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Mechanical Properties of Novel Reinforced Spray in Place Pipe Material With Potential Fully Structural Performance Application

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Many utility owners in the United States are actively searching for new and innovative rehabilitation techniques to help them regain control and repair large tracts of their networks; moreover, traditional open cut replacement is too costly and slow to keep up with demand. Many trenchless techniques such as Spray-In-Place Pipe (SIPP) lining have been adopted by municipalities to renew their aging pipeline systems. The further development of SIPP linings could benefit the water community in the United States and around the world. SIPP lining could play a key role in controlling the future expected burden caused by the aging distribution networks. This study aimed to investigate the mechanical properties of a newly proposed reinforced spray in place pipe (SIPP) lining material that boasts structural characteristics. This material is a spray applied two component polyurethane high build coating. Three forms of sample were investigated during these tests: (1) No Fiber-Baseline (2) Rigid-with one layer of carbon fiber (3) Rigid—with two layers of carbon fiber. Three types of tests are performed: tensile, flexural, and hardness tests. This study included both experimental and Finite Element Analysis (FEA). Target mechanical properties of proposed material can be improved by using carbon fiber (CF) as reinforcement and based on the results of this study, the SIPP lining material with two layers of CF reinforcement has the highest value of 8,067 psi and 16,534 psi during the tensile and flexural test, respectively.

Keywords: spray in place pipe, carbon fiber reinforcement, trenchless technology, mechanical properties, finite element analysis

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INTRODUCTION

Without a doubt pipeline systems, especially water distribution systems, play an essential role in our nation's infrastructure. As water infrastructure ages many authorities are concerned by the growing deficit in the repair and replacement of failing water mains (Ellison et al., 2010). The deterioration and aging of water and wastewater systems is an ever growing problem, traditional replacement is costly to perform, it becomes more costly when the disruption to everyday life are also factored. To ease these burdens many solutions have been developed to remedy aging infrastructure (Kharazmi, 2019). Many pipeline owners are now recognizing the need for rehabilitation methods to help control their systems (Selvakumar and Matthews, 2017). While rehabilitation techniques have been advancing steadily and despite large public investment few formal and quantitative evaluations

are being performed to determine if the technologies are performing as they should (Allouche et al., 2014).

Spray in place pipe (SIPP) is a trenchless technology rehabilitation method for pressure and non-pressure piping systems to possibly provide a structurally independent liner able to handle the operating pressure and all applied loadings. The main purpose of SIPP lining also can be applied as a monolithic coating to the interior of a pipe that will inhibit further corrosion and eliminate water quality deterioration caused by scaling, while restoring hydraulic capacity. No rehabilitation job is the same the type of repair used is determined after assessing the level of deterioration, location, cost, and any future plans for the system (Ellison et al., 2010; Motlagh et al., 2013). There are two primary material categories used for SIPP applications: cement mortar and polymers, polymers include materials such as polyurethane, polyurea, and eopoxy (Motlagh et al., 2013).

Rehabilitation liner solutions can be categorized into four classes based on their level of performance when exposed to internal pressure. These classes are described in **Table 1** (American Water Works Association, AWWA, 2001, 2021):

- Class I linings are essentially non-structural systems used primarily to protect the inner surface of the host pipe from corrosion and/or improve or maintain water quality. They are not intended to improve the structural performance of the host pipe and have a minimal ability to bridge any existing

TABLE 1 | General structural classifications objectives per AWWA M28.

Lining system characteristic	Non-structural	Semi-structural (interactive)		Fully structural
	Internal coating	Hole span	Hole span + ring stiffness	Structural resistance for all specified loads (internal and external)
	Class I	Class II	Class III	Class IV
Internal corrosion protection	✓	✓	✓	✓
Long-term adhesion to the host pipe	See note 1 below	✓	See note 2 below	See note 2 below
Hole span at MAOP		✓	✓	✓
Inherent ring stiffness (hydrostatic pressure or vacuum loads only)	See note 1 below	See note 1 below	✓	✓
Water tightness (positive connection to service taps and sealed at termination points or other discontinuities)		✓	✓	✓
Inherent ring stiffness (all static and dynamic external, hydrostatic, and vacuum loads)				✓
Pressure rating of lining ≥ MAOP of host pipe				✓
Lining survives anticipated host pipe failures				✓

1. The owner/engineer must specify whether vacuum loads exist. This is addressed through reliable adhesion to the host pipe, which is a characteristic of all Class II and some Class I linings, or inherent ring stiffness.
2. For Class III and IV linings, adhesion is not required to develop ring stiffness. However, it may be necessary to achieve a watertight seal (for example, at services and lining terminations). There are also situations where adhesion is not desirable, such as applications with broad temperature swings and in Class IV linings where the host pipe is anticipated to experience brittle failure modes.

TABLE 2 | Potential failure issues per (Matthews et al., 2012).

Potential issue	Description
Improper surface preparation	Surface preparation is important to the quality of the liner. If the surface is not cleaned well, the lining will adhere to surface contaminants, resulting in improper curing
Improper curing	A SIPP lining must cure well to become solid and if improperly cured, it will have reduced the performance
Finished thickness not achieved	Insufficient thickness can occur if the SIPP lining materials are formed or sprayed incorrectly, reducing materials properties. The permeability will increase and making leaks. Strength contribution is reduced, and the lining becomes more prone to cracking
Pinholes and surface defects	Pinholes have a higher probability of occurring in thin SIPP lining. Defects include a rough surface from particles in the material, insufficient flow, or defects in the host pipe. The proper formulation can reduce this effect
Structural failure	Pressurized host pipes and SIPP lining can develop cracks due to the internal pressure from normal operating conditions in the lined pipe and short-term pressure surge caused by water hammer
Liner leakage	The SIPP may be failed to adequately bridge gaps in pipe joints or hole/defects within-host pipe, which could cause continued leakage
Liner material degradation	Material degradation can lead to the reduction in properties over time, such as strength and resistance to permeation

discontinuities, such as corrosion holes, cracks, or joint gaps. Hence, they usually have minimal effect on reduction or elimination of existing leakage. Their use is indicated in pipes that have internal corrosion or tuberculation but are still in structurally sound condition and where current or future leakage is not the primary design objective.

- Class II and III linings are both interactive and semi-structural systems. When installed, Class II linings shall adhere to the wall of the host pipe. Class III linings may or may not achieve reliable adhesion to the host pipe but shall be sealed to establish or maintain hydrostatic integrity. Since the pressure rating and stiffness of such a lining is < that of the host pipe, some internal pressure loads are transferred to the host pipe, leading to their classification as interactive. Class II and III linings are required to independently sustain internal pressure loads at existing or future discontinuities in the host pipe, such as corrosion pits, holes, or joint gaps.
- Class IV linings, termed fully structural or structurally independent, possess the following characteristics:

1. Long-term hoop strength, when tested independently from the host pipe, = or > the strength required to withstand the MAOP of the host pipe.
2. Short-term hoop strength, when tested independently from the host pipe, = or > the strength required to withstand all anticipated short-term loads, such as negative pressures, occasional and recurrent surge pressures, and live loads.
3. The ability to survive the full range of anticipated failure modes of the host pipe without leakage or consequential damage to the lining.

Non-metallic pipe materials are used as an internal lining and standalone pipes in the oil and gas industry, constituting an emerging corrosion strategy. The non-metallic pipe materials are inherently susceptible to gradual damage due to creep, fatigue, permeation, processing defects, and installation blunder (Khalid et al., 2020). Potential failures of SIPP linings during the installation and operation along with their solutions are summarized below in **Table 2** (Matthews et al., 2012).

The objective of this study is the investigation of the mechanical properties related to Spray in Place Pipe (SIPP) lining materials with potential structural performance application; the study included three types of testing: tensile test, flexural test, and hardness test. Three different sample types were investigated in this study: (1) No Fiber-Baseline (2) Rigid-with one layer of carbon fiber (3) Rigid—with two layers of carbon fiber. The carbon fiber reinforces the SIPP system to allow it to carry higher loads than traditional SIPP material systems. This study included both lab testing and Finite Element Analysis (FEA).

This new material is a spray applied two component polyurethane, rapid curing, rigid structural lining system for high build coating. It is the wearing surface of the strong pipe Manufactured in Place Composite Pipe (MICP) system. It is designed to be robotically spray applied in sections up to 6 inches thick. The enhanced molecular design gives excellent mechanical properties with low exotherm and low shrinkage. It can be applied with or without carbon fiber reinforcement. When applied it cures rapidly for immediate return to service in pipe applications. This rigid coating is specifically designed for potable water applications. The SIPP resin properties used in this study summarized in **Table 3**.

TABLE 3 | Resin properties.

Specific gravity (g/cm^3)	1.16–1.23
Specific gravity (lbs/gal)	9.7–10.3
Viscosity at 73°F (cps)	2,500–2,800
Viscosity at 77°F (cps)	1,900–2,200
Viscosity at 100°F (cps)	1,200–1,500
Viscosity at 120°F (cps)	600–900
Solids by volume/weight	100%
Density	10.0 lbs/gal (1.20 g/cm^3)
Color	Blue

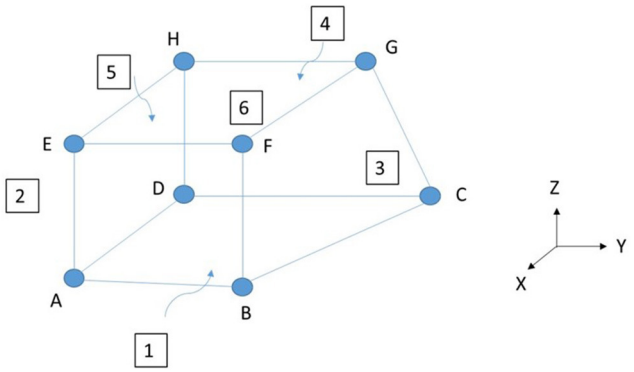

FIGURE 1 | SOLID65 3-D concrete solid element (reproduced from ANSYS manual).

TABLE 4 | Tensile test sample geometries.

Sample	Width (in.)			Thickness (in.)			Cross section Area (in^2)
	Beginning	Middle	End	Beginning	Middle	End	
1	0.48	0.48	0.48	0.28	0.27	0.27	0.13
2	0.72	0.72	0.72	0.32	0.32	0.32	0.23
3	0.72	0.72	0.72	0.57	0.57	0.57	0.41
4	0.72	0.72	0.72	0.59	0.59	0.59	0.43

NUMERICAL SIMULATION

The finite element analysis (FEA) is applied for simulating the behavior of tensile and flexural samples. In this study, three-dimensional (3D) FE modeling was performed using ANSYS software. In the three-dimensional modeling the solid65 unit is used (**Figure 1**). The solid65 unit is an 8-node solid element. An important part of this element is processing of non-linear material properties. Plastic deformation, fracture, three orthogonal directions of cracking, and creep (if needed) are included.

For tensile samples, one end of dog bone shape sample was considered rigid (rigid boundary condition) and tensile load was applied to the other end of the sample. Flexural samples are considered hinged (hinged boundary conditions) and only allowed to rotate in one direction at the supports while the load is applied at the top of the sample.

EXPERIMENTAL STUDY

Tensile Test

When a pipeline is subjected to an internal pressure, tensile stress can occur in the pipe. Therefore, tensile strength is a basic consideration in pipe design. This test method determines the tensile properties of unreinforced and reinforced samples using standard dumbbell-shaped test specimens. The objective of this study is to test and evaluate the innovative spray-in-place pipe (SIPP) material. This study is testing the tensile performance of the SIPP lining system on a rigid, rigid and carbon fiber

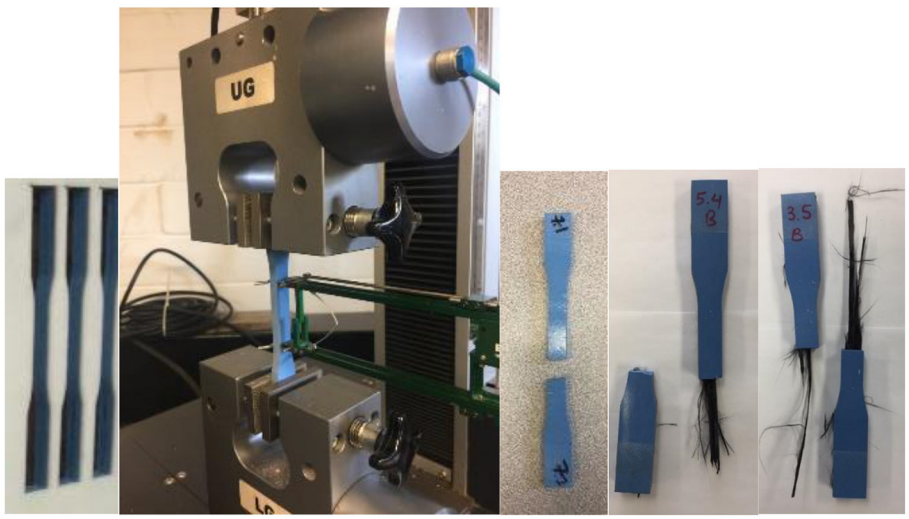

FIGURE 2 | Tensile test sample preparation, test setup and failed samples.

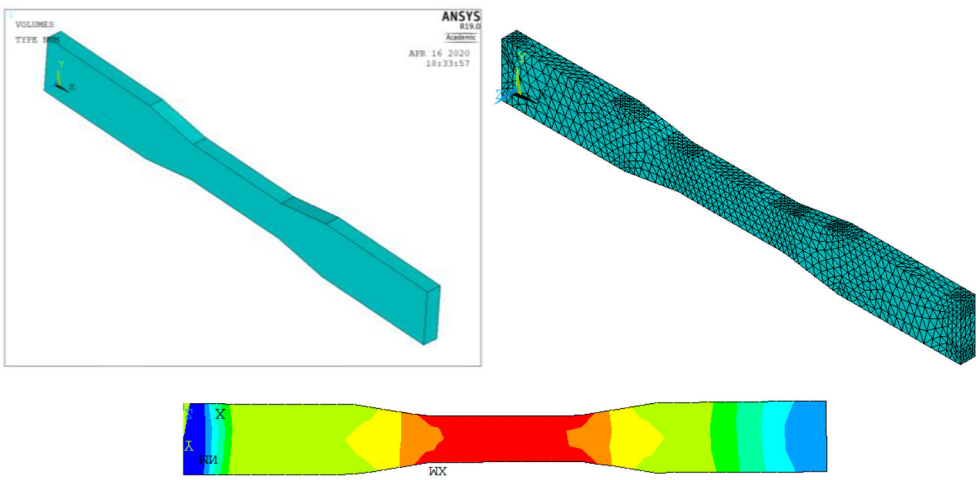

FIGURE 3 | FE tensile test.

(composite) layer. The carbon fiber provides reinforcement to the SIPP system to allow it to carry higher loads than traditional SIPP materials and systems.

The selection of materials dimensions and experiment procedure was followed using ASTM D683-2014 (American Society for Testing Materials, 2014). The test apparatus for conducting the long-term creep test was custom fabricated and this set-up was according to the ASTM requirements. A materials tensile strength is one of the most tested for and important properties for a material used in structural applications. The force

TABLE 5 | Tensile test result.

Sample	Condition of sample (thickness-reinforcement condition)	Type	Peak load (lb)	Tensile strength (psi)	FE, Peak load (lb)
1	~0.27"-no fiber-baseline	I	713	5433	763
2	~0.32"-rigid-with carbon fiber	III	1536	6671	1705
3	~0.57"-rigid—with carbon fiber	III	2936	7112	3288
4	~0.59-rigid—with two layers of carbon fiber	III	3440	8067	3921

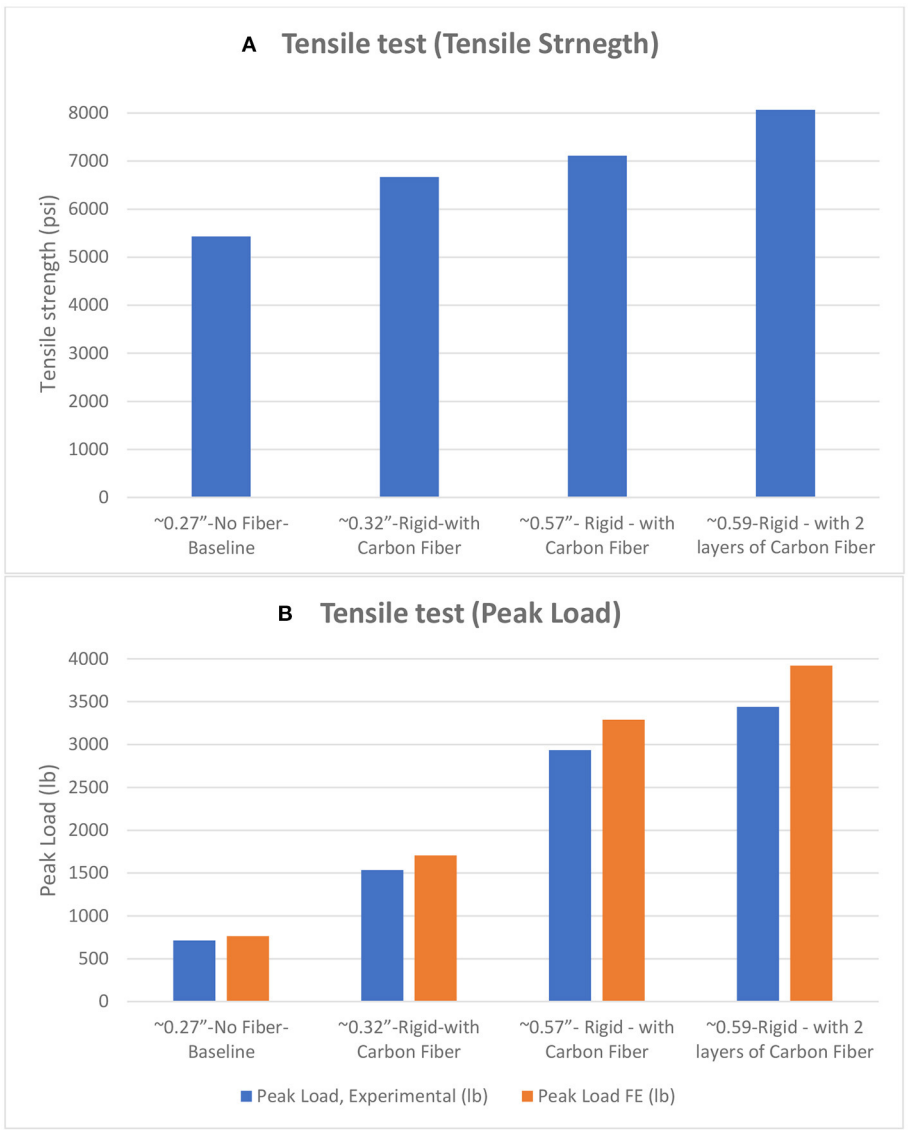

FIGURE 4 | Tensile tests results **(A)** Tensile strength (psi), **(B)** Peak load (lb) Experimental vs. FE.

per unit area required to break material is recorded also, it is known as the ultimate tensile strength or tensile strength at break of the material (Alzraiee et al., 2015). The dog-bone samples were mostly prepared and cut out of provided plate samples. The dimensions of the specimen such as the width and thickness were measured at three different locations. Cross sectional area was calculated from average width and thickness. The tensile test sample geometries are listed in **Table 4**.

The samples were cut using an OMAX waterjet at Louisiana Tech University as shown in **Figure 2**. The tensile test was conducted on four different specimen groups including ∼0.33" thickness-No Fiber-Baseline, ∼0.39" thickness-Rigid with Carbon Fiber, ∼0.57" thickness-Rigid with Carbon Fiber, and ∼0.60" thickness-Rigid with two layers of Carbon Fiber. The test was performed at a controlled temperature of 72 ± 2°F and a relative humidity of 50 ± 2%. The tensile testing machine is an ADMET universal testing machine of 10 KN maximum load. During the test, the tensile data was directly collected and analyzed by a computer connected to the testing instrument using MTestW licensed software. The setup of the experiment was performed using pneumatic powered grips (GP-16T) with 0.8-inch-wide maximum opening jaws, as shown in **Figure 2** were used in the test. During tensile testing the sample is pulled until failure the force that was required to make the sample fail is a critical measurement to have. **Figure 3** depicts the Finite Element Analysis (FEA) during the tensile test.

Tensile Test Calculations

$$\text{Tensile Stress}(\sigma) = \frac{P}{A}$$

where,

A = Average initial cross-sectional area (in^2),

P = Applied Force (lb).

The tensile test results for both experimental, and FEA show that the sample with two layers of carbon fiber has the highest tensile strength compared to other samples. Tensile strength has improved 26.8% with adding one layer of carbon fiber (CF) reinforcement and 48.5% by using two layers of CF reinforcements in compare with no-fiber-baseline samples. Seventeen percentage increment of tensile strength experienced in samples with two layers CF reinforcement in compare with

FIGURE 5 | Flexural test.

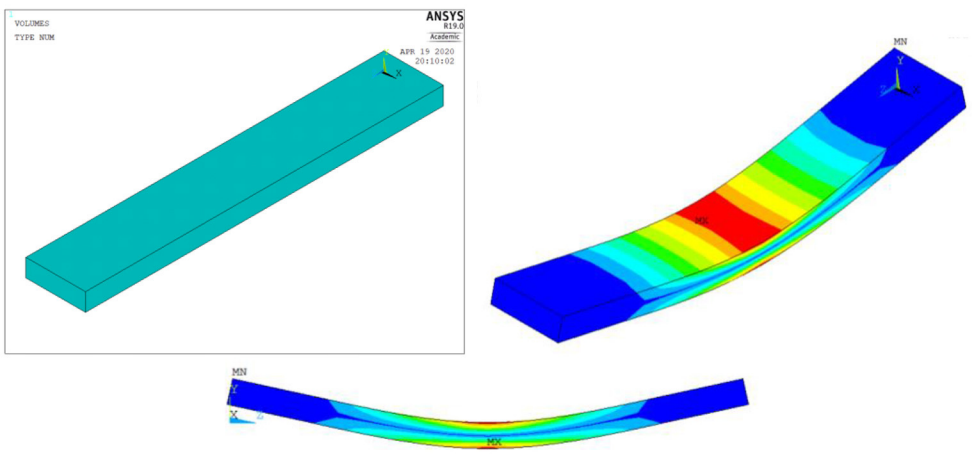

FIGURE 6 | FE flexural test.

one layer CF samples. The results also indicate that the sample with more thickness has the highest peak load compared to the same sample but with smaller thickness. **Table 5** shows the result for both lab and FEA during the tensile test. The presented results are the average of five samples for each type of the sample. **Figure 4** shows tensile strength and peak load results (Experimental and FE) of tensile tests for all specimens, respectively.

Flexural Test

Flexural loading is one of the most common types of loading experienced in practice. It is highly significant for determining

TABLE 6 | Flexural test results.

Sample	Width (in.)			Thickness (in.)			Peak load (lb)	Peak stress (psi)	FE, peak stress (psi)
	Beginning	Middle	End	Beginning	Middle	End			
1	0.97	0.97	0.97	0.32	0.32	0.34	154	8860	9568
2	0.98	0.98	0.98	0.39	0.39	0.39	355	14550	16006
3	1.97	1.98	1.97	0.53	0.58	0.58	546	13111	14815
4	2.18	2.18	2.17	0.7	0.60	0.55	743	16534	19014

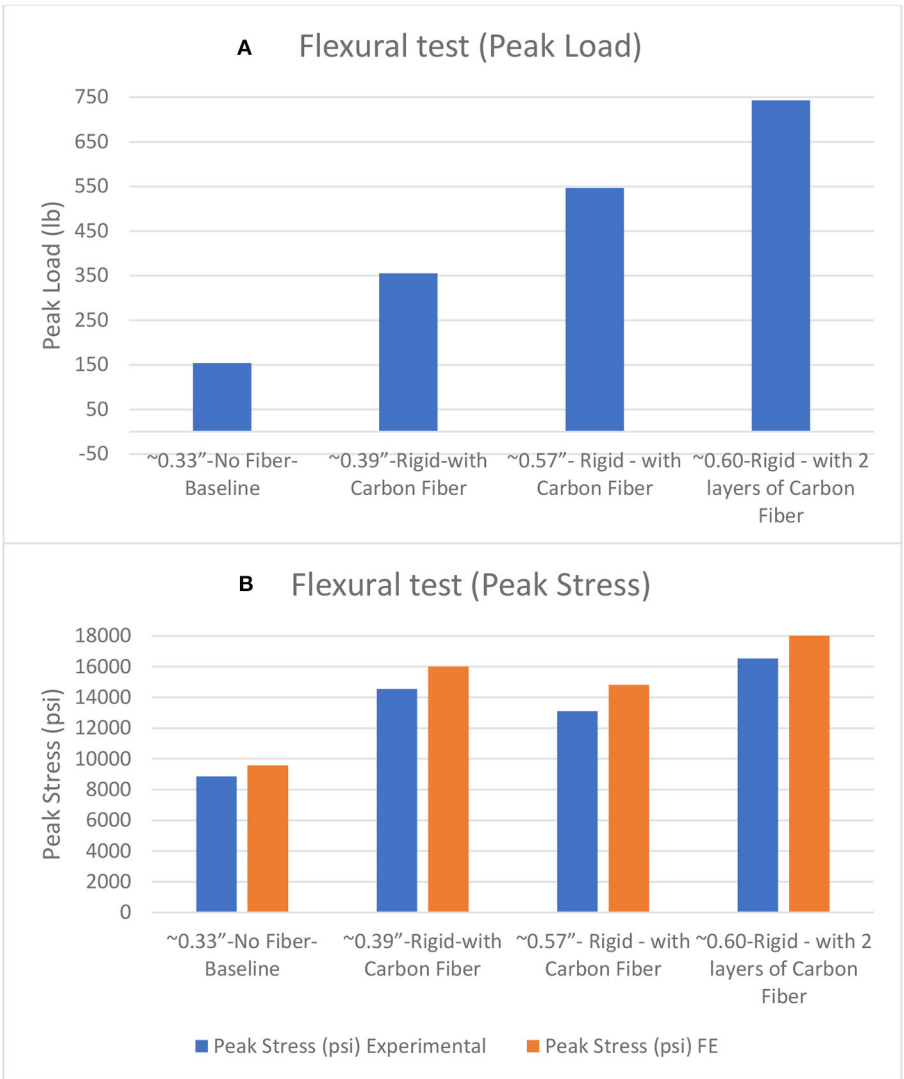

FIGURE 7 | Flexural tests results **(A)** Peak load (lb), **(B)** Peak stress (psi) Experimental vs. FE.

the value of the bending characteristics of the liner. During the flexural test, the various deformation components are dependent on the time and load. This test method describes the method for determining flexural strength of a material using standard rectangle shaped test samples. This test method is helpful to determine the peak stress a sample can withstand while in the shape of a simplified beam (Kharazmi, 2019).

When a pipeline begins to buckle, the pipe is no longer keeps in circle shape, so the bending moment which exists in the pipe increase. Therefore, bending is one of the typical factors which could affect the creep behavior of the pipe. It is necessary to investigate the viscoelastic behavior of the pipe material under flexure (Kanchwala, 2010). The test of liner flexural properties was performed following ASTM D790-2017 (American Society for Testing Materials, 2017). Peak load and maximum flexural stress are key parameters used to determine material structural capabilities (Alzraiee et al., 2015). The flexural test samples were mostly prepared and cut out of provided plate samples. The details of the provided plate samples are listed as follow: (1) ∼0.33" thickness-No Fiber-Baseline, (2) ∼0.39" thickness-Rigid with Carbon Fiber, (3) ∼0.57" thickness-Rigid with Carbon Fiber, and (4) ∼0.60" thickness-Rigid with two layers of Carbon Fiber. The samples were cut from the retrieved liner specimen using the OMAX waterjet at Louisiana Tech University. The flexural test was conducted on different specimens. The flexural test was performed on both the neat rigid samples and rigid samples with the carbon fiber layer. The carbon fiber provides reinforcement to the SIPP lining to allow it to carry higher loads than traditional SIPP materials and systems.

The test was performed at a controlled temperature of 72 ± 2°F and a relative humidity of 50 ± 2%. The testing machine is an ADMET universal testing machine of 10 KN maximum load. During the test, the data were directly collected by a computer connected to the testing instrument using MTestW licensed software, as showing in **Figure 5**. **Figure 6** illustrates the FEA.

The results of both lab study and FEA study for the flexural test found that the sample with two-layer carbon fiber reinforcement has the highest peak stress comparing the sample with no fiber reinforcement and with one layer of carbon reinforcement as shown in **Table 6**. Flexural peak stress has improved 56.1% with adding one layer of carbon fiber (CF) reinforcement and 86.6% by using two layers of CF reinforcements in compare with No-fiber-baseline samples. Furthermore, 19.5% increment of flexural peak stress observed in samples with two layers CF reinforcement in compare with one layer CF samples. Similar with the results of tensile tests, presented results at **Table 6** are the average of five samples for each type of the sample. **Figure 7** shows flexural peak load and flexural peak stress (Experimental and FE) results of performed flexural tests for all specimens, respectively.

Flexural Test Calculations

The maximum stress for each specimen in lb/in² is calculated using the fallow Equation:

$$Stress\ (\sigma)\ psi = \frac{3Pl}{2bd^2}$$

where, P = load (lb),

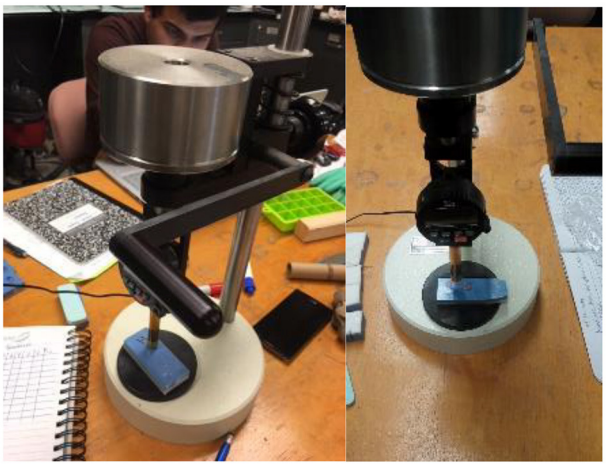

FIGURE 8 | Hardness test setup.

TABLE 7 | Hardness test result.

Sample	Hardness	Remark
1	71.6	∼0.33"-no fiber-baseline
2	74.0	∼0.39"-rigid-with carbon fiber
3	75.9	∼0.57"-rigid—with carbon fiber
4	75.2	∼0.60-rigid—with two layers of carbon fiber

L = Span (in),
b = Width (in),
d = Depth (in).

Hardness Test

The hardness test for all samples was performed by following ASTM D2240-2015 (American Society for Testing Materials, 2015). This standard test method uses a hardness gauge, which measures the impression hardness of plastics and rubbers. We measured the hardness on two different sides, and each side was tested 10 times to get an average hardness of the material (See **Figure 8**).

This test method uses the penetration of an indenter into the material under controlled conditions. Indentation hardness has been found to be inversely related to penetration of the selected indenter. All the samples were prepared and cut at Louisianan Tech University and been tested under standard laboratory conditions.

The results of hardness test in the lab found that the sample with one layer of carbon reinforcement (0.57"-Rigid—with Carbon Fiber) has the highest value compared to other samples as shown in **Table 7**. The study also found that the sample with no fiber reinforcement has the lowest value of hardness.

DISCUSSION AND CONCLUSIONS

The introduced and tested material is the resin for a two-component polyurethane, rapid curing, rigid structural lining system for high build applications. This rigid coating is

specifically designed for potable water applications. The objective of this study is to investigate the mechanical properties of newly introduced reinforced Spray in Place Pipe (SIPP) lining materials with fully structural performance; the study included three types of testing: tensile test, flexural test, and hardness test. There were three different material types investigated: (1) No Fiber-Baseline (2) Rigid-with one layer of Carbon Fiber and (3) Rigid—with two layers of Carbon Fiber. This study focuses on an innovative material and rehabilitation method in SIPP lining area, with the first "Fully-structural independent" performance

1. The tensile and flexural test results demonstrated the potential of fully structural application of this material specially with applying fiber reinforcement method.
2. One layer carbon fiber reinforced samples in compare with baseline samples experienced 26.8% higher tensile strength in average.
3. Double layers carbon fiber reinforced samples showed 17% and higher tensile strength in compare with one layer CF reinforced samples.
4. Max flexural stress improved 56.1% by adding one layer of CF in compare with samples with no reinforcement.
5. Double layers CF reinforced samples experienced 86.6 and 19.5% higher flexural stress in compare with No reinforcement samples and average of one-layer CF reinforced samples respectively.
6. 74.17 is the average hardness of proposed material.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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