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Feasibility of Using Recycled Waste Plastic in Concrete Pavements in Nebraska

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Waste plastic (WP) is a growing environmental concern due to its non-biodegradable nature, large-scale production, and harmful impact on natural resources. With nearly 75% of WP in the U.S. ending up in landfills, effective recycling strategies are urgently needed. In parallel, the limited availability of natural aggregates highlights the need for alternative materials in concrete construction. This study investigates the feasibility of using recycled waste plastic (RWP) in concrete mixtures, both as aggregates and fibers for rigid pavement applications in Nebraska. Concrete mixtures were prepared by partially replacing natural fine aggregates with recycled plastic aggregates (RPA) at replacement levels of 5%, 10%, and 15% by volume of the natural fine aggregates. Additionally, recycled plastic fibers (RPF) were incorporated into the mixtures at dosages of 0.5%, 1%, and 1.5% by total volume of the concrete. RWP materials underwent characterization tests to compare with traditional materials. A preliminary investigation evaluated fresh properties and compressive strength to assess suitability based on Nebraska Department of Transportation standards (NDOT), using the standard (47B) pavement mixture as a control. Mixtures meeting performance criteria were selected for further testing, including splitting tensile strength, flexural strength, and modulus of elasticity. Fracture behavior was assessed through semi-circular bending (SCB) tests. Also, durability was evaluated using the surface resistivity test, which assesses electrical resistivity as an indication of chloride ion penetration. Results showed that the inclusion of RWP aggregates can increase workability. Statistical analysis indicates that up to 10% RPA replacement does not significantly reduce compressive strength while satisfying the standard requirements set by the NDOT for paving applications. When RWP was used as fiber, a reduction in workability was observed. Nevertheless, the addition of RWP fibers had a positive influence on the flexural strength, ductility, and cracking resistance, with an optimum content of 1.5%. Surface resistivity confirmed acceptable durability performance with respect to NDOT requirements. Overall, incorporating RWP into concrete as aggregate or fibers offers a sustainable solution by reducing WP in landfills while maintaining or improving concrete performance for pavement applications.</td></tr>
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Abstract

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confirmed acceptable durability performance with respect to NDOT requirements. Overall, incorporating RWP into concrete as aggregate or fibers offers a sustainable solution by reducing WP in landfills while maintaining or improving concrete performance for pavement applications.

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Chapter 1 Introduction

1.1 Overview

Waste plastic (WP) has become a major environmental issue globally, with the increasing use of plastic products contributing to a growing accumulation of waste in landfills (Siddique et al., 2008). The U.S. Environmental Protection Agency (EPA) has collected and reported data on the generation and disposal of WP in the United States. Figure 1.1 shows that the total WP generated in the U.S. was approximately 35.7 million tons in 2018. The figure also reveals that only 8-10% of the WP was recycled, while 75-80% was disposed in landfills (US EPA, 2017). Considering the cost associated with landfilling and adverse environmental impact, recycling and reusing WP are becoming viable alternatives to reducing WP in landfills, and in turn, lowering environmental pollution, conserving natural resources, and saving energy (Hamada et al., 2024).

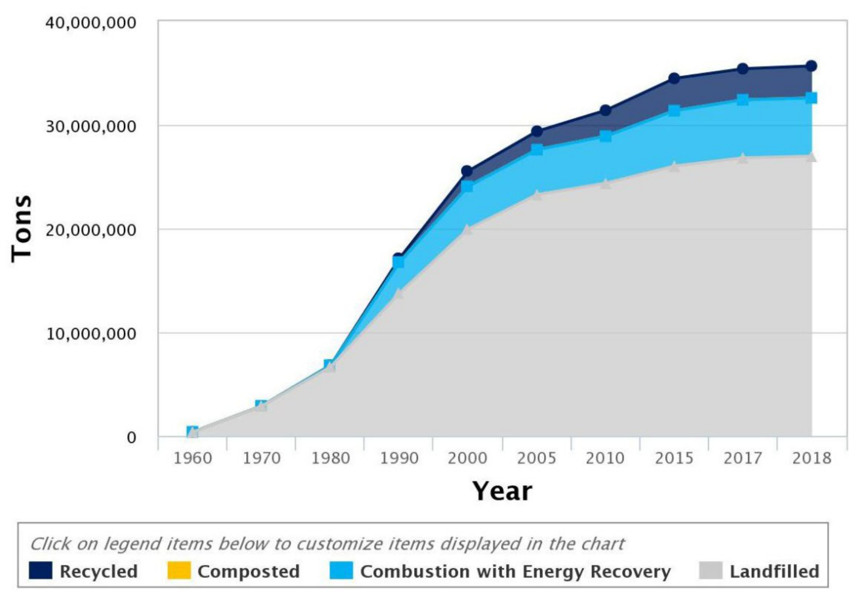


Figure 1.1 Total WP Generated (1960 – 2018), (US EPA, 2017)

Studies have indicated that incorporating recycled WP (RWP) into concrete can enhance the ductility and cracking resistance (Abu-Saleem et al., 2021; Ahmad et al., 2022; Liu et al., 2015; Saxena et al., 2018). Moreover, using RWP in concrete mixtures can reduce the volume of waste in landfills, decrease the demand for raw materials, and extend the service life of the structures, collectively contributing to lower maintenance (Ahmed et al., 2025; Khalel et al., 2025; Magbool, 2025; Mashaan et al., 2025; Shinde et al., 2025). There are various methods to integrate RWP with concrete for construction applications, such as by fully or partially replacing natural aggregates (Correia et al., 2014; Ismail et al., 2008; Sharma et al., 2016) or incorporating it as a fiber additive (Al-Hadithi et al., 2016; Huynh et al., 2023; Khalid et al., 2018) providing a valuable solution for managing WP.

In the field of transportation engineering, Portland Cement Concrete (PCC) pavements are extensively used, accounting for around 70% of the Portland cement used in the U.S. Particularly, the state of Nebraska heavily utilizes PCC pavements on major highways and airport runways. PCC pavements present an optimal chance for incorporating RWP as a partial substitute for natural aggregates or as other additives, such as fibers.

Given that different types of RWP interact differently with concrete materials, it is essential to verify the feasibility of incorporating RWP while considering the availability of materials commonly used in practice. This research contributes to both research and practice by comparing conventional PCC mixtures with PCC that integrates the RWP commonly generated in Nebraska, verifying the effects of RWP on PCC fresh and mechanical properties.

1.2 Research Significance

This research explores incorporating different types of RWP prevalent in Nebraska, such as Polyethylene (PE) and Polypropylene (PP). Based on available data, Nebraska generates more than 1.8 million tons of municipal solid waste annually, this volume includes an estimated

124,800 tons of PE and PP waste annually (Dahab, 1993). These materials can be found from post-consumer materials such as plastic bags, bottles, and food packaging (Geyer et al., 2017a; Eagan et al., 2017) or post-industrial activities such as in conveyor belts, industrial liners, wear-resistant components, packaging films, pipes, and injection molded parts (Al-Salem et al., 2009; Andrady et al., 2009; Ebnesajjad, 2012). While they are lightweight, cost-effective, and widely available, they also contribute heavily to the accumulation of WP in landfills (Siddiqui et al., 2013).

This study examines the use of Ultra-High Molecular Weight Polyethylene (UHMW) material as recycled plastic aggregates (RPA) to partially replace the natural fine aggregates based on the volume of the natural fine aggregates. As reported by Smith et al. (1980) and Zheng et al. (2004), UHMW material is extensively utilized across various industries like machinery, paper, and textiles, primarily due to its high tensile strength, low density, and outstanding chemical resistance (Latifi et al., 2022). In Nebraska, UHMW is a commonly available material due to its widespread use in agriculture and manufacturing industries, where it is employed in products such as conveyor belts, liners, and agricultural machinery components (Global Polymer Industries Leads North America in Custom-Molded U - NORTHEAST - 2018). The high availability of UHMW material in these sectors presents an opportunity to repurpose this material for sustainable construction applications.

Due to the low stiffness and flexibility of RPA particles, it is hypothesized that replacing part of the natural aggregate with RPA may reduce the brittleness of the concrete mixture and improve its crack resistance. Additionally, the presence of RPA potentially enhances the material's ability to absorb energy underloading and delays the initiation and propagation of micro-cracks (Kaur et al., 2020a; Zheng et al., 2021).

The study also examined utilizing PP as an additive recycled plastic fiber (RPF) by the total volume of concrete. In Nebraska, PP material is widely applied in packaging and agricultural purposes, making it readily available for recycling purposes (Wikipedia, 2025). The inclusion of RPF in concrete has been widely recognized for enhancing various performance aspects of the material, it can improve tensile and flexural strength, improve the post-cracking behavior and ductility of concrete, contributing to greater toughness and energy absorption capacity, and provide better cracking resistance (Kakooei et al., 2012; Latifi et al., 2022; Wang et al., 2025). However, this study proposes a novel approach by incorporating these RWP types into concrete mixtures as part of a sustainable waste management strategy.

As per the Nebraska Department of Transportation (NDOT) requirements, a mixture that produces a minimum compressive strength of 3,500 psi at 28 days, which is designated by 47B, should be used in all PCC pavement applications (Standard Specifications for Highway Construction, 2017). Thus, this research project aims to explore the effectiveness of using the selected RWP materials to partially replace the natural fine aggregates or to be added to the concrete mixture as fibers while meeting the required strength for pavement in the 47B category. Moreover, the project investigates the fresh and hardened properties of the proposed concrete mixtures to ensure the feasibility of its implementation.

1.3 Research Objectives

The ultimate goal of this multi-phase study is to evaluate the effectiveness of incorporating different types of recycled waste plastics (RWP) into concrete mixtures for PCC pavement applications, a strategy that could increase Nebraska's recycling rates while potentially enhancing the quality of concrete mixtures. The aims of Phase 1 of this study are to:

- Development of concrete mix that satisfy NDOT minimum requirements for PCC pavements, incorporating various types and proportions of RWP. The RWP is used in two forms: as RPA to partially replace natural fine aggregates by volume of the natural fine aggregates, and as RPF added by total volume of the concrete.

- Evaluation of the fresh and mechanical properties of the RWP proposed concrete mixtures, including fresh testing such as temperature, slump, air content, and unit weight, and mechanical testing such as compressive strength, splitting tensile strength, and flexural strength, which are commonly used for the initial assessment of concrete performance.
- Evaluation of the effects of utilizing RWP on stiffness, cracking resistance, and fracture behavior using the modulus of elasticity and Semi-Circular Bending (SCB) tests to determine the fracture energy and ductility index.
- Assess the durability and permeability characteristics, including the chloride ion penetration test to have a preliminary evaluation of the long-term performance of the concrete mixtures incorporating RWP materials.

1.4 Report Organization

The report is organized into five chapters. Chapter 1 provides an introduction, the research significance and the objectives of this project. Chapter 2 explores the available literature to summarize the current practice and developments in the field of PCC pavements and to identify the associated knowledge gap. Chapter 3 comprehensively presents the material characteristics and research methodology and highlights the mixing and testing procedure. Chapter 4 reports experimental investigation in both preliminary and in-depth stages. Including the evaluation and corresponding insights for the proposed concrete mixtures with the addition of RWP. The last chapter provides conclusions and recommendations for future research.

Chapter 2 Literature Review

Numerous research studies have been conducted on using recycled waste plastics (RWP) in concrete production applications. In this chapter, studies that examined the effects of utilizing RWP in concrete mixtures on the hardened and fresh-state properties of concrete are summarized. Additionally, studies on the sustainability and environmental impact of using RWP in concrete are reviewed.

2.1 Waste Plastic Generation

It is widely known that WP is a global challenge that adversely affects the environment (Khan et al., 2019). Particularly, it was demonstrated that the quantities of disposed plastic materials are increasingly growing, leading to WP accumulation in landfills and, in turn, risking the environment (Yaakob et al., 2016). As reported by Geyer et al., (2017b) the cumulative WP generation has significantly increased from approximately 2 million tons to 8,000 million tons between 1960 and 2020, as shown in Figure 2.1, with the current production rate, it is expected that the annual WP generation will exceed 25,000 million tons in 2050.

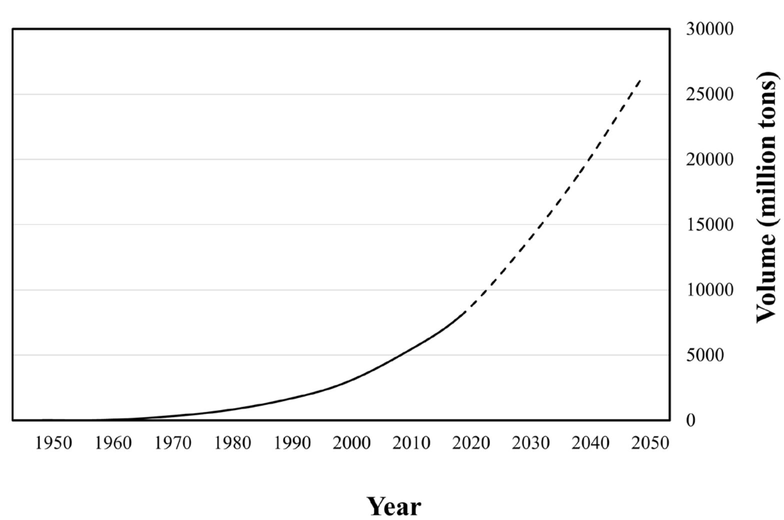


Figure 2.1 Cumulative WP generation and disposal (in million metric tons) (Geyer et al., 2017b).

Currently, WP is primarily managed through three main methods: incineration, landfilling, and recycling (Guo et al., 2023; Tota-Maharaj et al., 2022). Incineration can release harmful gases such as dioxins into the atmosphere, contributing to air pollution. Landfilling consumes substantial land resources and can result in the leaching of contaminants into soil and water resources, causing serious environmental threats. While recycling is considered the most environmentally friendly option, it is less frequently used. In the U.S., the recycling rate of WP is limited, with only 9% of WP being recycled, while around 72% are disposed of in landfills, and 19% are treated by incineration (France 24, 2022).

Regarding the recycled plastic types, plastics can be classified into different groups based on their source, structure, molecular forces, and temperature-dependent behavior. The plastic industry introduced a number-coding system for plastics. Each plastic type corresponds to a unique number from 1 to 7, as summarized in Table 2.1. Polypropylene (PP) and Polyethylene (PE) are globally considered the main types of WP, with a total annual production volume of 6.5 billion tons (Li et al., 2020). Similarly, another study by DUBOIS et al., (2020) indicated that PP and PE are the most predominant WP types in municipal solid waste (MSW), encompassing 32% and 29% of the total volume. The mechanical and physical characteristics of plastics are highly correlated to their type and purity.

Table 2.1 Plastic Recycling Numbers and Identification Codes [22].

Recycling No.	Symbol	Abbreviation	Polymer Name	Uses Once Recycled
1		PETE or PET	Polyethylene terephthalate	Polyester fibers, thermoformed sheet, strapping and soft drink bottles.
2		HDPE	High-density polyethylene	Bottles, grocery bags, recycled bins, agriculture pipe, base cups, car stops, playground equipment and plastic lamber.
3		PVC or V	Polyvinyl chloride	Plastic, fencing and nonfood bottles.
4		LDPE	Low-density polyethylene	Plastic bags, six-pack rings, various containers, dispensing bottles, wash bottles, tubing and various molded laboratory equipment.
5		PP	Polypropylene	Auto parts, industrial fibers, food containers and dishware.
6		PS	Polystyrene	Desk accessories, cafeteria trays, toys, videocassettes and cases, and insulation board and other expanded polystyrene products (e.g., Styrofoam).
7		Other	Acrylic, butadiene styrene, fiberglass, nylon, polycarbonate, etc.	

PE and PP are both members of the polyolefin family, which consists of polymers derived from olefin monomers such as propylene and ethylene, which are hydrocarbons with double bonds (Gahleitner et al., 2017; Olabisi et al., 2016). PE and PP are the most common types of polyolefins and have many favorable properties, including high strength, chemical resistance, durability, and ease of processing (Mark, 2004; Osman et al., 2019). Additionally, their versatility and low production cost make them highly attractive for both industrial and commercial applications such as packaging, automotive, agriculture, textiles, construction, and consumer goods (Chung, 2019; Gopanna et al., 2019). However, despite their advantages, both PE and PP present significant environmental challenges. Production and disposal of these polymers contribute to greenhouse gas emissions, including carbon dioxide (CO_2) and methane (CH_4), which intensify global warming and climate change concerns (Media et al., 2022). They are also highly resistant to natural degradation processes, and the extensive rate of production and consumption of these materials often results in the accumulation of landfills, which increases the risk of environmental pollution (Nature Sustainability, 2018; Tan et al., 2025).

Consequently, researchers have increasingly focused on exploring alternative approaches for managing these WP materials, including recycling and their incorporation into construction materials such as concrete to reduce the environmental impact while providing a cost-effective and sustainable solution (Daodu et al., 2025; Nanda et al., 2025). In addition to their availability and low cost, PP and PE plastics are characterized by predominant water resistance and can withstand a wide range of chemical and thermal conditions, making them highly suitable for integration with concrete (Ilyas et al., 2018). Moreover, it has been demonstrated that their incorporation into concrete can improve the serviceability by reducing the cracking and enhancing the long-term durability (Li et al., 2024; Pešić et al., 2016a).

One specific type of PE is Ultra High Molecular Weight Polyethylene (UHMW), which has extensive applications in agriculture and manufacturing, including products such as conveyor belts (Fiala et al., 2019; Portelli, 2023). As shown in Figure 2.2, the conveyor belt materials are typically thick and consist of many layers (Hakami et al., 2017). When shredded, they produce particles with shapes resembling natural aggregates, as illustrated in Figure 2.3. This characteristic makes UHMW a good candidate for replacing natural fine aggregates in concrete mixtures. On the other hand, PP is commonly found in various consumer products, such as plastic bags. When processed, these materials can yield fiber-like shapes, making PP particularly suitable for use as an additive to enhance the properties of concrete. Figure 2.4 illustrates the processing of PP plastic bags into fibers to use as an additive in concrete (Rafiq Bhat et al., 2023).

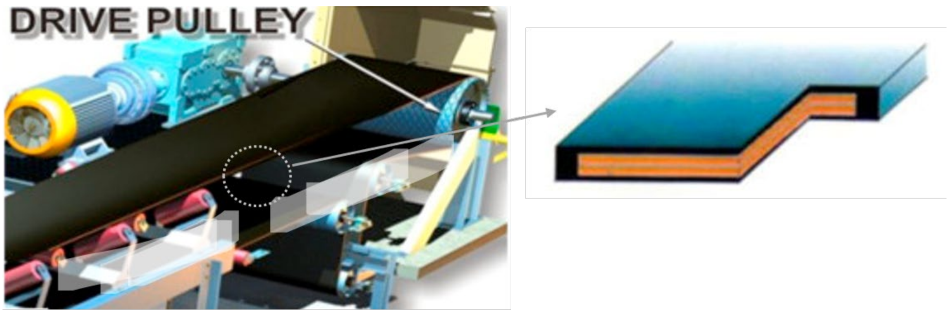


Figure 2.2 Conveyor belt system (Hakami et al., 2017).

Figure 2.3 Granular UHMW Particles Obtained After Shredding (Hongju, n.d.).

Figure 2.4 a) PP plastic bags at the construction site, b) PP fibers after shredding (Rafiq Bhat et al., 2023).

The common mechanical and physical properties of the selected plastics studied herein are listed in Table 2.2.

Table 2.2 Intrinsic properties of plastic (Thermo plastics | Designerdata, n.d.).

Parameter	**UHMWPE**	**PP**
Young's modulus (ksi)	83	192
Shear modulus (ksi)	33	58
Tensile strength (ksi)	4.4	5
Modulus of elasticity (ksi)	72.5	189
Elongation (%)	450	450
Compressive strength (ksi)	3.41	6.7
Bending strength (ksi)	0.8	6
Impact strength (Ibf.ft/in)	1.60	0.685
Density (Ib/ft3)	134	56
Friction coefficient	0.075	0.40
Water absorption (%)	0.01	0.01

2.2 Incorporating RWP as Aggregate and/or Fibers on Portland Cement Concrete

RWP possesses a diverse range of physical and mechanical properties, and incorporating these particles into concrete mixtures can impact its fresh and hardened properties (Babafemi et al., 2018; Ponmalar and Revathi, 2022). This section explores numerous research results that demonstrate the influence of incorporating RWP aggregates and fibers on concrete's fresh properties, mechanical performance, and crack resistance.

2.2.1 Fresh Properties of Concrete

A study conducted by Scanlon, (1994) investigated the impact of utilizing RPA on the workability of concrete mixtures. The findings of this study revealed that the workability of the concrete mixtures depends on the friction between the RPA particles and the cement paste, which is affected by the RPA shape and the content used. According to Thomas et al., (2016), improved slump value can be achieved when incorporating RPA within the concrete mixture, which is attributed to the fact that RPA particles have low absorption, resulting in an increased workability of the mixture.

In contrast, Akça et al. (2015) and Matar et al. (2019) investigated the influence of adding RPF on the workability of the concrete mixtures and found that the slump value decreases when RPF increases in the concrete. The reason behind this is not due to the plastic nature of RPF itself, but rather to the general effect of adding fibers to concrete. The presence of fibers alters the viscous property of concrete as they introduce internal friction and resistance within the mixture, making it thicker and reducing its flowability and resulting in lower slump values (Bhogayata et al., 2018). However, by optimizing the fiber dosage and using suitable chemical admixtures, this reduction in workability can be effectively controlled.

Additionally, it was observed that adding RWP to concrete reduces the density and increases the air content of the mixture (Rai et al., 2012). This is mainly because RWP particles are typically lighter and characterized by lower specific gravity compared to the natural aggregates, and their inclusion can lead to the formation of additional air voids within the mixture (Ferrándiz-Mas et al., 2013; Rashad, 2016). According to Babafemi et al. (2018), the increase in air content in concrete containing RWP can be attributed to many factors: (1) the irregular shape of RWP tends to trap more air bubbles inside the mixture; (2) the immiscibility of natural aggregates and RWP particles could cause improper compaction, leading to increased air voids; and (3) the hydrophobic nature of polymers can promote the formation of air bubbles inside the mixture.

2.2.2 Mechanical Properties of Concrete

Several studies have investigated the influence of incorporating RPA on the mechanical properties of concrete and reported that compressive strength, splitting tensile strength, modulus of elasticity, and flexural strength are reduced by increasing the percentages of RPA in concrete mixtures. A Jaivignesh et al. (2017a) study used RPA as a replacement for fine aggregate at 0%, 10%, 15%, and 20%, and observed that compressive strength and modulus of elasticity decreased by 9% to 17%, splitting tensile strength decreased by 10% to 24%, and flexural strength decreased by 20% to 30% compared to the control mixture, the recommended replacement level was up to 10%. Similarly, Alqahtani et al. (2017a) replaced natural fine aggregate with RPA at replacement levels ranging from 25% to 100%. They reported that compressive strength decreased by 15% to 62%, flexural strength was reduced by 27% to 44%, splitting tensile strength decreased by 12% to 31%, and modulus of elasticity was reduced by 11% to 54% compared to conventional concrete. An optimum replacement level of 25% was suggested based on the results.

Similar findings were revealed by Ismail et al. (2008) and Saikia et al. (2012a). Results indicated that the more RPA used, the greater the loss in mechanical strength for the concrete mixtures. This can be attributed to the weak bonding between RPA and the cement paste (Almeshal et al., 2020). Both Islam et al. (2016) and Jacob-Vaillancourt et al. (2018) highlighted three different reasons behind the reduction in concrete strength when RPA is used: (1) RPA have a lower strength and a lower stiffness compared to natural aggregate; (2) the interfacial transition zone between the RPA and cement paste exhibits low strength; and (3) the bonding developed between the RPA particles and the concrete is weak.

Also, numerous studies focused on adding PP as RPF to concrete and studied the resulting mechanical properties of different fiber dosages and sizes. Leong et al., (2020) used RPF at volume fractions of 0.15%, 0.3%, and 0.5%, with fiber lengths of approximately 0.5 inches. Their results indicated that the addition of RPF did not improve compressive strength but led to an increase of about 27% in both splitting tensile strength and flexural strength. Based on their findings, 0.5% was recommended as the optimal fiber dosage. Similarly, Memon et al., (2018) employed RPF at dosages of 0.2%, 0.25%, 0.3%, and 0.5%, with fiber lengths of approximately 1 inch. By adding a small dosage, the compressive strength decreased by 3%, while the flexural strength increased by 1%. The recommended dosage is 0.25% RPF to maintain the required strength performance.

In summary, the addition of RPF decreases the concrete's compressive strength and elastic modulus because of the low stiffness of the RPF (Liu et al., 2024; Memon et al., 2018). On the other hand, incorporating RPF has a positive impact on the splitting tensile and flexural strength as well (Altalabani et al., 2020; Leong et al., 2020). This improvement is primarily because this type of RPF has tensile force and can use it across cracks, effectively bridging them and delaying their propagation (Tošić et al., 2022).

2.2.3 Crack Resistance of Concrete

To evaluate the cracking resistance of concrete, it is essential to determine its fracture parameters. One of the most modern and effective methods for this purpose is the Semi-Circular Bending (SCB) test. The SCB test is a cracking test originally developed to evaluate the cracking resistance of rocks (Chong and Kuruppu, 1984), but has been heavily used by the asphalt research community to evaluate the cracking resistance of asphalt mixtures (Safazadeh et al., 2022; Wang et al., 2020).

More recently, it has gained increasing attention within the concrete research community (Ghodratnama et al., 2025; Mutnbak et al., 2025). In this test, semi-circular specimens are prepared by cutting cylindrical concrete samples in half and introducing a notch at the flat edge to initiate controlled cracking, as shown in Figure 2.5 (Ghodratnama et al., 2025). The SCB test is a three-point bending test, where a load is applied vertically at the midpoint of the curved surface while the specimen is supported at two points along its diameter (Sadat Hosseini et al., 2023). As the load is applied, the crack initiates at the tip of the notch and propagates upward. This test allows the assessment of key fracture parameters, such as peak load, crack propagation, fracture energy, and ductility index, which are essential for evaluating the cracking resistance and fracture behavior of concrete materials (Afshar et al., 2023; Su et al., 2019).

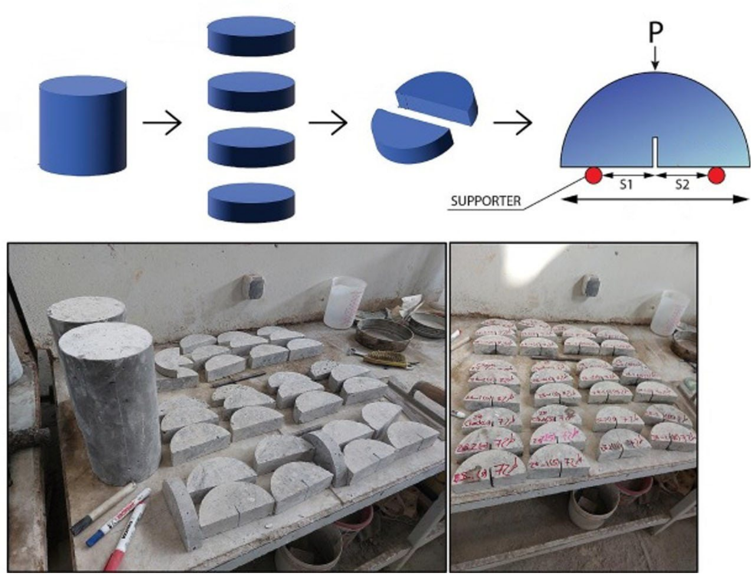


Figure 2.5 Steps for SCB specimen preparation (Ghodratnama et al., 2025).

Aziminezhad et al. (2020) investigated the fracture performance of concrete incorporating plastic particles using the SCB test. They found that utilizing plastic particles has changed the load-displacement curve compared to plain concrete, with improvements in both the displacement at peak load and the total displacement. The ductility index, defined as the ratio of maximum displacement to the displacement at peak load, also increased with the addition of plastic particles. This indicates that incorporating plastic into concrete enhances its ductility and reduces its brittleness.

Another important cracking parameter is the fracture energy (Gf). Gf represents the energy required for crack propagation per unit area of a specimen under tensile loading, and it is a key indicator of post-peak behavior and overall crack resistance in concrete. It is influenced by several factors, including the interfacial bonding between the cement paste and aggregates, as well as the microstructural heterogeneity of the concrete matrix (Gesoglu et al., 2017). Gf is commonly calculated as the area under the load-displacement curve divided by the product of the specimen thickness and the ligament length.

Guo et al. (2023) reported that incorporating plastic particles into concrete increased the area under the load-displacement curve, resulting in a corresponding rise in Gf. This enhancement was attributed to the energy-absorbing capacity and deformability of plastic particles, which delay crack initiation and propagation. In addition, the plastic particles act as crack-bridging elements, hindering crack growth and improving overall crack resistance. This improvement was further supported by crack pattern observations. While conventional concrete exhibited extensive and wide cracking, plastic-modified mixtures showed more localized and narrower cracks (Liu et al., 2015).

Similarly, Ahmad et al. (2022) and Shen et al. (2020) demonstrated that adding even small amounts of plastic to concrete significantly reduced the total crack area, maximum crack width, and the number of cracks at failure. On a microscale, Banthia et al., (2006) reported that plastic particles act as obstacles to microcrack development, slowing their initiation and delaying their propagation.

2.3 Potential drawback of using RWP in concrete

Babafemi et al. (2018) studied the bond interlocking mechanism between plastic particles and cement paste. Scanning Electron Microscopy (SEM) results, illustrated in Figure 2.6, showed that the bond between RPA and cement paste is weak due to differences in surface texture and the fact that plastics do not chemically react or form bonds with the cement matrix, unlike the natural aggregates. This is the major drawback and the key factor for the strength reduction.

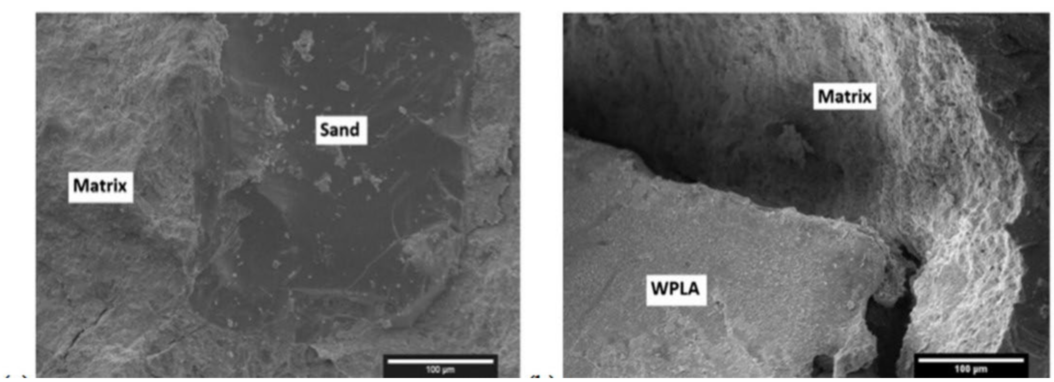


Figure 2.6 Scanning electron micrographs showing the microstructure of RPA and cement paste: (a)natural aggregate (NA); (b) recycled waste plastic aggregate (WPA), (Babafemi et al., 2018).

According to Abeysinghe et al. (2021), the bond interlocking mechanism between the particles depends on many factors, such as plastic particle surface area, shape, size, and plastic type. Goli et al. (2020) described the relation between the concrete strength and the surface areas of plastic particles. It was reported that the higher the surface area, the greater the interfacial transition zone volumes, which can lead to stronger bonding. Furthermore, Saikia et al. (2012a) confirmed that different shapes and sizes of RWP particles are attributed to different strengths of concrete with the same substitution levels of replacement.

Also, using rough and angular RPA with small sizes corresponded to improved bonding between the plastic and the surrounding cement matrix, as the rough materials create a larger surface area, allowing better interactions between the particles and leading to stronger and more durable concrete (Gu et al., 2016). Additionally, using short and thin RPF can result in enhanced bonding behavior and superior properties of concrete (Das et al., 2018). It was also shown that PE and PP plastic particles can develop an efficient bond with the cement paste due to their excellent physical and mechanical properties (Pešić et al., 2016b).

2.4 Sustainability and Environmental Benefits

Around the world, governments, research institutions, and construction companies are conducting research exploring the use of alternative sustainable materials. It is crucial to understand that "sustainable" encompasses the overall enhancement of the environment, economy, and society benefits by reducing the footprint while maintaining or enhancing the level of performance of construction projects (Abu Abdo et al., 2024).

Yaakob et al. (2016) and Pilapitiya et al. (2024) highlighted that WP can take hundreds or even thousands of years to fully decompose, given their chemical compositions and corresponding stability and durability. As a result, it can exist in nature from macro to nanoscale, facilitating its presence in soils, water resources, and human bodies, which makes it a real threat to human life (Huang et al., 2020).

Moreover, WP can significantly contribute to climate change as its production and disposal are associated with releasing large amounts of greenhouse gases like methane and carbon dioxide that accelerate global warming. Thus, managing WP is a global concern that necessitates urgent attention. Many researchers focus on studying the environmental benefits of incorporating RWP with concrete. Tahir et al., (2024) and Jaivignesh and Sofi, (2017b) showed that using RWP in different concrete applications can divert thousands of tons of WP from landfills, which can considerably reduce the negative environmental impact.

According to the Mineral Products Association (MPA), the demand for using sand-sized aggregates in concrete applications is becoming extremely high, given that approximately 44% of the global sand and gravel aggregate is used in concrete production (Ash, 2019). Needhidasan et al. (2020) and Thorneycroft et al. (2018) showed that replacing 10% sand by volume with RPA in concrete is a viable proposition that has the potential to save 820 million tons of sand annually, which represents approximately 2.5% of the global consumption of sand aggregates.

As reported on the Statista website, while landfilling costs vary across the U.S., it is generally considered an expensive method of waste disposal (Statista, n.d.). Specifically, the average MSW landfill fee in the U.S. was $56.8 per ton (Figure 2.7). The cost includes the fees for filling landfills and the long-term environmental cleanup required to manage methane emissions from decomposing WP. Dhawan et al. (2019) highlighted that recycling WP particles and using them in concrete applications can reduce landfill costs. This can also lead to the creation of new, cost-effective construction materials, considering both the low price and lightweight properties of RWP, resulting in faster insulation and reduced labor requirements (Gour et al., 2020). Alqahtani et al. (2017b) further revealed that the life cycle cost of one cubic foot of concrete mixtures utilizing RWP particles is 5% lower than that of conventional ones.

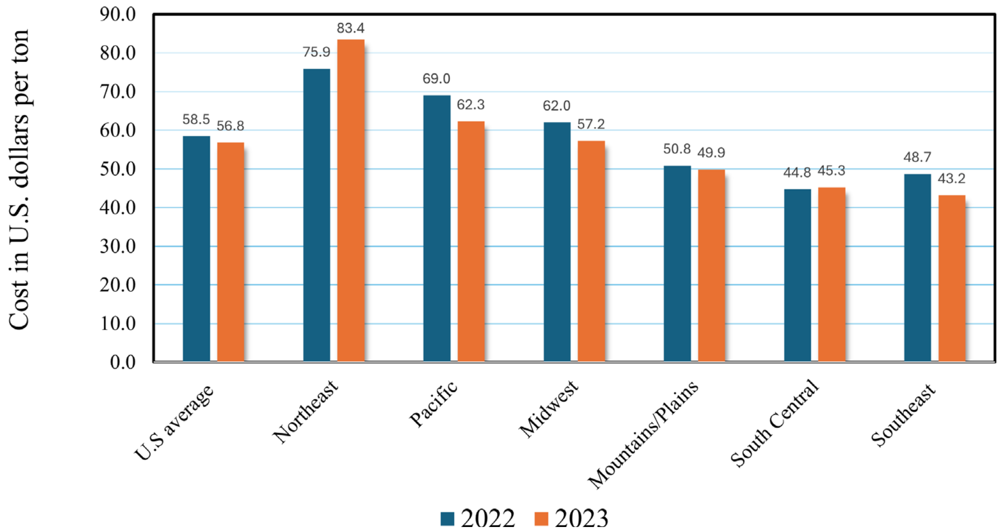


Figure 2.7 Average cost to landfill municipal solid WP in the United States by region (Statista, 2023).

2.5 RWP for PCC Pavements

PCC pavements are considered stiff roads that experience low deflections under traffic loading, and consequently long service life of around 20 years (Mohod et al., 2016). However, when exposed to heavy traffic and harsh environmental conditions, these pavements can develop small cracks that gradually propagate into larger ones, ultimately leading to surface deterioration and subsidence of the concrete layer (Li et al., 2024; Zhao et al., 2017). Given that, conventional concrete has durability issues including cracking, shrinkage, and brittleness. These limitations highlight the urgent need to explore effective methods for enhancing its mechanical and cracking resistance behavior. One promising approach is the incorporation of alternative materials, such as RWP, which have shown potential to improve the properties of concrete while addressing environmental concerns (Bertelsen et al., 2020; Khalel et al., 2021).

The incorporation of RWP can help enhance the mechanical properties, ductility, and cracking resistance in PCC pavements, which further extends the life span of roads and reduces the maintenance cost (Nili et al., 2010; Sadrolodabaee et al., 2024; Tahir et al., 2024). Moreover, the lower cost of RWP materials compared to natural aggregate will eventually reduce pavement construction costs (Mills et al., 2018).

PCC pavements have special requirements in terms of strength and durability. Hence, the amount of RWP used within the concrete mixtures should be carefully selected to achieve the required strength of the pavement. Several studies investigated the highest feasible percentages of RPA and RPF that can be used with concrete. Many studies showed the most appropriate replacement percentages of RPA to use in concrete are 5%, 10%, and 15% by volume, while the maximum recommended percentage of RPF is 2.5% by volume (Kaur et al., 2020b; Pešić et al., 2016a; Thorneycroft et al., 2018).

Chapter 3 Materials and Test Methods

This chapter outlines the materials utilized in this research and the testing methods to evaluate the concrete properties. It presents properties and details on the materials used for concrete pavement in Nebraska, including cement, limestone, sand and gravel, and RWP materials. Additionally, the test procedures for evaluating both fresh and mechanical concrete properties are discussed. All materials used in this study adhere to the Nebraska DOT standard specifications for concrete pavement construction.

3.1 Materials

3.1.1 Cement

Portland-Limestone Cement Type 1L with 15% limestone was used in the initial stage of this study, while Portland Cement Type IP, Portland cement with 25% Class F fly ash or Class N pozzolan was used in the later stages of this research.

3.1.2 Chemical Admixtures

A commercially available air-entraining admixture that meets the requirements of ASTM C260 was used as an air-entraining agent (AEA) with a dosage range of 0.125 to 1.5 fl oz/cwt (8-98 mL/100 kg) of cementitious materials. High-range water reducer that meets the requirements of ASTM C494 was used as the water-reducing (WR) agent for all mixtures with a dosage range of 2-15 fl oz/cwt (130-975 mL/100 kg) of cementitious materials.

3.1.3 Natural Aggregate (NA)

Local aggregates commonly employed in Nebraska for concrete pavement applications were used in this study as NA, such as limestone (LS) as coarse aggregate (Figure 3.1 a) and sand and gravel (SG) as fine aggregate (Figure 3.1 b).

Figure 3.1 NA used in this study: a) Limestone (LS) and b) Sand and Gravel (SG).

The natural aggregates were characterized in terms of specific gravity and absorption at saturated surface dry (SSD) condition in accordance with ASTM C127 and ASTM C128, respectively, and sieve analysis according to ASTM C136. The physical properties are presented in Table 3.1, and the aggregate gradation curves are presented in Figure 3.2.

Table 3.1 Aggregate properties.

Property	**SG**	**LS**
Specific Gravity	2.62	2.66
Absorption (%)	0.94	0.92
Fineness Modulus (FM)	3.9	7.02
Nominal Maximum Aggregate Size (in)	0.1870	0.75

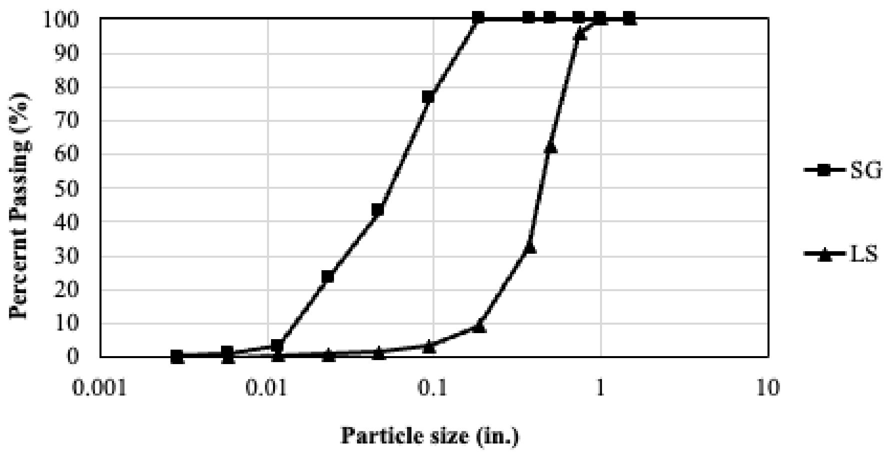


Figure 3.2 Gradation curves of natural aggregates used herein.

3.1.4 Recycled Waste Plastics (RWP)

Two types of recycled waste plastic (RWP) were used in this research, differing in type and shape, for distinct purposes, i.e, one as recycled plastic aggregate (RPA) and the other as recycled plastic fiber (RPF). The RWP samples were sourced from the First Star Recycling Company in Omaha, Nebraska.

Ultra-High Molecular Weight Polyethylene (UHMW) was used as fine RPA. The preparation process of the UHMW-RPA involved multiple stages. First, UHMW waste material was collected from used conveyor belts and transported to the processing facility. The collected WP was then sorted to remove any other materials. After sorting, the clean UHMW waste material underwent shredding using a shredding machine, which produces the material into fine particles. Finally, the shredded material is then collected and used as RPA for subsequent applications, as illustrated in Figure 3.3. Polypropylene (PP) was used as RPF and added to the concrete in different percentages, incorporated by the total volume as an additive material. As illustrated in Figure 3.4, the preparation process consisted of collecting the waste material from super sacks bags, followed by a sorting process, and then shredding by a shredding machine into fibrous particles, and subsequently processing into the final recycled PP fibers product (RPF).

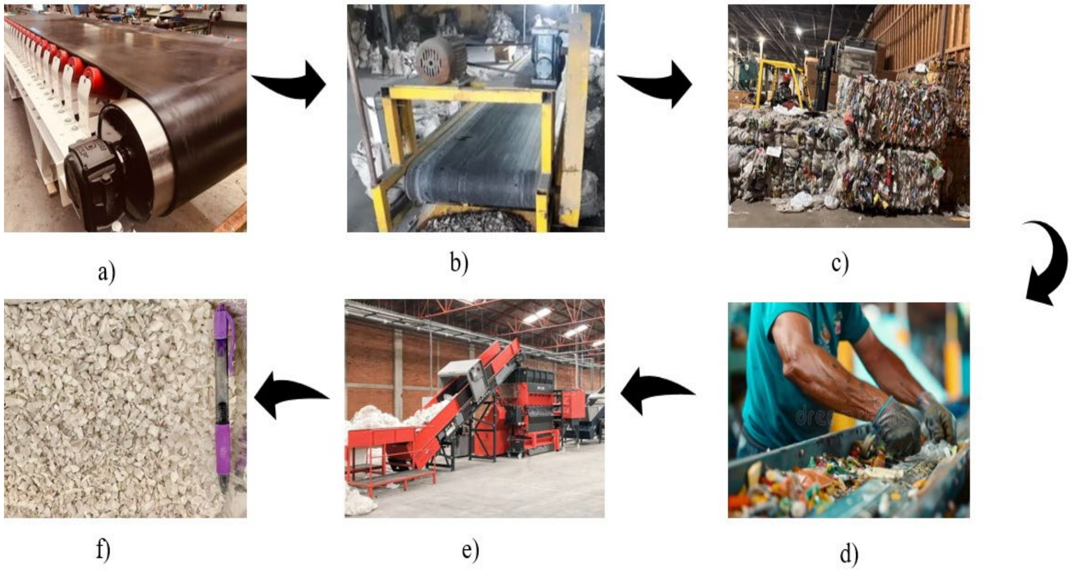


Figure 3.3 Illustrative images of UHMW RPA recycling process: a) UHMW conveyor belts origin material, b) UHMW waste material, c) WP Collecting and Storage, d) WP sorting, e) Shredding Machine, f) UHMW recycled plastic aggregate (RPA).

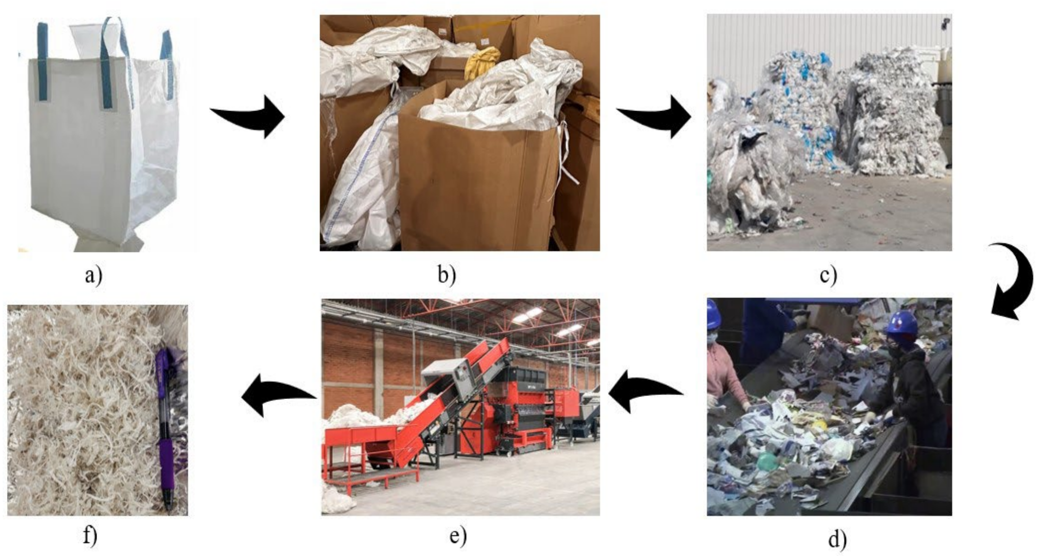


Figure 3.4 Illustrative images from RPF recycling process: a) PP super sack origin material, b) PP super sack waste material, c) WP Collecting and Storage, d) WP sorting, e) Shredding Machine, f) Recycled PP plastic fibers (RPF).

To facilitate comparison, all aggregates used in this study are arranged side by side and shown in Figure 3.5, allowing a visual assessment of their size and shape differences. All the mixtures used the RPA in a saturated surface dry condition.

Figure 3.5 LS, S&G, and RPA aggregates used in this study.

The characteristics of RWP were evaluated based on ASTM D 854 for specific gravity, ASTM C128 for water absorption, and ASTM C136 for particle size distribution and sieve analysis. Additionally, fine aggregate angularity according to AASHTO TP81 was conducted using the Aggregate Imaging Measurement System (AIMS) test, and Fourier Transform Infrared Spectroscopy (FTIR) was conducted in accordance with ASTM D5576 to analyze the chemical composition of the material. The results of all characterization tests are summarized in Table 3.2, while the gradation curve is plotted in Figure 3.6

Table 3.2 Physical properties of the studied RWP samples.

Plastic Type	Specific Gravity	Nomenclature adopted	Absorption (%)	Size	Source	Shape
UHMW	0.97	RPA	0.01	NMAS: 0.1870 in. (4.75mm)	Conveyor belts	Angular
PP	0.92	RPF	0.01	Length: 1 in. (25mm) Width: 0.003 – 0.2 in. (0.08 – 5 mm)	Supersacks plastic bags	-

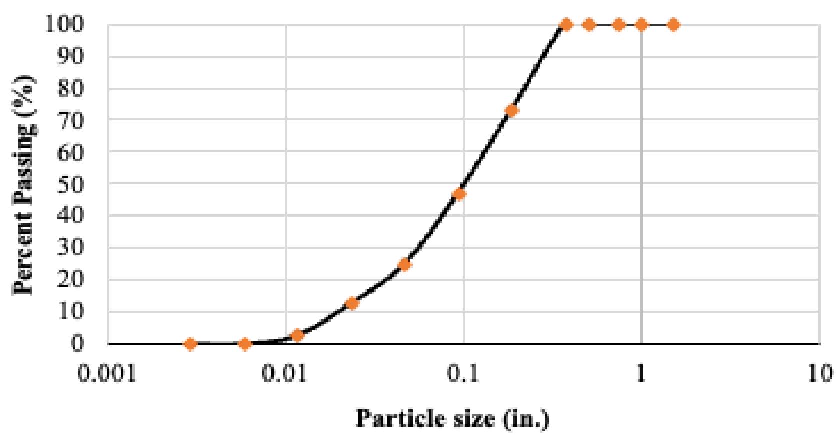
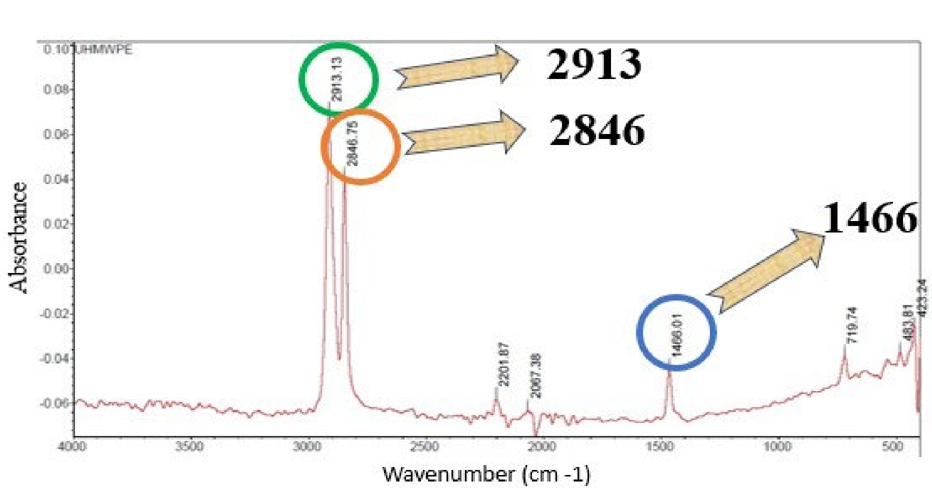


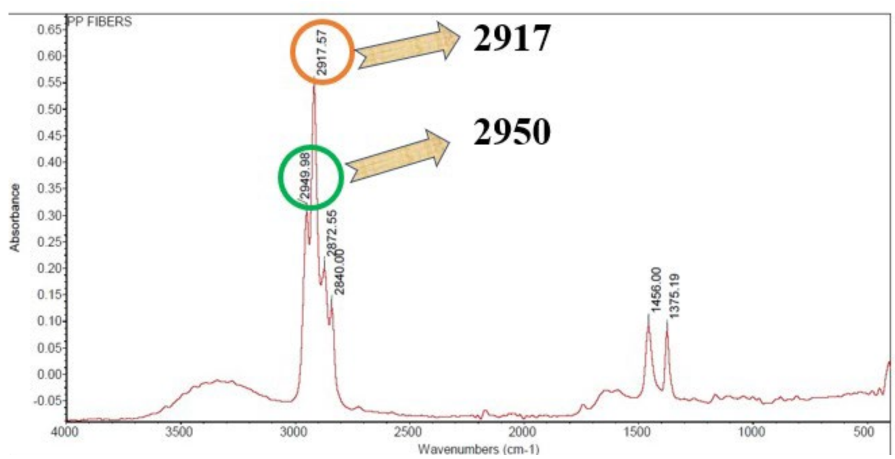
Figure 3.6 UHMW gradation curve.

In addition to commonly used physical characterization tests, additional tests, such as Fourier transform infrared spectroscopy (FTIR) and Aggregate Image Measurement System (AIMS) tests were added to identify the plastic type and shape properties, respectively.

FTIR is an imaging technique that measures the absorption of infrared (IR) radiation by a sample to analyze the components and observe the crystallographic structure of various polymer types at room temperature (Veerasingam et al., 2021). Infrared (IR) spectra provide a fingerprint of the polymer materials, with each absorption peak reflecting the vibrational modes of atomic bonds within the molecule. Because the atomic arrangement in each polymer is unique, every polymer produces a different IR spectrum. This makes FTIR spectroscopy a powerful tool for identifying the chemical components and the structure of polymer materials by comparing their spectra with a reference spectra (Chalmers, J. M. (2006)). The results of the FTIR test for different RWP particles are shown in Figure 3.7 respectively. The results illustrated that the PE and PP materials are pure polymers.



(a)



(b)

Figure 3.7 FTIR Testing Results for a) UHMW-RPA and b) PP-RPF.

The AIMS test is a computer-based digital imaging system that can measure the morphological characteristics of different types and sizes of aggregates (Masad, 2003). As shown in Figure 3.8, this technology has a microscope camera, different aggregate trays, and a back and top lighting system (Fletcher et al., 2003). Although this test can analyze many features, this study evaluated only the angularity of SG and UHMW-RPA. Angularity describes the sharpness of aggregate corners and is presented by the angularity index scale that ranges from 0 to 10,000 and is divided into four categories, as shown in Figure 3.9: low angularity (0–2100), which corresponds to rounded particles; medium angularity (2100–3975), associated with subrounded particles; high angularity (3975–5400), related to subangular particles; and extreme angularity (5400–10,000), representing angular particles.

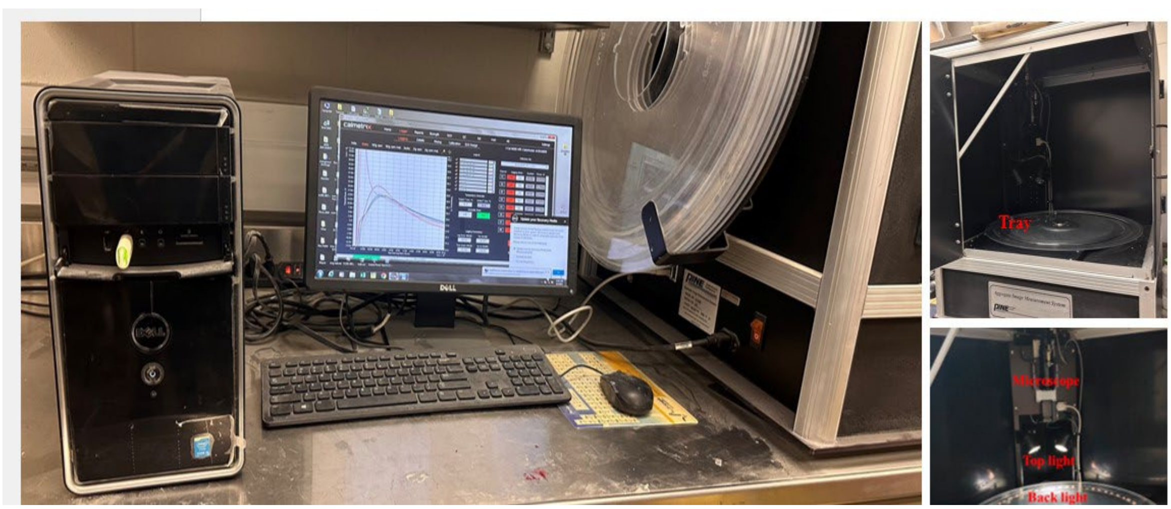


Figure 3.8 AIMS test setup.

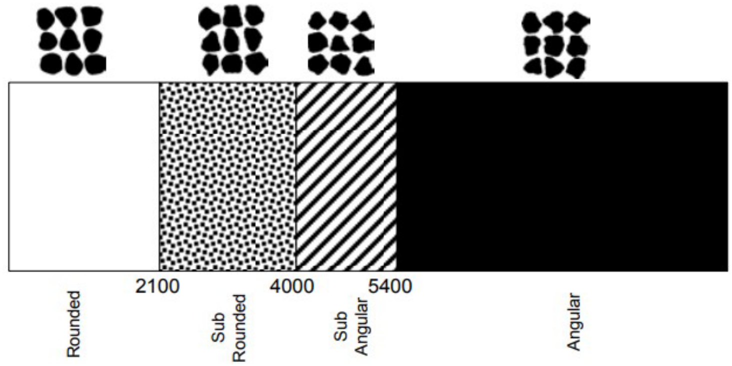


Figure 3.9 Aggregate Angularity Classification Chart (Masad, n.d.).

The AIMS test was conducted using 150 SG particles for each size, ranging from 0.0937 in. to 0.0029 in. (2.63 mm - 0.075 mm), and 150 UHMW-RPA particles for each of the 0.0937 in. (2.36 mm) and 0.0469 in. (1.18 mm) sizes. The results of the AIMS angularity distribution are shown in Figure 3.10 and Figure 3.11. The findings indicate that 93% of the SG particles fall within the low to moderate angularity range, whereas 77% of the UHMW particles fall within the moderate to high angularity range. This suggests that the UHMW particles are more angular than the SG.

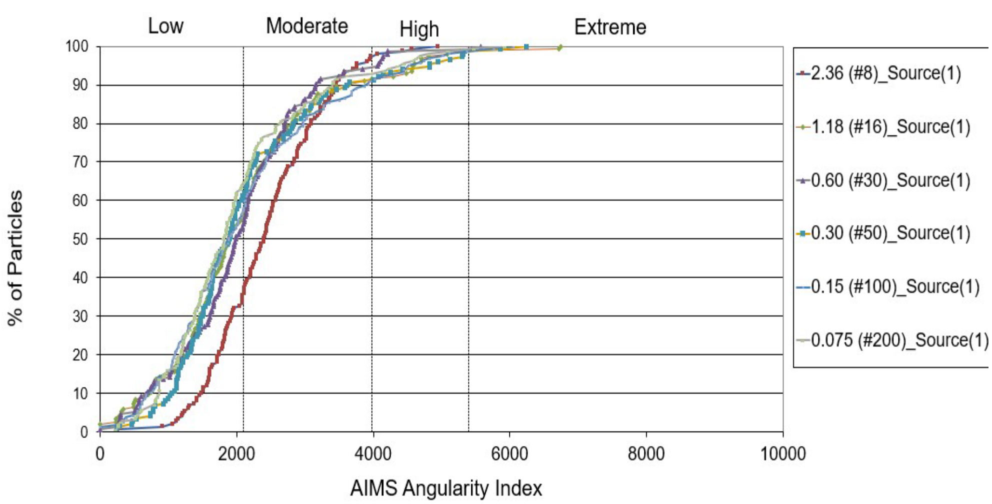


Figure 3.10 AIMS Angularity Testing Results for SG.

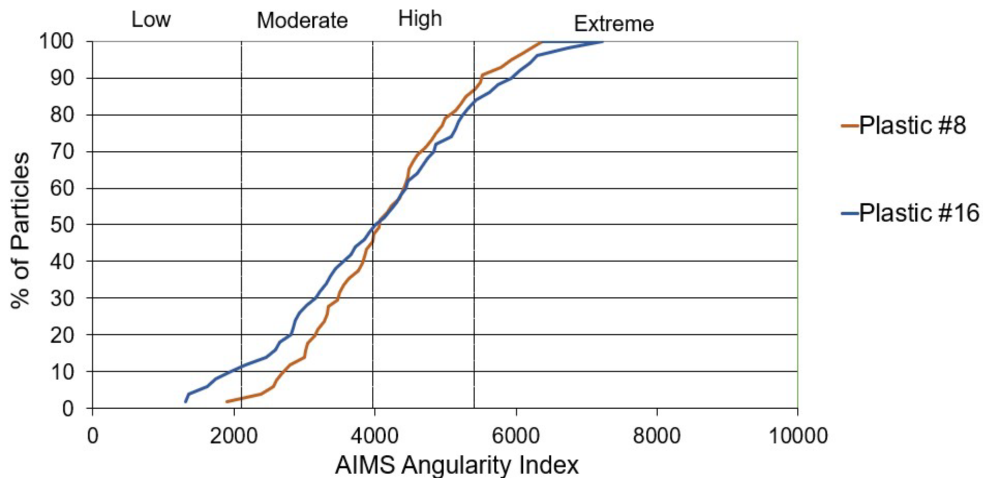


Figure 3.11 AIMS Angularity Testing Results for UHMW-RPA.

3.2 Studied Concrete Mixtures

A concrete mixture designated by 47B by Nebraska Department of Transportation (NDOT) is commonly used for pavement applications in Nebraska. As presented in the NDOT Pavement Manual, NDOT 47B concrete needs to have a minimum of cementitious materials of 564 lb. per cubic yard and a minimum compressive strength of 3,500 psi at 28 days. Furthermore, the max w/c is specified to be 0.45, and the total aggregate content ranges from a minimum of 2850 lb/cy to a maximum of 3150 lb/cy, consisting of 30% LS and 70% SG. Additionally, the required air content should be within 6.5% to 9%.

NDOT also requires a special gradation of 47B concrete mixture for PCC pavements in order to obtain well-graded blends of aggregate and eventually denser concrete. This gradation allows for improved air entrainment and reduces entrapped air voids, which influences the shrinkage mechanism by ensuring that fewer voids need to be filled with cement paste. Figure 3.12 represents the gradation of the 47B concrete mixture with the maximum and minimum tolerance.

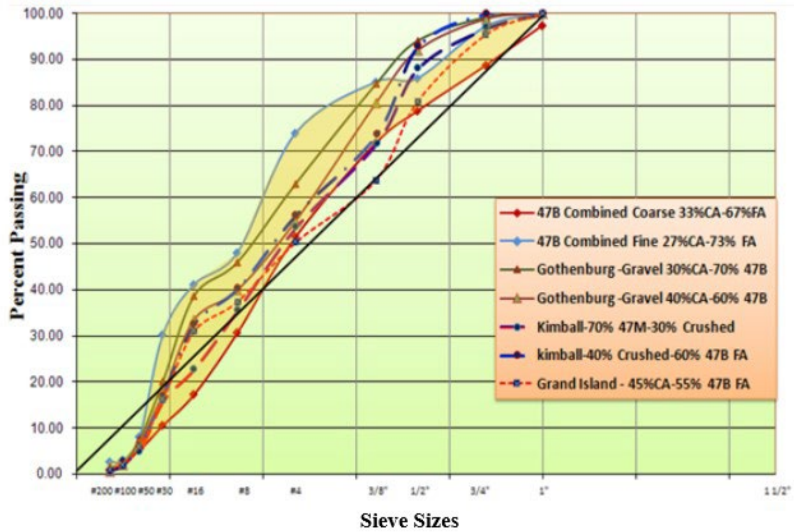


Figure 3.12 47B Standard- All Gradations Combined (NDOR Manual, 2018).

3.3 Mixture proportions

Initially, three WP-modified concrete mixtures were developed by incorporating UHMW-RPA material as a partial replacement for natural fine aggregate, with replacement levels of 5%, 10%, and 15% by volume of the natural fine aggregate, and cement type IL. Furthermore, other three concrete mixtures were studied using PP-RPF as additive material at dosages of 0.5%, 1%, and 1.5% by the total concrete volume. For all mixtures, the w/c ratio was maintained at 0.45, except for the mixture with 15% UHMW-RPA replacement. Based on the preliminary results, this mixture with a w/c ratio of 0.45 did not meet the required performance criteria. Therefore, the w/c ratio was reduced to 0.42 to enhance strength and ensure the desired performance. After the initial assessment, three new mixtures were produced using 0% RWP, 10% RPA, and 1.5% RPF, respectively. These mixtures had the same cementitious content from the initial assessment but used type IP cement and a w/c ratio of 0.42.

Mixtures were identified based on the type and dosage of the RWP material used. For example, RPA 5% refers to a mixture using recycled plastic aggregate (UHMW material) at a 5% replacement level of the natural fine aggregate, and RPF 0.5% refers to the use of recycled PP fibers added at 0.5% of the total concrete volume. Table 3.3 illustrates the mixture proportions used in this study. All mixtures were tested and evaluated to identify the suitable percentage of RWP that can meet the NDOT requirements for the concrete pavements.

Table 3.3 Studied mixture proportions

Mix ID	**Based Cement Type**	**Portland Cement (lb/cy)**	**w/c**	**Water (lb/cy)**	**LS (lb/cy)**	**SG (lb/cy)**	**RWP (lb/cy)**	**WR (fl.oz/cwt)**	**AEA (fl.oz/cwt)**
Control	IL	564	0.45	254	909	2121	0	8	1.2
RPA 5%	IL	564	0.45	254	909	2015	39	8	1
RPA 10%	IL	564	0.45	254	909	1909	79	8	1
RPA 15%	IL	564	0.42	237	909	1803	118	10	1
RPF 0.5%	IL	564	0.45	254	909	2121	8	8	1
RPF 1%	IL	564	0.45	254	909	2121	15	10	1
RPF 1.5%	IL	564	0.45	254	909	2121	23	12	1
Control	IP	564	0.42	237	909	2121	0	10	1.2
RPA 10%	IP	564	0.42	237	909	1909	79	10	1
RPF 1.5%	IP	564	0.42	237	909	2121	23	15	1

Figure 3.13 presents the flow chart and experimental plan adopted for this study. The process starts with the selection of RWP materials, including RPA and RPF, followed by material characterization. After characterization, mix designs are developed, consisting of a reference mixture (47B) along with mixtures incorporating varying replacement levels of RPA (5%, 10%, and 15%) and RPF (0.5%, 1%, and 1.5%).

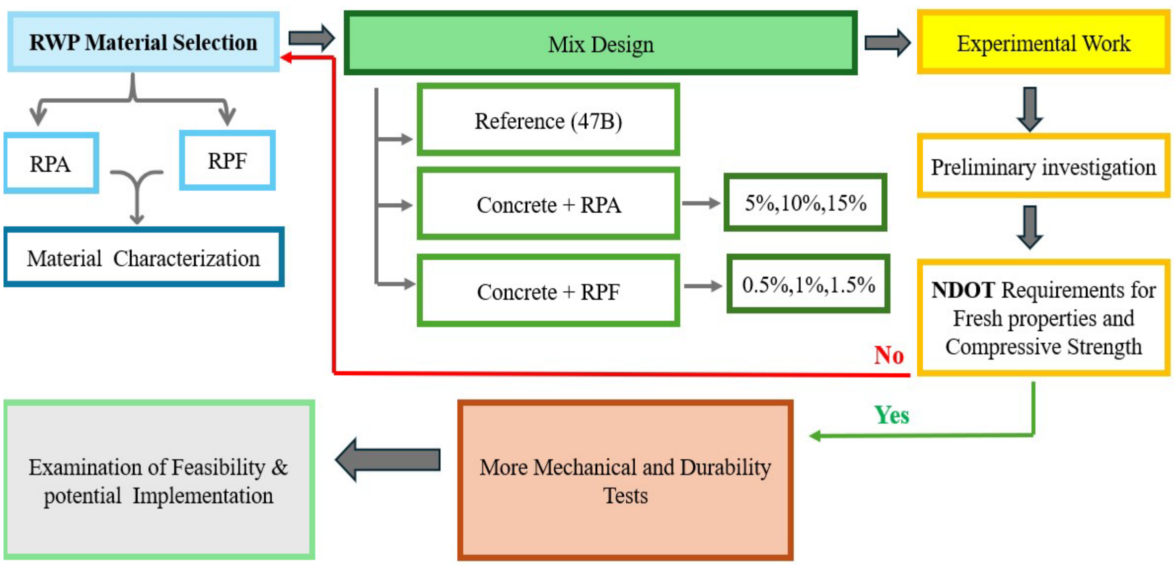


Figure 3.13 Flow chart of the experimental plan.

The experimental program proceeds with a preliminary investigation to assess the fresh properties and compressive strength of the mixtures in accordance with NDOT requirements. If the mixtures meet the NDOT specifications, further mechanical and durability tests are performed. However, if the requirements are not satisfied, alternative RWP materials are selected, and the process is repeated. Finally, the feasibility and potential for practical implementation of the developed mixtures were assessed based on their overall performance.

3.4 Concrete Mixing Procedure

A mechanical drum mixer with a capacity of 2 ft³ (0.06 m³) was used to prepare small concrete batches (ranging from 1 to 1.5 ft³) following the ASTM C192 standard. The mixing procedure used here began mixing the LS, SG, and RPA with roughly half of the batch's water for 30 seconds to generate enough entrained air bubbles. After this, cement and the remaining water with the admixtures were added and mixed for three minutes followed by three minutes of resting, and additional two minutes of mixing. In the case of mixtures using RPF, the fibers were added gradually after the concrete mixture became uniform. Figure 3.14 shows the mechanical drum mixer used. After mixing, fresh, mechanical and durability properties were assessed following different test methods presented in Table 3.4.

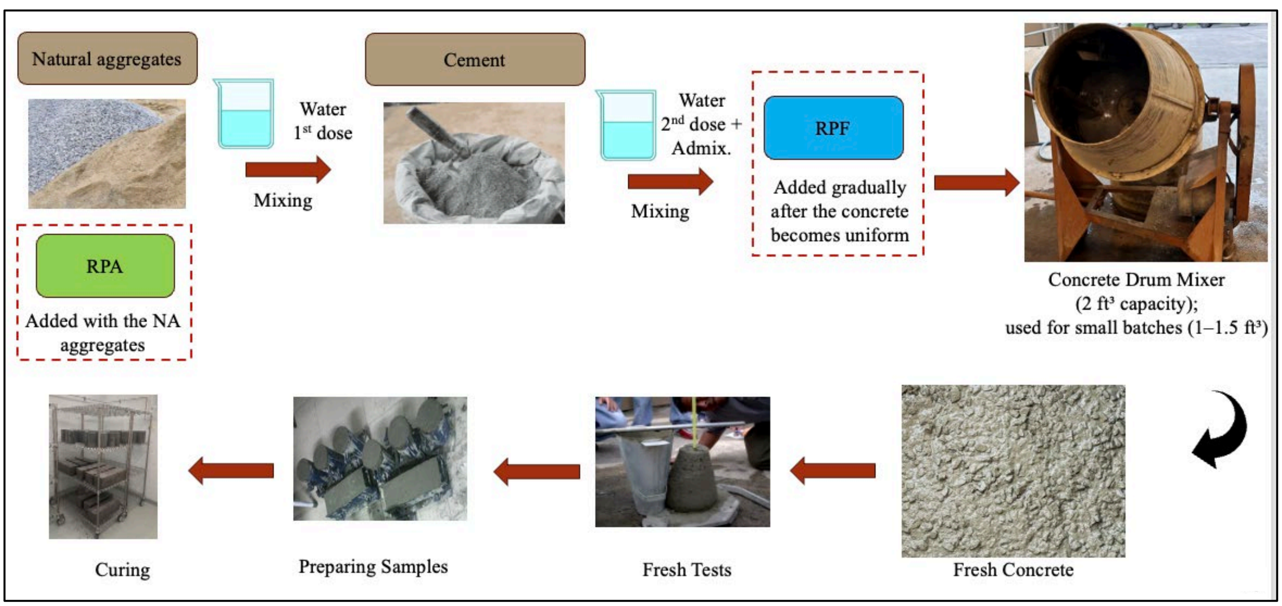


Figure 3.14 Concrete mixing procedure.

Table 3.4 Experimental Testing Plan.

Mix ID	Property	Test Method	Standard/Source
Fresh	Workability	Slump	ASTM C143 (AASHTO T119)
	Temperature	-	ASTM C1064
	Unit weight	-	ASTM C138 (AASHTO T121)
	Air content	Pressure method	ASTM C231 (AASHTO T152)
Mechanical	Compressive strength	Compression	ASTM C39 (AASHTO T22)
	Flexural Strength	Third point bending	ASTM C78 (AASHTO T97)
	Modulus of elasticity	-	ASTM C469
	Splitting tensile strength	-	ASTM C496
	SCB Test	-	AASHTO - T 394
Durability	Surface resistivity	Electrical resistivity	AASHTO TP 95-14

3.5 Fresh Concrete Properties

Fresh concrete properties were tested immediately after mixing. Temperature, slump, unit weight, and air content were measured in this stage.

3.5.1 Temperature

The temperature of fresh concrete was measured using the thermometer probes according to ASTM C1064. The thermometer penetrated three inches inside the concrete for two minutes before recording the temperature (Figure 3.15).

Figure 3.15 Fresh concrete temperature measurement.

3.5.2 Workability

The slump testing was done to measure the workability and the consistency of concrete in accordance with ASTM C143 as shown in Figure 3.16. The specifications for slump are in the range of 1.0 – 3.0 in. for paving construction applications.

Figure 3.16 Slump test.

3.5.3 Unit Weight

The unit weight testing of concrete was conducted in a 0.25 ft^3 container following ASTM C138 as shown in Figure 3.17. NDOT does not have special requirements regarding the unit weight.

Figure 3.17 Unit weight measurement.

3.5.4 Air Content

The air content was tested according to ASTM C231 as shown in Figure 3.18. NDOT requires an air content range of 6.5% to 9.0% for concrete pavement constructions.

Figure 3.18 Air pressure measurement (meter type-B).

3.6 Specimens Casting and Curing

The number of samples cast and tested per batch for the mechanical and durability properties of each mixture is presented in Table 3.5.

Table 3.5 Sample counting

Test	**Sample Geometry**	**Sample Count**	**Test Age**	**Curing Time**
Compressive Strength	4"x8" cylinder	3	7-days	7-days
		3	14- days	14-days
		3	28-days	28-days
Flexural Strength	6"x6"x20" prism	3	28-days	28-days
Modulus of Elasticity	4"x8" cylinder	3	28-days	28-days
Splitting Tensile Strength	4"x8" cylinder	3	28-days	28-days
SCB Test	2" thick semi-circular sample	3	56-days	28-days
Electrical Resistivity	4"x8" cylinder	3	28 & 56-days	28-days

All samples were cast in accordance with ASTM C192. After casting, the specimens were demolded after 24 hours and subsequently stored in water at 72°F (22°C) for various curing periods depending on the type of test and the targeted advancing evaluation.

Different geometries of specimens were prepared for each mechanical test: cylindrical samples 4 in. x 8 in. (100 mm x 200 mm) for compressive strength, splitting tensile strength, modulus of elasticity, and electric resistivity (Figure 3.19 a), and 6 in. x 6 in. x 20 in. (150 mm x 150 mm x 500 mm) prisms (beams) for flexural strength (Figure 3.19 b). The Semi-Circular

Bending (SCB) test sample preparation is shown in Figure 3.20. Cylinders with a diameter of 6 in. (150 mm) and a height of 12 in. (300 mm) were cast and cured for 28 days. Then, the cylinders were cut into discs with a thickness of 2 in. (50.8 mm). These discs were further halved to obtain the SCB specimens with a notch length of 0.59 ± 0.05 in. (15 ± 2 mm) and a width of 0.393 in. (1 mm).

Figure 3.19 Concrete Samples a) 4 in. x 8 in. cylinder b) 6 in. x 6 in. x 20 in. beam.

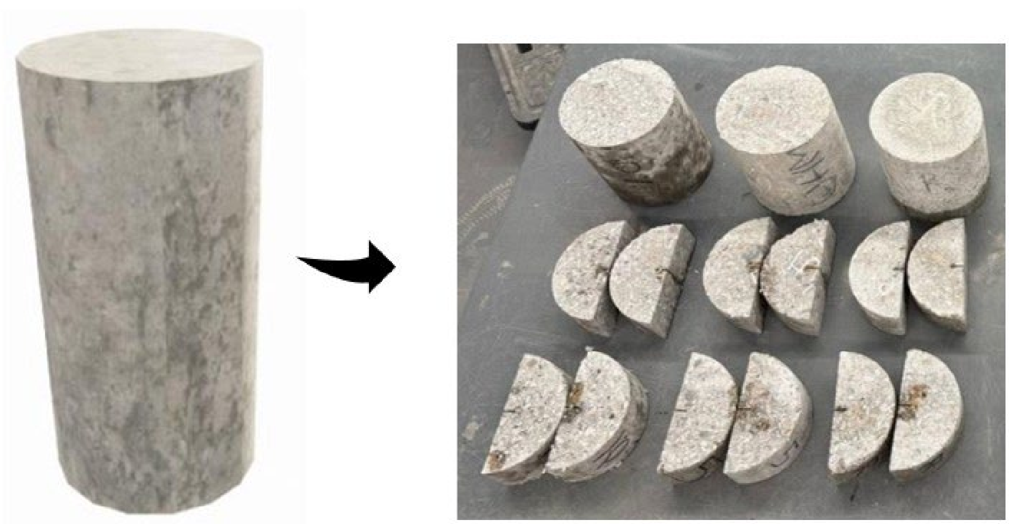


Figure 3.20 a) Cutting a cylindrical sample, b) Preparing samples for the SCB test.

3.7 Mechanical Properties

3.7.1 Compressive Strength

The compressive strength test was conducted in accordance with ASTM C39. Figure 3.21 shows a sample before and after the test. For each mixture, three cylindrical specimens measuring 4 in. x 8 in. (100 mm x 200 mm) were prepared to be tested at 7, 14, and 28 days of curing. The average compressive strength and standard deviation were calculated and reported. NDOT specifies a minimum compressive strength of 3,500 psi at 28 days for concrete pavement projects.

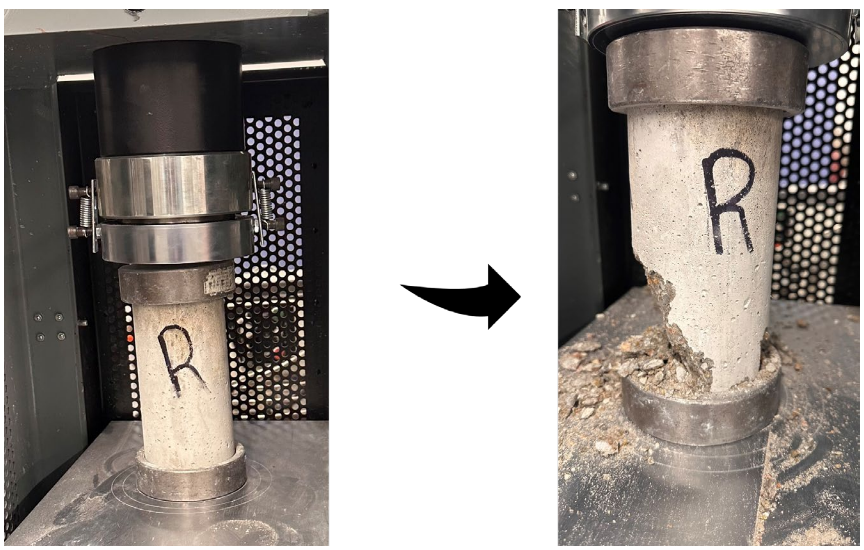


Figure 3.21 Sample subjected to compressive strength test before and after failure.

3.7.2 Flexural Strength

Flexural strength or the modulus of rupture of concrete was tested in accordance with ASTM C 78 (Standard Test Method for Flexural Strength of Concrete), using a simple beam with third point loading as shown in Figure 3.22. Three specimens of 6 in. x 6 in. x 20 in. (150 mm x 150 mm x 500 mm) were tested in air-dry conditions after 28 days of curing and the average was reported.

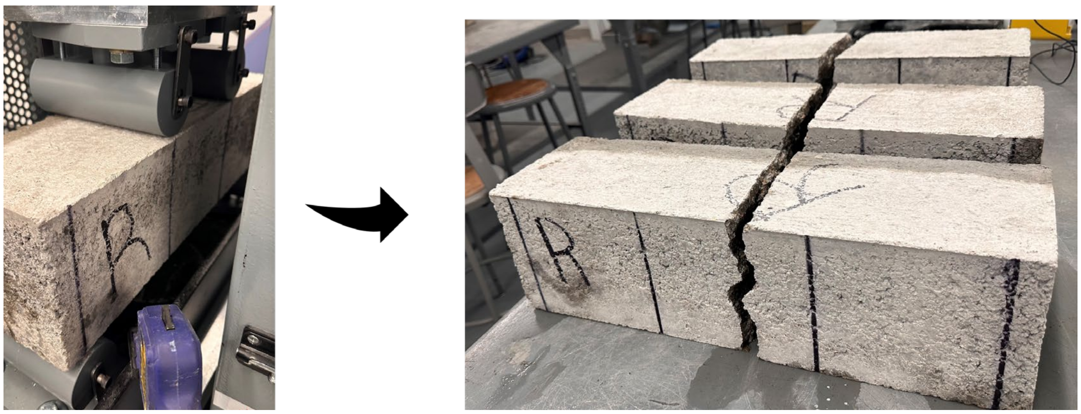


Figure 3.22 Third point bending flexural test setup and samples after test.

3.7.3 Splitting Tensile Strength

The splitting tensile strength of concrete was tested following ASTM C496, using cylindrical specimens of 4 in. x 8 in. (100 mm x 200 mm) as shown in Figure 3.23. Three specimens were tested after 28 days of curing, and the average tensile strength was reported.

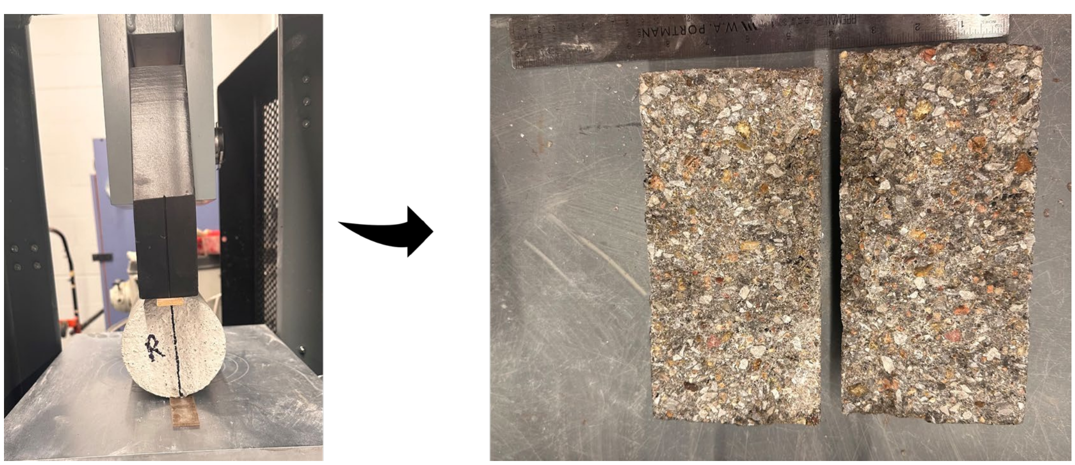


Figure 3.23 Splitting tensile strength test setup and the two halves after test.

3.7.4 Modulus of Elasticity

The modulus of elasticity test (MOE) (Figure 3.24) was performed according to ASTM C469 to evaluate the stiffness of concrete. Three 4 in. x 8 in. (100 mm by 200 mm) cylinders were tested after 28 days of curing, and the average value was reported.

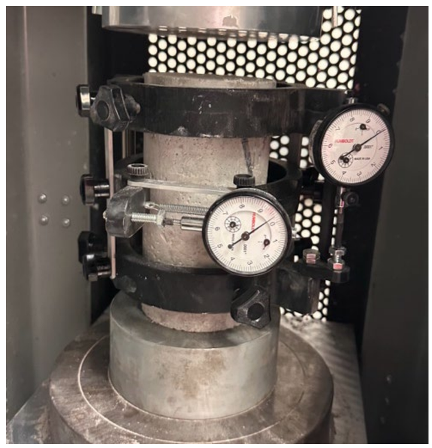


Figure 3.24 Test setup for Static Modulus of Elasticity.

3.7.5 Semi-Circular Bending (SCB)

Since there is no standard procedure to perform the SCB test in concrete materials, this study adopted the AASHTO-T 394 procedure used to evaluate the cracking resistance of asphalt concrete for pavement applications. Three 2 in. (50.8 mm) thick semi-circular specimens with a notch length of 0.59 ± 0.05 in. (15 ± 2 mm) were prepared. Before testing, the specimens were conditioned at a room temperature of 77°F (25°C) for at least two hours. At 56 days, the SCB specimens were tested using a hydraulic universal testing machine (UTM) under a loading rate of 0.5 mm/min, as shown in Figure 3.25. The specimens were placed on pinned supports with a span of 5 in. (130 mm), and the force–displacement responses were recorded. Crack propagation on the specimen surface was captured using a high-resolution camera. The average results from the three specimens were calculated and reported.

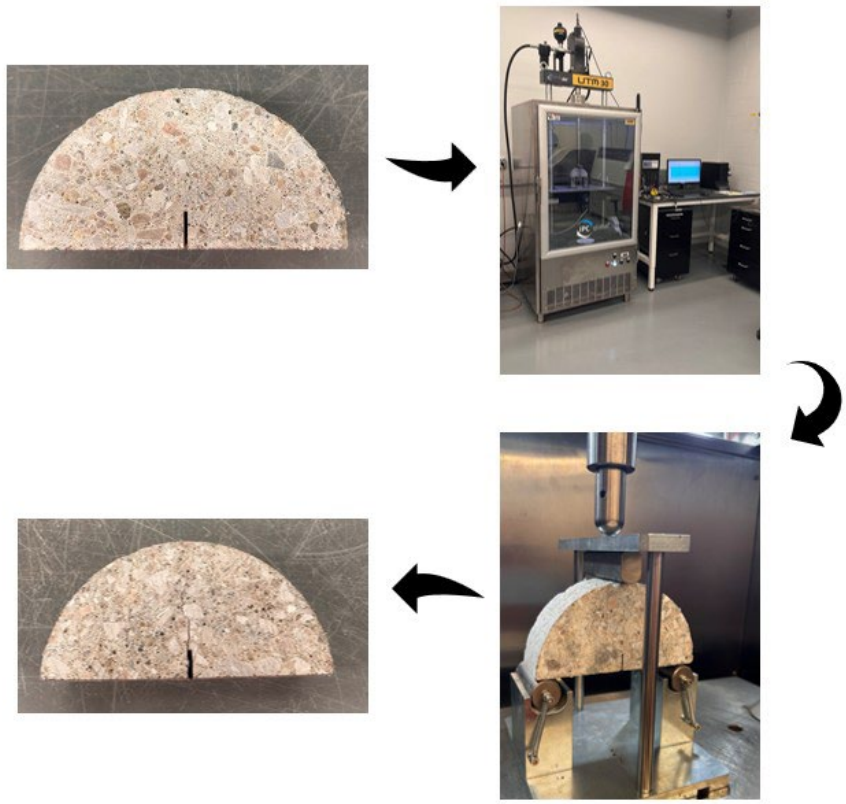


Figure 3.25 Test setup for SCB test.

3.8 Durability Properties

3.8.1 Surface Resistivity

Surface resistivity was measured using 4 in. x 8 in. (100 mm x 200 mm) concrete cylinders in accordance with AASHTO TP 95-14 (Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration) as shown in Figure 3.26. The peripheral surface of three saturated surface-dry (SSD) specimens was tested at 28 and 56 days. The average resistivity value and standard deviation were reported. Results were then compared to Table 1 in AASHTO TP 95-14 to categorize the chloride ion penetrability of the mixture.

Figure 3.26 Test setup for surface resistivity of concrete.

Chapter 4 Laboratory Test Results and Discussion

This chapter outlines the experimental investigation of the fresh and mechanical concrete properties of the studied mixtures, as well as the initial assessment of the concrete durability.

4.1 Concrete Mixtures using Portland Cement type IL

4.1.1 Fresh Concrete Properties

Modifying a concrete mixture by incorporating new materials such as RWP can significantly influence its fresh properties, such as slump, unit weight, and air content. To verify that the fresh properties of the modified mixtures remained within acceptable limits, tests were conducted to measure temperature, slump, unit weight, and air content. These properties were measured immediately after mixing for all mixtures and are summarized in Table 4.1.

Table 4.1 Fresh Concrete properties.

Mix ID	**Temperature (◦F)**	**Slump (in)**	**Unit weight (pcf)**	**Air content (%)**
Control	68	1.5	142.0	6.7
RPA 5%	71	1.7	139.7	6.9
RPA 10%	77	2.0	136.3	7.2
RPA 15%	80	2.2	133.7	7.8
RPF 0.5%	70	1.4	142.1	7.0
RPF 1%	71	1.2	142.5	7.4
RPF 1.5%	72	1.0	142.8	8.0
Target Range	Comparison Only	1-3 in	Comparison Only	6.5% - 9%
Standard	ASTM C1064	ASTM C143	ASTM C138	ASTM C231

The results in Table 4.1 indicate that incorporating RPA increased workability, as reflected in higher slump values. This improvement can be attributed primarily to the lower water absorption of RPA compared to natural aggregates, which leaves more free water available in the mixture and enhances workability. Similar observations have been reported by Taha and Nounu (2009) and Ismail and Al-Hashmi (2008), who noted improved slump in concrete mixtures with RPA particles due to lower absorption characteristics.

Conversely, the incorporation of RPF reduced workability, as indicated by the decrease in slump. This observation is consistent with previous studies, where the addition of fibers generally led to reduced flowability in fresh concrete. Banthia and Gupta (2006) and Yazıcı et al. (2007) reported that adding fibers generally hinders the movement of the concrete mixture by introducing internal friction. Furthermore, Bhogayata et al. (2018) explained that fibers alter the rheological properties of concrete, increasing its viscosity and internal resistance, which results in a thicker mixture with lower slump values.

Despite these changes, all mixtures remained within the acceptable slump range of 1 in. to 3 in. It was also observed that replacing natural aggregates with RPA led to a decrease in unit weight due to the low specific gravity of plastic, while the inclusion of RPF slightly increased it.

Furthermore, the incorporation of RWP materials resulted in an increase in air content across all mixtures. However, values remained within NDOT's specified range of 6.5% to 9%. The rise in air content can be attributed to several factors associated with the characteristics of RWP. As noted by Babafemi et al. (2018), the irregular shape of RWP particles tends to increase the entrained air, while the poor compatibility between RWP and natural aggregates can hinder proper compaction, leading to increased voids. Additionally, the hydrophobic nature of polymers promotes air bubble formation within the mixture.

4.1.2 Compressive Strength

Figure 4.1 presents the compressive strength test results of all mixtures. The NDOT minimum requirement of 3,500 psi for 28 days strength in PCC pavements is indicated by a dotted line in the figure.

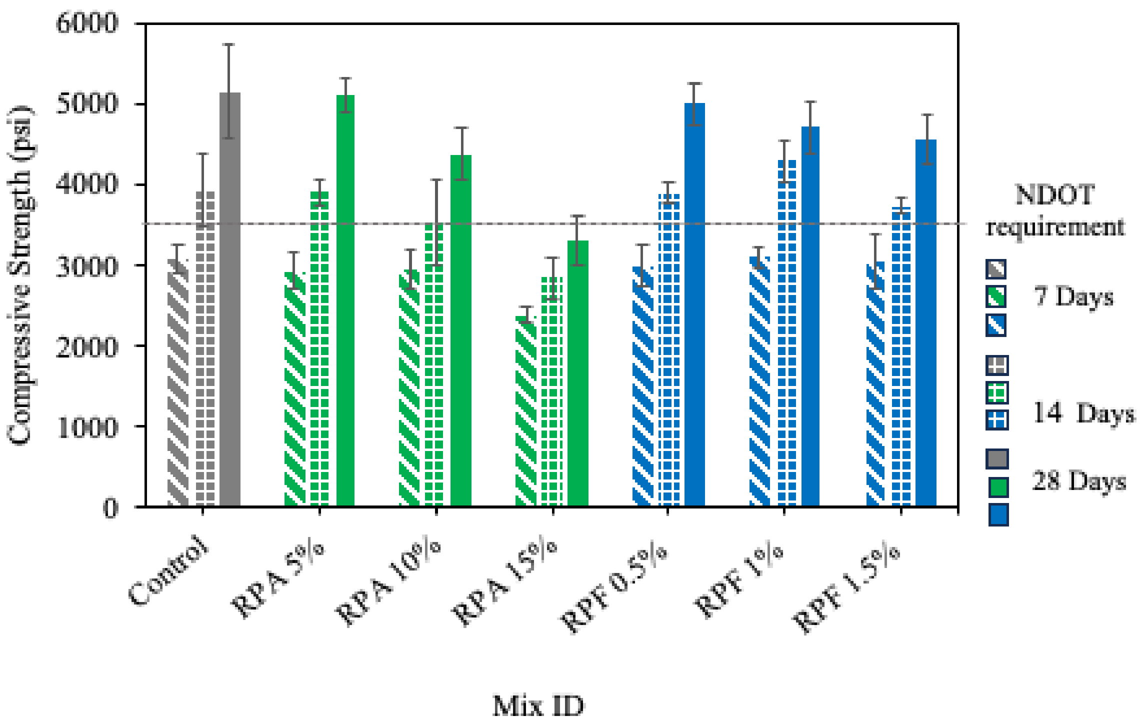


Figure 4.1 Comparison of compressive strength results of all preliminary RWP mixtures.

Based on the average results, all RPA and RPF modified mixtures exhibited lower compressive strength compared to the control one. At 28 days, both RPA 5% and RPA 10% mixtures met NDOT's required strength, showing strength reductions of approximately 1% and 15%, respectively, compared to the control mixture. However, the RPA 15% mixture failed to meet the required strength, exhibiting a reduction of approximately 36%. Likewise, the use of 0.5% RPF resulted in a 3% decrease in compressive strength, while 1.0% and 1.5% RPF content led to reductions of 8% and 12%, respectively. Despite these reductions, all mixtures containing RPF still meet the NDOT strength requirement. Similar trends have been reported in several studies investigating the use of RWP as aggregates and fibers (Almeshal et al., 2020; Gesoglu et al., 2017; Raghatate Atul, 2012; Silva et al., 2013). The lower stiffness of RWP in comparison with natural aggregate could lead to a decrease in the overall concrete strength, as supported by Jaivignesh et al. (2017a) and Rahmani et al. (2013). Additionally, the potential low bonding between RWP and the cement paste could lead to a weak interfacial transition zone (ITZ), resulting in a reduction in the maximum compressive strength. The same observations were found by Choi et al. (2005) and Kou et al. (2009).

To further verify the significance of the difference between the results, a Tukey's Honestly Significant Difference (HSD) test was performed at a confidence level of 95% by conducting an Analysis of Variance (ANOVA). Table 4.2 presents Tukey's HSD results for the compressive strength test of the RWP mixtures at different ages. After running Tukey's HSD analysis, all mixtures were categorized into groups (A, B, and C). Mixtures in the same group are not significantly different from each other. However, if the group design changes between mixtures, it indicates a statistically significant difference. Group A represents the highest values, followed by B, while group C corresponds to the lowest. At 28 days, the results showed that the control with all RPA mixtures were classified in group A, except for RPA 15%, which was placed in group B. This indicates that RPA 15% had a lower compressive strength and was statistically different from the others, while the remaining RPA mixtures showed no reduction and were statistically similar to the control. Additionally, all RPF mixtures were grouped together in group A, suggesting no statistically significant difference in compressive strength between them and the control.

Table 4.2 Tukey's HSD results for compressive strength test of the RWP mixtures.

Mix ID	7 days				14 days				28 days			
	Mean (psi)	**N***	**SD***	**Group**	**Mean (psi)**	**N***	**SD***	**Group**	**Mean (psi)**	**N***	**SD***	**Group**
Control	3076	3	178	A	3956	3	455	A	5157	3	579	A
RPA 5%	2943	3	214	A	3911	3	153	A	5115	3	209	A
RPA 10%	2947	3	240	A	3542	3	258	B	4382	3	324	A
RPA 15%	2390	3	99	B	2850	3	255	C	3302	3	308	B
RPF 0.5%	3001	3	256	A	3908	3	121	A	5011	3	262	A
RPF 1%	3118	3	126	A	4306	3	263	A	4722	3	319	A
RPF 1.5%	3054	3	331	A	3740	3	96	A	4566	3	316	A

*Note: N: Number of the samples; SD: Standard deviation of the samples.

Figure 4.2 illustrate the failure patterns for the proposed mixtures under the compressive strength test. At 28 days, all specimens developed vertical cracks, and the control mix showed significantly more severe cracking. The images demonstrate that incorporating RWP into concrete changes the cracking behavior, resulting in narrower, less aggressive cracks and a noticeable reduction in both crack width and overall cracked area. The results at this stage demonstrate that an optimized mixture can be achieved using a 10% RPA with a w/c ratio of 0.45 (equivalent to 79 pounds of UHMW per cubic yard of concrete) or adding 1.5% RPF with a w/c ratio of 0.45 (equivalent to 23 pounds of PP fibers per cubic yard of concrete). Based on the preliminary investigation results, the mixtures containing 5% and 10% RPA, as well as 0.5%, 1%, and 1.5% of RPF, satisfied NDOT's requirements for fresh properties and minimum compressive strength for concrete pavement applications.

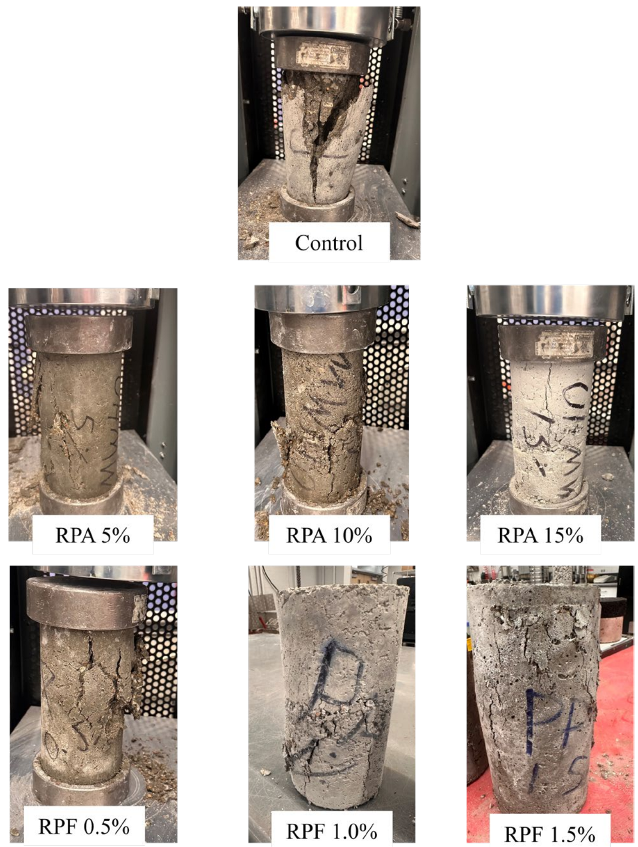


Figure 4.2 Failure pattern for RWP mixtures under compressive strength test.

4.1.3 Splitting tensile strength

Figure 4.3 shows the 28 days splitting tensile strength results for all mixtures with the AASHTO predicted values (shown as a dotted line in the figure).

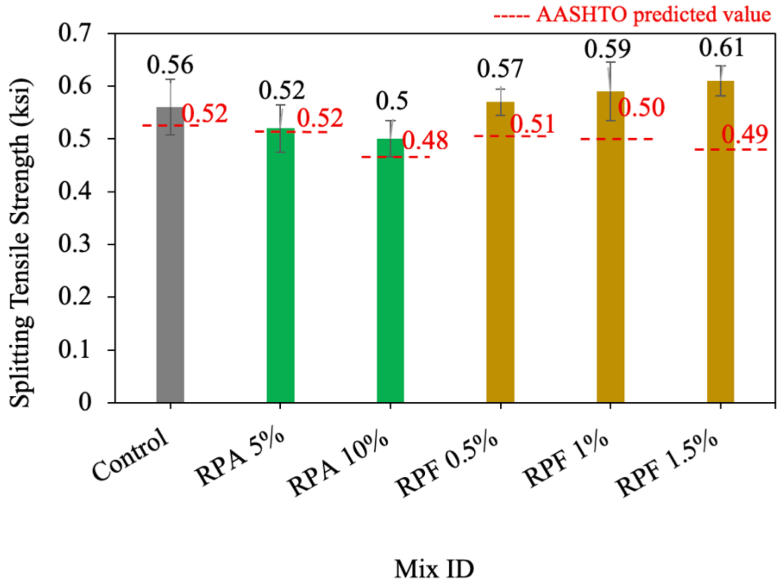


Figure 4.3 Splitting tensile strength results of all RWP mixtures at 28 days.

The inclusion of RPA led to a reduction in splitting tensile strength for all mixtures compared to the control, with the 5% and 10% RPA mixtures exhibiting decreases of approximately 6% and 11%, respectively. This is consistent with findings from previous studies, which reported that replacing natural aggregates with RPA can weaken the bond between the aggregate and cement paste due to the smooth, hydrophobic surface of plastic materials, leading to lower tensile capacity (Bhogayata and Arora, 2018; Saikia and De Brito, 2012). In contrast, adding RPF improved splitting tensile strength, with increases of about 3%, 6%, and 10% observed in mixtures containing 0.5%, 1.0%, and 1.5% RPF. Similar improvements have been reported in the literature, where the inclusion of RPF was found to bridge microcracks and enhance post-cracking behavior, thereby improving tensile performance, increasing crack resistance, and contributing to overall better mechanical behavior of the concrete (Al-Tulaian et al., 2016; Siddique et al., 2008).

Tukey's HSD results for the splitting tensile strength of the RWP mixtures is presented in Table 4.3, showing that all mixtures were statistically similar, except for RPA 10%, which was placed in group B, indicating it had significantly lower strength than the others.

Table 4.3 Tukey's HSD results for splitting tensile strength test (28 days).

Mix ID	**Mean (ksi)**	**N***	**SD***	**Group**
Control	0.56	3	0.053	A
RPA 5%	0.523	3	0.045	A
RPA 10%	0.5	3	0.034	B
RPF 0.5%	0.57	3	0.025	A
RPF 1.0%	0.59	3	0.056	A
RPF 1.5%	0.61	3	0.028	A

*Note: N: Number of the samples; SD: Standard deviation of the samples.

Table 4.4 presents a comparison between the AASHTO predicted values calculated using Equation 1 (AASHTO C5.4.2.7) and the corresponding experimental results for splitting tensile strength for various concrete mixtures. The data show that the experimental values are consistently higher than the predicted ones across all mixes, especially for RPF mixtures.

$$f_t = 0.23 \sqrt{f'_c} \quad (1)$$

where:

f'_c= compressive strength of concrete (ksi).

Table 4.4 Comparison between the AASHTO predicted value and the experimental values for the splitting tensile strength test.

Mix ID	AASHTO Predicted Value (ksi)	Experimental value (ksi)	% Difference
Control	0.52	0.56	7.7%
RPA 5%	0.52	0.523	0.2%
RPA 10%	0.48	0.5	4.2%
RPF 0.5%	0.51	0.57	11.8%
RPF 1%	0.5	0.59	18%
RPF 1.5%	0.49	0.61	24.5%

The observed failure patterns under the splitting tensile test in Figure 4.4 show that the control concrete specimen typically fractured into two separate pieces upon failure. In contrast, the RWP modified concrete exhibited narrower, less pronounced cracks and remained in one piece after testing, indicating improved crack control.

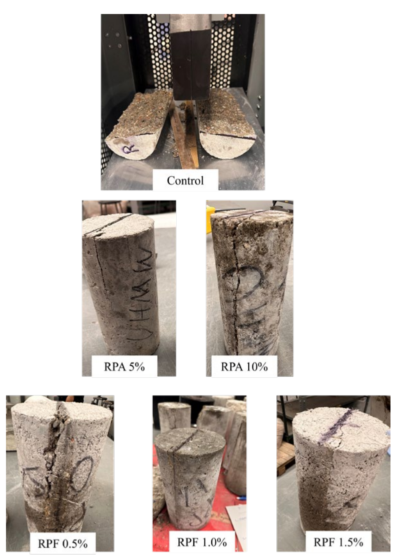


Figure 4.4 Failure pattern for RWP mixtures under splitting tensile strength test.

4.1.4 Flexural strength

The modulus of rupture results after a 28-day curing period and the AASHTO predicted values for the studied mixtures are illustrated in Figure 4.5.

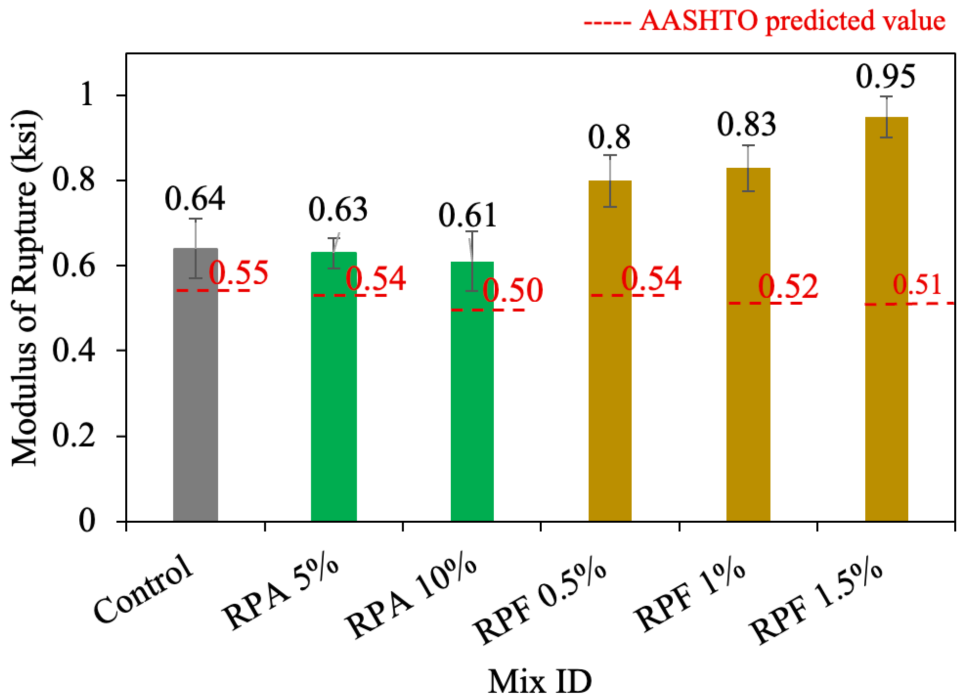


Figure 4.5 Modulus of rupture results of all RWP mixtures at 28 days.

It can be observed that the flexural strength of all RPA-optimized mixtures was lower than that of the control. In particular, the RPA 5% and RPA 10% mixtures showed reductions in modulus of rupture of approximately 2% and 4%, respectively. The reduction is primarily attributed to the weak interfacial bonding between the cement paste and RPA, as discussed before (Frigione, 2010; Gesoglu et al., 2017; Saikia and De Brito, 2012).

On the other hand, the results from adding RPF reveal that the mixtures achieved higher flexural strength than the control mixture. The RPF 0.5%, 1%, and 1.5% mixtures showed an increase in modulus of rupture of approximately 24%, 30%, and 48%. Similar trends have been reported in the literature, where RPF were shown to enhance flexural performance by bridging microcracks and increasing resistance to crack propagation in fiber-reinforced mixtures (Leong et al., 2020; Memon et al., 2018).

These findings were confirmed by Tukey's HSD results as shown in Table 4.5. The analysis grouped the control and RPA mixtures in group C, indicating no significant difference among them. The RPF 0.5% mixture was placed in group B, while the RPF 1% and 1.5% mixtures were categorized in group A, reflecting a progressive increase in flexural strength compared to the control. This grouping highlights the statistically significant differences in flexural performance among the mixtures.

Table 4.5 Tukey's HSD results for modulus of rupture test of the RWP mixtures.

Mix ID	**28 days**			
	Mean (ksi)	**N***	**SD***	**Group**
Control	0.64	3	0.07	C
RPA 5%	0.63	3	0.036	C
RPA 10%	0.61	3	0.07	C
RPF 0.5%	0.8	3	0.061	B
RPF 1%	0.83	3	0.054	A
RPF 1.5%	0.95	3	0.048	A

*Note: N: Number of the samples; SD: Standard deviation of the samples.

Table 4.6 compares the AASHTO predicted values calculated using Equation 2 (AASHTO C5.4.2.6) with the experimental results obtained for the modulus of rupture test for different concrete mixtures. In all cases, the experimental values exceeded the predicted ones, with the most significant differences observed in the mixtures containing RPF.

$$f_r = 0.24\,\lambda\,\sqrt{f'_c} \qquad (2)$$

where:

λ = concrete density modification factor (taken as 1.0 for normal weight concrete).

f'_c = compressive strength of concrete (ksi).

Table 4.6 Comparison between the AASHTO predicted value and the experimental values for the modulus of rupture.

Mix ID	**AASHTO Predicted Value (ksi)**	**Experimental value (ksi)**	**% Difference**
Control	0.55	0.64	16%
RPA 5%	0.54	0.63	16.7%
RPA 10%	0.5	0.61	22%
RPF 0.5%	0.54	0.8	48%
RPF 1%	0.52	0.83	60%
RPF 1.5%	0.51	0.95	86%

Figure 4.6 shows that all the beams exhibited a mid-third crack pattern at failure in the flexural strength test. In the RWP mixtures, both the crack width and length were reduced compared to the control specimens, indicating improved crack resistance.

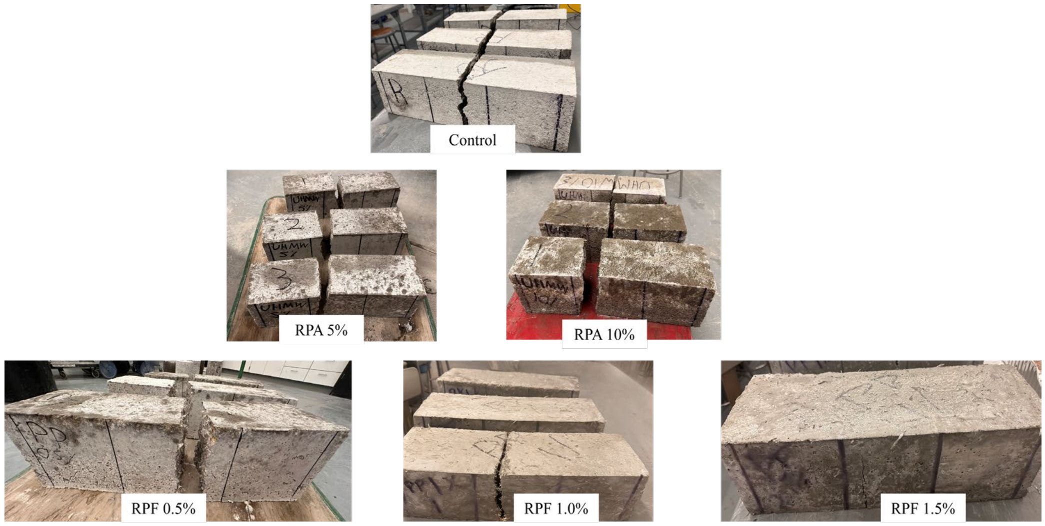


Figure 4.6 Failure pattern for RWP mixtures under flexural strength test.

4.1.5 Modulus of Elasticity strength (MOE)

Figure 4.7 presents the measured MOE at 28 days with the AASHTO predicted values (shown as a dotted line in the figure) for all mixtures.

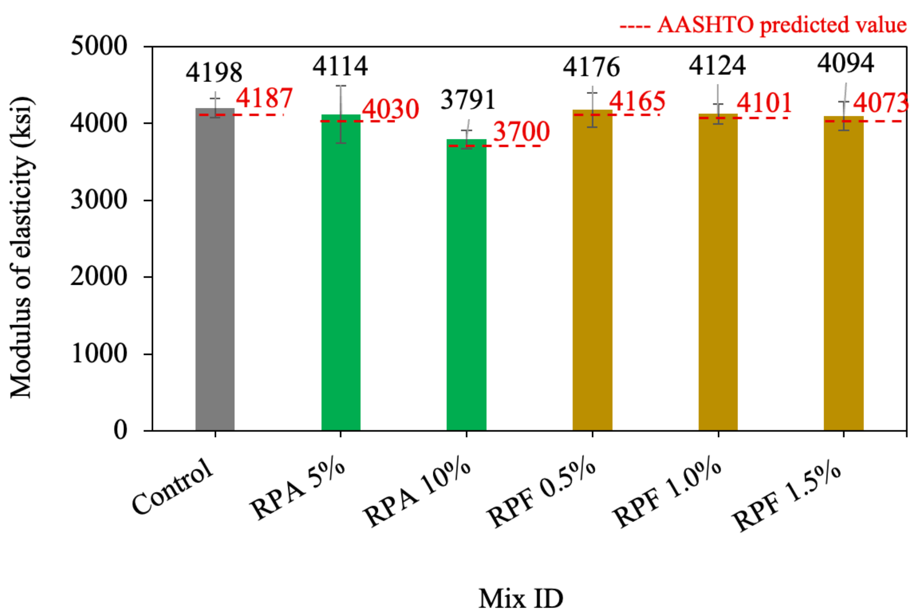


Figure 4.7 Modulus of elasticity results of all RWP mixtures at 28 days.

The results indicate that all optimized mixtures exhibited reductions in MOE compared to the control one. Specifically, MOE decreased by approximately 2% and 10% for mixtures containing 5% and 10% RPA, respectively. Likewise, the incorporation of RPF led to slight decreases in MOE, with reductions of about 0.5%, 2%, and 2.5% observed for mixtures containing 0.5%, 1.0%, and 1.5% RPF, respectively. The reduction is attributed to the low stiffness of the RWP compared to the natural aggregate, and this observation was verified in many studies (Alqahtani et al., 2017a; Liu et al., 2024). Statistically, as shown in Table 4.7, Tukey's HSD results indicated that all mixtures fell within the same group, suggesting no significant difference in MOE among the mixtures.

Table 4.7 Tukey's HSD results for the modulus of elasticity test of the RWP mixtures.

Mix ID	**28 days**			
	Mean (ksi)	**N***	**SD***	**Group**
Control	4198	3	125	A
RPA 5%	4114	3	375	A
RPA 10%	3791	3	121	A
RPF 0.5%	4176	3	223	A
RPF 1%	4124	3	128	A
RPF 1.5%	4094	3	188	A

*Note: N: Number of the samples; SD: Standard deviation of the samples.

The AASHTO predicted modulus of elasticity values were calculated using Equation 3 (AASHTO C5.4.2.4), and Table 4.8 compares the values with those experimentally determined for various concrete mixes. In all cases, the experimentally measured MOE values are slightly higher than those predicted by AASHTO, with the two sets of values being very close overall.

$$E_c = 120{,}000 \text{ K1 } w_c^{2.0} \, {f'}_c^{\,0.33} \qquad (3)$$

Where:

K1 = concrete factor for source of aggregate (taken as 1.0).

wc = the unit weight of concrete (kcf).

${f'}_c$ = compressive strength of concrete (ksi).

Table 4.8 Comparison between the AASHTO predicted value and the experimental values for the modulus of elasticity.

Mix ID	**AASHTO Predicted Value (ksi)**	**Experimental value (ksi)**	**% Difference**
Control	4187	4198	0.3%
RPA 5%	4030	4114	2%
RPA 10%	3700	3791	2.5%
RPF 0.5%	4165	4176	0.3%
RPF 1%	4101	4124	0.5%
RPF 1.5%	4073	4094	0.6%

4.1.6 Semi-circular bending (SCB) test

The SCB tests for the proposed mixtures were conducted at 56 days. Figure 4.8 presents the load-displacement curve and the corresponding cracking path for the control mixture, while Figure 4.9 and Figure 4.10 illustrate the same for all mixtures containing RPA and RPF.

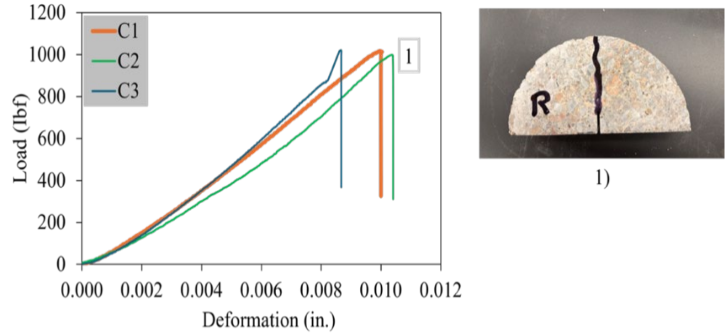
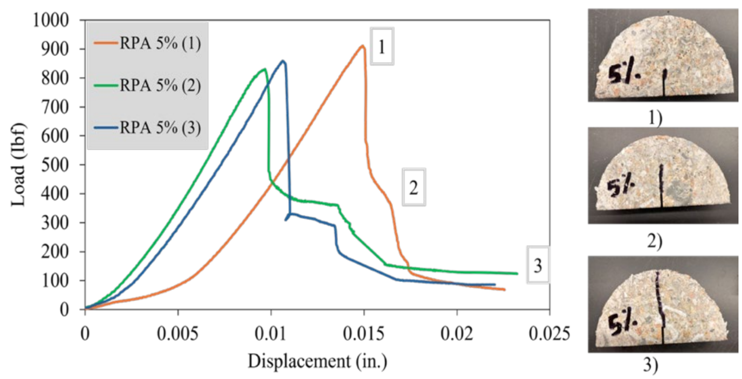
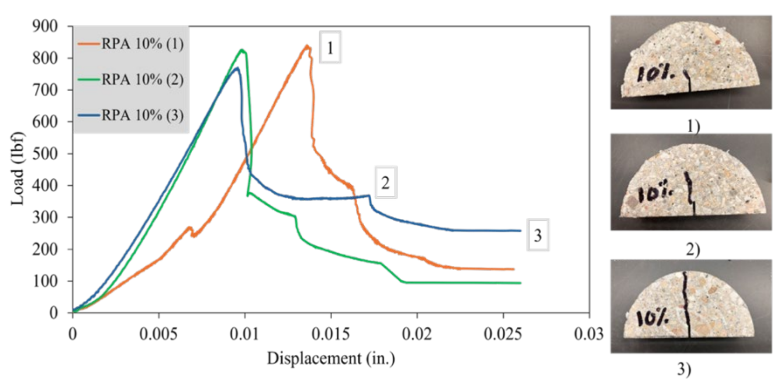


Figure 4.8 Load-Displacement curve for the control mixture.



(a)



(b)

Figure 4.9 Load-Displacement curve for RPA- mixtures, a) RPA 5%, b) RPA 10%.

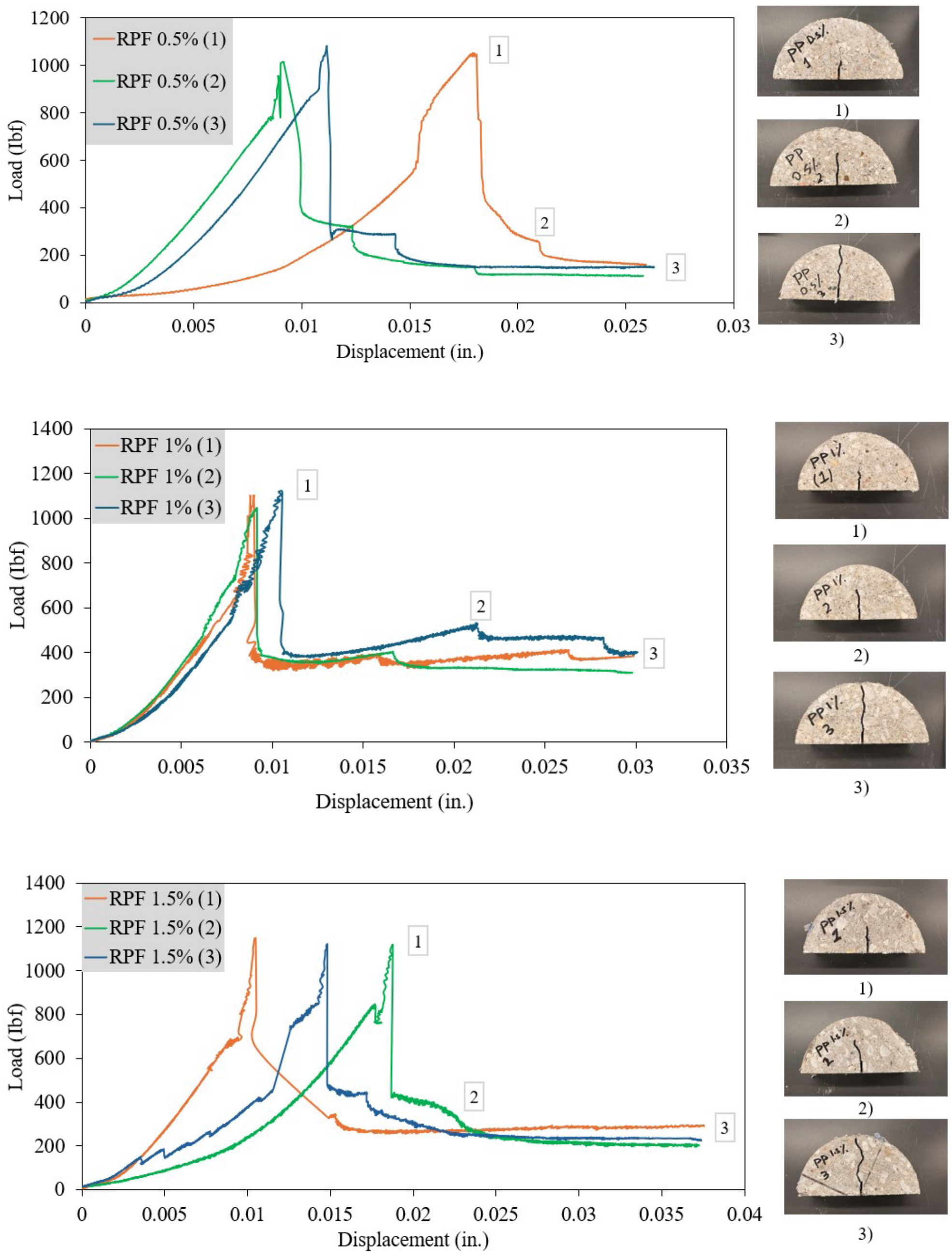


Figure 4.10 Load-Displacement curve for RPF-mixtures, a) RPF 0.5%, b) RPF 1%, c) RPF1.5%.

In the control mixture, the load-displacement curve displays a sharp peak followed by an immediate drop, indicating a brittle failure. The cracks initiate at the notch and propagate rapidly to the end of the specimen, indicating that failure occurs suddenly at the peak load. In contrast, when RPA and RPF are added to concrete, the load-displacement behavior changes significantly. The curves become wider, and the total displacement at failure increases, suggesting improved ductility and energy absorption. The invisible microcracks started to form around the notch. As the load increases and approaches the peak load (Point 1 in the figures), the cracks become visible and propagate slowly. By the time the curve reaches Point 2, the cracks typically extend to the middle of the specimen, but it is still partially restrained by the RWP particles. These particles act as bridges within the matrix, preventing the crack from propagating. This crack-bridging effect continues until the specimen reaches Point 3, where the RWP particles lose their load bearing capacity, and the crack finally propagates through the entire cross-section, resulting in failure. This more gradual and controlled failure mode highlights the beneficial role of RWP in enhancing the fracture resistance of the mixtures by increasing the ductility, delaying crack growth, and allowing for greater deformation before failure.

Also, an increase in residual capacity with higher RPF content was observed. This phenomenon indicates that the RPF-concrete mixtures maintain a greater portion of the load-carrying ability after cracking, due to the bridging effect of fibers across the crack surfaces. This observation was verified by Banthia and Gupta (2006), with higher fiber dosages, the number of fibers available to resist crack opening increases, leading to improved post-crack strength, toughness, and ductility. This enhancement reflects the material's ability to absorb more energy and undergo larger deformations without sudden failure.

Figure 4.11 illustrates the peak load values for all mixtures and Table 4.9 shows the results from the statistical analysis. The results indicate that all RPA modified mixtures experienced reductions in the peak load by approximately 15% and 19% due to the low stiffness of RPA compared to natural aggregates. In contrast, the mixtures containing RPF showed increases in peak load of 4%, 8%, and 11%, respectively. This improvement aligns with a study done by Aziminezhad et al. (2020), which demonstrated that incorporating RPF enhances the load-bearing capacity in concrete mixtures.

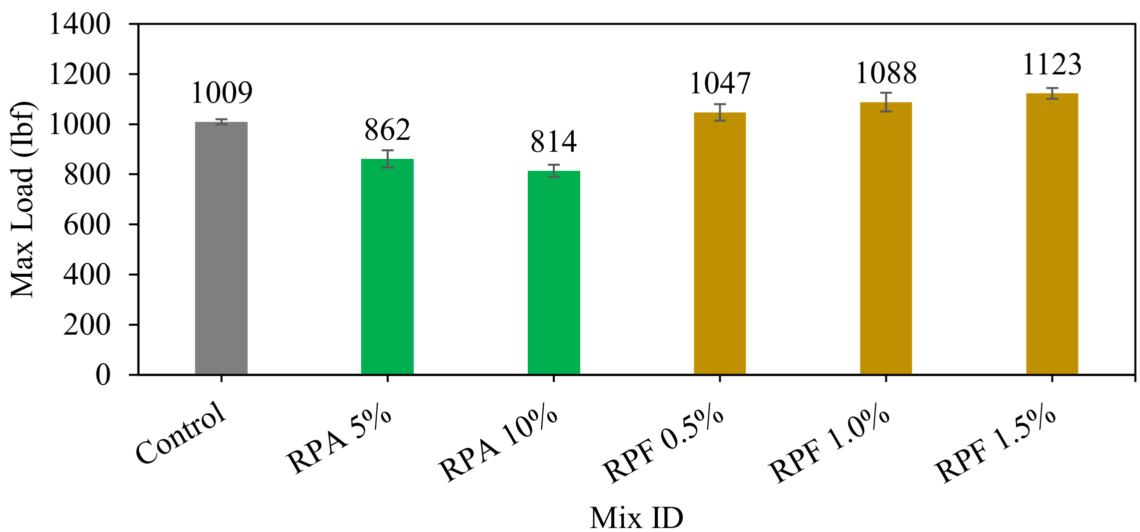


Figure 4.11 SCB peak load results of all RWP mixtures at 56 days.

Table 4.9 Tukey's HSD results for the SCB peak load of the RWP mixtures.

Mix ID	**56 days**			
	Mean (lbf)	**N***	**SD***	**Group**
Control	1009	3	10.3	B
RPA 5%	862	3	34.2	C
RPA 10%	814	3	24.2	C
RPF 0.5%	1047	3	33	A
RPF 1%	1088	3	37.3	A
RPF 1.5%	1123	3	21.5	A

*Note: N: Number of the samples; SD: Standard deviation of the samples.

The Tukey's HSD results in Table 4.9 confirm these findings by grouping the mixtures based on their performance: the control mixture was placed in group B, RPA mixtures were assigned to group C, indicating a decrease in peak load compared to the control, and RPF mixtures fell into group A, reflecting an increase. This classification underscores the statistically significant differences in the peak load among the different types of mixture.

The ductility index (DI) results are presented in Figure 4.12. It can be observed that the DI increased across all mixtures incorporating RWP. For the RPA mixtures, the ductility index increased by approximately 92% and 135% compared to the control. The RPF mixtures showed even more significant improvements, with increases of about 67%, 200%, and 225%, respectively. The same observation was reported by Aziminezhad et al. (2020), who found that incorporating RWP can increase the DI in concrete mixtures. These results suggest that incorporating RWP particles enhances the ductility of concrete and reduces its brittleness.

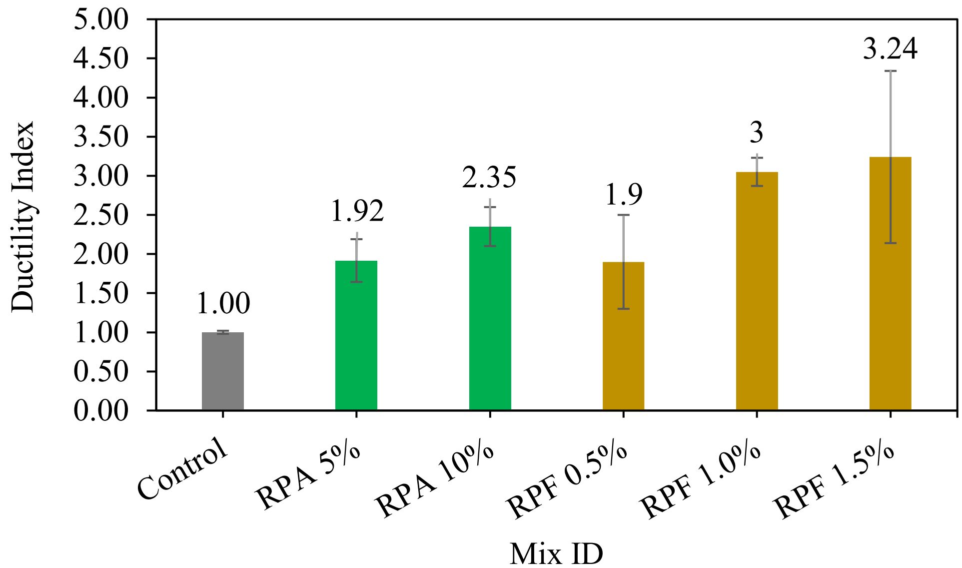


Figure 4.12 Ductility Index results of all RWP mixtures at 56 days.

Tukey's HSD results in Table 4.10 further support this observation, indicating that all RWP mixtures were classified in group A, while the control mixture was placed in group B. This grouping confirms that the addition of RWP significantly increases the DI compared to the control.

Table 4.10 Tukey's HSD results for Ductility Index of the RWP mixtures.

Mix ID	**56 days**			
	Mean	**N***	**SD***	**Group**
Control	1.0	3	0.02	B
RPA 5%	1.92	3	0.27	A
RPA 10%	2.35	3	0.25	A
RPF 0.5%	1.9	3	0.6	A
RPF 1%	3	3	0.2	A
RPF 1.5%	3.24	3	1.1	A

*Note: N: Number of the samples; SD: Standard deviation of the samples.

Additionally, Figure 4.13 shows the area under the load-displacement curve. The area under the curve increased across all RWP-modified mixtures, indicating that the concrete can absorb and dissipate more energy than the control mixture. Specifically, for RPA 5% and 10%, they increased by 17% and 49%. Also, the RPF-modified mixtures exhibited increases of 52%, 147%, and 163%, respectively. Guo et al. (2023) reported comparable findings, demonstrating that the incorporation of RWP can significantly enhance the energy absorption capacity of the mixtures.

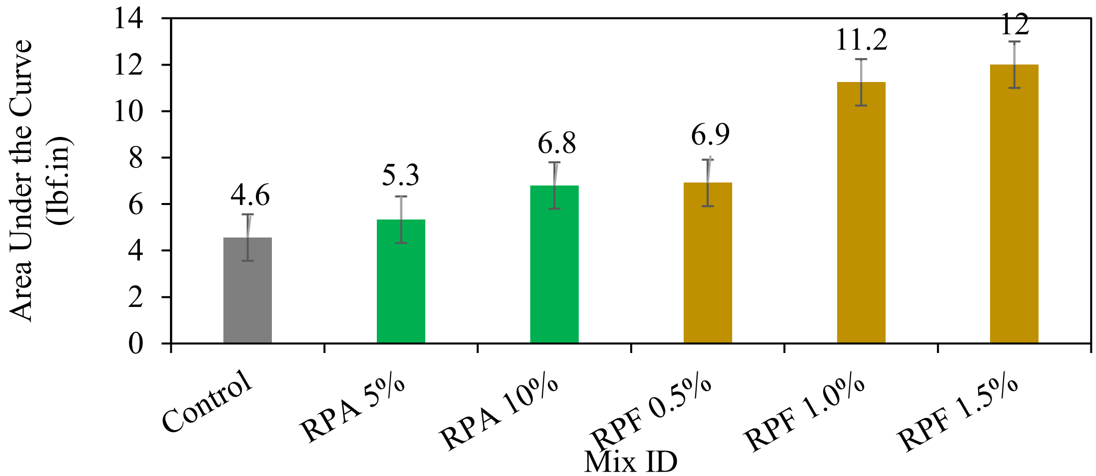


Figure 4.13 Area under the curve results of all RWP mixtures at 56 days.

Tukey's HSD results in Table 4.11, all mixtures were categorized in group B, except for RPF 1.0% and 1.5%, which were placed in group A. This indicates that these two RPF mixtures were statistically different from the others and exhibited significantly higher energy absorption capacity.

Table 4.11 Tukey's HSD results for the area under the curve of the RWP mixtures.

Mix ID	**56 days**			
	Mean (lbf.in)	**N***	**SD***	**Group**
Control	4.6	3	0.73	B
RPA 5%	5.3	3	0.7	B
RPA 10%	6.8	3	1	B
RPF 0.5%	6.9	3	0.2	B
RPF 1%	11.2	3	1.2	A
RPF 1.5%	12.0	3	0.9	A

*Note: N: Number of the samples; SD: Standard deviation of the samples.

The final fracture parameter, fracture energy (Gf), is illustrated in Figure 4.14. An overall increase in Gf was observed across all RWP-modified mixtures, indicating an enhanced ability of the concrete to absorb energy and resist crack propagation. For the RPA mixtures, Gf increased by approximately 14% and 45% for the 5% and 10% replacement levels, respectively. The RPF mixtures showed even more substantial improvements, with increases of around 47%, 140%, and 147% for 0.5%, 1.0%, and 1.5% RPF, respectively. Liu et al. (2015) also observed that adding RPF notably improved the Gf of the mixtures, confirming the effectiveness of fiber reinforcement in enhancing crack resistance.

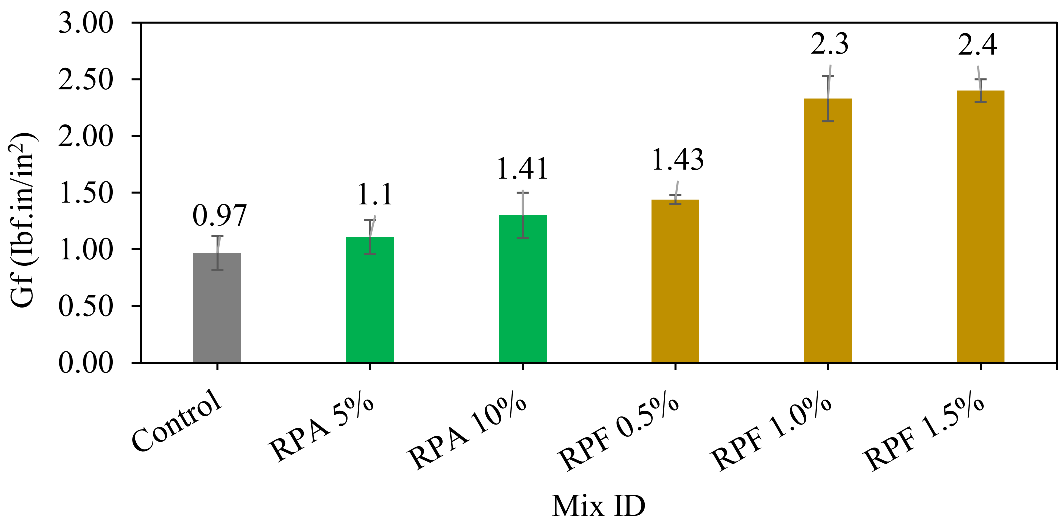


Figure 4.14 Fracture energy results of all RWP mixtures at 56 days.

Tukey's HSD results are presented in Table 4.12. It can be observed that all modified mixtures exhibited significantly higher Gf values than the control. The control mixture exhibited the lowest fracture energy (Gf) values and was categorized in group C. The RPA mixtures with RPF 0.5% showed higher Gf values than the control and were placed in group B, indicating a statistically significant improvement. The RPF 1% and 1.5% mixtures achieved the highest Gf values and were classified in group A, reflecting a statistically significant enhancement compared to both the control and RPA mixtures.

Table 4.12 Tukey's HSD results for fracture energy of the RWP mixtures.

Mix ID	**56 days**			
	Mean (Ibf.in/in^2)	**N***	**SD***	**Group**
Control	0.97	3	0.15	C
RPA 5%	1.1	3	0.15	B
RPA 10%	1.41	3	0.2	B
RPF 0.5%	1.43	3	0.04	B
RPF 1%	2.3	3	0.2	A
RPF 1.5%	2.4	3	0.1	A

*Note: N: Number of the samples; SD: Standard deviation of the samples.

4.1.7 Durability property

Figure 4.15 presents the surface electrical resistivity of all proposed mixtures. The AASHTO TP95 standard for defining the resistivity level of concrete is also presented in Table 4.13.

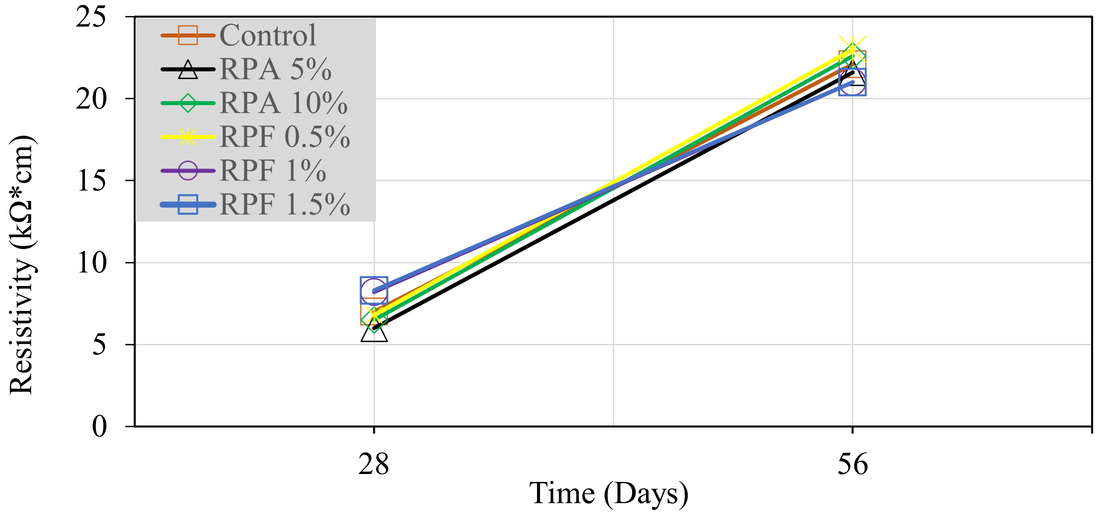


Figure 4.15 Electrical resistivity (surface) results of all RWP mixtures.

Table 4.13 Susceptibility of Chloride Ion Penetration (AASHTO TP 95).

Electrical Resistivity (kΩ-cm)	**Chloride Ion Penetration**
<12	High
12-21	Moderate
21-37	Low
37-254	Very Low
>254	Negligible

The results at 28 days indicate that all optimized mixtures have a high level of chloride ion penetration. On the other hand, at 56 days, all mixtures have electric resistivity within the range 21 to 37, indicating low chloride ion penetration and good durability. According to Tukey's HSD results in Table 4.14 at 56 days, all mixtures were categorized in the same statistical group, showing no significant differences among them. This suggests that incorporating RWP does not affect the chloride ion penetration of concrete.

Table 4.14 Tukey's HSD results for electrical resistivity (surface) test of the RWP mixtures.

Mix ID	**28 days**				**56 days**			
	Mean (kΩ-cm)	**N***	**SD***	**Group**	**Mean (kΩ-cm)**	**N***	**SD***	**Group**
Control	7	3	0.12	B	22	3	1.3	A
RPA 5%	6	3	0.3	B	21.6	3	4.7	A
RPA 10%	6.5	3	0.03	B	22.6	3	2.4	A
RPF 0.5%	6.8	3	0.1	B	23	3	1.7	A
RPF 1%	8.2	3	0.7	A	21	3	0.6	A
RPF 1.5%	8.3	3	0.15	A	21	3	1.2	A

*Note: N: Number of the samples; SD: Standard deviation of the samples

Results of the in-depth investigation have shown that all the proposed mixtures except RPA 15% satisfy NDOT minimum requirements for concrete pavements concerning workability, strength, and durability. All the optimized mixes also performed better ductility and cracking resistance than the current 47B mixture.

4.2 Concrete Mixtures using Portland Cement type IP

4.2.1 Fresh Concrete Properties

Fresh properties for the mixtures using IP cement and w/c are summarized in Table 4.15.

Table 4.15 Fresh Concrete properties.

Mix ID	Temperature (◦F)	Slump (in)	Unit weight (pcf)	Air content (%)
Control	75	1.25	141.8	7
RPA 10%	73	3	135.8	8
RPF 1.5%	77	1.0	142.3	8.3
Target Range	Comparison Only	1-3 in	Comparison Only	6.5% - 9%
Standard	ASTM C1064	ASTM C143	ASTM C138	ASTM C231

The same trends can be observed as those obtained for the previous mixtures using IL cement, i.e., the incorporation of RPA increased workability, as reflected in higher slump values. This can be related to the lower water absorption of RPA compared to natural aggregates, which leaves more free water available in the mixture and enhances workability. Conversely, the incorporation of RPF reduced workability, as indicated by the decrease in slump. Fibers generally led to reduced flowability in fresh concrete.

Despite these changes, all mixtures remained within the acceptable slump range of 1 in. to 3 in. It was also observed that replacing natural aggregates with RPA led to a decrease in unit weight due to the low specific gravity of plastic, while the inclusion of RPF slightly increased it. Furthermore, the incorporation of RWP materials resulted in an increase in air content across all mixtures. However, values remained within NDOT's specified range of 6.5% to 9%.

4.2.2 Compressive Strength

Figure 4.16 presents the compressive strength test results of the studied mixtures produced with IP cement and w/c of 0.42.

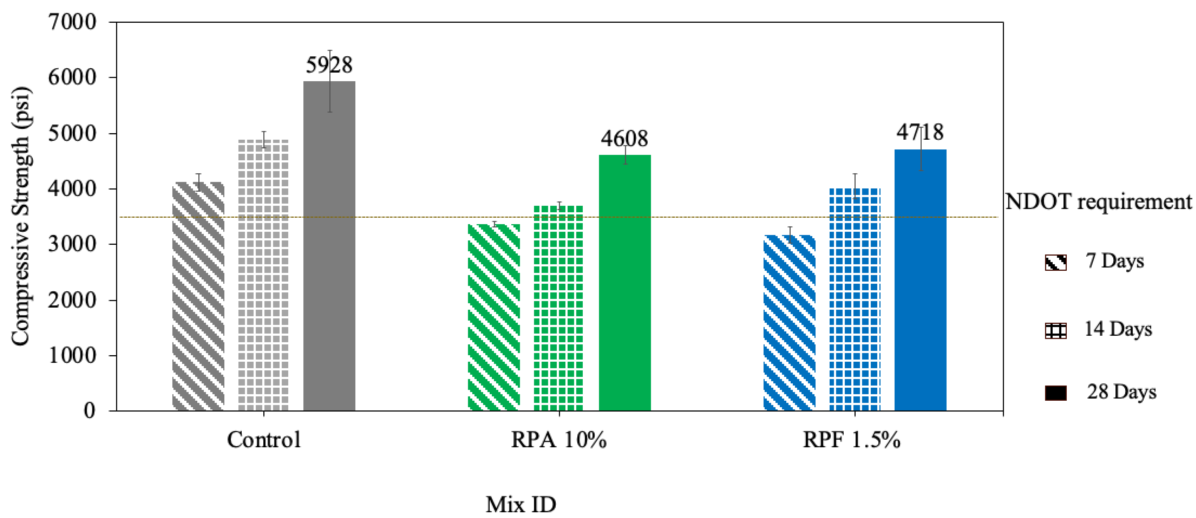


Figure 4.16 Comparison of compressive strength results of RWP mixtures produced with IP cement and w/c of 0.42.

Based on the average results, all RPA and RPF modified mixtures exhibited lower compressive strength compared to the control one. Despite these reductions, all mixtures containing RPF still meet the NDOT strength requirement. At 28 days, both RPA 10% and RPF 1.5% mixtures met NDOT's required strength.

4.2.3 Splitting Tensile Strength, Modulus of Rupture, and MOE

Figure 4.17 presents the 28-day splitting tensile strength, modulus of rupture (MOR), and modulus of elasticity (MOE) results, along with the corresponding statistical groupings for mixtures produced with IP cement and a w/c ratio of 0.42. It can be observed that the addition of 10% RPA reduced the splitting tensile strength while maintaining the modulus of rupture and MOE compared to the control samples. However, the incorporation of 1.5% RPF did not significantly affect the splitting tensile strength or MOE but improved the flexural strength, indicating enhanced flexural performance likely due to microcrack bridging and increased resistance to crack propagation in fiber-reinforced mixtures.

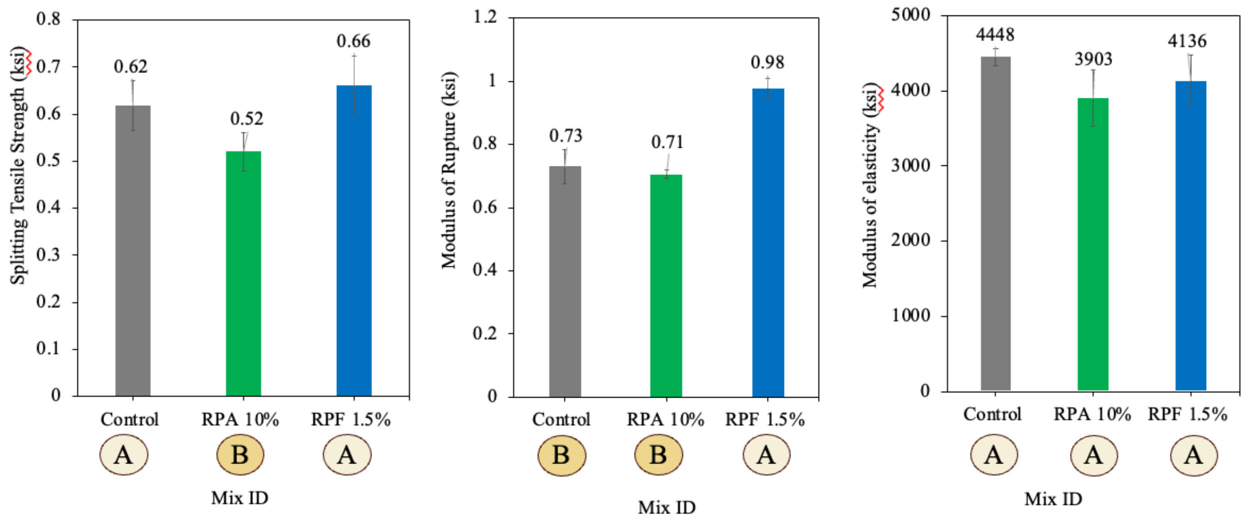


Figure 4.17 Splitting tensile strength, modulus of rupture, and MOE results of RWP mixtures produced with IP cement and w/c of 0.42 at 28 days.

Chapter 5 Conclusions and Recommendations

The primary goal of this multi-phase study is to verify the feasibility of using RWP for concrete pavement applications. In this Phase 1 study, we evaluated the performance of concrete mixtures incorporating various types and proportions of RWP, either as recycled plastic aggregates (RPA) or recycled plastic fibers (RPF). The findings indicate that it is possible to replace the natural fine aggregate by up to 10% RPA by volume of the natural fine aggregates or add up to 1.5% RPF by the total volume of concrete, while still meeting the minimum requirements for both fresh and hardened properties of concrete. Based on the results of this experimental study, the following conclusions are drawn:

- Material characterization results, including FTIR and AIMS analysis, confirmed that the RWP materials used in this study are pure polymers. Furthermore, the UHMW-RPA particles were found to be more angular compared to the natural fine aggregate.
- Replacing natural fine aggregate with RPA tends to increase the workability of the concrete mixture, whereas the addition of RPF decreases workability and results in a thicker mixture. Incorporating RWP as aggregates or fibers into concrete increases the air content of the mixture. Replacing part of the natural fine aggregates with RPA particles reduces the unit weight, primarily due to the lower specific gravity of the plastic materials compared to traditional aggregates.
- Statistical analysis results of the compressive strength test and splitting tensile strength values can be reduced with the incorporation of RPA, where values are still above the minimum NDOT criteria for up to 10%. The addition of RWP had no effect on the studied mixture's MOE.
- Flexural strength results indicated that incorporating RPA had no significant effect on the modulus of rupture. In contrast, the addition of RPF led to a progressive increase in flexural strength compared to the other mixtures, by bridging microcracks and improving post-cracking behavior.
- A comparison between the experimental mechanical results and the values predicted by AASHTO LRFD equations shows that the measured strengths are generally higher than the predicted ones, particularly when RPF is added to the concrete. These findings suggest that a correction factor greater than 1 may be appropriate when using this type of aggregate. For the MOE test, the experimental and predicted values are very close.
- Results from the SCB test clearly show that incorporating RWP in concrete changes

the load-displacement behavior, leading to increased maximum displacement at failure, a larger area under the curve, and an enhanced ductility index compared to the control mixture. This shift indicates a transition in the concrete's behavior from brittle to ductile, allowing more deformation before failure.

- Also, an increase in the residual capacity with adding RPF content was observed. This phenomenon indicates that the RPF-concrete mixtures maintain a greater portion of the load-carrying ability after cracking, potentially due to the bridging effect of fibers across the crack surfaces. This enhancement reflects the material's ability to absorb more energy and undergo larger deformations without sudden failure.
- The incorporation of RWP had no significant effect on chloride ion penetration, suggesting that durability performance was maintained across all mixtures.

Overall, RWP-modified mixtures demonstrated improved cracking resistance and ductility compared to the 47B control mix, while still meeting NDOT's minimum requirements for concrete pavement applications. This approach not only enhances performance but also offers a sustainable solution for the construction industry and supports increased recycling efforts in Nebraska.

5.1 Expected Benefits

This project demonstrated the technical feasibility and benefits of incorporating recycled plastics into concrete. Both recycled plastic aggregates (RPA) and recycled plastic fibers (RPF) enhanced ductility and fracture energy without compromising fresh or hardened properties. This approach can enhance concrete performance while also offering a sustainable solution for the construction industry and supporting increased recycling efforts in Nebraska.

The use of recycled plastic contributes to significant environmental gains, reducing landfill waste and promoting circular economy practices. Overall, the project provides initial evidence that this innovation can help build a more sustainable, and resilient infrastructure for Nebraska, with high potential for direct application by NDOT.

5.2 Recommendations for Future Work

The successful initial evaluation confirms that plastic concrete has the potential for broader development and adoption across the state. However, additional evidence is needed. It is recommended to conduct durability testing and field demonstration projects to justify the constructability and performance of the concrete that incorporates waste plastic. Therefore, we recommend implementation include:

- Evaluating critical long-term performance properties including drying shrinkage, freeze–thaw resistance, wet–dry cycling, and permeability, to ensure suitability for Nebraska’s harsh climate and NDOT specifications.
- Scaling up production methods, moving from laboratory-scale mixes to ready-mix production processes to validate material handling, workability, and constructability under field-like conditions.
- Implementing pilot-scale pavement sections to assess real-world performance, durability, and serviceability over time.

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