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Reinforcement of Cement with Polypropylene Mesh

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REINFORCEMENT OF CEMENT WITH POLYPROPYLENE MESH

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Materials Science and Engineering

by
Charles Nikon
August 2019

Accepted by:
Dr. Igor Luzinov, Committee Chair
Dr. Konstantin Kornev
Dr. Prasad Rangaraju
Dr. Jeffery Owens
ABSTRACT

Concrete is one of the world’s most widely used building materials for many reasons including: relatively low cost, moldability, and high compressive strength. This high compressive strength is perfect for most construction applications where the building is subjected to constant and well known static forces. However, due to concrete’s brittle nature, crack formation and ultimately failure will occur when it is exposed to dynamic or tensile loading; concrete is often subjected to such conditions in highway and military applications. Polymeric fibers, namely Polypropylene (PP), are often added to the concrete mix in order to promote toughness and impact resistance, improving the survivability of concrete under such loading conditions. In this work we consider PP mesh in lieu of fibers as impact modifier for cement based structures. In brief, we have studied the effect of the mesh addition to cement mortar on physical properties, including impact resistance. It is suggested that mesh reinforcement can offer better improvements to toughness due to its connectivity and, therefore, ability to serve as macro scale reinforcement. Samples were prepared using a cement mortar mixture of constant composition (large aggregates were excluded due to the cm-scale sample size) and reinforcement with ~ 2% by volume of varying sized PP meshes. The samples were subjected to compression, tensile splitting, and impact testing in order to quantify their mechanical properties. The effect of mesh geometry and distribution on sample properties were investigated. Additionally, the properties of mesh reinforced samples were compared to those of fiber reinforced and non-reinforced samples. In the future, hybrid...
geometry reinforcements will be investigated alongside with mechanical modeling of the composite systems.
ACKNOWLEDGMENTS

I would first like to express my sincerest appreciation and gratitude for the support of my advisor, Dr. Luzinov. His constant presence was a driving force to push me along during this journey, and his ingenuity made progressing along so much easier. Having him as an advisor was truly a pleasure.

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Lastly I would like to thank the ORISE program and the U.S. Air Force Civil Engineer Center for their financial support, without which none of this would be possible, as well as Clemson University and the MSE department for providing the infrastructure that allowed this to blossom.
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CHAPTER 1

1.1 - Introduction

The effectiveness of concrete as a construction material is readily witnessed by observing the buildings and infrastructure around oneself and seeing sidewalks, foundations, buildings, and parking garages all made of the material. It can withstand the burden of holding up incredible amounts of weight, and as such is used in such a capacity with great success. However, when subjected to unpredictable non-compressive strains, its flaw as a brittle material is exposed; tensile and impact forces will quickly propagate and topple the sturdiest of concrete monuments. There is no readily available material, especially on a worldwide scale, that can replace concrete’s combination of price, strength, and ease of use in terms of construction, and so it is of great interest to design a way to improve concrete’s capacity under such conditions, primarily through the improvement of toughness. The primary method for improving toughness in concrete is through the addition of ductile fibers, which arrest the growth of cracks throughout the brittle matrix. Concrete reinforced with fibers is conveniently called Fiber Reinforced Concrete (FRC). While this is a convenient method, as fibers can simply be added into a mixture and poured in with the concrete, it lacks some ability for optimization. There are limited availabilities for geometric arrangement of the reinforcing material when using fibers, and the lack of long range connectivity may not fully utilize ductile materials abilities to halt crack growth. The scope of this research is to investigate the effectiveness of more complex reinforcing material geometries and orientations on toughness and impact resistance, primarily through the use of layered mesh.
This research will study the effects of mesh geometry and orientation on the compressive strength, tensile splitting strength, elastic modulus, toughness, and impact resistance of cementitious composites reinforced with PP mesh. The topics covered are as such:

- **Chapter 2:** Literature review on the history, applications, properties, reinforcement types, and testing methods for FRC materials
- **Chapter 3:** A description of the experimental procedures used throughout this work
- **Chapter 4:** An investigation of the effects of anisotropic PP reinforcement (layered mesh) on mechanical properties such as compressive strength, tensile splitting strength, and elastic modulus
- **Chapter 5:** An investigation of the effects of isotropic PP reinforcement (fibers, chopped mesh, and combinations including layered mesh) on mechanical properties such as compressive strength, tensile splitting strength, and elastic modulus
- **Chapter 6:** A description of the development of impact testing procedures for use with the materials utilized in this work. The influence of PP reinforcement of both isotropic and anisotropic geometries on impact behavior is investigated.
- **Chapter 7:** Closing remarks, conclusions, and future work for this research
1.2 - References


CHAPTER 2

Literature Review of Fiber Reinforced Concrete Composites and Impact Resistance

2.1 - Introduction

Concrete is an essential material throughout the world when it comes to construction. Strong in compression, relatively inexpensive, able to be molded into practically any shape, its popularity is quickly understood. Being a brittle material, it is primarily used in situations where large static compressive loads are present, a column or a sidewalk for example. It is in situations such as these where it excels as a construction material; its brittle nature is predictable and reliable under such conditions. However, often static compressive loading conditions cannot be guaranteed, and tensile or impact loads may appear. Such loads will force crack formation within concrete due to its brittle nature, which can ultimately lead to failure \(^1\). Concrete is unable to plastically deform in order to dissipate energy, thus cracks form along aggregate and cement mortar boundaries. This transition zone between aggregate and cement mortar, known as the Interfacial Transition Zone (ITZ), is widely known to be a source of weakness within concrete and the location of initial crack formation \(^2,3\). Concrete is not stable or predictable in such situations. Additionally, the reaction of concrete to impact loads is also related to the strain rate of the applied load.
Figure 2.1 – Types of Impact Loading (Reproduced with Permission from Reference 4)

Figure 2.1 displays some real life situations where a more energy absorbent material is needed. It is to be noted, however, that the compressive strength of concrete under uniaxial loading is shown to increase with increasing strain rates. Additionally, tensile strength is also known to increase with increasing strain rates, however this is not to be confused with an improvement in fracture resistance under high strain rates. Thus, for situations where failure is not acceptable and impact loads may be expected, such as a highway median or a wall surrounding a military base, plain Portland cement concrete is not a satisfactory material. The toughness of the concrete used in such a situation needs to be increased. One developed method is through the addition of inorganic or organic fibers into the cement mixture. Extensive research and interest into the creation of FRC began in the 1960’s. These fibers are able to bridge the growth of cracks, and then dissipate energy along the cement-fiber interface. Not only does this increase the toughness of the material, allowing it to absorb more impact load before failure, it also prevents the occurrence of catastrophic failure within the material; fiber reinforced concrete is able to

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<td>$10^{-7}$</td>
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<td>Pile driving; airplane impact; vehicle hitting bridge pier; hard impact</td>
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<td>Special hydraulic machine with high-capacity servo-valves; impact test; impact or drop weight machine, Split-Hopkinson pressure bar</td>
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maintain structural integrity even after the formation of initial cracking\(^8\). This is critical for safety in many real life situations.

**Figure 2.2** – Fiber Pullout Schematic (Reproduced with Permission from Reference 7)

Through the mechanism of fiber pullout, as shown in Figure 2.2, crack propagation is halted. In order for the crack to continue to grow, energy has to first be exerted into debonding the fiber-cement interface, resulting in the fiber being “pulled out” of the cement matrix, causing failure. Zone 5 within Figure 2.2 shows what may potentially happen if fibers are not properly mixed or are spaced too far apart; cracks will be able to form and propagate uninhibited. Fiber geometry, orientation, and adhesion with the
cement mortar are factors that influence the effectiveness of an inserted fiber on the increase in material toughness. It is for these very reasons that a variety of fibers are used for concrete reinforcement. Of these, some of the most common are steel fibers, polypropylene (PP) fibers, and glass fibers. Other synthetic and natural fibers are also employed, where natural fibers can be used for sustainability and ecological purposes.

2.2 – Applications

Some specific applications for fiber reinforced concrete include: 1) Runways (where slabs of FRC half of the thickness of plain concrete may be used); 2) Tunnel Linings and Slope Stabilization (shotcrete, a form of concrete that is sprayed in its liquid state instead of poured, can be mixed with fibers and sprayed in place of setting up mesh linings); 3) Blast Resistant Structures (military fortifications where the toughness of concrete being used is critical for defense); 4) Thin Shelled/Curved Structures (added ductility of FRC allows for thinner curved structures to be constructed); 5) Dams and Hydraulic Structures (to prevent damage caused by large debris).

2.3 – Testing of FRC

Typical testing of FRC materials involves flexural bending testing, from which toughness may be calculated, and compressive testing. Three/Four point bending tests are conducted, where a FRC sample is deflected up to a certain deflection at a specific strain rate. The area underneath the load/deflection curve is used as an indication of energy absorbing ability. ASTM Standard C1609/1609M provides specifications for
such testing. Impact testing, with impact resistance also being a manifestation of
toughness, is much less standardized however, and often involve the use of relatively
large samples weighing hundreds of kilograms and being measured in dimensions of feet
14, 15. “Hitherto, the compressive response of fiber reinforced concrete under impact
loading has not been investigated due to lack of proper measurement techniques for the
compressive toughness under impact” 4. Investigating literature will uncover many
varying forms of testing in regard to impact toughness, be it a drop weight test or
launching a fast moving projectile at a FRC target. Being a highly strain-rate sensitive
system, varying methods may produce varying results. Additionally, the reporting of
impact toughness may take many different forms. Some may report results as a function
of how many impacts a sample can take at a given energy before cracking/or failure will
occur (as is seen in Figure 3), while others may report the impact toughness as the
energy of impact that cracked/fractured the sample. Even further analysis of impact
resistance may include measurements of depth of penetration, cratering, and debris
blowback 16. A list of relevant ASTM tests for testing the properties of FRC materials can
be found here:

**ASTM C1116/C1116M** – Covers the requirements of premixed FRC that is
delivered the customer. This standard does not cover the curing procedure once
delivered to the customer. The standard specifies mixing, batching, delivery,
slump tolerances, and delivered product testing protocol. For most mechanical
tests, FRC simply needs to exceed the performance of plain concrete mixed
without the same ratio without the fibers.
ASTM A820/A820M – Covers the basic requirements for steel fibers to be used in FRC. Outlines five categories of steel fibers: Type I – Cold-Drawn Wire, Type II – Cut Sheet, Type III – Melt-Extracted, Type IV – Mill Cut, Type V – Modified Cold Drawn Wire. Covers required tensile and bending requirements. Permissible sizes for each type of steel fiber is covered.

ASTM C1666/1666M – Covers the basic requirements for alkali resistant glass fibers to be used in FRC. Outlines three categories of glass fibers: Type I – Roving, Type II – Chopped Strands, Type III – Textiles. Covers minimum mechanical properties, alongside with minimum composition to guarantee alkali resistance.

ASTM C1609/1609M – Covers the specifics for flexural strength testing of FRC samples. It specifies geometries and testing procedures for samples to be used in a three point bending test. It provides formulas for the calculation of stresses and the modulus of rupture. Provides specific loading rates based on size and deflection. Area under the load-deflection curve may be used as an indication for a materials energy absorption ability.

2.4 – Fiber Properties

The fibers utilized within reinforced concrete all have very differing properties in terms of strength, adhesion, and ductility, and it is these differences that influence their selection for use within concrete over one another. For example, at low impact strain rates, steel fiber reinforced concrete shows much better crack growth prevention and
increased toughness over polypropylene reinforced concrete. However, due to the
viscoelasticity, strain sensitivity, of polypropylene, at high impact strain rates,
 polypropylene reinforced concrete approaches the toughness of steel reinforced concrete.
Additionally, steel fibers exhibited a more consistent fiber pull out than polypropylene at
high impact loads due to the fracturing of polypropylene fibers before they are able to
pull out and absorb energy. This is an important factor to consider, as a stronger fiber will
be able to withstand stronger loads without snapping ⁴. However, steel fibers may have
limited use in toughness improvement due to their comparatively large size, resulting in
poor ability to bridge microcracks, and may be prone to rusting in the highly alkaline
environment of cementitious materials ¹⁷, ¹⁸. Fibers added to the concrete need some level
of ductility in order to be able to transfer energy; fibers are able to plastically deform and
dissipate energy while the concrete itself is not. Short fibers, typically under 100mm in
length, are used and are mixed into the cement mixture before pouring in quantities of up
to 5% by volume. There has been some investigation into the relationship of fiber
orientation and strength, in addition to the effects of the pouring method to fiber
orientation in the product ¹⁹-²¹.

Depending on the application, steel or polymeric fibers may be preferred. Some
reasons why polymeric fibers, namely PP, may be preferred: cheaper, ductile, well
mixing, non-corroding, thermally stable, chemically inert, higher pull out resistance, and
hydrophobic surface that does not interfere with the cement hydration process ²².
Advantages for steel fiber include a stronger fiber that exhibits higher toughness at lower
strain rates ⁴. In military applications, where FRC may be exposed to high speed
projectile impact, it is shown that through the increasing of steel fibers to a high compressive strength concrete, the cratering effect of projectile impact may be mitigated. Glass fibers are often used for non-structural applications. Load bearing applications are avoided as the glass fibers often interact with the alkali nature of the concrete, losing strength over time. This alkali-silica reaction is also detrimental to the strength of the cement itself, so the reactivity of the glass fibers needs to be well known. Glass fibers also lack the ductility of PP fibers, which may reduce energy absorbing ability. They can be used as a replacement for natural stone in locations without access to stone, and to make thinner architectural components, making them cheaper and more environmentally conscious, as less cement is used.

2.5 - FRC Optimization

One of the most influential parameters in determining the increased toughness of a FRC, is the volume percentage of fiber added to the system. With increasing volume content of fiber, it is typical to see higher toughness within a material.
Figure 2.3 – Impact Strength versus Percentage of Polypropylene Fiber Volume Fractions at: (a) First Crack and (b) Failure Strength (Reproduced with Permission from Reference 24)

As can be seen in Figure 2.3, an increase of fiber volume content shows a consistent increase in the number of blows for crack appearance/failure during an impact testing procedure. This is directly related to the toughness of the concrete. Additionally seen in Figure 2.3, is the comparison between FRC containing silica fume with those not containing silica fume. It can be seen that a synergistic effect is witnessed, as the addition of silica fume further increases toughness of the concrete. The addition of polypropylene fiber to concrete lowers compressive strength, due to it being a lower modulus material and through the introduction of porosity created between cement and fiber. However, the addition of silica fume is able to increase the compressive strength of the concrete beyond that of reference, and additionally increase the toughness of the material. The silica fume
is able to reduce the newly created porosity and further strengthen the concrete via pozzolanic reaction, where silica fume reacts with a cementitious material to form more Calcium Silicate Hydrate (this is the prominent compound of cement that provides strength)\textsuperscript{25-27}. This is to show that fiber reinforcement can be used alongside with pozzolanic materials in order to reach desired properties in concrete.

\textbf{Figure 2.4} – Crack Propagation of PP Reinforced Concrete (a – plain, b - 0.2\% fiber, c – 0.3\% fiber, d – 0.5\% fiber) (Reproduced with Permission from Reference \textsuperscript{24})

\textbf{Figure 2.4} shows the trend for smaller cracks to form as a result of impact testing as volume percentage of fiber increases. For this particular system, at 0.5\% fiber content, catastrophic failure was avoided, as the ductile reinforcement promoted smaller crack formations. Spacing and fiber concentration are sufficient to bridge the cracks that would have formed, and extend the usefulness of the FRC sample.
The adhesion between fiber and cement is also largely influential on the toughness of FRC. Through the manipulation of the fiber surface or fiber geometry, the pull out strength for the fiber pull out mechanism to occur can be increased. Increasing the surface roughness of the fibers through methods such as exposure to alkaline surface treatment or plasma treatment has been shown to potentially increase the toughness of the FRC. By increasing the surface roughness of the fibers, the physical interaction between fiber and cement increases.

Figure 2.5 – Surface Comparison of Treated and Non-Treated PP Fiber (A is untreated, B is treated) (Reproduced with Permission from Reference 22)

The surface of the treated PP fiber is clearly rougher than the untreated fiber, and single fiber pullout testing, where the resistance to pulling of a single fiber from a cement paste
is measured, showed five times more resistance from the treated fiber (5.1 N/mm vs .9 N/mm).

Figure 2.6 – Flexural Strength of Treated PP Specimens (Reproduced with Permission from Reference 22)

Flexural strength is an indicator of ductility and toughness, thus increasing the surface roughness of fibers may be a viable method of increasing the toughness of FRC. Another potential method for increasing the interaction between fiber and cement is by coating the fiber with reactive groups that may bond with the cement matrix. Varieties of a shaped fibers are also available, designed to increase resistance to pull out.
2.6 - Polypropylene Fibers

The scope of this research focuses primarily on the influence of Polypropylene (PP) as a reinforcing material within cementitious material to improve toughness and impact resistance. While steel fibers tend to be the most commonly used due in fiber reinforcement, PP fibers have the advantage of being lighter, more ductile and easier to distribute within cement, resulting in a better distribution of fibers throughout the reinforced material. These properties make PP fibers excellent for crack bridging within a cement based composite, as well as making a lighter composite material. In addition, PP does not react with the alkaline cement matrix and is produced in large scale at low costs, further giving it merit as a reinforcement material. PP reinforced FRC is widely seen to provide improvements to toughness and crack resistance, desirable traits for impact resistance. PP can further be treated by various means of chemical or physical treatment to alter surface properties, influencing the adhesion between PP and cement matrix.
While the use of PP reinforcement in the form of fibers is widely studied, the effects of 3D structure reinforcement are much less investigated. Specifically, layered mesh reinforcement is of interest, as it is suggested that the long range connectivity may improve energy absorption, therefore improving impact resistance. It is seen that mesh reinforcement within cementitious materials improves flexural strength and toughness, as well as being especially useful for the reinforcement of thin samples\textsuperscript{38-40}. Utilizing 3D reinforcement allows for much more optimization of reinforcement structure and geometry compared to fiber reinforcement, which is primarily distributed randomly throughout the cement matrix. PP is a commonly used material for Fused Deposition Modeling (3D Printing), which would allow for the endless creation of 3D geometries for use as reinforcement in cement composites\textsuperscript{41,42}. As such, 3D reinforcement needs to be further studied in order to harvest the potential benefits of using optimized 3D geometries over randomly distributed fibers.
2.7 - Conclusion

Concrete is an incredibly convenient construction material. Its properties are highly tailorable through manipulation of aggregate, water to cement ratio, quality of ingredients and admixtures. However, its brittle nature can make it unsuitable for applications where ductility or toughness are required. Through the addition of various fibers to concrete, ductility and toughness can be improved. The major conclusions from analysis of literature are outlined below:

- Toughness measurements are usually performed through a more standardized flexural testing, or through the implementation of impact testing. Toughness may be reported as the area underneath the load-deflection curve when using flexural testing, or in terms of the number of repeated blows needed to break or energy at break for impact testing.

- Of various types of fiber reinforcement, short cut fibers made of steel, polypropylene, or glass are most common. Through the crack bridging mechanism, fiber additives are able to halt the propagation of cracking through concrete. This mechanism depends on the resistance of a fiber to being pulled out, along with the strength that the fiber itself can withstand. Steel fiber reinforcement tends to provide a tougher concrete at low strain rates, while polypropylene tends to perform similarly from a toughness perspective at higher strain rates.
• With increasing volume percentage of added fibers, the toughness of FRC is improved, but this is limited to below 5% by volume due to mixing/consistency issues and decreasing compressive strength.

• PP is of interest as a reinforcement material due to its low cost, crack bridging ability, and the relative ease of using it as a 3D reinforcement, be it through pre-made mesh or 3D printed structures.
2.8 - References


CHAPTER 3

Experimental Protocol

3.1 – Materials

The samples used in this work were all prepared using Type I/II Portland Cement, a widely available cement powder that is used for most general purpose applications. Filtered, washed, and ignited Millipore sand with a particle size ranging from 0.2 to 0.8 mm, and deionized water were also used in sample fabrication. Type I/II Portland Cement was chosen for its availability, and for the purpose of reflecting wide scale applicability of the reinforcement techniques discussed in this work. Very fine and washed sand was used for consistency in sample preparation, as commercially available has a much larger and widely distributed grain size. The samples made in this work are relatively small in comparison to the scale used in most concrete applications/research, as such larger and more widely distributed sand may cause large fluctuations in sample structure. For the purposes of expedited production and small scale testing, non-standardized methods were utilized in the testing and production of samples, specifically in regards to sample size, mixing procedures and compaction techniques. These protocols do not conform to ACI or ASTM standards, but make reference or comparison to them for guidance. Compaction techniques beyond pressing by hand were not utilized to avoid disturbing the geometrical structure of reinforcement in an unforeseen and non-reproducible fashion. Pure cement mortar samples produced with the methods used are shown to adhere to the minimum 28 day strength requirement described by ASTM C150,
as is further described in Section 4.3.1. Deionized water was used for standardizing samples by limiting the exposure to varying elements that would be present in tap water. Aggregates were not used in this work due to the small sample size, hence the term cement mortar will be used throughout this work instead of concrete. Cement mortar is a combination of cement, sand, and water, while concrete contains the same materials with the addition to large aggregates. Polypropylene (PP) was added as reinforcing agent in the form of mesh and fiber. Reinforcement was added at 2% by volume to avoid mixing issues that arise with increasing fiber content, as described in Section 2.4. While this issue will not affect the production of mesh reinforced samples, as the layers are added after the cement has been mixed, this percentage of volume reinforcement is retained for comparison between samples. Mesh reinforcement could potentially be added in much larger volume dosages. The properties of the added PP materials can be found in Sections 4.2.1 and 5.2.1.

3.2 – Sample Preparation

A water/cement/sand ratio of 0.5/1.0/2.25 was used for all samples. This specific ratio was taken from a typical concrete mixture, with the large aggregates removed from the mixture. During mixing, the dry materials are first weighed and placed into a metal tumbler, which is used during mixing. Water is then added immediately prior to mixing. The amount of each material used per batch was 44.4g of water, 88.8g of cement, and 200g of sand, which will allow for enough cement mortar when mixed to create 6 cylindrical samples, with dimensions of roughly 36mm in diameter and 16mm in height. Polystyrene Greiner CELLSTAR® multiwell culture plates were used as the molds for
samples. If chopped mesh or fiber reinforcement was used, it would be added to tumbler just prior to the addition of water.

Once measured and placed in the tumbler, the materials were mixed using a Caframo BDC 1850 stirrer/rotary mixer (Figure 3.1). They would first be mixed at 125 rpm for 1 minute to intermix the layers of sand and cement within the tumbler, and then at 300 rpm for 5 minutes. The cement mortar was then poured into the molds, and pressed down by hand to minimize air bubbles. If mesh layers were used as reinforcement, the cut layers would be added after a section of cement mortar was poured, and then pressed down by hand. For example, if three layers of reinforcement were needed, a layer would be added when the mold is roughly a quarter full, another added when the mold is roughly half full, and the final layer when the mold is roughly three-quarters full. This allows for the layers to be as evenly distributed as possible, while maintaining a solid layer on either side of the sample. Figure 3.2 shows a typical PP layer that would be added during molding, alongside a sample containing the mesh. After the samples had been pressed down, excess material was scraped off using a glass slide to achieve a flatter surface.
Figure 3.1 – Rotary Mixer

Figure 3.2 – PP Mesh Layer and Fabricated Sample
The cement samples were allowed to cure for 24 hours at room temperature, before they were removed from their molds and placed in a desiccator. The desiccator was filled with deionized water to just below the elevated surface upon which samples were placed. The desiccator was sealed using a lid lined with vacuum grease, and placed in an oven at 85° C to steam cure for 72 hours. Steam curing is a method of accelerating the curing process of concrete by allowing the material to cure in a humid environment at elevated temperatures, allowing for the quicker production of samples \(^3\). 28 days of curing at room temperature is the standard upon which concrete and cement mortar strength is referenced \(^1\). As outlined in Section 4.3.1, the steam cured samples surpass the required strength described in ASTM Standard C150 \(^1\). After 72 hours of steam curing, samples are removed from the oven and kept at room temperature until tested.

### 3.3 – Sample Testing

Samples were subjected to compressive, tensile splitting, and impact testing. All procedures are detailed in Chapters 4-6.

### 3.4 – Quality Control

During compression testing, a sudden decrease in compressive strength was witnessed while testing plain cement mortar samples created using the same methods, but at different times. The stress versus strain curves between these samples can be seen in Figures 3.3 and 3.4. It can be seen that the maximum compressive stress dropped from roughly 40,000 N to 17,000 N. Due to the nature of cement powder, it may hydrate over time when in an humid environment. The cement used in this research was stored in large
coated canvas sacks, that once opened cannot be resealed. As such, it was suspected that the cement used for making the samples exhibiting poor mechanical properties was created using cement that had absorbed and reacted with water present in the air via humidity, resulting in a partially reacted cement powder.

![Figure 3.3 – Load versus Strain for “Good” Plain Cement Samples](image)

![Figure 3.4 – Load versus Strain for “Poor” Plain Cement Samples](image)
In order to determine if the cement powder was significantly hydrated, Thermo Gravimetric Analysis (TGA) was conducted on the suspected powder. Figure 3.5 shows two peaks before 100° C, showing more partial formation of C-S-H gel and other crystalline phases relative to the fresh anhydrous sample, when compared to a reference seen in Figure 3.6. Crystalline phases, while present in cured cement, are not expected to be seen in anhydrous cement powder. While the quantities of crystalline phases is quite small, it is suspected that the partial hydration may affect the mixing behavior and quality of samples creating using the hydrated powder. Additionally, a larger peak at 100° C for the old cement powder compared to fresh cement powder indicates more water present in the system from exposure to humidity. Upon replacing the cement with a newly purchased sealed bag, sample properties returned to expected values. Cement powder was stored in sealed containers from this point onwards.
Figure 3.5 – TGA Curve for Fresh and Old Cement Powder

C-S-H Gel Formation
Figure 3.6 – TGA Curve Reference for Anhydrous Cement (Top) and Hydrated Cement (Bottom) (Reproduced with Permission from Reference 4)
3.5 – References


CHAPTER 4

Mechanical Properties of Layered Reinforced Systems

4.1 – Introduction

This chapter is dedicated to the characterization of mechanical properties of cement mortar samples reinforced with the addition of PP mesh of various sizes. Specifically, three varieties of PP mesh were utilized as toughening material for the cement mortar, each of which having unique thickness, porosity, and pore size. Upon completion of cement curing, PP reinforced samples were subjected to both tensile splitting and compression tests to investigate the effects of the ductile PP reinforcement on mechanical properties. Tensile splitting reveals a material’s resistance to cracking under tensile strain, while compression testing determines the compressive strength of a material. Due to cementitious materials commonly being utilized in construction and load bearing purposes, these properties are vital to their performance. The relationship between mesh geometry on compression strength, elastic modulus, and splitting tensile strength was investigated.

It was seen that there appears to be a positive correlation between the pore size of the mesh reinforcement used and the mechanical properties of the composite material and mechanical properties, where finer meshes displaying worse compressive strength and modulus. The elastic modulus of toughening mesh layers was shown to increase with increasing mesh thickness.
4.2  –  PP Meshes

4.2.1  –  Characteristics of PP Meshes

The effectiveness of a toughening additive is not only dependent on its mechanical properties, but also on its geometry and distribution within the matrix being toughened\(^1\). As such, in order to investigate the influence of mesh geometry on mechanical and impact properties, three various types of PP mesh were utilized in our experiments. The dimensions for these meshes are presented in Table 4.1. Sizing describes the amount of openings per square inch. 7x5 would indicate that in a square inch of mesh, there is a grid of holes present with a spacing of 7 holes in one direction, and 5 holes in the other direction, for a total of 35 holes. Porosity was calculated by using the hole dimensions provided by the manufacturer along with the mesh sizing. For example, PPM-1 with a sizing of 7x5, has holes with the dimensions of 0.1 x 0.16 in, resulting in a hole with an area of 0.016 in\(^2\). Since the sizing is 7x5, this means there are 35 holes per square inch., for a total hole area of 0.56 in\(^2\) per square inch of mesh, resulting in 56% porosity.

<table>
<thead>
<tr>
<th>Mesh Name</th>
<th>Sizing*</th>
<th>Hole Width (mm)</th>
<th>Hole Length (mm)</th>
<th>Thickness (mm)</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPM-1</td>
<td>7x5</td>
<td>2.54</td>
<td>4.06</td>
<td>0.9</td>
<td>56 %</td>
</tr>
<tr>
<td>PPM-2</td>
<td>11x15</td>
<td>1.4</td>
<td>2.03</td>
<td>0.48</td>
<td>72.6 %</td>
</tr>
<tr>
<td>PPM-3</td>
<td>28x25</td>
<td>0.64</td>
<td>0.76</td>
<td>0.35</td>
<td>52.5 %</td>
</tr>
</tbody>
</table>
Each of the three meshes used possessed different geometries, with PPM-1 having the largest pores and PPM-3 having the smallest pores, as can be seen in Figure 4.1. The porosity and pore size of the mesh used as reinforcement may have a significant influence on the final properties of the reinforced cement composite. It is foreseen that the size of opening will affect the ability of viscous cement mortar paste to penetrate through mesh layers. Poor penetration might result in the formation of voids and defects within the cement mortar upon curing.

DSC measurements were made on each of the meshes to investigate their respective thermal properties and levels of crystallinity. Figure 4.2 shows DSC scans for PPM-1, PPM-2, and PPM-3, and their associated melting points and heat of fusions. Table 4.2 summarizes this data, and additionally displays the percent crystallinity for
each mesh. Percent crystallinity is calculated by dividing the theoretical heat of fusion for 100% crystalline PP, 207 J/g, by the measured heat of fusion for each sample\(^2\). PPM-1, PPM-2, and PPM-3 were shown to have similar melting points of 145, 148, and 148°C respectively. This falls within the expected range of melting temperatures for semi-crystalline PP, which can range anywhere from 75-160°C \(^3\). Degree of crystallinity was calculated to be 36, 36, and 40% for PPM-1, PPM-2, and PPM-3 respectively. This indicates that the PP composing each type of mesh is very similar. It is seen that PPM-3 has a slightly higher degree of crystallinity, which may be a reflection of the relatively larger amount of processing required to produce a finer mesh.

\[\text{Figure 4.2 – DSC for PPM-1, PPM-2, and PPM-3 (Heating Rate of 10 °C/min)}\]
Table 4.2 – Mesh Thermal Properties

<table>
<thead>
<tr>
<th>Mesh</th>
<th>Melting Temperature (°C)</th>
<th>Heat of Fusion (J/g)</th>
<th>Crystallinity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPM-1</td>
<td>145</td>
<td>74.18</td>
<td>36</td>
</tr>
<tr>
<td>PPM-2</td>
<td>148</td>
<td>74.15</td>
<td>36</td>
</tr>
<tr>
<td>PPM-3</td>
<td>148</td>
<td>82.34</td>
<td>40</td>
</tr>
</tbody>
</table>

4.2.2 – PP Mesh Layer Arrangement

As it is discussed in Chapter 3, samples are prepared with 2% by volume of PP mesh reinforcement. Upwards of 2% by volume tends to be the upper working limit of fiber reinforcement, as workability begins to suffer at higher levels of reinforcement\textsuperscript{4,5}. Due to varying thickness and porosity of the three varieties of mesh used, different amounts of layers are needed to achieve this 2% by volume of reinforcement for each mesh reinforcement.
Figure 4.3 – Mesh Layer Distribution of Samples: A) Plain Cement Mortar; B) PPM-1 Reinforced; C) PPM-2 Reinforced; D) PPM-3 Reinforced

Figure 4.3 shows the number of mesh layers utilized for each type of mesh reinforcement. For PPM-1, PPM-2, and PPM-3, the respective amount of layers used were two, three, and four.

4.3 – Results and Discussion

4.3.1 – Compression Testing

Compression testing is employed in order to determine the compressive strength of cement mortar samples. Compressive strength is a vital property for load bearing applications, and it is desired to retain as much strength as possible upon toughening with lower strength PP mesh.
Compression testing was performed at a strain rate of 1 mm/min until maximum load is achieved on an Instron Model 5582 Compression Tester, using the sample arrangement shown in Figure 4.4. Disc samples were placed with circular surfaces making contact with the compression plates, leaving the mesh layers inside the cement samples parallel with compression plates. Disc samples have a diameter of 36mm and a height of 16mm.

Figure 4.4 – Compression Testing Setup
Figure 4.5 shows the determined compressive strengths for the plain cement mortar and toughened samples. The compressive strength of plain cement mortar was found to be roughly 43 MPa, well above the 28 day strength of 28 MPa required by ASTM standard C150 for Type I cement. The addition of PP reinforcement at 2% by volume was shown to decrease strength by roughly 30% as an average trend. It is shown that compressive strength was lower as finer mesh was used within the composite, as can be seen by the continuous decrease in strength going from the large mesh (PPM-1) to the small mesh (PPM-3). We associate this phenomenon to the fact that as pore size within the mesh become smaller, it becomes more difficult for viscous cement mortar to fully penetrate and create an interlocking system between layers of mesh. As the cement cures,
this would result in the presence of voids and a smaller cross section of connected cement mortar.

**Figure 4.6** – Image of Layer Voids

Special samples were created to investigate the effect of mesh pore size on presence of voids located within the mesh composite layers. A single piece of mesh was placed in the bottom of molds used for making typical disc samples, and cement mortar was added on top. These samples were prepared using the same procedures as typical disc samples, aside from not being steam cured. This was to avoid disturbing the interlayer structure when handling the samples before they have cured. Upon completion of curing, the samples were removed from their molds and inspected using a Meiji Techno RZ Series stereo microscope. The captured images, shown in **Figure 4.6**, demonstrate the presence of voids within the mesh layers. It can be seen that voids within PPM-3 layers can be as large as the size of an entire pore, whereas voids present in PPM-1 only make a small portion of the pore size. Smaller pores are more difficult for cement
mortar to penetrate than larger pores, and may require additional mechanical compaction to decrease void presence. It is to be noted that the presence of voids will be reduced with proper compaction techniques, however this was avoided to minimize the perturbation of the PP reinforcement geometry.

### 4.3.2 – Elastic Modulus

In cementitious materials, elastic modulus is directly related to compressive strength, so it is expected for the modulus to decrease with the addition of ductile PP material. Additionally, PP has an elastic modulus of 1-1.6 GPa while typical concrete mixes can reach an elastic modulus of upwards of 60 GPa\(^7,^8\). Elastic modulus of the PP mesh was measured using compression testing, where a square sample of PPM-1 was compressed at a strain rate of 1 mm/min. Due to the geometry of the mesh, the exact surface area placed under stress was difficult to determine, potentially resulting in an underestimate of the elastic modulus. **Figure 4.7** shows an image of the surface of a section of PPM-1. It can be seen that a distinct raised surface exists, resulting in compression of just this region during compression testing.
Using ImageJ, it was measured that roughly 16.5% of the mesh area consisted of these raised areas. Measurement Technique shown in Figure A.1 of the Appendix.

**Figure 4.8** displays compression data for the tested PPM-1 sample, where the linear portion of the graph was used for elastic modulus calculation. Using the 16.5% surface area estimate, the elastic modulus was measured to be roughly 0.13 GPa, well below the expected value of PP. This may be a result of overestimating the effective surface area during compressive testing, in combination with this testing being conducted at the lower strength testing limit of the Instron Model 5582 Compression Tester. As a result, further calculations involving the elastic modulus of PP will use a value of 1 GPa for simplicity.
and comparison to known values\textsuperscript{7}.

\textbf{Figure 4.8} – PPM-1 Mesh Sample Compressive Testing

ACI Code 318, \textbf{Eq. 4.1}, was used to estimate the elastic modulus of cement mortar and PP reinforced composite samples based upon measured compressive strengths, where $E$ is elastic modulus, $W_c$ is the density of the cement mortar composite, and $F'_c$ is the compressive strength\textsuperscript{9}. Density of plain cement mortar was measured to be 2.1 g/cm\textsuperscript{3}, while the density of the PP reinforced composites was 2.076 g/cm\textsuperscript{3}.

This code is not empirically derived for application onto PP reinforced cement composites, and its use is for that of comparison amongst reinforced and unreinforced samples. The calculated elastic moduli are not to be seen as a representation of the actual elastic modulus if measured, but act as a representation of relative material properties between the various samples.

\begin{equation}
E = (W_c)^{1.5} \left(33\sqrt{F'_c}\right) \tag{4.1}
\end{equation}
A trend similar to that observed in Figure 4.5 is seen here in Figure 4.9. Elastic modulus is found to decrease by roughly 15-20% as PP mesh is added, with finer meshes displaying the largest decrease in elastic modulus. It is expected for the elastic modulus of cement mortar to decrease with the addition of a soft additive such as PP.

In order to estimate the effective elastic modulus of the PP composite layers within the composite, an equation for the isostrain condition was used to formulate Eq. 4.2. For the combined layer of PP mesh and cement mortar, an ideal isostrain condition is assumed under compression in order to estimate the effective modulus of this layer. We conducted these estimations with the understanding that the cement mortar matrix is interconnected throughout the composite within these samples, our purpose here is to
conduct relative comparison between the various mesh sized reinforcements using the same assumptions. In the model below, Figure 4.10, the mesh and cement mortar composite layer is exposed to equal compression from both sides, resulting in equal strain in both materials. Warping of the layer would be witnessed otherwise, resulting in a non-cylindrical shaped sample if tested beyond the elastic limit. This was not seen in any tested samples.

Figure 4.10 – Isostrain Model
The estimated layer modulus found using the isostrain model, corresponding to Figure 4.10 and Eq 4.2, is then applied to estimate the effective modulus of the entire composite material by applying its value into an ideal isostress condition, where the reinforcement layer and cement matrix are exposed to the same stress. The model, Figure 4.11 below shows the entire sample being exposed to equal compression from both sides, resulting in equal stress throughout the material, as the composite layers and pure cement mortar layers will have varying strain.

Figure 4.11 – Isostress Model
Using Eq. 4.2, we can estimate effective layer elastic modulus based upon the elastic modulus of plain cement mortar, elastic modulus of the PP mesh (which is assumed to be 1 GPa), and the porosity of the mesh. $E$ is the elastic modulus of a material, while $F$ is the volume fraction of a material. The elastic modulus of plain cement mortar was found to be roughly 27 GPa, as is seen in Figure 4.9. The volume fraction of cement is equal to the porosity of the mesh, as cement will fill the voids. The volume fraction of PP will be the remaining fraction of material.

$$E_{Layer} = (F_{Cement})(E_{Cement}) + (F_{PP})(E_{PP}) \quad (4.2)$$

![Figure 4.12 – Elastic Modulus of Layers (Estimated by Eq. 4.2)](image-url)
Figure 4.12 shows the predicted elastic moduli of reinforcement layers consisting of cement mortar located within pores and PP mesh. Layers composed of PPM-2 and cement mortar were calculated to have an effective elastic modulus of 19.8 GPa, the highest of the three mesh reinforcements. This is due to PPM-2 having the highest porosity, 72.6%, of the three meshes, as can be seen in Table 4.1. It is of interest to note, that although PPM-2 is calculated to have the strongest composite layer in terms of elastic modulus of the three layered systems, Figure 4.5 indicates that pore size is a more influential factor on compressive strength, as can be seen by the trend of compressive strength decreasing with decreasing pore size.

In order to estimate the elastic modulus of the entire layered composite system, an equation for the isostress condition was used to derive Eq. 4.3, as the cement mortar matrix will experience the same stress under compression as the reinforcement layers. The elastic modulus of the composite is calculated using the elastic modulus of plain cement mortar, elastic modulus of reinforcement layers (as calculated in Figure 4.12), and the volume fraction of the layers.

\[ E_{Composite} = \frac{1}{\frac{E_{Cement}}{F_{Cement}} + \frac{E_{Layer}}{F_{Layer}}} \]  

\[ (4.3) \]
Figure 4.13– Elastic Modulus of Layered Reinforced System (Estimated by Eq. 4.3)

Figure 4.13 again shows a similar trend to the one illustrated in Figure 4.12, where elastic modulus is seen to increase with increasing porosity. These values contradict the elastic moduli determined for layered samples in Figure 4.9, which are based purely on compressive strength as seen in Eq. 4.1. Eq. 4.3 predicts higher elastic modulus values than Eq. 4.1, which is due to Eq. 4.3 not accounting for the presence of air voids and defects that will naturally be reflected in calculations made using Eq. 4.1 due to the presence of air voids and defects resulting in a decrease of compressive strength. If Eq. 4.1, Eq. 4.2, and Eq. 4.3 are assumed to be applicable, the difference between the predicted values in Figure 4.9 and Figure 4.13 can be found by adding an
air volume term to Eq. 4.2, assuming that air voids due to mesh reinforcement are contained within the reinforcing layers. This results in Eq. 4.4.

\[ E_{Layer} = (F_{Cement})(E_{Cement}) + (F_{PP})(E_{PP}) + (F_{Air})(E_{Air}) \] (4.4)

By setting \( E_{Composite} \) in Eq. 4.3 equal to the values predicted in Figure 4.9, \( E_{Layer} \) can be calculated. When \( E_{Layer} \) is placed into Eq. 4.4, the air content of each reinforcing layer can be calculated.

Figure 4.14—Elastic Modulus of Layered Reinforced System
These results are seen in Figure 4.14. It is estimated that PPM-2 reinforcement layers would contain over 48% air by volume. It is suspected that although PPM-2 has larger pores than PPM-3, the extra porosity acts as a multiplier for the effect of void formation during fabrication. PPM-1 has the lowest estimated air content, supporting the notion that larger pores allow for more thorough penetration of cement through the reinforcement layer.

4.3.3 – Splitting Tensile Strength

Due to concrete’s brittle nature, it is susceptible to failure under tensile loading conditions\textsuperscript{10}. Mechanical behavior of cementitious materials is fairly predictable under constant loading conditions, however, the behavior of these materials becomes difficult to anticipate when subjected to impact and tensile forces. Therefore, it is important for cementitious materials to have significant resistance to tensile stress. In order to investigate the resistance of cementitious samples to crack formation under tensile conditions, tensile splitting tests were conducted, where a sample is placed under compression perpendicular to its top surface, creating tensile stress\textsuperscript{11}.

In this work, tensile splitting was performed at a strain rate of 1 mm/min until maximum load is achieved on an Instron Model 5582 Compression Tester, using the arrangement shown in Figure 4.15. Disc samples are placed with circular surfaces perpendicular to the compression plates, forcing the contact surface into tension.
Figure 4.15 – Tensile Splitting Setup
Figure 4.16 – a) Tensile Splitting Strength of Layered Reinforced Systems, b) Area under Splitting Curve for Layered Reinforced Systems
Figure 4.16a shows the tensile splitting strength for the tested layered reinforced systems. Splitting strength was calculated following the ASTM standard C496, Equation 4.5, where $T$ is the splitting tensile strength, $P$ is the maximum load applied by the instrument before cracking, and $l$ and $d$ are the length and diameter of the samples.11

$$T = \frac{2P}{ld} \quad (4.5)$$

Figure 4.17 – Determining Maximum Tensile Splitting Load

At the peaks displayed in Figure 4.17, a crack instantaneously appears and propagates across the circular face. It is the load at this point that was used in determining the splitting strength. Figures A.2-A.5, found in the Appendix, show the area underneath the Load vs Strain tensile splitting curves for the samples in Figure 4.16. The area underneath the curve up to the cracking load is a reflection of toughness, with a larger area being more indicative of energy absorption. However, reinforced samples were often seen to have a lower measured area, despite displaying better impact resistant behavior,
as is seen in Chapter 6. This may be indicative of a different initial cracking mechanism, where in mesh reinforced samples, a surface crack appears at lower loading due to the crack not penetrating through the entire sample, but only up to the outer mesh layers. As such, it was seen in Figure 4.16b that energy absorption before a surface crack appeared decreased with the addition of mesh reinforcement, with energy further decreasing with smaller mesh sizes. Unreinforced mortar samples displayed a splitting strength of 1.5 ± 0.06 MPa. The usage of layered mesh systems showed a decrease in splitting strength by roughly 10%. However the trend of finer meshes causing larger reductions in physical properties is not visible here, with PPM-3 showing a higher splitting strength value than PPM-1. One of the possible reasons is arresting of microcrack growth by air pockets. It is of note that despite causing a reduction in splitting strength, layered mesh reinforcement is able to stitch samples together as the crack propagates, as is seen in Figure 4.18. Unreinforced samples simply crumble upon removal from compression loading, while reinforced samples are capable of remaining as one continuous body.
Figure 4.18 – Stitching Effect of Mesh Reinforcement
Conclusions regarding the effects of layered PP mesh reinforcement on the mechanical properties of cement mortar are as follows:

- The addition of 2% by volume PP mesh layer reinforcement results in a decrease of compressive strength of 30%, with compressive strength further decreasing with decreasing pore size.
- Decrease in mechanical properties with decreasing pore size can be attributed to lower PP properties and the inability for cement mortar to penetrate smaller pores before curing.
- Same trend is seen for elastic modulus, with elastic modulus decreasing by 15-20% with the addition of PP mesh layer reinforcement.
- Effective elastic modulus of reinforcement layers and composite systems were calculated using isostress and isostrain assumptions. Modulus is predicted to increase with increasing mesh porosity.
- Air content was estimated to be lower in the largest mesh size, supporting the trend of strength decreasing with decreasing pore size.
- Splitting tensile strength seen to decrease by roughly 10% with the inclusion of PP mesh layer reinforcement, however the trend of decreasing properties with decreasing pore size is not seen here; samples reinforced with PPM-3 were shown to have the highest strength of the three reinforced samples, as air pockets may arrest crack growth. Reinforced samples are held together by mesh after fracture, prolonging usability beyond that of unreinforced samples.
4.5 – References


CHAPTER 5

Mechanical Properties of Isotropic Reinforced Systems

5.1 – Introduction

This chapter is dedicated to the characterization of mechanical properties of isotropically reinforced cement mortar. PP fiber and chopped PP mesh flakes were mixed directly into cement mortar mix, and used as a uniformly non-directionally distributed reinforcing material. PP fiber and PP mesh flakes were also combined with layered mesh to investigate the effects of combining the two forms of reinforcement; anisotropic and isotropic samples were subjected to both tensile splitting and compression tests, where the influence of reinforcement orientation within the composite on mechanical properties was investigated.

Isotropic PP reinforcement was observed to retain more compressive strength and elastic modulus than anisotropic layered reinforcement systems. Improved properties were found upon combining isotropic reinforcement with layered reinforcement, while a negative effect was witnessed upon combining PP fiber and PP mesh flakes.
5.2 – Isotropic PP Reinforcement

5.2.1 - Isotropic Reinforcement

While the previous chapter focused on the effect of anistropic reinforcement geometry on mechanical properties, this chapter is reporting on the influence of reinforcement orientation within the matrix being toughened on mechanical properties. The mechanical properties of isotropically reinforced samples were investigated, along with mixed reinforced samples that combine isotropic reinforcement with anisotropic mesh layers. It is foreseen that a uniform distribution of reinforcing material will result in more effective crack bridging throughout the composite, ultimately resulting in a higher toughness.

PPM-2 mesh, cut into roughly 10x10 mm flakes, and PP fiber were used as isotropic reinforcement. PP fibers were 0.25mm in diameter, and cut to roughly 20mm in length. These materials, seen in Figure 5.1, were added directly into the cement mortar mixture during mixing in order to evenly distribute them throughout the cement matrix. PPM-2 mesh was used for the flakes due to its intermediate sizing and promising preliminary impact testing results, which will be discussed in Chapter 6.
5.2.2 - Isotropic Reinforcement Arrangement

Samples were prepared with 2% by volume of reinforcement. PP fiber and PPM-2 flakes were added directly to the cement mortar mix in order to promote uniform distribution. Mixed reinforcement samples contained 1% by volume of isotropic reinforcement (PP fiber or PPM-2 flakes), combined with a 1% by volume of layered PPM-3 mesh. PPM-3 mesh was used as layered reinforcement due to two mesh layers conveniently being roughly 1 volume percent of reinforcement. Samples combining 1% by volume of PP fiber and 1% by volume of PPM-2 flakes were also created. Sample structure can be seen in Figure 5.2.
5.3 – Results and Discussion

5.3.1 – Compression Testing

Following the same procedure and set up as described in Chapter 4.3.1, compression testing was performed on samples with added isotropic reinforcement. Figure 5.3 shows the determined compressive strengths for plain cement and isotropically toughened samples. The compressive strength of plain cement mortar was found to be roughly 41.5 MPa. It is to be noted that this value differs slightly from the
reported value of 43 MPa in Chapter 4.3.1, as is seen in Figure 4.5. This is due to a new batch of plain cement mortar samples being created for testing in conjunction with the preparation of isotropic samples. To account for this difference in strength, normalized values for PPM-2 and PPM-3 reinforced samples are added to figures containing compressive strength and elastic modulus data for reference; PPM-2 and PPM-3 values were normalized by multiplying the original values by the ratios of the compressive strength of the new versus old plain cement batches, \( \frac{41.5}{43} \). The addition of 2\% by volume of PP fiber was shown to decrease compressive strength to 30.4 ± 7.4 MPa, while the addition of PPM-2 flakes was shown to decrease compressive strength to 33.3 ± 5.2 MPa. While PP fiber reinforced samples appear to follow the trend of a roughly 30\% reduction in strength with the addition of 2\% by volume PP reinforcement, the addition of PPM-2 flakes resulted in a loss of only roughly 20\%. This is an indication of possible improvement due to the use of isotropic reinforcement, especially when compared to the normalized values for PPM-2 and PPM-3 mesh reinforced samples, which are lower than all but PP Fiber + PPM-2 Flake reinforced samples. We suggest that this may be as a result of less localized “weak spots” or voids, as seen in Figure 4.6, as this reinforcement is evenly distributed throughout the sample. Compare this to the layered system, where these voids will be concentrated along mesh layers.
Compressive strength values for the mixed reinforcement samples showed much more variability. Samples reinforced with a combination of PPM-2 flakes and PPM-3 layered mesh displayed slightly less reduction in compressive strength in comparison to PPM-2 flake reinforced samples, with a measured value of 34 ± 6.7 MPa. This would
indicate a synergistic effect when combining isotropic PP reinforcement with layered mesh. This effect is further supported with improvement in overall compressive strength upon the addition of 1% by volume of PP fiber and 1% by volume of PPM-3 layered mesh; a slight improvement in compressive strength was recorded, with a measured value of 42 ± 4.6 MPa, compared to the strength of plain cement mortar of 41.5 ± 2.3 MPa. It is supposed that PP fiber within the cement mortar is able to penetrate mesh reinforcement layers, filling in potential locations for void formation upon curing, removing “weak spots”. Conversely, samples reinforced with 1% by volume of PP fiber and 1% by volume of PPM-2 flakes showed a further reduction in compressive strength compared to samples reinforced purely with either PP fiber or PPM-2 flakes. We suggest that during mixing of these samples, fibers and mesh flakes aggregate together, resulting in the formation of soft PP regions which lower the strength of the reinforced composite. These regions may essentially act as large soft inclusions due to the much lower strength of PP in comparison to cement mortar.

5.3.2 Elastic Modulus

ACI Code 318, see Eq. 4-1, was again used to estimate the elastic modulus of tested samples. Figure 5.4 shows estimated elastic moduli for tested isotropic and mixed reinforcement samples. Plain cement mortar was estimated to have an elastic modulus of 26.5 GPa. Samples reinforced with 2% by volume of PP fiber were estimated to have an elastic modulus of 22.3 GPa, a reduction of roughly 16% in comparison to plain cement mortar. PPM-2 flake reinforced samples showed a slight improvement in elastic modulus
in comparison to PP fiber reinforced samples; PPM-2 flake toughened samples had an estimated elastic modulus of 23.3 GPa. It is to be noted that both of these isotropically reinforced systems displayed a larger retention of elastic modulus and compressive strength compared layered mesh systems; Figure 4.7 displays a reduction in elastic modulus of upwards to roughly 20% for layered reinforced systems, well above the magnitude in reduction seen for isotropic and mixed reinforcement systems (aside from non-synergistic PP fiber/PPM-2 mesh mixed reinforcement samples).

Figure 5.4 – Elastic Modulus of Isotropically and Isotropically/Anisotropically Reinforced Systems

1) Normalized PPM-2 + Cement; 2) Normalized PPM-3 + Cement
5.3.3 – Splitting Tensile Strength

Following the same procedure and set up as described in Chapter 4.3.3, compression testing was performed on samples with added isotropic reinforcement. Figure 5.5 shows the determined splitting tensile strengths for plain cement and isotropically toughened samples. For this batch of samples, plain cement mortar was found to have a splitting tensile strength of roughly 2 MPa. It was anticipated that upon the addition of PP to the cement matrix, splitting tensile strength would decrease similarly to the results seen in Figure 4.16. This is witnessed for samples reinforced isotropically with either PP fiber or PPM-2 flakes, with PPM-2 flakes showing a smaller reduction in splitting tensile strength than PP fiber reinforced samples; splitting tensile strength for PP fiber samples was found to be 1.5 ± 0.2 MPa, while the splitting tensile strength for PPM-2 flake reinforced samples was found to be 1.9 ± 0.02 MPa.
Figure 5.5 – a) Tensile Splitting Strength of Isotropically Reinforced Systems, b) Area under Splitting Curve for Isotropically Reinforced Systems
Varied results are seen for mixed reinforcement samples, similarly to what is seen in Section 5.3.1. Samples toughened with a combination of PPM-2 fiber and PPM-3 mesh were shown to have similar splitting strength to samples reinforced only with PPM-2 mesh flakes, while samples reinforced with a combination of PP fiber and PPM-2 flakes were shown to have the weakest splitting strength of the three types of mixed reinforcement samples. This further supports the lack of synergy upon combining flakes and fibers as a means of reinforcement. However, samples reinforced with a combination of PPM-2 flakes and PPM-3 mesh were seen to have a splitting tensile strength of $2.59 \pm 0.29$, a 30% increase to plain cement mortar. It was expected for the addition of soft material to decrease the splitting strength of cement mortar based upon the “rule of mixtures”, indicating a synergistic effect for a combination of PPM-2 flakes and PPM-3 mesh; it is suggested that the evenly distributed flakes halt the formation of micro cracks that would propagate from the mesh layer, increasing the composite’s ability to withstand tensile stress. PPM-2 Flake reinforced samples displayed the largest area under the curve before failure, indicating a greater ability to absorb energy before catastrophic cracking. All combinations of reinforcement were also seen to improve energy absorption before failure relative to plain cement mortar aside from PP fiber reinforcement. Curves for area measurement for Figure 5.5b can be found in Figures A6-A11 of the Appendix.

It was seen in Figure 4.18 that layered mesh reinforcement was able to stitch samples together after cracking, maintaining one continuous body. Figure 5.6 shows PP fiber reinforcement is also capable of holding a sample together upon crack formation. Samples reinforced only with PPM-2 flakes showed this mechanism as well, however
due to the short length of the flakes, the sample will only be stitched together for a small amount of strain.

Figure 5.6 – PP Fiber Reinforced Sample after Tensile Splitting
5.4 – Conclusion

Conclusions regarding the effects of isotropic and mixed PP reinforcement on the mechanical properties of cement mortar:

- The addition of isotropic PP reinforcement decreases the compressive strength of cement mortar by roughly 30%. The magnitude of strength reduction strength appears to be minimized upon the combination of PP fibers and PPM-3 mesh. It is suggested that due to fibers replacing voids within mesh pores.
- Isotropic reinforcement displays less reduction in compressive strength and elastic modulus than layered reinforcement.
- Splitting tensile strength is improved upon addition of PPM-2 flakes and PPM-3 mesh as reinforcement, indicating a synergistic effect.
- Compressive strength and elastic modulus of samples reinforced with a combination of PP fiber and PPM-2 flakes are shown to decrease beyond that of samples reinforced only with one or the other. It is suggested that agglomeration occurs between the two additives during mixing, results in the creation of soft defect regions.
5.5 – References

CHAPTER 6

Impact Testing of Isotropic and Anisotropic PP reinforced Systems

6.1 – Introduction

This chapter is dedicated to the investigation of impact properties of both isotropic and anisotropic PP reinforced samples. Samples are subjected to two methods of impact testing: sequential impact where damaged samples are exposed increasing impact loads, and single impact where samples are exposed to impact with one load. Testing was monitored using a high speed camera, and ImageJ and Virtual Dub were used to evaluate impact energy and rebound height for tested samples. Larger samples were also fabricated to obtain more consistent rebound results. The relationships between reinforcement type, rebound height, impact energy, and sample integrity were investigated.

It was found that PP reinforced samples clearly displayed superior impact resistance in comparison to plain cement mortar samples. A correlation between surface crack length and impact resistance was observed. Large reinforced samples exposed to single impact testing showed a clear increase to rebound height in comparison to large plain cement mortar samples, indicating that PP reinforcement is able to redirect impact energy away, thus arresting crack propagation.
6.2 – Impact Testing Procedure

While identifying mechanical properties such as compressive strength, splitting tensile strength, and elastic modulus are vital for understanding the behavior and practicality of PP reinforced cement composites, it is necessary to conduct impact testing in order to measure the effects of PP reinforcement on cement mortar toughness. Impact testing methods for concrete do exist, however they typically involve the testing of samples much larger in size than what is used in this research\textsuperscript{1,2}. Scales for these methods often involve dropping weights from upwards of 20 feet, using drop weights up the scale of hundreds of kilograms, and samples with dimensions measured in meters.

To this end, a customized apparatus was constructed for impact testing, shown in Figure 6.1. Originally, a 1.22m (4ft) polycarbonate tube with a 12.7mm (½") inner diameter was secured to a wooden beam and attached to a ring stand. The polycarbonate tube was later replaced because of warping that occurred due to exposure to heat generated from lighting sources necessary for use with a high speed camera needed for measurements. A steel tube with similar dimensions was then used instead. An opening was cut into the bottom of the steel tube to allow backlighting to pass to the high speed camera, as is seen in Figure 6.2. A clamp was built to secure samples during impact testing, as seen in Figure 6.3, where the sample is placed in the middle and radially fastened using equally spaced bolts. Samples were then placed underneath the tube and struck with various weights dropped from the top of the tube, a height of 1.2192m (4 ft). Weights were created by cutting 12.7mm (½") diameter steel rods into various lengths and rounding one end into a hemispherical surface (Figure 6.4). The parameters of each
weight used can be found in Table 6.1. A MotionPro X3 high speed camera with a Micro-Nikkor 105 mm lens was used to record and calculate impact velocity and rebound height, to quantify results of the impact testing. Impacts were recorded at 1000 frames per second, and imaging software ImageJ and Virtual Dub were used for analysis.

**Figure 6.1** – Impact Testing Apparatus
Figure 6.2 – Metal Impact Testing Tube

Figure 6.3 – Metal Clamp for Impact Testing
Two testing protocols were used for impact testing: sequential and single impacts. Under the sequential protocol, samples were struck beginning with rod 1, and ascending in mass with each sequential blow. Testing concluded once samples became fractured. This protocol was used to investigate the behavior of damaged samples as they were subjected to subsequent impacts that roughly doubled in impact energy. Under the single impact testing protocol, samples were subjected to a single blow of ~3 or ~5 J (rods 4 or 5). This protocol was used to investigate the behavior of pristine samples.
6.3 – Results and Discussion

6.3.1 Sequential Impact

All samples tested were identical to the ones reported in Chapters 4 and 5. Tested samples included: Plain, PPM-1, PPM-2, PPM-3, and PPM-2 Flakes. Impact velocity and rebound height were calculated using high speed camera footage of the impact test. ImageJ was used to calculate impact velocity by measuring the distance covered by the impact rod over several frames before impact, as is seen in Figure 6.5, and dividing by the time elapsed between frames.

Figure 6.5 – Representative Impact Velocity and Rebound High Speed Images

The width of the outer tube is known, and is used to calibrate measurements. It is to be noted that these initial tests were conducted using the polycarbonate tube, prior to its replacement. This results in slightly variable impact velocities due to friction and warping; impact velocities ranged from roughly 3.5 to 4.6 m/s, with rod 2 typically being
recorded at the lower end of the spectrum. The heaviest three rods were typically recorded at values above 4 m/s. This results in a range of possible impact energies of roughly 0.2 to 5.5 J, calculated using the formula for kinetic energy, where \( m \) is the mass of the impact rod in kg, and \( v \) is the velocity of the rod at impact in m/s:

\[
k = \frac{1}{2} mv^2 \quad (6-1)
\]

The typical values of impact energy are posted in Table 6.1. On occasion, impact rods will rebound beyond the camera frame, requiring calculation to determine peak rebound height. This was done by mapping the distance travelled by the impact rod after impact. A point on the rod was marked after impact and its distance from the impact surface was measured. This was considered to be time moment zero (the frame number was recorded for subtraction for subsequent frames). Every several frames forward, the distance of this same point on the rod from the original point in space was measured, and the associated frame number was recorded. This was continued until the impact rod returned back into the camera frame, where a final recording was noted. The length in time of each frame was known, so the moment of time of each recorded position could be calculated based on frame numbers. The positions in space were then graphed versus time, and fitted with a second degree polynomial. This is due to the impact rod being under a state of acceleration due to gravity, where air resistance is ignored, is expected to follow Eq 6.2, where \( x(t) \) is the position of the rod at any point in time, \( a \) is the acceleration due to gravity, \( v_0 \) is the initial velocity of the rod after impact, and \( x_0 \) is the position of the rod at time equal to zero.
\[ x(t) = \frac{1}{2} at^2 + v_0 t + x_0 \quad (6-2) \]

**Figure 6.6** displays images of an impact rod in various points in time after impact, with lines measuring the distance of the rod tip from the strike surface of the sample. These positions and time moments are shown in **Table 6.2**. This data is fitted to **Eq 6.2**, providing an effective \( a \) term.

**Figure 6.6** – Representative Impact Velocity and Rebound High Speed Images

<table>
<thead>
<tr>
<th>Time Moment (ms)</th>
<th>Position (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3.354</td>
</tr>
<tr>
<td>6.965</td>
<td>11.793</td>
</tr>
<tr>
<td>17.91</td>
<td>24.401</td>
</tr>
<tr>
<td>31.84</td>
<td>37.937</td>
</tr>
<tr>
<td>47.76</td>
<td>50.892</td>
</tr>
<tr>
<td>58.705</td>
<td>57.943</td>
</tr>
<tr>
<td>172.135</td>
<td>54.351</td>
</tr>
</tbody>
</table>
It is expected for an ascending body, without the influence of pressure and air resistance, to display deceleration of 9.8 m/s² due to gravity, where down is considered the positive direction, however curve fitting consistently found the impact rod to decelerate at a rate of 11 to 12 m/s². This likely a result of friction within the polycarbonate tubing slowing the rods ascent after impact, one reason for its future replacement with a steel tube, and air pressure.

For each test, non-absorbed energy by the sample upon impact was calculated based upon the rebound of each strike; the potential energy of the rod after impact when it has reached its peak rebound was calculated using Eq 6.3 where m is the mass of the...
rod, \( g \) is acceleration due to gravity, and \( h \) is the rebound height. This was termed as the non-absorbed energy.

\[
Non \text{ Absorbed Energy} = mgh \quad (6-3)
\]

Initially, it was not known if a large rebound was desired or not, as a greater rebound might indicate less energy absorption, and therefore a reduced impact resistance.

However, it was seen that reinforced samples generally displayed larger rebounds while sustaining noticeably less damage than plain cement mortar samples (Figure 6.8). It is suggested that the addition of mesh reinforcement is able to divert energy away from the sample, and return a portion to the impacting object, resulting in less energy absorption by the reinforced sample. This would mean that less energy is available for crack formation, which is supported by contrasting the images of reinforced and unreinforced samples struck with similar impact energies.

![Figure 6.8](image)

**Figure 6.8** – Sequential Impact Damage Rod 3, Plain Cement (Left) versus PPM-1 (Right):

(Samples Impacted by Rod 1, 2, and 3 Once Each in Sequential Order)
Unreinforced samples were either destroyed or heavily damaged after being struck with rod 3, while reinforced samples showed minimal signs of cracking at these impact energies. Figures 6.9-6.15 display non-absorbed impact energy values for samples subjected to sequential impact testing, where it is seen that plain cement samples failed with impact of ~2J (rod 3), aside from a single sample which failed upon ~3J impact (rod 4). Reinforced samples were seen to “survive” sequential impact up to roughly ~5J impact (rod 5).
Figure 6.9 – Non-Absorbed Energy for Sequential Impact for Plain Cement Samples and Images of Impact Damage (Impact 1 Images Show No Damage)

*Impact 5 is shown as 0 Non-Absorbed Energy due to sample being destroyed and unable to be tested
Figure 6.10 – Non-Absorbed Energy for Sequential Impact for PPM-1 + Plain Cement

Samples and Images of Impact Damage (Impact 1 Images Show No Damage)
Figure 6.11 – Non-Absorbed Energy for Sequential Impact for PPM-2 + Plain Cement

Samples and Images of Impact Damage (Images Unavailable for Impacts 1-3)
**Figure 6.12** – Non-Absorbed Energy for Sequential Impact for PPM-3 + Plain Cement

Samples and Images of Impact Damage (Impact 1 Shows No Damage)
Figure 6.13 – Non-Absorbed Energy for Sequential Impact for Chopped PPM-2 + Plain Cement Samples and Images of Impact Damage (Impact 1 Images Show No Damage)
Figure 6.14 – Non-Absorbed Energy for Sequential Impact for PP Fiber + Plain Cement Samples (*Images Unavailable)

(TESTED USING METAL TUBE)

Figure 6.15 shows the state of most PP-reinforced samples after sequential impact testing, ranging from rod 1 to rod 5. Reinforced samples are clearly damaged upon impact with ~5J (rod 5) (scabbing/cracking/back-blow), yet remain one continuous body. Unreinforced samples fragment into separate pieces at lower energies of impact. Non-Absorbed energy is seen to decrease after ~3J of impact for reinforced samples,
aside from PP-Fiber reinforced samples where there is a large deviation in rebound behavior due to increased penetration that is not visible in other reinforced samples. It is at this point that PP reinforcement is inhibiting the growth of large cracks once the cement matrix is no longer capable of energy absorption, resulting in delayed failure. Visually, more damage is clearly visible on plain cement samples at comparable energies to reinforced samples. It is to be noted that the impact strike surface changes in between strikes as the crater enlarges and deepens upon sequential impact. More energy transfer may be possible with the a larger surface area during impact, which is believed to influence the lower rebound energies of PP Fiber reinforced samples which are more prone to penetration.

![Figure 6.15](image)

**Figure 6.15** – PPM-3 Sample after Sequential Impact Testing

(Struck by All Rods)
6.3.2 Single Impact Testing

The same assortment of samples as in sequential impact testing were utilized in single impact testing, where they were subjected to only one individual strike of either ~3.5J (rod 4) or ~5J (rod 5). Figures 6.16-6.21 display non-absorbed energy values for samples subjected to single impact testing. Images of samples after impact are placed above the corresponding impact energy within each figure. While visual evidence clearly shows greater integrity of reinforced samples compared to plain cement samples (plain cement samples are fractured into pieces after single impact with rod 5), differentiation between the reinforced samples is challenging. Plain cement shows a decrease in rebound height from ~3.5 to ~5J impact, which is not readily seen from reinforced sample data. This decrease may be attributed to the energy absorption limit of the plain cement mortar, where cracks finally propagate throughout the entire material. As was seen previously in Figure 6.9-6.14, reinforced samples were still able to absorb and redirect energy away from crack propagation after impact with ~3J (rod 4), while plain cement samples failed with impact of ~2 and ~3J (rods 3 and 4). It is suggested that this ability to redirect energy from crack propagation results in an increase in non-absorbed energy when comparing ~3.5 and ~5J (rod 4 and rod 5) single impact for reinforced samples.
Figure 6.16 – Non-Absorbed Energy for Single Impact for Plain Cement Samples

(Samples Subjected to Single Strike from Rod 4 or 5)

*No Image for 5J Impact, Plain Cement Sample Shattered at this Impact
Figure 6.17 – Non-Absorbed Energy for Single Impact for PPM-1 + Plain Cement Samples

(Samples Subjected to Single Strike from Rod 4 or 5)
Figure 6.18 – Non-Absorbed Energy for Single Impact for PPM-2 + Plain Cement Samples

(Samples Subjected to Single Strike from Rod 4 or 5)
Figure 6.19 – Non-Absorbed Energy for Single Impact for PPM-3 + Plain Cement Samples

(Samples Subjected to Single Strike from Rod 4 or 5)
Figure 6.20 – Non-Absorbed Energy for Single Impact for Chopped PPM-2 + Plain Cement Samples

(Samples Subjected to Single Strike from Rod 4 or 5)
Figure 6.21 – Non-Absorbed Energy for Single Impact for PP Fiber + Plain Cement Samples

(Samples Subjected to Single Strike from Rod 4 or 5)
In order to further quantify the effectiveness of various PP reinforcement, the total surface crack length of the non-strike surface of single impact tested samples was measured. A smaller total crack length would be an indication of greater impact resistance and material energy absorption. The non-strike surface, the opposite side of the sample exposed to impact testing, was photographed and the visible cracks were measured and recorded using ImageJ. This process can be seen in Figure 6.22. Total crack length measurements can be seen in Figure 6.23. Measurements for ~5J (rod 5) impact for plain cement samples are not present due to fracturing and non-retention of a continuous body after ~5J (rod 5) impact. As is expected, total surface cracking is greater for higher energy impact (~3.5J compared to ~5J). Plain cement exposed to ~3.5J (rod 4) impact displays greater total surface crack length than any reinforced sample at ~3.5J (rod 4) impact. Additionally, plain cement exposed to ~3.5J (rod 4) impact displays similar total crack length to reinforced samples exposed to ~5J (rod 5) impact, indicating similar damage with less impact energy.
Figure 6.22 – Crack Length Measuring Protocol for Single Impact Testing
Figure 6.23 – Non-Strike Surface Crack Lengths for Single Impact Testing
Total measured crack length for PP Fiber and PPM-2 Flake samples were very similar for both ~3.5 and ~5J (rod 4 and rod 5) impact. This is likely due to their similarities as a form of isotropic reinforcement, as opposed to the anisotropic layered systems where mesh geometry appears to have a strong influence on mechanical properties (as discussed in Chapter 4). Additionally, PP Fiber and PPM-2 Flake samples show larger amounts of cracking after ~5J (rod 5) impact than any other reinforced samples. It is suggested that due to the structure of layer reinforced mesh samples, cracking may occur along the surface of the mesh layers where fiber bridging is occurring, while in the isotropically reinforced systems, PP Fiber and PPM-2 Flakes, there is no preferential location for cracking to concentrate due to the uniformity of reinforcement within the matrix, resulting in more cracks being revealed on the surface. PPM-3 layered samples displayed significantly smaller amounts of cracking upon impact with ~3.5J (rod 4), but displays similar, yet slightly smaller, values upon impact with ~5J (rod 5). Based upon the mechanical properties of layered reinforcement systems described in Chapter 4, it would be expected for PPM-3 layered samples to exhibit worse performance in comparison to PPM-1 and PPM-2 due to containing smaller pores that would result in void formation. However, this does not appear to be the case in regards to resistance of crack propagation. This may be attributed to PPM-3 having more pathways for crack propagation to occur on due to its finer size amount of links and air pockets; it will be less likely for cracks to converge on the same path, inhibiting the growth of large cracks.
6.3.3 Large Sample Impact Testing

Large samples were created for impact testing in order to reduce the error resulting in the use of small samples; large samples will be able to absorb more energy, mitigating the influence of external factors, such as sample vibration during testing, as the magnitude of the created energy fluctuations in relation to the energy absorbing capability of the sample will be minimized. As was seen in Figures 6.16-6.21, differentiation of impact behavior between reinforced samples was challenging. In using large samples, we seek to clarify these distinctions. Large samples were created using the same procedures as previously tested small samples, but with a different mold. A rigid polystyrene rectangular mold with base dimensions of 14 x 10 ½ cm was used. Samples were poured to be roughly 1 cm in height, and samples remained within the mold during testing, instead of using the clamp seen in Figure 6.3. Two variants of reinforced large samples were created: plain cement reinforced with single layer of PPM-1 mesh (roughly 2% by volume), and plain cement reinforced with 2% by volume of chopped PPM-2. Samples were secured during impact testing using magnets secured to the magnetic table upon which the impact testing apparatus rests. A tested large sample can be seen in Figure 6.24.
Large samples were exposed to single impact testing protocol, where they were either struck by rod 4 or 5. **Figure 6.25** displays non-absorbed energy values for tested large samples struck by ~7J impact (rod 5). It can be clearly seen that single layer PPM-1 reinforced samples displayed distinctly higher non-absorbed energy values compared to plain cement and chopped PPM-2 reinforced samples. This can also be clearly seen in the
large visual difference in rebound seen in Figure 6.26, in addition to the evidence of fragmentation seen in the plain cement sample. Chopped PPM-2 reinforced samples did not exhibit improvement over plain cement samples, conversely to what would be expected from single impact testing of smaller samples. It is suggested that the due to the geometry of the larger samples, much of the chopped PPM-2 reinforcement is distributed too far away from the impact site to influence the impact behavior dramatically. Additionally, the large samples are much thinner in relation to surface area in comparison to the small disc samples. This results in a much smaller concentration of chopped mesh immediately under the impact site. This indicates that layered mesh reinforcement is a superior reinforcement over isotropically distributed reinforcement in thin, relative to geometry, samples.
Figure 6.25 – Rebound Height of Large Samples under Rod 5 Impact

(Single Strike from Rod 5)

(TESTED USING METAL TUBE)
Figure 6.26 – Rebound of Large Samples under Rod 5 Impact, Plain Cement (Left) versus Single Layer PPM-1 (Right)
Samples subjected to single impact from rod 4 were analyzed using a Meiji Techno RZ Series stereo microscope. Figure 6.27 displays a visual side-by-side comparison of cracking and cratering in large samples after ~3.5J (rod 4) impact. The crater left at the impact site is much more clearly defined in the plain cement sample, in addition to the outward branching cracks appearing much wider than that of the single layer PPM-1 reinforced sample. Figure 6.28 displays crack width measurements taken 2.54 cm (1 inch) from the center of the crater, where it can be seen that the unreinforced sample has cracks roughly three times wider than those seen in the reinforced sample. This is a clear indication of the crack prevention abilities of layered mesh reinforcement.

Figure 6.27 – Large Sample Single Rod 4 Impact, Plain Cement (Left) versus Single Layer PPM-1 (Right)
Figure 6.28 – Crack Measurements of Large Sample Single Rod 4 Impact (2.54 cm from Center), Plain Cement (Left) versus Single Layer PPM-1 (Right)
6.4 - Conclusion

Conclusions regarding the effects of PP reinforcement on impact properties of cement reinforced samples:

- PP reinforcement greatly improves the impact resistance of cement; under sequential impact loading, plain cement mortar samples shattered at loads between 2-3 J, while all reinforced samples “survived” impact upwards of 5J.

- Layered PP reinforcement increases rebound and impact resistance as it is able to redirect energy away from crack formation, and even return a portion of energy back to the projectile.

- PP reinforcement inhibits crack growth, with finer mesh reducing crack growth the most due to an abundance of pathways for cracking to occur on.

- Layered PP reinforcement prevents penetration by the impact projectile more so than isotropic reinforcement, and is ideal for reinforcing thin objects.

- Large samples displayed more consistent results, and clearly show more rebound is to be expected when layered PP reinforcement is used to improve impact resistance.
6.5 - References


CHAPTER 7

Conclusion

7.1 - Conclusions

PP mesh was successfully utilized as a reinforcing material for FRC, as toughness and impact resistance were readily improved. The effectiveness of mesh as a reinforcing material are highlighted by its ability to maintain integrity within a reinforced sample after cracking and by its ability to improve impact resistance within thin samples. Key points of this research are:

- The fineness of mesh reinforcement is influential on mechanical properties, as decreasing pore size results in the creation of air pockets when cement is not able to penetrate layers before curing, resulting in lower compressive strength

- The addition of 2% by volume PP reinforcement results in a roughly 30% decrease in compressive strength, with some reinforcement combinations exhibited more strength retention due to potential synergy. It is believed that fiber and mesh combinations may mitigate strength loss due to fibers penetrating and filling in voids within mesh layers. An opposite effect is seen on combination with fibers and chopped mesh due to potential agglomeration during mixing

- A method for conducting impact testing for small samples was successfully developed utilizing a high speed camera and imaging
software. Relationships between rebound and impact resistance were observed, and made clearer when testing larger samples. Rebound height is seen to increase with impact resistance, as PP mesh reinforcement is able to redirect energy back into the projectile in addition to dissipating energy along the cement-polymer interface

- Samples reinforced with PP reinforcement were seen to survive impacts upwards of 2.5 to 3 times the energy of unreinforced samples
- Layered mesh reinforcement reduces penetration upon impact in comparison to isotropic reinforcement due to the connectivity of the mesh being able to absorb energy from a small area of impact

### 7.2 – Future Work

This research has shown the potential of mesh as a means of concrete reinforcement, and as such has shown the potential of optimizing reinforcement geometry. Through the use of simulations and calculations, optimal geometries could potentially be designed for specific impact and mechanical stresses. The utilization of 3-D printing could be especially useful in the creation of such reinforcements. The addition of strong nanomaterials to the matrix could also be investigated in order to mitigate the loss of strength upon addition of ductile material to a cement matrix, while still retaining toughness and impact resistance. Increasing the scale of these samples to implement standardized techniques such as the Schmidt hammer and resonance testing is important to further legitimize this work.
Area of the larger highlighted area, encompassing a repeating unit of the mesh, is measured as 30.563 mm$^2$, and the smaller area, encompassing all of the area of the repeat
unit aside from the raised area is measured as 25.518 mm². This results in a raised area of roughly 16.5% for the entire mesh.

**Figure A.2** – Tensile Splitting Curve Area Up To Cracking Load for Plain Cement
Figure A.3 – Tensile Splitting Curve Area Up To Cracking Load for PPM-1
Figure A.4 – Tensile Splitting Curve Area Up To Cracking Load for PPM-2
Figure A.5 – Tensile Splitting Curve Area Up To Cracking Load for PPM-3
Figure A.6 – Tensile Splitting Curve Area Up To Cracking Load for Plain Cement (Batch 2)
Figure A.7 – Tensile Splitting Curve Area Up To Cracking Load for Chopped PPM-2

Sample 1

Area = 17.66831
FWHM = 0.01921

Sample 2

Area = 15.687
FWHM = 0.10336
Figure A.8 – Tensile Splitting Curve Area Up To Cracking Load for PP Fiber
Figure A.9 – Tensile Splitting Curve Area Up To Cracking Load for PP Fiber + PPM-2 Flakes
Figure A.10 – Tensile Splitting Curve Area Up To Cracking Load for PP Fiber + PPM-3

Mesh
Figure A.11 – Tensile Splitting Curve Area Up To Cracking Load for PPM-2 Flakes +

PPM-3 Mesh
The area underneath the curve up to the cracking load is a reflection of toughness, with a larger area being more indicative of energy absorption. However, some reinforced samples were often seen to have a lower measured area, despite displaying better impact resistant behavior, as is seen in Chapter 6. This may be indicative of a different initial cracking mechanism, where in mesh reinforced samples, a surface crack appears at lower loading due to the crack not penetrating through the entire sample, but only up to the outer mesh layers.