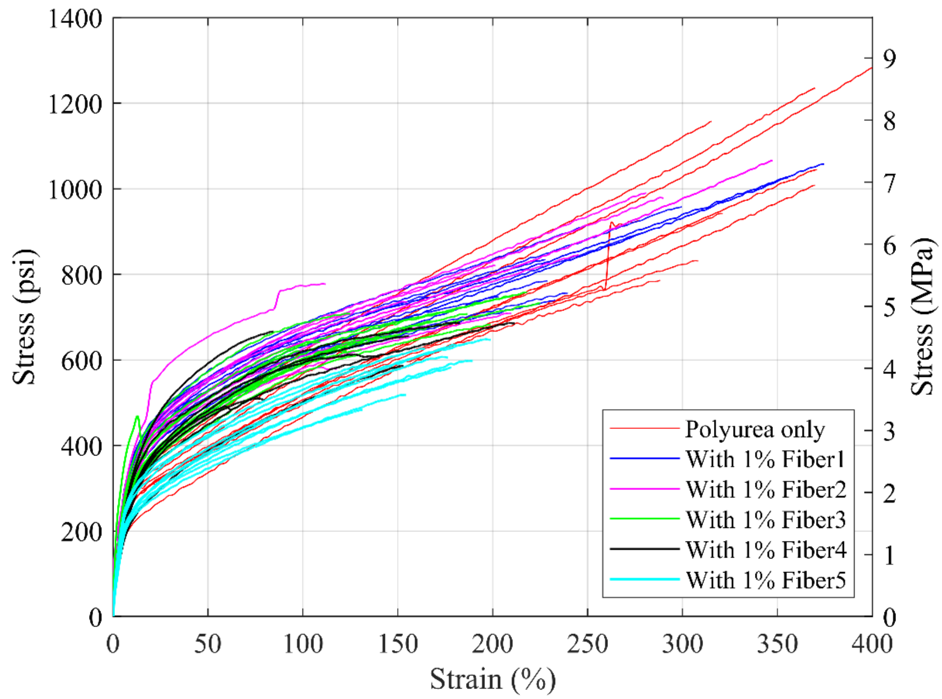
(b)

(a) (c)

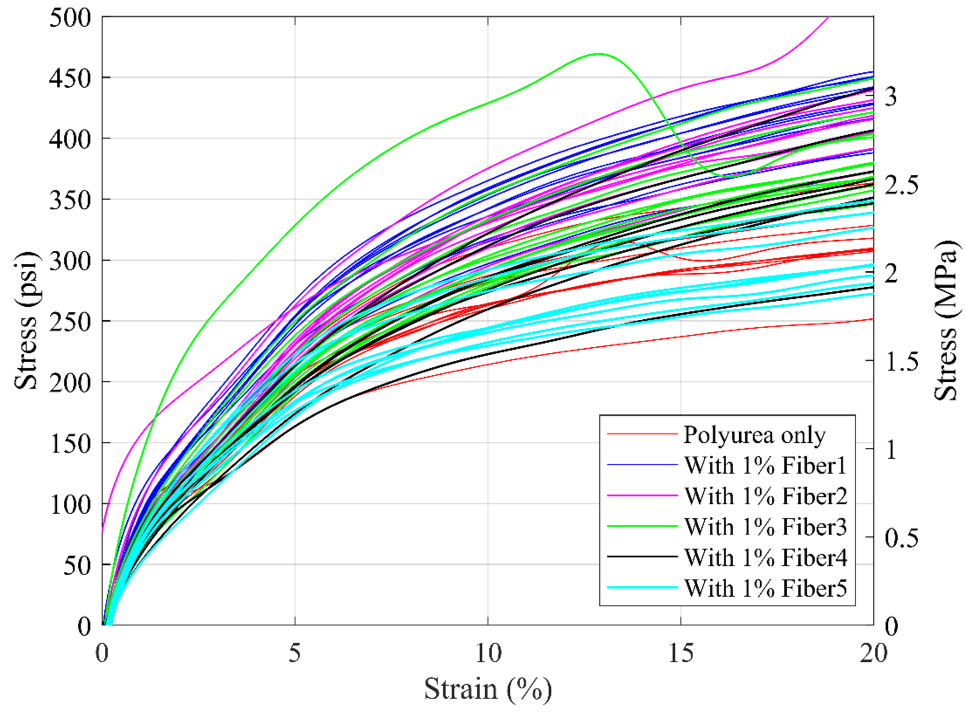
Figure 10: (a) Polyurea mixed with fiber poured into flat sheet (b) Polyurea sheets indicating random site sampling for coupons (c) ASTM D638 Type IV Die cut-out coupons

Monotonic tension test results

Load and displacement data acquired by the Instron Machine is post-processed to get stress-strain values for the tests. Engineering stress values are calculated by dividing the load values by the initial coupon sectional area at the narrow section, i.e., desired failure location. Engineering strain values are obtained by dividing the extension values to the original grip spacing measured at the start of the test. Figure 11 shows the average tensile stress-strain plot generated by averaging the stress values at constant strain values from all tested coupons for different die types of different polyurea material.



(a)



(b)

Figure 11: Tensile test results for polyurea mixed with different types of fibers showing stress-strain up to (a) maximum strain (b) 20% strain

In figure 11(a), it can be observed that the ultimate strain of the polyurea decreases by adding the fibers. However, from general observation of the stress-strain curves, we observed only a minimal increase in the initial capacity and the stiffness of the polyurea material after adding the fibers. The results do not show a promising increase. The low percentage volume of fibers and the human error incorporated by the manual mixing process could be the reason for inconsistency in the results. Efforts are being made to come up with and feasible research plan for the polyurea fiber mix design study.

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