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**APPLICATION OF THE POLYUREA COATING
ON HIGH-PERFORMANCE ORGANIC AGGREGATE CEMENTITIOUS
MATERIALS**

by

HYUNGJOO CHOI

A THESIS

**Submitted in partial fulfillment of the requirements
for the Master of Science in Engineering
in
The Department of Civil and Environmental Engineering
to
The School of Graduate Studies
of
The University of Alabama in Huntsville**

HUNTSVILLE, ALABAMA

2011

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Hyungsoo Choi
(student signature)

10/28/11
(date)

THESIS APPROVAL FORM

Submitted by Hyungjoo Choi in partial fulfillment of the requirements for the degree of Master of Science in Engineering in Civil Engineering and accepted on behalf of the Faculty of the School of Graduate Studies by the thesis committee.

We, the undersigned members of the Graduate Faculty of The University of Alabama in Huntsville, certify that we have advised and/or supervised the candidate on the work described in this thesis. We further certify that we have reviewed the thesis manuscript and approve it in partial fulfillment of the requirements for the degree of Master of Science in Engineering in Civil Engineering.

H.A. Ponten Jr 10/21/2011 Committee Chair
(date)

John [Signature] 10/21/11

Ashraf Alhamdani 10/24/11

Teng Keong Ooi 10/24/11

H.A. Ponten Jr Department Chair

Greg [Signature] 10/28/11 College Dean

Rhonda Kay Haede 12/5/11 Graduate Dean

ABSTRACT
The School of Graduate Studies
The University of Alabama in Huntsville

Degree Master of Science in Engineering College/Dept. Engineering/Civil and
Environmental Engineering

Name of Candidate Hyunjoo Choi

Title Application of the Polyurea Coating on High-performance Organic Aggregate
Cementitious Materials

This research focuses on developing a polyurea coating on high-performance cementitious composite material reinforced with poly(vinyl butyral) (PVB) and poly(vinyl alcohol) (PVA) fiber as the sole aggregate. To evaluate the effect of the polyurea coating, experimental tests were conducted such as compressive and flexural strength and drop-weight test. Results show that coated cylindrical specimens with polyurea produce similar results to the uncoated specimens. Results of the polyurea coated specimen showed increases of ultimate strength and strain, modulus of elasticity and toughness of lightweight, PVB and PVA fiber reinforced specimens. In particular, PVA fiber reinforced concrete beams featured significant strain-hardening behavior with great increase of modulus of elasticity and toughness. Drop-weight test results show that applying polyurea coating on the bottom seems to produce better results.

Abstract Approval: Committee Chair H.A. Pontefi
 Department Chair H.A. Pontefi
 Graduate Dean Rhonda Kay Shaede

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CHAPTER I

INTRODUCTION

1.1 Problem Statement

In civil infrastructure and building construction, cement-based materials have been extensively used as the most common and important material but many studies have shown disadvantages. The ordinary cement-based concrete consists of two phase: cement paste matrix and aggregate. The properties of the constituents and the interaction between them determine the behavior of the material [1]. Methods have been introduced to improve the interaction between the cement paste matrix and the aggregate within the Interfacial Transition Zone (ITZ) which, as the weakest region, governs many important properties such as strength, permeability and durability [2,3].

Since the need for new organic, non-siliceous, materials has been increasingly growing, previous research [4,5] introduced a non-siliceous organic and environmentally friendly aggregate by employing Poly(vinyl butyral) (PVB) powder as a total replacement of aggregate in concrete mix and with Poly(vinyl alcohol) PVA fiber as a reinforcement. Both PVB and PVA are lightweight and physically tough and have strong interaction on a molecular level in ITZ.

When it comes to long term performance of concrete structure, which is exposed to severe environmental conditions such as a pier, dock and suspension and stayed bridge, critical safety issues have been discovered due to corrosive attack and chemical wear. Studies introduced polyurea coatings for enhancing moisture proofing and preventing corrosive attacks on concrete structures. Polyurea coatings shows special characteristics such as reducing water absorption, improving chemical wear and frost resistance [6-8]. In addition, polyurea is a good construction material because of its great flexibility, excellent elongation characteristics, rapid-cure rate, and wide service temperature range (-50 °C to -150 °C) [9].

In this research, the effect of a polyurea coating on lightweight, PVB and PVA concrete was evaluated; experimental tests were conducted such as compressive, flexural strength and drop-weight test. For compressive and flexural test, a lightweight concrete which has density approximately 1500kg/m³ (93.6 pcf) was also tested as a comparison. Coated and uncoated cylindrical specimens were placed at a specially constructed environmental chamber for wet and dry exposure. The specimens were exposed to 100 cycles with 4 hours of wetting and 8 hours of drying to determine the durability of lightweight and PVB concrete. Load-deflection and stress-strain curves were obtained in order to evaluate ultimate strength and strain, modulus of elasticity and toughness. Drop-weight test were conducted to observe dynamic response and failure pattern. Four point bending tests and drop-weight tests were conducted and the tests were recorded with a high speed camera (15 frames per second).

1.2 Research Objectives

The objectives of this research are

1. Investigate the mechanical properties of PVB and PVA concrete;
2. Investigate the effect of the polyurea coating on lightweight, PVB and PVA fiber reinforced concrete;
3. Evaluate the compressive strength of lightweight and PVB concrete under room temperature and wet/dry conditions with different coating condition;
4. Study the flexural behavior by obtaining load-deflection and stress-strain curve to evaluate ultimate strength and strain, modulus of elasticity and toughness;
5. Study the energy absorbing capacity of polyurea on PVB and PVA concrete with various coating conditions (plain, top, bottom, both).

1.3 Research Significance

This research mainly focuses on determining the mechanical properties of Poly(vinyl butyral) (PVB) and Poly(vinyl alcohol) PVA fiber concrete as the sole aggregate and studying the effect of polyurea coatings on high-performance cementitious composite material. PVB concrete mixes were tested and developed to improve workability, strength and durability. Experimental tests were undertaken by applying polyurea on PVB concrete with wet/dry exposure, studying the flexural behavior and conducting drop-weight test with various coating conditions.

1.4 Outline of the Thesis

This thesis presents the application of polyurea coatings on PVB and PVA concrete which is reinforced with Poly(vinyl alcohol) (PVA) fiber and Poly(vinyl butyral). Experimental tests such as compressive strength, four point bending and drop weight test, were conducted.

- Chapter II: Theoretical Background
- Chapter III: Sample Preparation
- Chapter IV: Experimental Procedure
- Chapter V: Test Results
- Chapter VI: Conclusion and Discussion for Future Research

CHAPTER II

THEORETICAL BACKGROUND

2.1 Introduction

In this chapter, a literature review of Poly(vinyl butyral) (PVB) and Poly(vinyl alcohol) (PVA) concrete and polyurea is presented. The following contents are presented: (1) Review of ITZ (Interfacial Transition Zone), (2) Introduction of Poly(vinyl butyral) (PVB) and Poly(vinyl alcohol) (PVA) with general background, eco-friendly properties and advantages, (3) Introduction of polyurea with historical and general background, chemical analysis, properties, applications and future trend.

2.2 Review of ITZ (Interfacial Transition Zone)

The wall effect in the Interfacial Transition Zone (ITZ) characterizing its microstructure and hydration progress has been studied by many researchers. In cement-based materials, the interaction between aggregate and matrix within the ITZ is an important factor that governs the strength of concrete. During casting mobile phases and iron have a tendency to flow slightly faster near the wall of the aggregate due to decreased permeability and thus the spatial arrangement of anhydrous grains becomes looser in the vicinity of aggregate particles. As a result, the space around aggregate is less

effectively filled by hydration products with greater tendency for CH ($\text{Ca}(\text{OH})_2$) and, the porosity and the W/C ratio increase from the bulk material to the surface of the aggregate particles [10,11]. This is referred to as the 'wall effect'. Therefore, the ITZ is defined as the weakest region of the mix which governs many important properties of concrete such as strength, permeability and durability [2,3].

Studies have been introduced to improve the interaction between aggregate and matrix in the ITZ, by reducing the size of the aggregates [12,13], using basalt and quartzite as aggregates [14], or replacing the cement by certain amount of ultrafine additions such as silica fume and metakaolin [16-19]. However, those methods could not be a decisive solution to replace aggregates since those are siliceous and do not show improvement of the interaction between atoms and molecules. Previous research [4,5] introduced a non-siliceous organic aggregate by employing Poly(vinyl butyral) (PVB) powder as a total replacement for aggregate and Poly(vinyl alcohol) PVA fiber as a reinforcement.

2.3 Introduction of Poly(vinyl butyral) (PVB) and Poly(vinyl alcohol) (PVA)

2.3.1 General Background of PVB

Poly(vinyl butyral), PVB, is a member of the class poly(vinyl acetal) resin material which is usually used in applications that require strong binding, optical clarity, adhesion to many surfaces, toughness and flexibility. PVB retains the clarity of the coating and offers reactive hydroxyl groups for cross linking with thermoplastic characteristics and a special combination of properties for coating or adhesive application. PVB as an aggregate is completely insoluble in cement water mixes and is highly alkali

resistant. PVB is produced by the well-known reaction between aldehydes and alcohols [20,21]. The structure of poly(vinyl butyral) is shown in Figure 2.1.

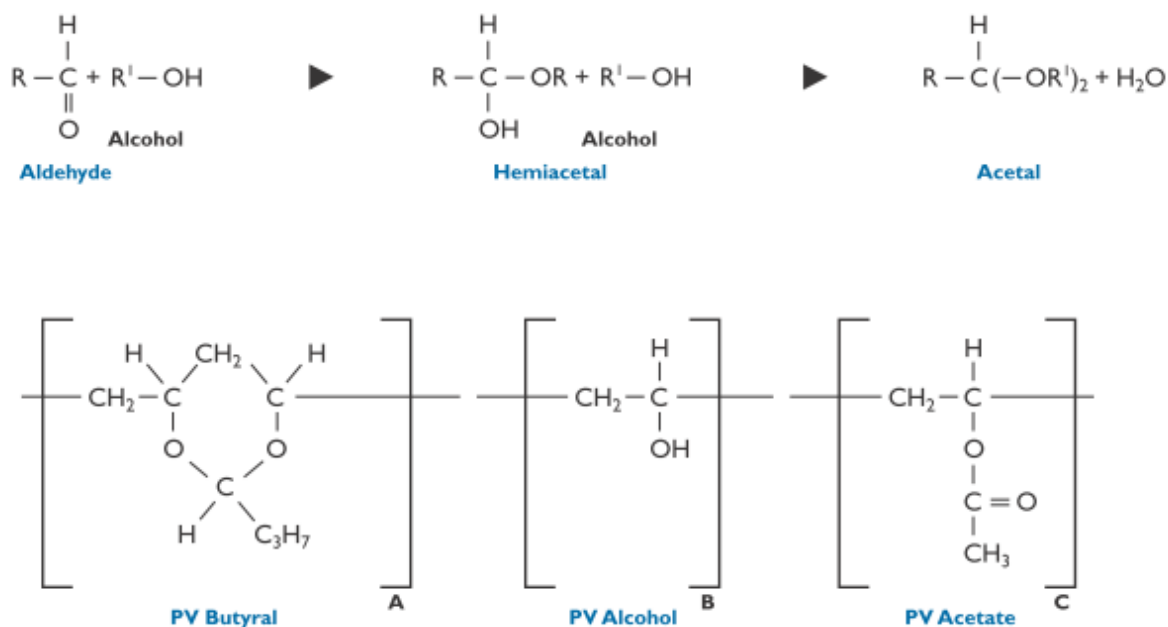


Figure 2.1 Structure of Poly(vinyl butyral) (PVB) [20]

PVB resins generally are soluble in alcohols, glycol ethers and certain mixtures of polar and non-polar solvents and shows very marked viscosity increases as resin solids increases. Butvar B-79, which has lower hydroxyl contents, permits solubility in a wider variety of organic solvents. The presence of both butyral and hydroxyl groups permits solution in mixtures of alcohol and aromatics. Butvar resin was pioneered by Monsanto as the key ingredient for automotive safety glass interlayers in the 1930s. It has widespread uses in automotive and architectural applications for laminated safety glass. Nowadays, the applications using PVB as key ingredient include, but not limited to, ceramic binders, inks/dry toners, wood coatings, wash primers, composite fiber binders, and structural adhesives [20]. In this research, Butvar B-79 and Mowital B-75H were used to replace the total aggregate.

2.3.2 General Background of PVA

Poly(vinyl alcohol) (PVA) is a synthetic material which is produced from poly(vinyl acetate) [22]. PVA reacts with the aldehyde to form six-membered rings primarily between adjacent intramolecular hydroxyl groups. The structural feature of PVA is shown in Figure 2.2. PVA is a white powder with a specific gravity in the range of 1.2-1.3 and a glass transition temperature of around 80°C [23]. This powder can be formed and extruded into PVA fibers.

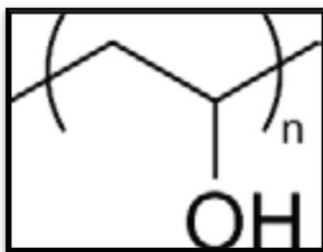


Figure 2.2 Chemical Structural Feature of Poly(vinyl alcohol) (PVA) [10]

Treating PVA fiber with a concentrated aqueous solution of sodium sulfate which contains certain amount of formaldehyde and sulfuric acid is the most important operational process in manufacture of textile fibers for transforming them into insoluble products in water [5]. As a result of the treatment, it will produce formal groups as shown in Figure 2.3.

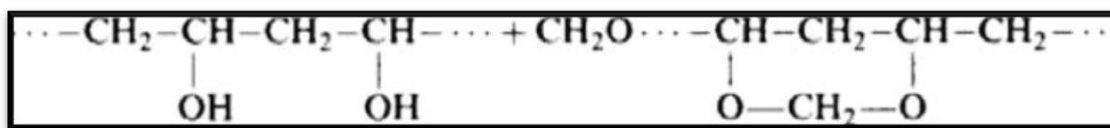


Figure 2.3 Formal Groups of PVA Fiber [23]

Hydroxyl groups (OH) of neighboring PVA macromolecules may also participate in the formation of formal groups. After such treatment, PVB fiber becomes insoluble. In comparison with other synthetic fibers, PVA fibers show a higher rate of water absorption [23]. Since PVA fiber is hydrophilic material, there is a great challenge in composite design. The fibers tend to rupture instead of being pulled out due to strong bonding strength to the cementitious matrix [24].

PVA fibers typically have a high tensile strength between 1,600 and 2,500 MPa and show high alkaline resistance and high modulus [25]. Poly(vinyl alcohol) (or PVA) fiber is considered one of the most suitable polymeric fibers used as the reinforcement of concrete because of the high strength, alkaline resistance and good bonding strength with cementitious matrix [26]. Table 2.1 lists the properties of PVA fiber.

Table 2.1 Properties of Kuraray PVA fiber [27]

Properties /Fiber type	Tensile Strength	Young's Modulus	Specific Gravity
Units	N/mm ²	kN/ mm ²	-
RECS 7	1600 (1.6 GPa)	39	1.3

2.3.3 Eco-Friendly Properties and Advantage of PVB and PVA

Poly(vinyl butyral) (PVB) resins have been employed in a wide array of industrial and commercial applications. These special resins offer unique and impressive performance, as well as outstanding versatility. Butvar resins have a combination of properties that make them a key material in a variety of successful formulations. Some of these properties are: outstanding binding efficiency, optical clarity, adhesion to a large number of surfaces, and toughness combined with flexibility [20].

Since PVB resins contain carbon, hydrogen and oxygen, under free-air combustion conditions (I-value = 1), it can be disposed of in as environmentally friendly way and also combusts into carbon dioxide and water without leaving any residue. For this reason, PVB poses no waste disposal problems [28].

According to the FDA (U.S. Food and Drug Administration), PVA resin, which is the raw material of PVA-fiber, is designated as a safe material. As can be seen in Figure 2.4, PVA's chemical structure is based on only carbon, hydrogen and oxygen. Harmful substance such as dioxin and ammonia are not created when it is burned. However, carbon dioxide is generated during burning since PVA fiber consisted of carbon, hydrogen and oxygen and water [27].

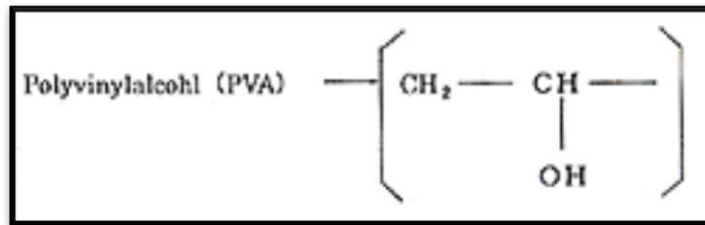


Figure 2.4 Chemical Structure of PVA [27]

2.4 Introduction of Polyurea

2.4.1 Background of Polyurea and Polyurethane

Polyurea and Polyurethane are polymeric materials that became widespread in the coating industry. Polyurethane was first developed by Otto Bayer and coworkers in the late 1930s and early 1940s [29]. In 1948, Hill and Walker evaluated thermal properties / melting points of various polymer systems [30]. They compared the properties of polyesters, linear polyethylene, polyurethanes, polyamides and polyureas.

They found that the polyureas had far superior thermal properties and an extremely high melting point [31].

Work in the 1970's utilized modified polyamines and high levels of plasticizers and solvents to achieve a sprayable system for coating work [32]. In the early 1980's, polyurea Reaction Injection Molding (RIM) was used to produce a variety of automotive exterior body panel and fascia (bumper covers) parts by applying the two-component polyurea elastomeric coating / lining technology [31,33], as schematically shown in Figure 2.5.

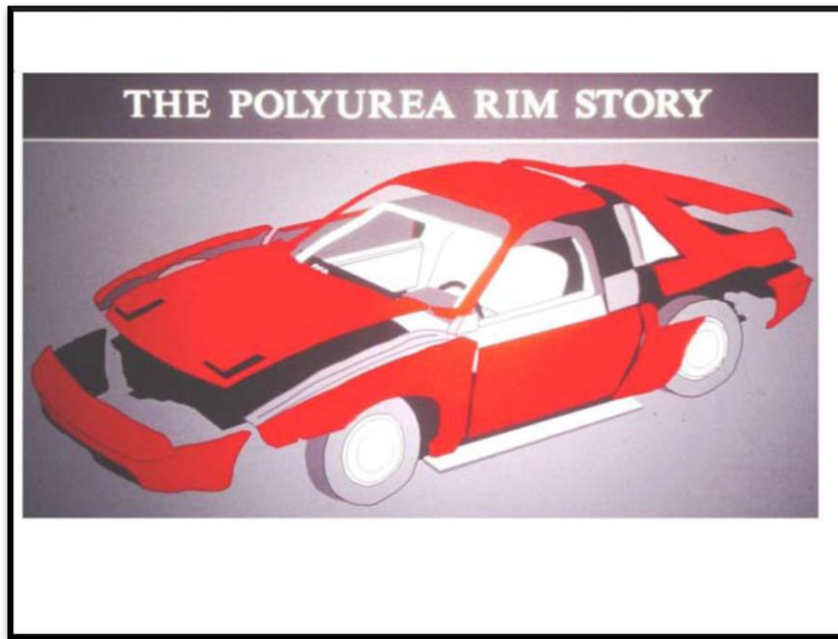


Figure 2.5 Polyurea Reaction Injection Molding (RIM) [31]

The two-component fast set polyurea coating/lining technology was first introduced by Dudley Primeaux of the Texaco Chemical Company to the industry and its first commercial application was as a roofing system in 1989 [31,34,35,36]. The National Association of Corrosion Engineers (NACE) published a technical report on polyurea system to compare polyurea to polyurethane [37]. In 2000, the Polyurea Development

Association (PDA) defined polyurea system [31]. Nowadays, polyurea has a wide range of uses in the coating industry.

2.4.2 Chemical Analysis of Polyurea

Polyurea and polyurethane are general names for the materials widely used in coating industry. The main distinguishing characteristic between polyurea and polyurethane is terminated resins. The main components of polyurethane are di- or polyisocyanate molecules (cyanate functional group -NCO) and polyols (hydroxyl functional group -OH). Polyurethane yields hydroxyl terminated (-OH) resins. An exothermic reaction process, the two components form extended chains and networks bonded by urethane groups -O(CO)(NH)- [31].

The polyurea is that amine terminated (-NH_2) resins are used. Polyols are substituted by amine molecules (functional group -NH_2) so that the urea bonding -(NH)(CO)(NH)- replaces the urethane bonding -O(CO)(NH)- (shown in Figure 2.6).

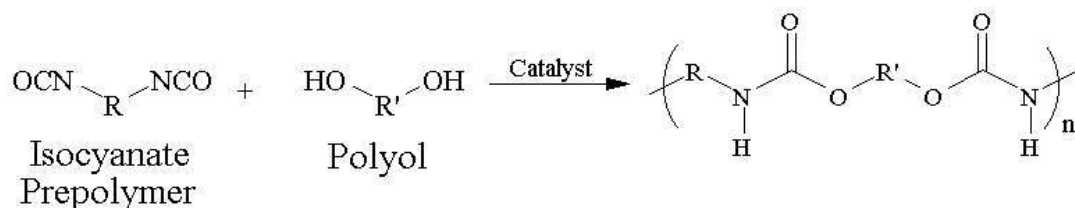


Figure 2.6 Polyurethane Formation Reactions [32]

The reaction of amine terminated resins with the isocyanate component which is highly reactive, results in the formation of a urea linkage. Also, the reactions that generate the polyurea usually are faster than those for polyurethane [38,39]. Figure 2.7 shows polyurea formation reactions.

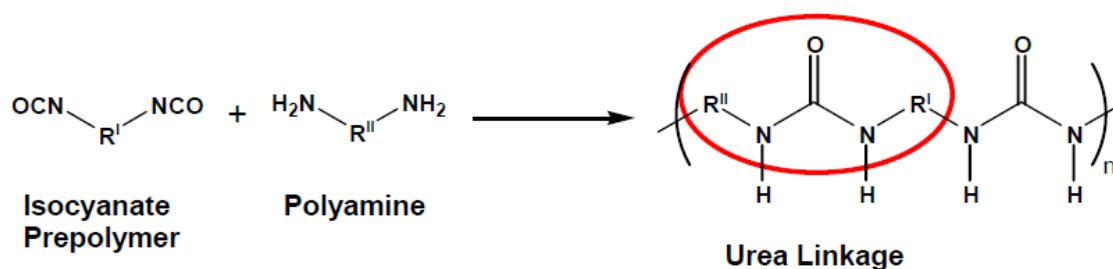


Figure 2.7 Polyurea Formation Reactions [40]

Because of chemical reaction between isocyanate (NCO) and amine ($-\text{NH}_2$) during polyurea coating process, the health hazard caused by polyurea producing process should not be ignored. Both, Polyurea and Polyurethane, employ isocyanate-functional oligomers as crosslinkers. The primary component of polyurethane is a hydroxyl-functional polyol (acrylic, polyester or other) and the component of polyurea is an amine-functional oligomer. This chemistry shares the health risks with the use of reactive isocyanates which can produce eye, skin and respiratory sensitization. This requires high level of worker protection during the polyurea producing process [41,42].

2.4.3 Properties of Polyurea on PVB Concrete

The physical property of polyurea varies with its composition. Generally, the service temperature ranges between -50 to -150°C . The elongation at tearing can be as high as 800% [38]. There are chemical reactions between Butvar resins and urea groups. Crosslinking of the PVB is carried out by reaction for ureas bonding, $-(\text{NH})(\text{CO})(\text{NH})-$, which has thermosetting resins (Figure 2.8). The availability of the functional hydroxyl groups in Butvar resins for condensations is an important consideration. A small amount of Butvar resin into thermosetting compositions will markedly improve toughness, flexibility and adhesion of the cured coating [25].

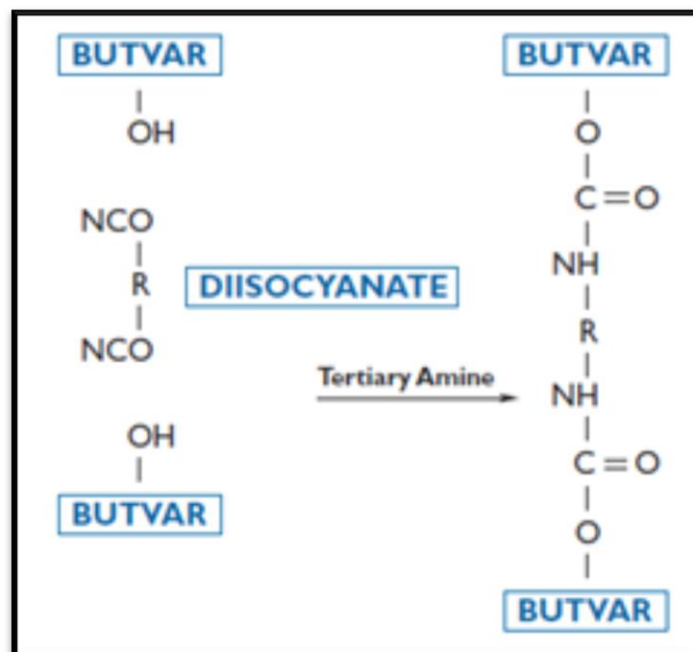


Figure 2.8 Reactions of Between Butvar with Isocyanates [20]

As for mechanical property, polyurea displays a very stiff nearly-elastic response to volumetric deformations, whereas (above T_g : Glass Transition Temperature) its shearing response at moderate pressures and strain rates is soft and viscoelastic, so that its laterally unconfined axial deformation is nearly incompressible [38,39].

Furthermore, because of many physical and chemical properties, advantages of polyurea as a coating material include tolerance to extreme weather, moisture resistance, fast curing, solventless formulation, high tensile strength, great flexibility, impact resistance, abrasion resistance and chemical resistance [41,43].

2.4.4 Application and Future Trend of Polyurea

Polyurea has a wide range of uses as a coating. It is largely used as moisture, corrosion as well as chemical proof protection for pipeline coating, bridge coating, tank coating, roof coating, joint fill and so on [44]. Rapid curing time, toleration of higher service temperatures and humidity tolerance of polyurea may be commercially advantageous [38].

However, many benefits and advantages of polyurea were not fully appreciated. Recent studies, however, have shown promising mechanical responses for polyurea that are not limited to only the coating applications but venture into critical applications such as reinforcement of metal structures against blast and impact loads [38].

Hare [45] describes the three steps for successful coating, namely surface preparation, wetting, and adhesion. The proper formulations of a polyurea system help to ensure a strong bond of the elastomer to a substrate surface. Unfortunately, this does not always guarantee an adequate bond or defect-free coating. The potential for an improperly prepared surface, an undesirable substrate surface tension, or a substrate that can excessively out-gas is present at many job-sites. Any of these possibilities can lead to blisters or pinholes in the applied polyurea coating, leading to catastrophic delaminations of the entire coating in worst-case scenarios [46]. The high elasticity of polyureas leads to their use in sealing and caulking systems as well as coating. They are widely used over concrete (where their crack bridging properties are advantageous) and flooring coatings in areas subject to heavy wear. Their fast curing speed makes the curing reaction insensitive to high humidity or substrate moisture, which would interact with polyurethane chemistry [41]. The future of the polyurea technology is very promising. Current market

sales are approximately 18 – 20 million gallons of system worldwide [31]. Epoxy modification can be used to further enhance their toughness and adhesion [42]. Table 2.2 shows some applications of polyurea in construction and other industries.

Table 2.2 Applications of Polyurea in construction and industries [47]

Polyurea applications in construction	Other polyurea applications
Roof coatings Flat roof repair Waterproofing membranes Secondary containment Car park decks Bridges Offshore	Pipe protection Inner pipe repair Tank coatings Truck bed liners Freight shop liners Bulk transport wagon liners Conveyer belts

CHAPTER III

SAMPLE PREPARATION

3.1 Properties of Constituent Material

3.1.1 Cement

Type I normal Portland cement for general-purpose was used. The specific gravity of the cement, which determined by ASTM C 188, is 3.15g/cm³. Composition of Type I normal Portland cement is described in Table 3.1.

Table 3.1 Composition of Cement and Metakaolin [48]

Parameters	Cement	Metakaolin
SiO ₂ (%)*	20.6	52 – 54
Al ₂ O ₃ (%)	5.07	42 – 44
FeO ₃ (%)	2.09	1 – 1.4
CaO (%)	63.9	0.1
MgO (%)	1.53	< 0.1
Na ₂ O (%)	0.15	< 0.05
K ₂ O (%)	0.73	< 0.4
TiO ₂ (%)	-	< 3
SO ₃ (%)	2.53	< 0.1
Loss on Ignition	1.58	< 1
Specific Gravity (g/cm ³)	3.15	2.60
Fineness (>44μm, %)	-	5

3.1.2 Metakaolin

The metakaolin (MK) has trade name ‘PowerPozz’ and manufactured from W.R. Grace & Co. In this research, the metakaolin which determined by ASTM C-618, Class N specifications for Natural and Calcined Pozzolans were used [48]. It has white color and is obtained from purified kaolin clay which acts as a catalyst to accelerate the hydration procedure and the pozzolanic reaction by removing calcium hydroxide (CH) [49].

Metakaolin behaves as ‘filler’ by narrowing the interfacial transaction zone (ITZ) and also helps to reduce the amount of bleeding and to yield more homogenous material. This is called the ‘Filler effect’ [50]. In this research, around 10 percent of cement by weight was replaced with metakaolin to increase strength. The composition of metakaolin is shown in Table 3.1.

3.1.3 Poly(vinyl butyral) (PVB)

3.1.3.1 Butvar B-79

Butvar B-79 is one type of Poly(vinyl butyral) (PVB) resins and it has the lower hydroxyl contents than other types of butyral resin. It is a thermoplastic and soluble resin and has a unique combination of properties for coating or adhesive application. The addition of PVB to a system can improve adhesion, toughness and flexibility properties [4,20] Figure 3.1 shows B-79 powder.

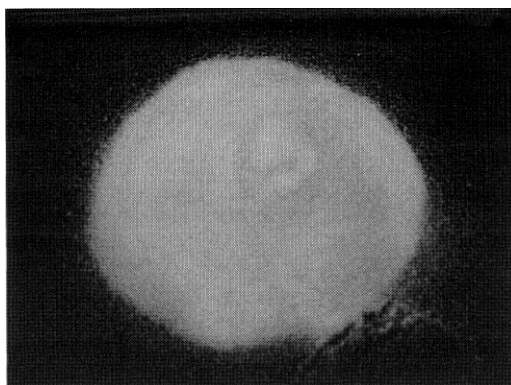


Figure 3.1 B-79 Powders [4]

In addition, cross-linking of the polyvinyl butyrals is carried out by reaction with various thermosetting resins, such as phenolics, epoxies, ureas, diisocyanates and melamines. The availability of the functional hydroxyl groups in Butvar resins for condensations of this kind is an important consideration in many applications [20].

Poly(vinyl butyral) withstands strong alkalis but is subject to some attack by strong acids. However, when employed as components of cured coatings, their stability to acids, as well as solvents and other chemicals, is improved greatly [20, 51]. Properties of B-79 are shown in Tables 3.2, 3.3 and 3.4.

Table 3.2 Physical Properties of Butvar Resin B-79 (white, free-flowing powder) [51]

Property	Units	ASTM Methods	B-79
Molecular wt. (Weight Average in Thousands)	-	1	50-80
Specific Gravity 23°/23° (± 0.002)	cp.	D792-50	1.083
Water absorption (24 hours)	%	D570-59aT	0.3
Hydroxyl contents expressed as % polyvinyl alcohol	-	-	11.0 – 13.5
Acetate contents expressed as % polyvinyl acetate	-	-	0-2.5
Butyral contents expressed as % polyvinyl butyral, approx.	-	-	88

Table 3.3 Resistance and Organic Solvents of Butvar Resin B-79 [51]

Property	B-79	ASTM Method
Resistance to:		
Weak acids	Excellent	D543-56T
Strong acids	Excellent	D543-56T
Weak bases	Excellent	D543-56T
Strong bases	Excellent	D543-56T
Organic solvents:		
Alcohols	Poor	D543-56T
Chlorinated	Fair	D543-56T
Aliphatic	Fair	D543-56T
Aromatic Esters	Poor	D543-56T
Esters	Poor	D543-56T
Ketones	Poor	D543-56T

Table 3.4 Mechanical Properties of Butvar Resin B-79 [51]

Property	Units	ASTM Methods	B-79
Tensile strength:			
Yield	10 ³ psi	D638-68T	5.8-6.8
Break	10 ³ psi	D638-68T	4.6-5.6
Elongation:			
Yield	%	D638-68T	8
Break	%	D638-68T	110
Modulus of elasticity (Apparent)	10 ⁵ psi	D638-68T	2.8-2.9
Flexural strength yield	10 ³ psi	D790-59T	10.5-11.5
Hardness, Rockwell:			
M	-	D758-51	100
E	-	D758-51	5
Impact strength Izod, notched 1/2" x1/2"	ft.lb./in.	D256-56	0.8

3.1.3.2 Mowital M-B75H

Mowital M-B75H manufactured by Kuraray Specialties Europe (KSE) is another type of Poly(vinyl butyral) (PVB). It is also a thermoplastic material that is soluble in a large number of organic solvents and can be cross-linked. The cross-linking capacity depends on the number of OH groups available for the reaction. Generally, the Mowital

B75H indicates the increasing degree of polymerization or molar mass and thus it is of great importance for the thermal and mechanical properties and the viscosity in solution. It has range 20 to 75 and invariably contains a certain percentage of hydroxyl groups. A small percentage of acetyl groups always remain in the Mowital polymer chain from the upstream transesterification while polyvinyl acetate is converted to polyvinyl alcohol [28]. The properties of Mowital M-B75H are shown in Table 3.5.

Table 3.5 Properties of Mowital M-B75H [28]

Property	Unit	B-75H
Non-volatile content	wt - %	>97.5
Polyvinyl alcohol contents*	wt - %	18-21
Polyvinyl acetate content*	wt - %	0-4
Viscosity*	mPa·s	60-100
Glass transition temperature	°C	73
Water absorption	wt - %	4-6
Bulk density	g/l	200

*Hydroxyl groups, in terms of polyvinyl alcohol

*Acetyl groups, in terms of polyvinyl acetate

*10% solution in ethanol

The properties of the various grades are mainly determined by their molecular weights and their degree of acetalisation. Mowital grades are soluble in a broad variety of organic solvents. They show good compatibility with plasticizers and other resins. Since Poly (vinyl butyral) contains only carbon, hydrogen, and oxygen, it can be disposed of in an environmentally friendly way under controlled conditions. It can be combusted into carbon dioxide and water without leaving any residue [28].

3.1.4 Poly(vinyl alcohol) (PVA) Fiber

High-performance fiber, namely Poly(vinyl alcohol) (PVA) fiber manufactured by Kuraray Co. Ltd of Japan, was used in this research. (See Figure 3.2) Some of the physical and mechanical properties of the fiber are shown in Table 3.6. RECS 7 which is one of the types of PVA fibers was used and the fiber volume fraction V_f stayed constant at 0.6%, since prior study [4] showed good correlation at the lower fiber volume fraction ($<0.6\%$) in terms of the impact energy between analytic and test data. The deviation at higher fiber volume fraction ($>0.9\%$) is caused by the formation of multi-crack planes where more energy is dissipated. The fiber volume fraction was calculated by Equation (3.1)

$$V_f = \frac{\rho_m W_f}{\rho_f W_m + \rho_m W_f} , \quad (3.1)$$

where ρ_m is the density of matrix, ρ_f is the density of fiber, W_m is the weight of matrix and W_f is the weight of fiber. PVA fibers have high tensile strength and a high modulus of elasticity and it develops a molecular and chemical bond with the cement during its hydration and curing process [25].

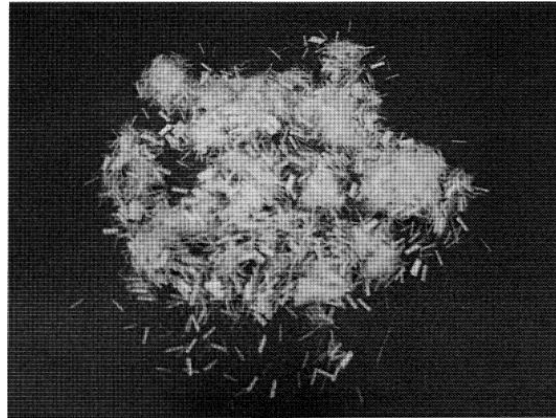


Figure 3.2 PVA Fibers [4]

Table 3.6 Physical and Mechanical Property of Kuraray PVA Fiber (RECS 7) [23]

Properties/ Fiber type	Diameter	Thick -ness	Cut length	Young's Modulus	Density	Specific Gravity
Units	mm	dtex	mm	kN/mm ²	g/cm ³	-
RECS 7	0.027	7	6	39	1.19 – 1.31	1.3

3.1.5 Super Plasticizer

The Sika® ViscoCrete® 2100 high range water reducing admixture was added to the concrete in order to reduce the amount of water in PVB concrete mixture. It satisfies the requirements for ASTM C-494 type A and F [52]. In liquid form, it has a specific gravity of 1050 kg/m³ and a dry content of 20%.

The combined high range water reduction and superplasticizing action of Sika ViscoCrete 2100 provide the following benefits in hardened concrete:

- 1) Higher ultimate strengths allow for engineering design flexibility and structural economies.
- 2) Reduced water cement ratios produce more durable, dense concrete with reduced permeability.
- 3) Highly effective plasticizer reduces surface defects in concrete elements and improves aesthetic appearance [53].

3.2 Development of the Mixture Proportion

3.2.1 Proportion of the Mixture

3.2.1.1 PVB and PVA Fiber Concrete

This research focuses on one type of PVB and PVA fiber concrete mix enhanced with Butvar B-79 and Mowital M-B75H as a sole aggregate. Considering particle size and density of the two type of PVB aggregate, B-79 and M-B75H were used together [4] and both B-79 and M-B75H replaced coarse and fine aggregate in the developed mix. When PVB concrete mix was developed, there were two important factors which should be satisfied workability and strength.

To improve strength, around ten percent by weight of metakaolin was added to replace cement for the ‘filler effect’. Metakaolin behave as ‘fillers’ by narrowing interfacial transaction zone (ITZ) and also helps to reduce the amount of bleeding and to yield more homogenous material. To improve workability, Sika® ViscoCrete® 2100 high range water reducing admixture was used. For PVA fiber mix, V_f stayed constant at 0.6%. Table 3.9 shows mixture proportion for both the PVB and PVA fiber Concrete.

Table 3.9 Mixture Proportion of PVB and PVA fiber Concrete (kg/m³)

	PVB	PVA Fiber
Cement	833	833
MK	79.3	79.3
B-79	182.4	182.4
B -75	119	119
Water	364.5	365
SIKA	26.7	26.7
PVB Fiber		7.9
$V_f(\%)$	0	0.6
W/C	0.43	0.43
Density	1490	1499

* V_f =Fiber Volume Fraction

3.2.1.2 Lightweight Concrete

Lightweight concrete was prepared to have the same density of the PVB concrete for the purpose of comparing the performance of both under the same condition. Beach sand and lightweight sand was used for total aggregates whereas B-79 and M-B75H were used for PVB concrete. Sika® ViscoCrete® 2100 high range water reducing admixture was used to improve workability. The lightweight concrete mixture proportioning table is shown in Table 3.10.

Table 3.10 Mixture Proportion of Lightweight Concrete (kg/m³)

Cement	508.93
Beach Sand	147
Lightweight Sand	728
Water	246.8
Sika	23
W/C	0.53
Density	1539

3.3.2 Mixing Procedure of PVB and Lightweight Concrete

3.3.2.1 Mixing Procedure of PVB and PVA Concrete

First of all, two separate bowls were required for all aggregates and cementitious materials. For the first bowl, B-79 and M-B75H were placed together then mix by hand till they looked homogenous. All cementitious materials (cement and metakaolin for this research) were placed together into another bowl then mix by hand until they looked homogenous as well. Next, the mixed B-79 and M-B75H were moved into mixer (Hobart) and mix for 1 minute on speed 1. Then, around 80% of water was added and mixed for 4 minutes on speed 1. The mixture seemed too wet due to the water absorption characteristic of PVB aggregates. Mixed B-79 and M-B75H and water absorbed B-79 and M-B75H are shown in Figures 3.3 and 3.4, respectively.

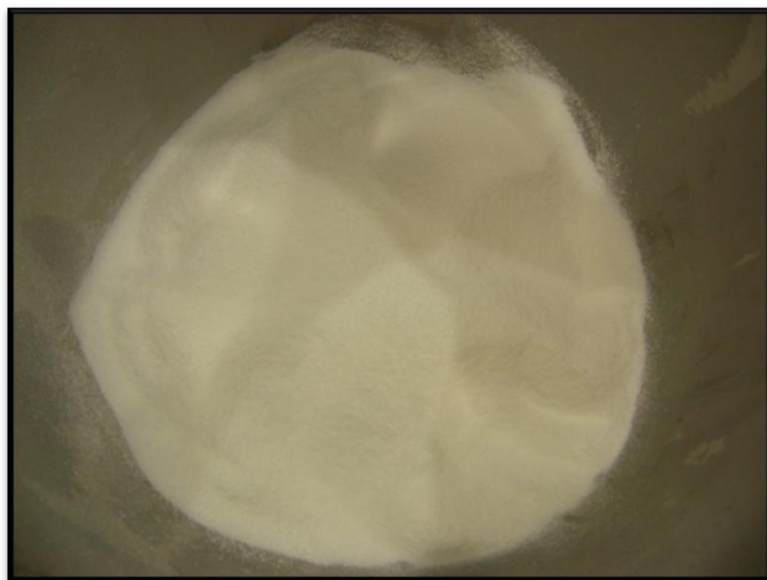


Figure 3.3 Mixed B-79 and M-B75H



Figure 3.4 Water Absorbed B-79 and M-B75H

For the next step, all cementitious materials were placed into the wet PVB mix and mixed for 5 minutes on speed 2. In this step, it was recommended to cover the mixer or put masks on due to dusts from cementitious materials. After the cement powder was added, the mix looked like dry clay dough and it is shown in Figure 3.5. After the rest (around 20%) of the water and Sika superplasticizer was added, it was mixed together for 3 minute on speed 1, and it became soupy and workable and it is shown in Figure 3.6. Around ten minutes of vibration time was required when placing PVB mix into (cylindrical, beam, plate) molds.



Figure 3.5 Add Cementitious Materials

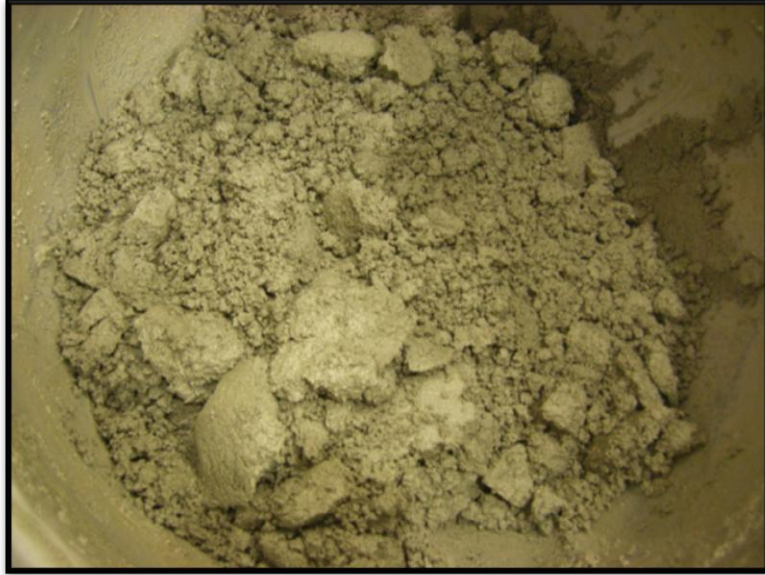


Figure 3.6 Add Sika Superplasticizer (Sika) Solution and 20% of Water

The mixing procedure of PVB concrete can be described in the following steps:

1. Prepare two separate bowls.
2. Place B-79 and M-B75H into a bowl then mix them together by hand.
3. Mix Metakaolin and cement together by hand in another bowl.
4. Place mixed B-79 and M-B75H mixture in the (Hobart) mixer then mix for 1 min on speed 1.
5. Add approximately 80% of water and mix for 4 min on speed 2.
6. Add cement and metakaolin mixture and mix together for 5 min on speed 2.
7. Add Sika superplasticizer (Sika) solution and rest of water then mix for 3 min on speed 1.

For PVA fiber reinforced concrete mix, fibers were added at the last step of PVB concrete mixing procedure. It is shown in Figure 3.7.



Figure 3.7 Add PVA Fibers (RECS 7)



Figure 3.8 Finishing of the PVB Fiber Mixture

After PVA fibers were added, the mixture became stiff and clumped. Vibration was required to make it spread to fit the molds. The mixing procedure of PVA concrete can be described in the following steps:

1. Prepare two separate bowls.
2. Place B-79 and M-B75H into a bowl then mix them together by hand.
3. Mix Metakaolin and cement together by hand in another bowl.
4. Place mixed B-79 and M-B75H mixture in the (Hobart) mixer then mix for 1 min on speed 1.
5. Add approximately 80% of water and mix for 4 min on speed 2.
6. Add cement and metakaolin mixture and mix together for 5 min on speed 2.
7. Add Sika superplasticizer (Sika) solution and rest of water then mix for 3 min on speed 1.
8. Add PVB fiber and mix for 5 minutes on speed 1.

3.2.2.2 Mixture Procedure of Lightweight Concrete

Beach sand and lightweight sand was placed together in the (Hobart) mixer then mixed for 2 minute on speed 1. Cement and 80 percent of water were added together into mixer then mixed for 3 minute on speed 2. The mixture seemed too dry. Sika, high range water reducing admixture, and the rest of the water was mixed well then it was added to the mix slowly and gently. After adding the Sika and the rest of the water, the mix became workable. The mixing procedure of lightweight concrete can be described in the following steps:

1. Place beach sand and lightweight sand in the (Hobart) mixer then mix them for 2 min on speed 1.
2. Add cement and pour 80 % of water and then mix 3 min on speed 2.
3. Add Sika superplasticizer solution and the rest of the water and mix on speed 2 for 2 min

3.4 Mold Construction

For the four point bending test specimens, three 12 x 12 x 0.5 in wooden molds were manufactured and each mold yielded 6 beams (12x4x0.5). (Actually, dimension of mold was a bit bigger than 12x12x0.5 because of lost of dimension by cutting.) Molds were covered with plastic film to avoid rough surfaces of ply wood and to have smooth concrete surfaces. Figure 3.9 shows an example of a constructed mold for making the flexural test specimens.



Figure 3.9 Constructed Mold for Flexural Test (24x24x0.5in)

In addition, two wooden molds were constructed for weight-drop (impact) test and each mold had dimension of 24x24x1.5 in and yielded 4 specimens (12x12x1.5 in). One mold was for PVB concrete and another for PVA concrete which is reinforced PVA fiber (RECS 7). A constructed mold for drop weight test (24x24x1.5in) is shown in Figure 3.10.



Figure 3.10 Constructed Mold for Drop Weight Test (24x24x1.5in)

3.5 Placing and Curing

3.5.1 Placing

In this research, the mechanical vibrator was used to place concrete for 10 min. For PVB concrete, it looked dry when placing but as it was vibrated, it became workable. By comparing PVA fiber reinforced concrete, placing PVB concrete showed better workability because PVA fibers made concrete mix become stiffer. After 3 days, both the PVB and PVA concrete became hard and no separation with the mold was found. Figure 3.11 shows placing PVB concrete to constructed mold and harden batch after 3 days and Figure 3.12 shows placing PVA Fiber Reinforced Concrete (Left) and Harden Mold (Right).



Figure 3.11 Placing PVB Concrete to Constructed Mold and Harden Batch after 3days

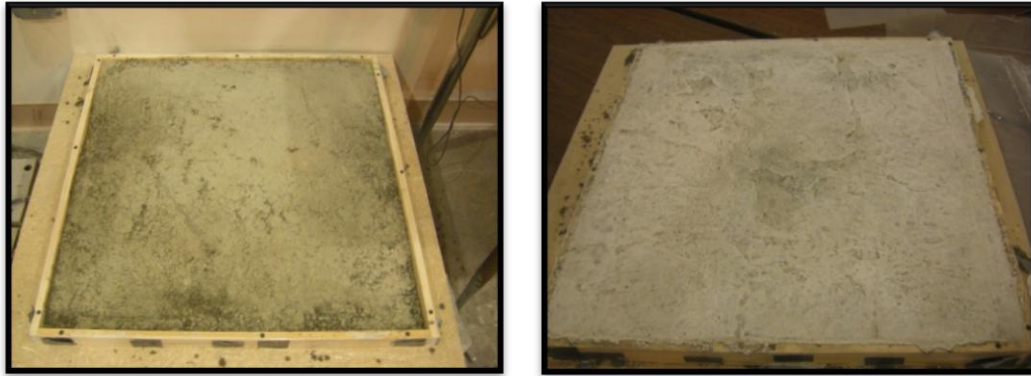


Figure 3.12 Placing PVA Fiber Reinforced Concrete (Left) and Harden Mold (Right)

3.5.2 Curing

This research establishes constant curing condition scenarios and all of the specimens applied following curing process. After 3 days in the mold, specimens were placed into water for another 3 days to improve strength. After 7 days of curing, specimens were distributed for different curing scenarios such as room temperature, water and wet/dry curing (with fresh water or salinity water).

To apply the polyurea coating on cured concrete, 24 hours of room temperature curing, after 3 days of water curing, was done to make sure the surface of concrete was completely dry. Therefore, polyurea coating was conducted after 7 days of curing. Detail of the curing process is shown in Figure 3.13.

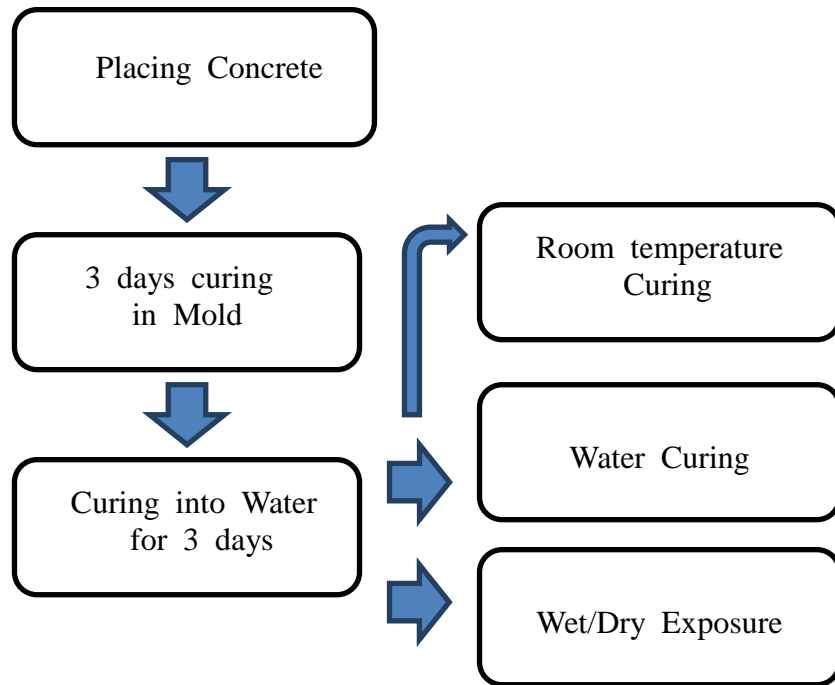


Figure 3.13 Curing Process

3.6 Wet/Dry Exposure

Wet/Dry behaviors were evaluated by using the environmental chamber which was placed in the Materials Labs at the Department of Civil and Environmental Engineering of UAH. It is schematically shown in Figure 3.14. This chamber utilized two 9500 electronic timers and an industrial dryer to cycle specimens constantly (hot air at 95° F averages and 90% humidity). Figure 3.15 shows the 9500 electronic timer and the industrial dryer.

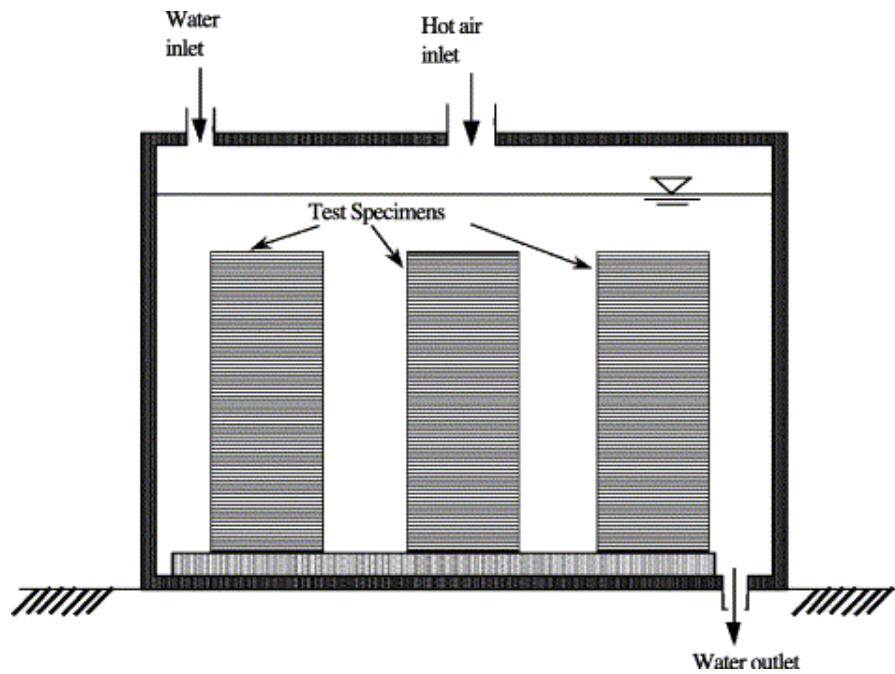


Figure 3.14 Schematic of the Wet-Dry Exposure Setup



Figure 3.15 9500 Electronic Timer and Industrial Dryer

The cylindrical specimens were subjected to salt water environments. Seawater was simulated using 35ppt (Parts per thousand, 35 grams of salt per 1000 gram of water) which is approximately the content of salt found in the ocean. For one cycle, 4 hours for wet and 8 hours for dry were conducted. Specimens were exposed to 100 cycles of wetting and drying for 50 days. After exposure, the specimens were tested in compression to determine the strength properties. Fresh water was used for comparison with same cycle of exposure periods. The environmental chamber is shown in Figure 3.16.

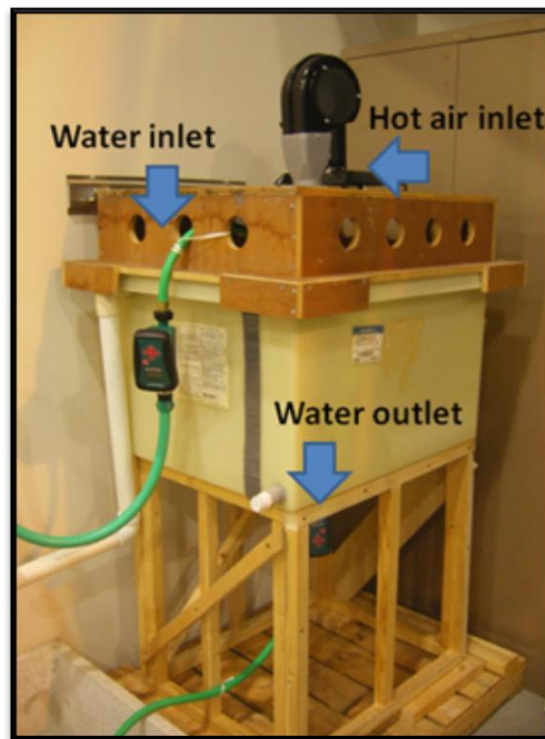


Figure 3.16 Environmental Chamber

3.7 Polyurea Coating

In this study, white polyurea manufactured by Creative Material was sprayed to all of the specimens at approximately 60 psi. It has a gel-time (The period of time when the resin changes from a liquid to a non-flowing gel) of about 30 sec and full curing time of about 30 min to 1 hour depending on humidity and temperature. For the cylindrical specimen, the top and bottom surfaces were not coated to conduct compressive strength test. The beam specimens were fully encapsulated with polyurea. The specimens for drop-weight (impact) test were applied sprayed in various coating scenarios such as uncoated, top, bottom and both side with coating. The Lateral sides did not have polyurea applied.

3.7.1 Preparation of High-level of Protection

Since the component of polyurea is an amine-functional oligomer, this chemistry shares the use of reactive isocyanates which can produce eye, skin and respiratory sensitization then a high-level of protection and ventilation system is required for safety issues during polyurea coating process. All of body was fully protected by wearing respirator, coveralls and protective gloves. Preparation of polyurea coating is shown in Figure 3.17.



Figure 3.17 Preparation of Polyurea Coating

3.7.2 Thickness of Polyurea

Having constant thickness was another issue to applying the polyurea coating on PVB concrete because the thickness of the polyurea is a critical factor which possibly changes its material behavior or characteristics. Through trial and error, a set amount of time was used in order to achieve a constant thickness on all of the specimens. Covering all voids on the concrete surfaces and avoiding wrinkles of the coated surface was the key to applying constant thickness of polyurea. Figure 3.18 shows coated 3 by 6 cylindrical (left), plate (12x12x1.5in) (center) and beam (24x4x0.5in) (right), respectively.



Figure 3.18 Coated 3 by 6 Cylindrical (left), Plate (12x12x1.5in) (center) and Beam (24x4x0.5in) (right) Specimen

3.8 Summary

In this chapter, the properties of constituent material were introduced. Development of mixture proportion and procedure of PVB and PVA fiber reinforced concrete were studied. Constant placing and curing scenario set for applying polyurea coating technology.

1. This research focus on one type of PVB and PVA fiber concrete mix which are enhanced with Butvar B-79 and Mowital M-B75H as a sole aggregate. Both B-79 and M-B75H completely replace coarse and fine aggregates in the developed mix.
2. Lightweight concrete mix was developed to make a comparison to the PVB mix, density (1500 kg/m^3). Beach sand and lightweight sand was used for aggregate.
3. It is established that all of the specimens followed a similar curing process.
4. The cylindrical specimens were exposed to sea water environments with simulated 35ppt (Part per thousand, 35 grams of salt per 1000 gram of water)

salinity water. Specimens were exposed to 100 cycles of wetting and drying for 50 days.

5. A high-level of protection and ventilation system is required for safety issues during the polyurea coating because this chemistry shares the use of reactive isocyanates.

CHAPTER IV

EXPERIMENTAL PROCEDURE

4.1 Compressive Test

4.1.1 Test Preparation

A total of 30 3 by 6 in cylindrical specimens were prepared and each specimen followed the curing scenario outline previously. (See Figure 4.1) All of the specimens can be divided into two categories, uncoated and coated with polyurea. Lightweight concrete, which has same density as the PVB concrete (1500kg/m^3), was used for comparison with the PVB specimens. All specimens were tested to determine the ultimate strength (ASTM C39) [54] and the effect of polyurea with wet/dry exposure (fresh water and salinity water). The test result is typically the average of at least three specimens.

Table 4.1 lists the summary of the test conditions for the cylinder specimens.



Figure 4.1 PVB (left), Lightweight Concrete (center) and Coated Concrete (right)

Table 4.1 Summary of the Test Conditions for the Cylinder Specimens

Coating Condition	Uncoat with polyurea		Coat with polyurea		
Curing condition/ Type of concrete	PVB	Light weight	PVB	Light weight	Total
Room temperature	3	3	3	3	12
Wet/Dry (Fresh water)	3	-	3	-	6
Wet/Dry (Sea water)	3	3	3	3	12
Total	12	6	12	6	30

4.1.2 Test Instrument

Compressive strength was evaluated by using a compressive testing machine manufactured by Forney. All 3 by 6 in specimens were cured for 28 days. The setup for the compressive strength tests for an uncoated specimen, a coated specimen and the machine controller is shown in Figure 4.2.

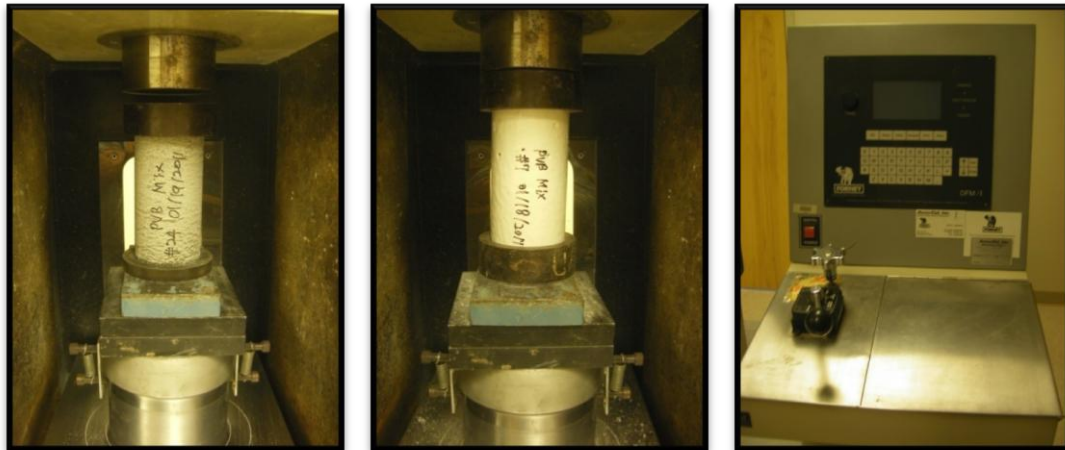


Figure 4.2 Compressive Strength Test for Uncoated Specimen (left), Polyurea Coated Specimen (center) and Machine Controller (right)

4.2 Beam Flexural Test

4.2.1 General Preparation of Flexural Test

In accordance with ASTM C78/78M-10 [55], the four point bending (pure bending) tests were conducted to evaluate flexural behavior of PVA fiber reinforced composite cementitious material and polyurea coated specimens. Table 4.2 shows summary of the preparation of flexural test.

Table 4.2 Summary of Preparation for the Flexural Test

Coating Condition	Uncoated with polyurea			Coat with polyurea			
Curing condition/ Type of concrete	PVB	PVA fiber	Light weight	PVB	PVA fiber	Light weight	Total
Room temperature	3	3	3	3	3	3	18

4.2.2 Preparation of Strain Gage

To evaluate stress-strain behavior, a general purpose Vishay Micro-measurements & SR-4® strain gage was mounted on the bottom surface and it was placed at the center of each beam. Surface preparation was required in order to develop a proper substrate for gage bonding on all beam specimens because concrete surfaces are usually uneven, rough, and porous. Figure 4.3 shows Vishay Micro-measurements & SR-4® for general purpose strain gage and Figure 4.4 shows prepared surfaces for placing a strain gage.



Figure 4.3 Vishay Micro-measurements & SR-4® for General Purpose Strain Gage



Figure 4.4 Prepared Surfaces for Placing a Strain Gage

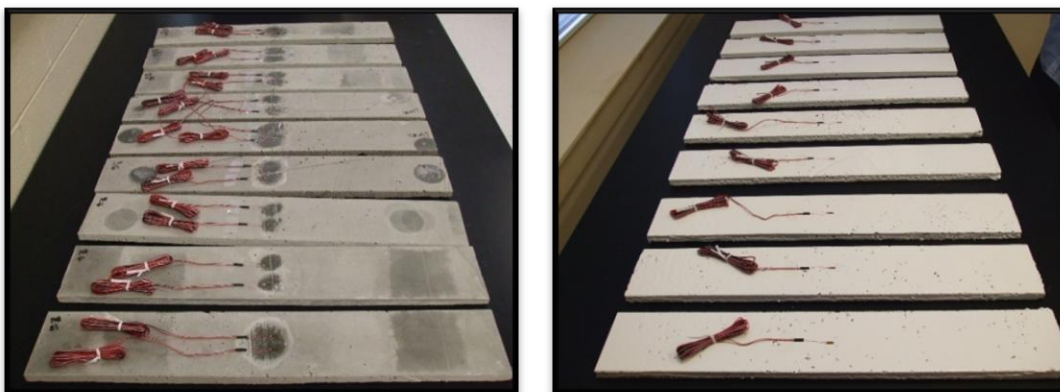


Figure 4.5 Placed Strain Gages on Uncoated Beam (left) and Coated with Polyurea Beam (right)

4.2.3 Test Setup

In accordance with ASTM C78/78M-10[55], the beams were tested in four point bending (pure bending) with a MTS 810 insight Dual Transformer, 820 XFMR-DUAL. A high speed camera set up to capture the flexural behavior of the beams. A speed rate of 0.05 in/min for the uncoated specimens and 0.15 in/min for the coated specimens was selected because of limited memory capacity with the camera system. Figures 4.6 and 4.7 show the four point bending test apparatus and high speed camera acquisition system, respectively.

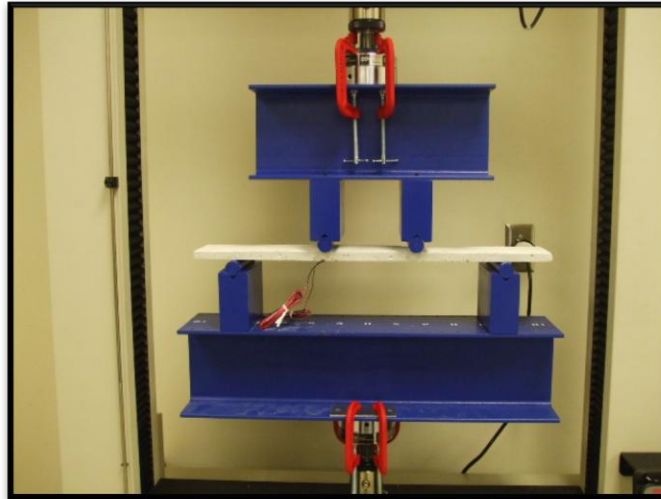


Figure 4.6 Four Point Bending Test Apparatus



Figure 4.7 High Speed Camera Acquisition Systems

4.3 Drop-Weight Impact Test

4.3.1 Test Preparation

Drop-weight impact tests were conducted according to ASTM D7136-07 (Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop-Weight Impact Event) [56]. The purpose of the drop-weight test is to observe the dynamic response and failure pattern of the specimens under the different coating scenarios. The drop-weight impact test was performed using a balanced, symmetric laminated plate. Impact damage is imparted through out-of-plane, concentrated impact (perpendicular to the plane of the laminated plate) using a drop weight.

4.3.2 Construction of Impact Device

Figure 4.3 shows the schematic of the impact device with cylindrical tube impactor guide mechanism according to ASTM D7136-07 (Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop-Weight Impact Event) [56].

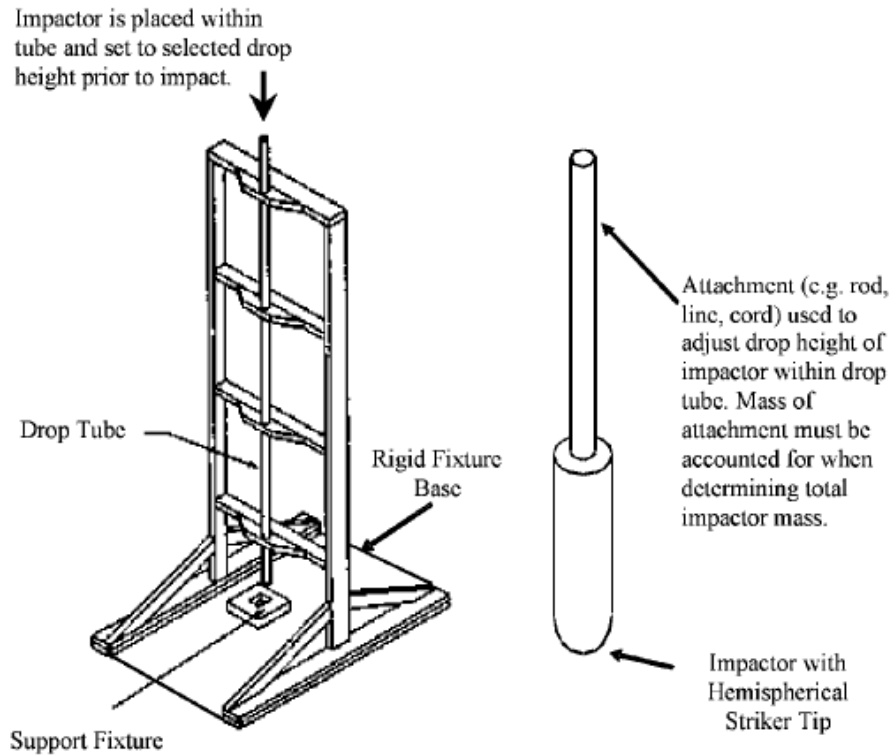


Figure 4.8 Schematic of Impact Device with Cylindrical Tube Impactor Guide Mechanism [56]

An impactor was built with a steel rod and a concrete filled pvc pipe. It has a mass of 5.35kg (11.8 lbm) with a smooth hemispherical striker tip with a diameter of 16 mm (0.625 in) and a hardness of 60 to 62 HRC as specified in the Test Methods. In order to achieve the desired weight, 150 lb/ft³ concrete was poured into the pvc-pipe. Four clamps were used to restrain the specimen during impact each clamp had a minimum holding capacity of 1100 N (200 lbf).

The damage resistance is quantified in terms of type of damage in the specimen. The damage response is a function of the test configuration; comparisons are made between materials with identical test configurations, test conditions, and so forth [56].



Figure 4.9 Impactor and Frame (left, center) and Impact Device (right)

4.3.3 Calculation

We assume that impactor had free drop by gravity and friction loss between the outer pvc pipe and impactor was ignored. Equation (4.1) shows that impact energy calculation.

$$E_i = \frac{mv^2}{2} , \quad (4.1)$$

where E_i is measured impact energy-in, Joules (J) and m is mass of impactor in kg

$$V_f = V_i + 2g(s - s_i) , \quad (4.2)$$

where $g = 9.81\text{m/s}^2$ and s_i is initial displacement and s is final displacement, respectively.

$$t = \sqrt{\frac{2s}{g}} . \quad (4.3)$$

To decide the drop-height, practice tests were conducted on PVB and PVA fiber concrete by changing drop height. Table 4.3 lists initial specimen set-up and Table 4.4 shows elapsed time, velocity and impact energy.

Table 4.3 Initial Specimen Set-up

Coating Condition	Uncoat with polyurea		Coat with polyurea		
Curing condition/ Type of concrete	PVB	PVB fiber	PVB	PVB fiber	Total
Room temperature	2	2	2	2	8

Table 4.4 Elapsed Time, Velocity and Impact Energy

Uncoated	Coated	Drop Height (ft)	Elapsed Time (sec)	Impact velocity (m/s)	Given Impact Energy (J)
PVB #1	PVB #3	4 ft	0.499	4.89	64
PVB #2	PVB #4	6 ft	0.61	5.99	96
PVA fiber #1	PVA fiber #3	6 ft	0.61	5.99	96
PVA fiber #2	PVA fiber #4	8 ft	0.71	6.92	128

The decision was made to coat specimens with polyurea with different coating scenarios such as uncoated, top, bottom, top and bottom coating. Based on calculations of the impact energy, analyzing failure mode and through trial and error, it was decided to test with a constant drop height of 8ft which gives an impact energy of 128J (Joule) at a velocity of 6.9 m/s. Tables 4.5 and 4.6 list failure modes of the specimens and finalized specimen set-up, respectively.

Table 4.5 Failure Mode of Specimens

Uncoated	Drop Height (ft)	Failure Mode
PVB #1	4	*F
PVB #2	6	F
PVA fiber #1	6	**S
PVA fiber #2	8	F
Coated		
PVB #3	4	S
PVB #4	6	S
PVA fiber #3	6	S
PVA fiber #4	8	S

*F is Fail

** S is Success (No cracks)

Table 4.6 Finalized Specimen Setup

Coating Condition	Plain	Top	Bottom	Top and Bottom	Total
PVB	2	2	2	2	8
PVA fiber	2	2	2	2	8

The different failure modes of the uncoated and coated PVB-PVA reinforced concrete are shown in Figure 4.10 and 4.11.

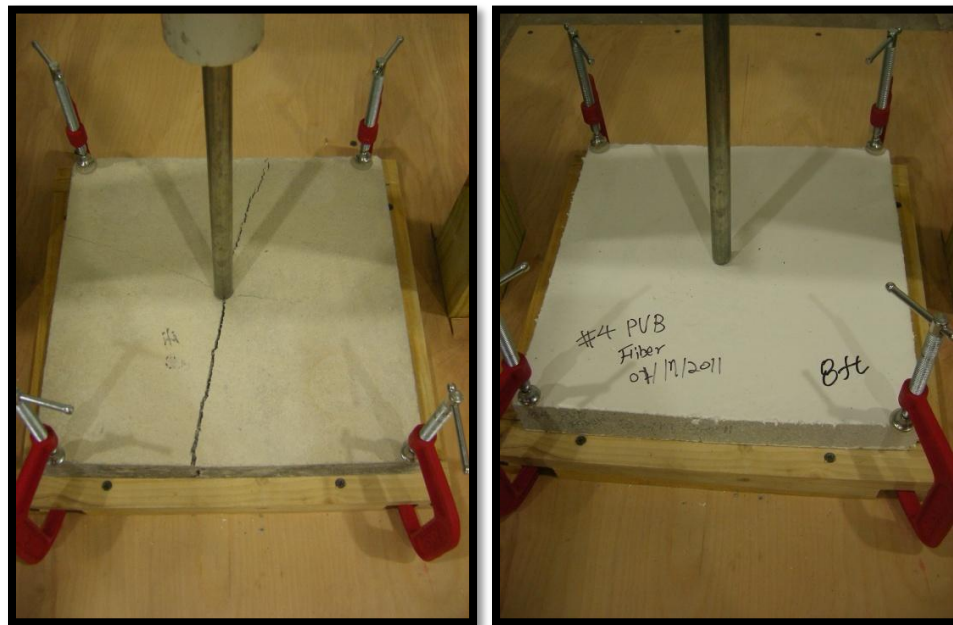


Figure 4.10 Front Side of Uncoated PVA Concrete (left) and Coated PVA Concrete (right) after 8 ft Free-Drop

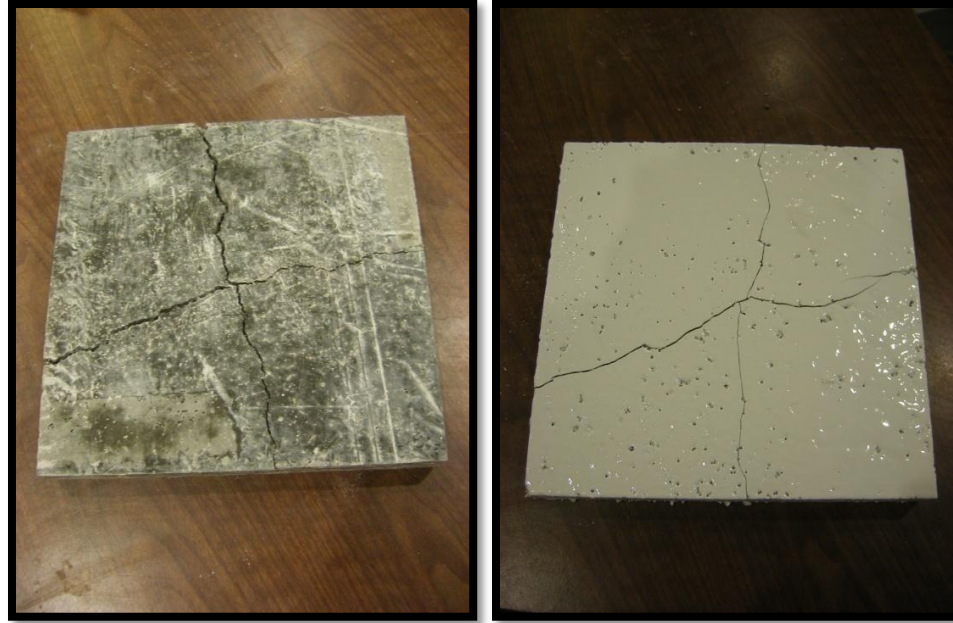


Figure 4.11 Reverse Side of Uncoated PVA Concrete (left) and Coated PVA Concrete (right)

4.4 Summary

In this chapter, experimental procedure including compressive, four point bending and drop-weight test was explained.

1. For compressive strength test, a total of 36 3 by 6 in cylindrical specimens were prepared.
2. Four point bending (pure bending) tests were conducted to evaluate the flexural behavior of lightweight, PVB and PVA fiber reinforced composite cementitious material and polyurea coated specimens with high speed camera.
3. A strain gage was mounted on bottom surface of each beam to evaluate the stress-strain behavior.

4. The purpose of the drop-weight test is to observe the dynamic response and failure pattern of polyurea coated PVB and PVA fiber reinforced concrete with a constant drop height of 8ft.

CHAPTER V

TEST RESULTS AND DISCUSSION

5.1 Compressive Test Results

As shown in Table 5.1, the PVB concrete specimen, replaced total aggregate with Butvar B-79 and Mowital M-B75H, has a compressive strength around 34 MPa (4916 psi) with water to cement ratio of 0.43 and density 1500kg/m³ (93.6 pcf). By comparison, the lightweight concrete shows a compressive strength of 26 MPa (3719 psi). PVB concrete showed higher compressive strength than lightweight, as shown in Figure 5.1.

Table 5.1 Test Result of Compressive Strength Test

Coating Condition	Uncoat with polyurea		Coat with polyurea
Type of concrete/ Curing condition	Lightweight	PVB	PVB
Room temperature	*3719 ** (25.6)	4916 (34)	4771 (30.8)
Wet/Dry (Fresh water)	-	5135 (35.4)	5685 (39.2)
Wet/Dry (Sea water)	-	4363 (30)	4650 (32)

*All units are in psi (lb/in²)

**All units are in () MPa (N/mm²)

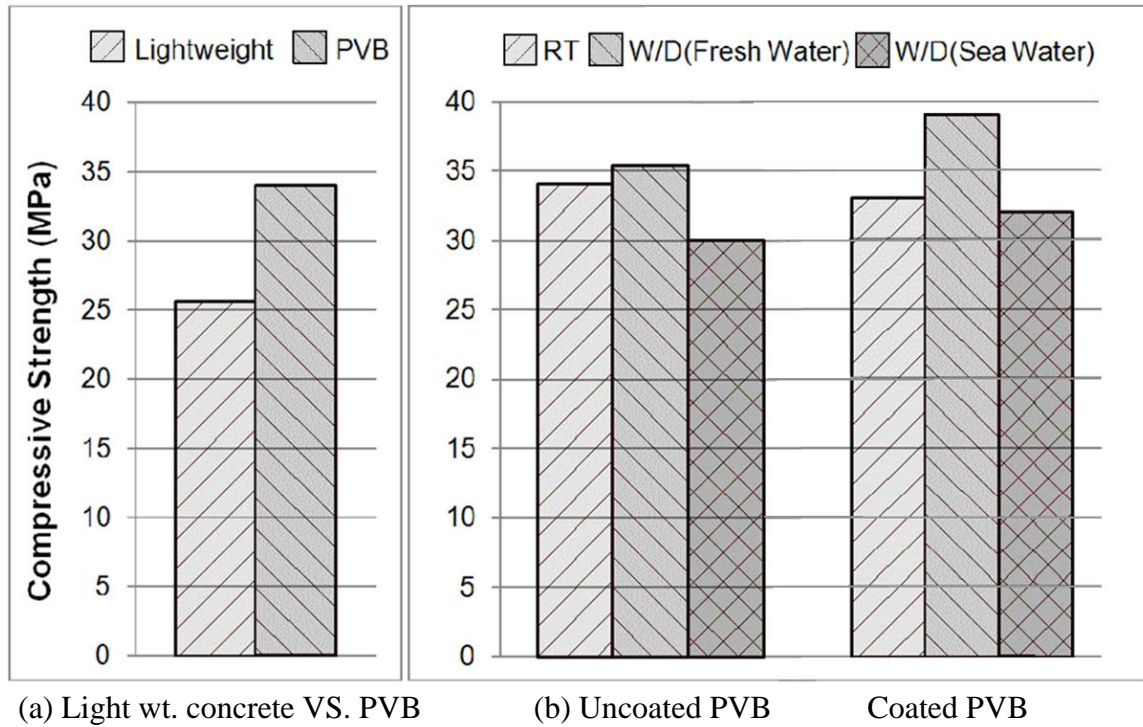


Figure 5.1 (a) The Comparison of the Compressive Strength and (b) Effect of Wet/Dry Exposure Uncoated and Coated with Polyurea of PVB Concrete

The wet/dry exposure with fresh water shows a positive effect on the compressive strength of both uncoated and coated cylindrical specimens. The compressive strength of the coated PVB concrete improves from 33 MPa to 39 MPa because the specimens went through a long period of curing and strength development from the aging process due to high humidity and high heat. After exposing 100 cycles of wet/dry in salt water the compressive strength of the uncoated PVB concrete, decreased from 34 MPa to 30 MPa, as shown in Figure 5.1. However, polyurea coating seem to produce no adverse effect because of the unique characteristics of polyurea such as wear resistance, moisture proofing and tolerance of extreme temperatures.

5.2 Flexural Test Results

The flexural load-deflection relationship was determined from the four-point bending test. In this research, all experimental tests were videotaped with a high speed camera system to view the flexural behavior of the beam specimens. Load vs. displacement curves and stress vs. strain curves were drawn for polyurea reinforced PVB concrete specimens with constant fiber volume fraction ($V_f=0.6\%$). Figure 5.2 shows the bending test of uncoated and coated PVA fiber reinforced concrete beam before and after failure.

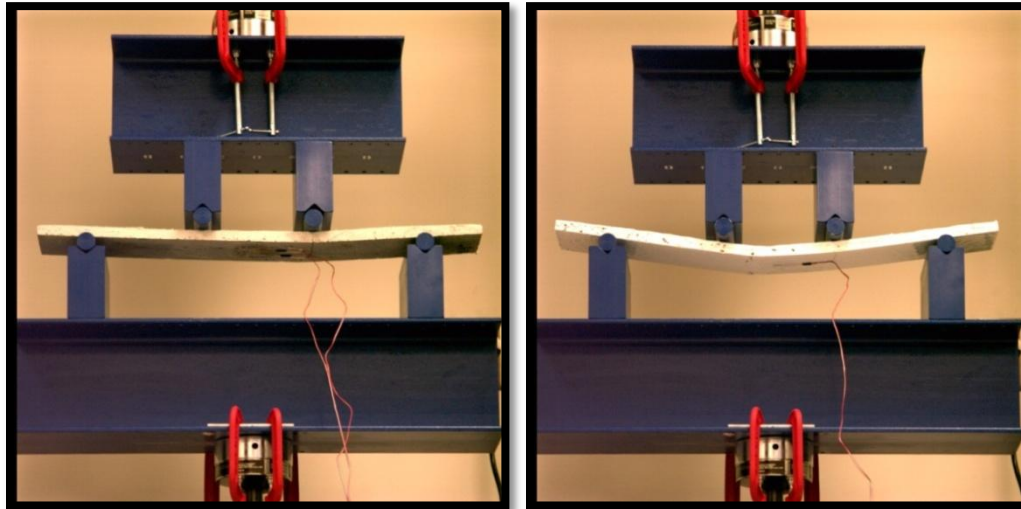


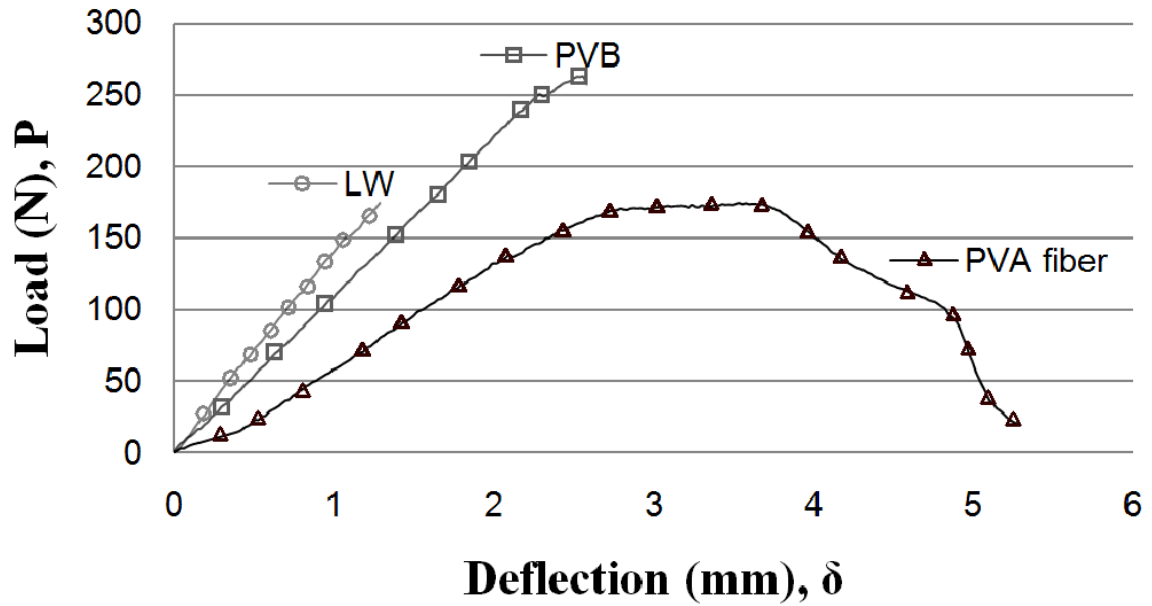
Figure 5.2 Bending Test of Uncoated and Coated PVA Fiber Reinforced Concrete Beam

5.2.1 Effect of Polyurea Coating on Flexural Load-Deflection Curves

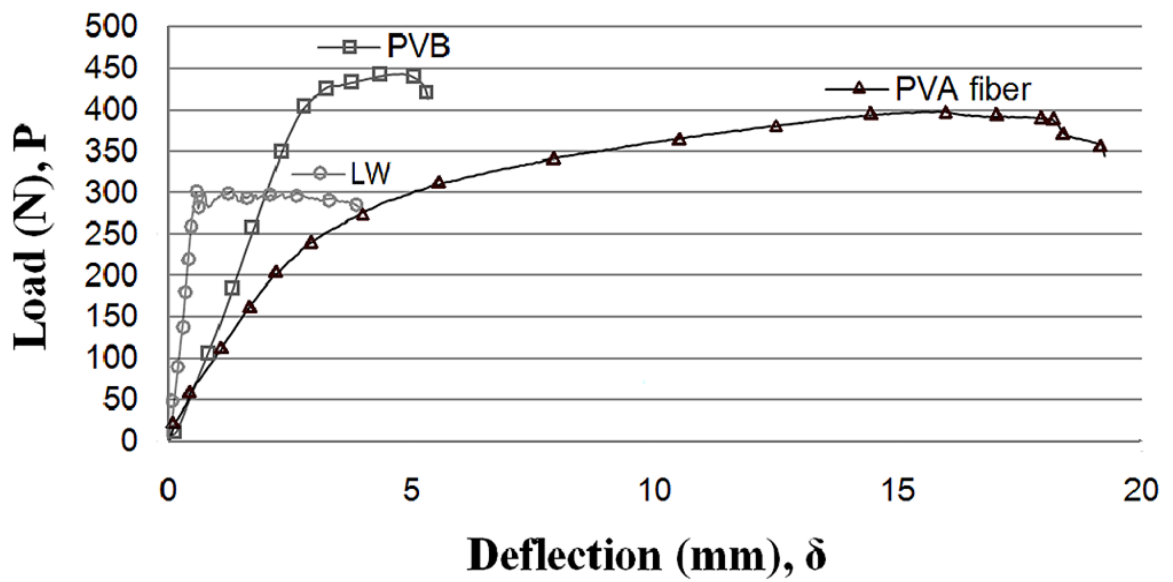
Load-deflection behaviors of lightweight, PVB and PVA fiber were determined for different coating conditions. In the case of uncoated concrete specimens, the PVB specimen has the highest ultimate flexural load (262N) but the PVA fiber reinforced

specimen has higher deflection compared with lightweight and PVB concrete. The maximum deflection and load of PVA fiber concrete is 0.529 cm at 174N. Both PVB and PVA fiber seemed to feature strong chemical bond in interfacial transition zone (ITZ) which results in higher load-deflection values than the lightweight concrete.

As can be seen in Figure 5.3, polyurea coating shows improvement of the ultimate flexural load and deflection on the lightweight, PVB and PVA fiber concrete. Encapsulated of the PVB concrete shows a higher flexural load and deflection than lightweight concrete. PVA fiber concrete has significant nonlinearity in the load-displacement behavior during loading. Its maximum flexural load is 398 N at deflection of 1.97 cm. When comparing uncoated PVA fiber concrete to coated PVA fiber concrete, the polyurea coating improves maximum load by 129%.



(a) Load-Displacement of Uncoated Specimens



(b) Load-Displacement of Polyurea Coated Specimens

Figure 5.3 Flexural Load-Deflection Curves

5.2.2 Effect of Polyurea Coating on Stress-Strain Curves

To evaluate the flexural behavior of PVB and PVA fiber reinforced concrete beams, a stress-strain curve was drawn. Lightweight concrete beams were made for comparison. As it can be seen in Figure 5.4 (a), uncoated lightweight, PVB and PVA fiber concrete has mostly linear material behavior up to failure. PVB and PVA fiber has higher ultimate stress and strain compared to the lightweight concrete. Additionally, concrete beams encapsulated with polyurea see an increase the ultimate stress of lightweight, PVB and PVA fiber concrete specimens by 52%, 21% and 57% percent, respectively.

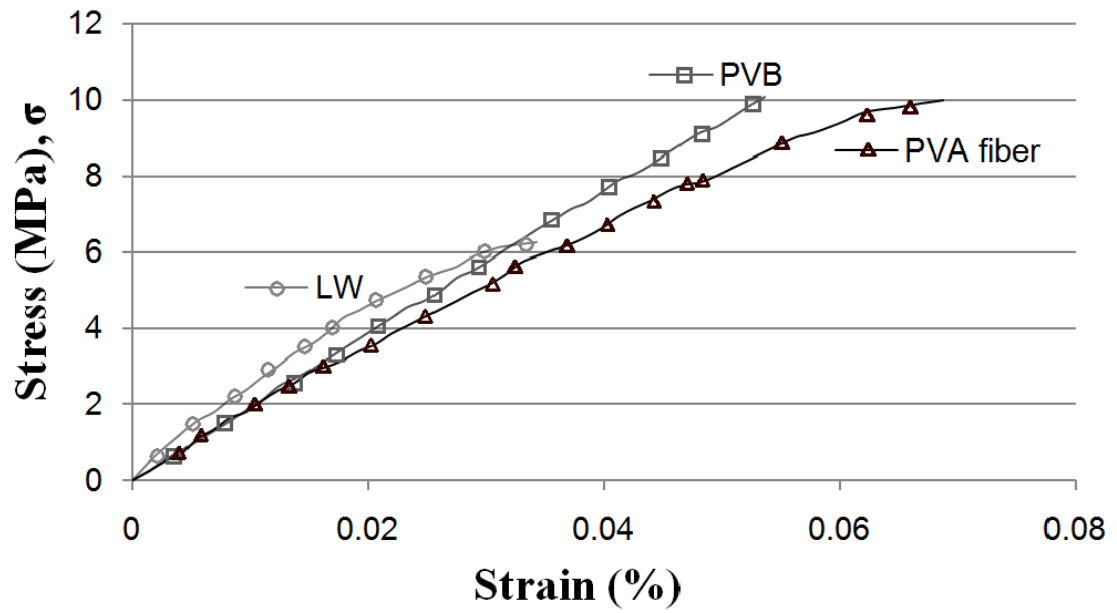
PVA fiber reinforced concrete beams features high interfacial frictional stress and strong chemical bond and shows significant strain-hardening behavior which the elastic strain is recovered as the material returns to its equilibrium state in Figure 5.4 (b). It observes that ultimate strain of PVB and PVA fiber concrete improves 268% and 838.5%, respectively, when coated.

As can be seen in Table 5.2, the Modulus of Elasticity, which measures the resistance of a material to elastic deformation under load, was calculated and it shows that the flexibility of polyurea coating composite material is higher than the uncoated because of the lower modulus of elasticity.

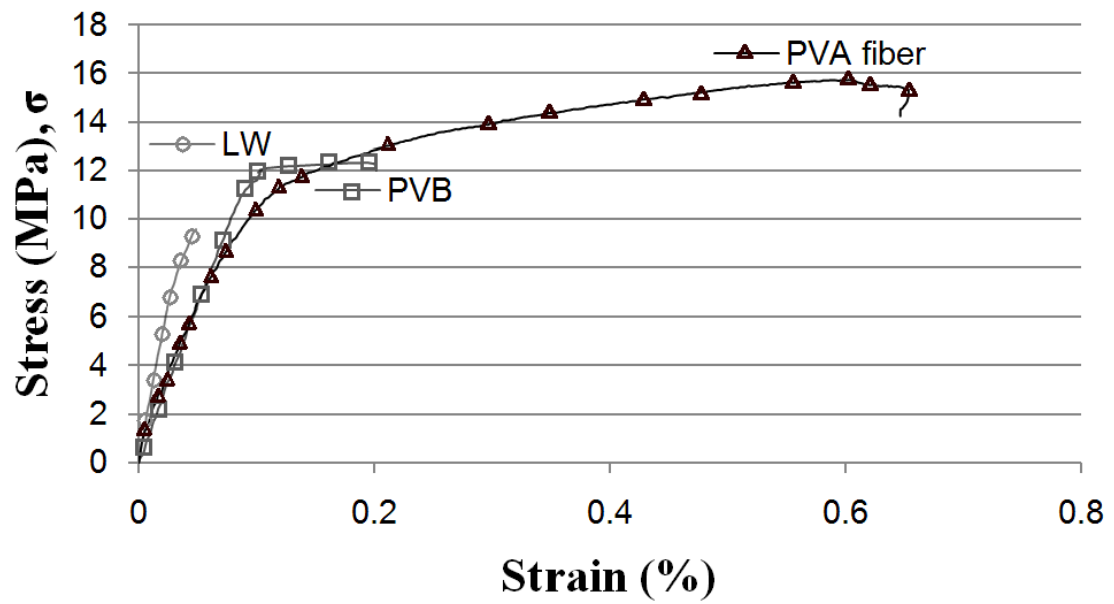
The Modulus of Toughness, which has been referred to as the energy absorption capacity and strain-energy density, was estimated by integrating the area under the stress-strain diagram. The results show that polyurea coated lightweight, PVB and PVA fiber concrete specimens increase their modulus of toughness by 118%, 585 % and 2053% respectively as shown in Figure 5.4. Significantly, PVA fiber reinforced beams with polyurea show the greatest improvement in terms of flexibility.

Table 5.2 Summary of Flexural Test Results

		Ultimate Stress, σ , (MPa)	Ultimate Strain, ϵ , (%)	Modulus of Elasticity, E (GPa)	Modulus of Toughness, u , (MJ/m ³)
Uncoated	Lightweight	6.3	0.034	23.2	1.34 (10^{-3})
	PVB	10.1	0.055	18.8	2.81 (10^{-3})
	PVA fiber	10	0.069	16.6	3.94 (10^{-3})
Coated	Lightweight	9.6	0.049	23.9	2.92 (10^{-3})
	PVB	12.3	0.202	12.6	19.24 (10^{-3})
	PVA fiber	15.7	0.645	9.5	84.83 (10^{-3})



(a) Stress-Strain Curve of Uncoated Specimens



(b) Stress-Strain Curve of Polyurea Coated Specimens

Figure 5.4 Flexural Stress-Strain Curves

5.3 Weight Drop Test Results

Based the calculation in Chapter 4, analyzed failure mode of initial tests and through trial and error, the drop height and resulting impact energy were decided to be 8ft for all specimens. Those results have an impact energy of 128J (Joule) and a velocity of 6.9 m/s. Dynamic response and failure pattern was observed for polyurea coated PVB and PVA fiber reinforced concrete.

As can be seen in Table 5.3, the results can be observed by comparing between uncoated and coated with polyurea on the top and bottom. Uncoated PVB and PVA concrete failed at the given impact energy of 128J. Otherwise, the addition of polyurea coating on top and bottom prevents failure of both PVB and PVA concrete.

Table 5.3 Failure Mode of Specimens

(a) PVB Concrete

	Coating Condition	Failure Mode (Front/Reverse)
PVB #1	Plain	F / F
PVB #2	Plain	F / F
PVB #3	Top	F / F
PVB #4	Top	F / F
PVB #5	Bottom	S / S
PVB #6	Bottom	S / S
PVB #7	Both	S / S
PVB #8	Both	S / S

(b) PVA fiber Concrete

	Coating Condition	Failure Mode (Front/Reverse)
PVA fiber #1	Plain	F / F
PVA fiber #2	Plain	F / F
PVA fiber #3	Top	S / F
PVA fiber #4	Top	S / F
PVA fiber #5	Bottom	S / S
PVA fiber #6	Bottom	S / S
PVA fiber #7	Both	S / S
PVA fiber #8	Both	S / S

*F is Fail

** S is Success (No cracks)

In the case of applying polyurea coating on the top, PVA fiber reinforced concrete produced no damage on top surfaces; however, PVB concrete showed failure on the top. By analyzing failure patterns, applying polyurea coating on the bottom seems to show better results. Figures 5.5 and 5.6 show the failure pattern of polyurea coating on the top and bottom.

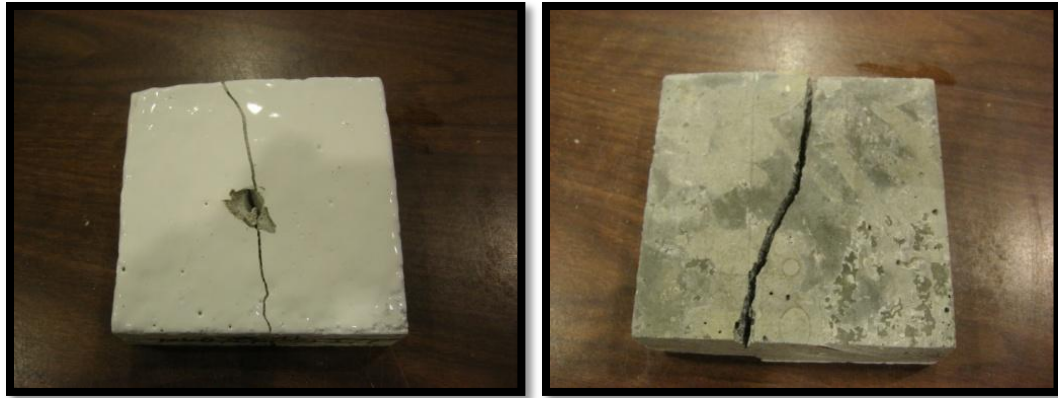


(a) Plain PVB Concrete (left) and Plain PVA Concrete (right)



(b) Addition of Polyurea Coating on Top and Bottom of PVB (left) and PVA (right)

Figure 5.5 Failure Pattern of Plain vs. Polyure Coated Concrete



(a) Front Side (left) and Reverse side of #3 PVB Concrete



(b) Front Side (left) and Reverse Side of #3 PVA Concrete

Figure 5.6 Failure Pattern of Polyurea Coating on the Top

Failure pattern of polyurea coating on the bottom is shown in Figure 5.7. Both PVB concrete and PVB reinforced concrete are showing no cracks on the top and bottom. Applying polyurea coating on the bottom seems to show better results than coating on the top.



(a) Front Side (left) and Reverse Side of #5 PVB Concrete



(b) Front Side (left) and Reverse Side of #5 PVA Concrete

Figure 5.7 Failure Pattern of Polyure Coating on the Bottom

CHAPTER VI

CONCLUSION AND DISCUSSION FOR FUTURE RESEARCH

6.1 Conclusion

In this study, Poly(vinyl butyral) PVB was used as total replacement of aggregate. The PVB was reinforced with Poly(vinyl alcohol) PVA fiber was used as a reinforcement. Lightweight concrete with equal density was made as a comparison. Compressive strength with various curing condition, four point bending and drop-weight tests were conducted to determine the effect of polyurea coating on high-performance cementitious composite materials. From the test results, several conclusions can be drawn as follows:

1. PVB concrete shows a compressive strength of 34 MPa (4900 psi) with low density 1500 kg/m³ (93.6 pcf). By comparison, lightweight concrete shows a compressive strength of 26 MPa (3719 psi) with equal density. The wet/dry exposure with fresh water shows a positive effect on the compressive strength of both uncoated and coated cylindrical specimens due to the fast aging process with high humidity and heat. The unique characteristics of the polyurea protect the concrete during wet/dry exposure with salt water.

2. Both PVB and PVB reinforced with PVA fiber concrete may feature strong chemical bonds in the interfacial transition zone (ITZ) which results in higher load-deflection value than lightweight concrete. Uncoated PVB specimens show higher ultimate flexural load than lightweight. PVA fiber reinforced PVB specimens with a fiber volume fraction of 0.6% have the highest deflection values compared with lightweight and PVB concrete.
3. Polyurea coating shows the improvement of the ultimate flexural load and deflection on lightweight concrete, PVB coated, and PVB reinforced PVA fiber concrete. Coated PVB concrete has a higher flexural load and deflection than lightweight concrete. PVA fiber reinforced concrete beams show significant nonlinearity in the load-displacement behavior during loading.
4. All of the uncoated concrete specimens show mostly an elastic behavior from stress-strain curve. Both PVB concrete and PVB reinforced with PVA fiber has higher ultimate stress and strain compared to the lightweight concrete. Polyurea coating increase stress and strain of lightweight, PVB and PVB reinforced with PVA fiber reinforced specimens. In particular, PVA fiber reinforced concrete features significant strain-hardening behavior which the elastic strain is recovered as the material returns to its equilibrium state.
5. Special features of polyurea with PVB concrete (with and without PVA fibers) make it possible to improve flexibility, energy-absorption characteristic and strain-energy density.
6. Drop-weight tests were conducted for analyzing failure pattern and crack image based on recorded video from high speed camera system. Plain PVB and PVB

reinforced with PVA concrete failed with the given impact energy of 128J. Applying polyurea on the top surface of the PVA fiber reinforced concrete prevented cracks from forming on the coated surface; however, PVB concrete showed failure on the coated top surface. By analyzing the failure patterns, it was concluded that applying polyurea on the bottom surface seems to produce better results.

6.2 Discussion for Future Research

6.2.1 Analysis of Failure Pattern of Cylindrical Specimens

A – Study of the effect of the thickness of polyurea on the mechanical properties of the cementitious specimens.

B – Study of the effect of different environmental conditions on the failure mechanism of both coated and uncoated specimens.

6.2.2 Analysis of Failure Pattern of Beams

Study the effect of the thickness of polyurea on the flexural strength, stress-strain behavior and failure mechanism.

6.2.3 Discussion for Drop-Weight Tests

More data is needed to verify our results. The effect of varying the drop height and specimen size on the failure load and failure mode should also be investigated.

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