FEASIBILITY OF USING RECYCLED PLASTIC SHREDS AS PARTIAL REPLACEMENT OF AGGREGATE IN THE GRANULAR BASE OF PAVEMENTS

by

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Abstract

The increase in the generation of plastic wastes every year is causing great awareness among consumers over the disposal of these wastes due to limited landfill capacity. This study investigates the feasibility of incorporating recycled plastic into the granular base of pavement as a replacement for natural aggregate. The process to recycle plastic waste was studied, and potential providers of the material were identified and theoretical proportions were suggested. A preliminary trial mix containing 95% aggregates and 5% shredded plastic was prepared in the laboratory using the sieve analysis and the moisture-density relationship tests. The results were compared with results obtained for a control material without plastic. The results from the standard proctor test demonstrated that with the inclusion of 5% shredded PET, the material required 2% less water and the maximum dry density dropped by 21%. Considering that the availability of plastic was a limitation, recommendations are provided to facilitate further research.

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Table of Content

List of Figures

List of Tables

List of Abbreviations

ASTM	American Society for Testing and Materials
CBR	California Bearing Ratio
HDPE	High-Density Polyethylene
ITSM	Indirect Tensile Stiffness Modulus
LDPE	Low-Density Polyethylene
MDD	Maximum Dry Density
NBDTI	New Brunswick Department of Transportation and Infrastructure
OMC	Optimum Moisture Content
PC	Polyester Concrete
PET	Polyethylene Terephthalate
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl Chloride
RAP	Reclaimed Asphalt Pavement
RCA	Recycled Ceramic Aggregate
RLAT	Repeated Load Axial Test
SCC	Self Compacting Concrete

1 Introduction

1.1 Background

The incorporation of waste materials in road construction is becoming a significant topic for engineering researchers, as there is a need to improve the structural capacity of pavements and develop alternative means to recycle waste materials. Abukhettala (2016) stated that the utilization of recycled wastes in road construction had indicated improvements in specific properties of pavements, depending on the characteristics of the recycled material. Recyclable materials such as plastic wastes, scrap tires, blast furnace slag, bottom and fly ashes, glass, waste rock, recycled concrete aggregates, reclaimed asphalt pavement, steel slag are typically used as partial replacement of aggregate during road construction (Schroeder, 1994).

1.2 Problem Definition

Every day, kilometers of new roads are built in different countries around the world using several tons of raw materials and natural stocks. In order to meet the demands from the construction industry, the production of aggregate materials has been causing severe disruption to the environment at large, owing to the depletion of natural resources (Akbulut & Gurer, 2007; Athanasopoulou & Kollaros, 2015; Drew et al., 2002). Zoorob & Suparma (2000) reported that approximately 12,500 tons of virgin aggregates are consumed per kilometer during the construction of pavements, and a maximum of 75% of these materials can be replaced depending on the type of the recycling material. To reduce the hazardous effect during the production of aggregate and the cost of road construction, previous case studies on the incorporation of recycled materials as partial replacement of aggregate have indicated changes in the properties of pavement such as resilient modulus, permanent deformation, bearing capacity, moisture-density ratio and so on. This report will focus on the feasibility of incorporating recycled plastic shreds as partial replacement of aggregate in the base layer of the pavement structure.

1.3 Goals and Objectives

The goal of this research is to evaluate the feasibility of using recycled plastic shreds as partial replacement of aggregate in the base layer of pavement. In achieving this goal, the following objectives were undertaken to complete the research:

1. Reviewing and gathering previous experimental studies on the effect of incorporating different waste materials as partial replacement of granular material.
2. Reviewing the incorporation of recycled plastic waste in civil infrastructure.
3. Conduct a theoretical design to determine the maximum proportion of shredded plastic that could be used as partial replacement of aggregate in the granular base of pavement.
4. Conducting sieve analysis and moisture-density relationship test, on a trial mix obtained by partially replacing 5% of virgin material with plastic shreds.

1.4 Scope

The scope of this study comprises of the theoretical and experimental investigation of incorporating recycled plastic shreds as partial replacement of granular material in the base layer of pavement. Since this is an exploratory research, most of the effort was put into reviewing the literature and finding potential providers of the recycled plastic. The laboratory investigation is restricted but intends to serve as the foundation for further research.

1.5 Report Structure

The remainder of this report is structured as follows:

Chapter 2 contains a background study of pavement and plastic. This includes a definition of both materials, types of pavement, components of pavement, types of plastic, disposal of plastic and the process on how waste plastics are recycled. It also contains a review of relevant literature and information pertaining to this research, which includes the utilization of waste material into granular material, use of recycled plastic in concrete with more emphasis on road construction.

Chapter 3 describes the preliminary investigation conducted during this study which includes the standards used and sources of the materials used for the project

Chapter 4 provides a background on the laboratory test that would be conducted as well as future potential tests that need to be carried out.

Chapter 5 provides a necessary discussion about the results obtained from the laboratory test.

Chapter 6 entails a summary of the conclusion gathered from the report and feasible recommendations towards future research on this topic.

2 Literature Review

2.1 Overview of Pavements

Transportation facilities include roads and highway, rails, ports, airports, and others. This report focuses on one of the elements of roads and highway called pavement, which transfers the vehicular load to the underlying soil. There are two major types of pavement: flexible pavement and rigid pavement. Flexible pavement consists of several layers that include a bituminous material surface course which is mostly asphalt concrete, an underlying base and subbase course which can either be gravel or crushed rock and then the subgrade which is the natural soil. This type of pavement distributes the vehicular load across all the layers such that the load which is being transferred from the surface is distributed over a large area of the subgrade (Shanmukha, 2016). Rigid pavement, on the other hand, consists mostly of a surface layer which is made up of Portland cement concrete and the subgrade. In a few cases, a base layer is placed between both layers. For this type of pavement, the vehicular load is transferred from the surface directly to the subgrade (Yoder & Witczak, 1975). Figure 1 shows the load distribution on the surface of both flexible and rigid pavement.

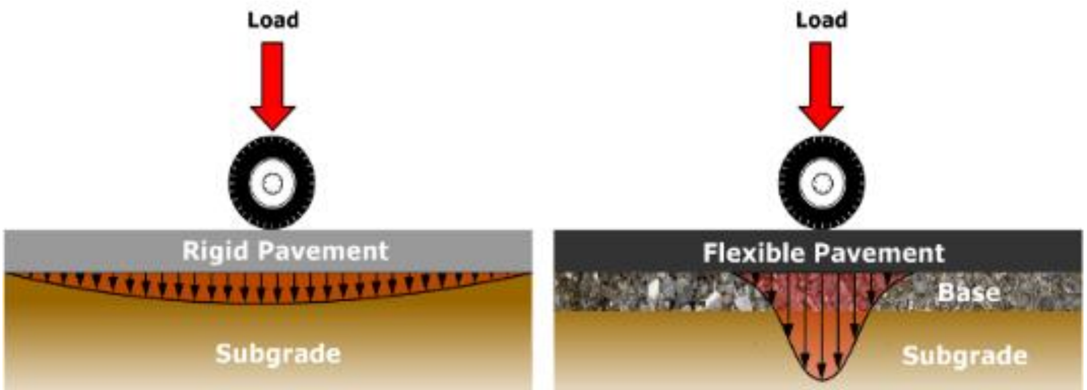

Figure 1. Load Distribution of Flexible and Rigid Pavement (Muench et al., 2003)

Granular base and subbase have the greatest thickness of pavement structure. Aggregates such as sand and gravel, crushed rock, and so on are used as granular base or subbase in the pavement. This structure plays a significant role in both flexible and rigid pavement (if used) by absorbing the direct load coming from the surface, therefore, reducing the load being transferred to the subbase and subgrade. For an application, appropriate aggregate size and gradation are used depending on the kind of pavement to be built or the load subjected to the granular base and subbase. The materials are then spread evenly in thin layers to a thickness of about 150mm to 200mm after which a heavy compacting equipment rolls over it (Chesner et al., 1998).

2.2 Overview of Plastics as a Waste Material

The production of plastic globally has continued to rise in recent decades. In 2013, approximately 299 million tons of plastic were produced, representing a 4% increase compared to 2012 (Le Guern, 2018). According to the United Nations Environmental Program, between 22% and 43% of the plastic used worldwide is disposed of in landfills, resulting in a waste of resources, valuable space, and groundwater pollution. However, recovery and recycling remain insufficient, as millions of tons of plastics end up in landfills and oceans each year (Gourmelon, 2015). Plastic waste represents a valuable resource, which can be profitably redirected back into the economy (Oyake-Ombis et al., 2015). Table 1 shows the various classes of plastic and their sources.

Table 1. Classes of Plastic (Seaman, 2012)

1	2	3	4	5	6	7
PET	HDPE	PVC	LDPE	PP	PS	OTHER
polyethylene terephthalate	high-density polyethylene	polyvinyl chloride	low-density polyethylene	polypropylene	polystyrene	other plastics, including acrylic, polylactic fibers, nylon, fiberglass
soft drink bottles, mineral water, fruit juice container, cooking oil	milk jugs, cleaning agents, laundry detergents, bleaching agents,	trays for sweet, fruit, plastic packing (bubble foil) and food foil to wrap the foodstuff	crushed bottles, shopping bags, highly-resistant sacks and most of the wrappings	furniture, consumers, luggage, toys as well as bumpers, lining, and external borders of the cars	toys, hard packing, refrigerator trays, cosmetic bags, costume jewelry, CD cases, vending cups	

Polyethylene Terephthalate (PET) was identified as the most common type of plastic. Therefore, emphasis was placed on PET bottles for this report. PET is a long-chain polymer belonging to the generic group of polyesters. It is semi-crystalline and the most used thermoplastic polyester (Webb et al., 2012). PET is one of the polyesters which is formed by a polymerization reaction between an acid and alcohol (Sinha et al., 2010). PET is a polymer which has a low permeation of gas through the material, it is durable, strong, easy to handle, and is thermally and chemically stable (Awaja & Pavel, 2005). PET is widely used in forming parts of automobiles, lighting product, food packaging, electronics, sports tools, x-ray sheets, houseware, textile, power tools and photographic applications (Sinha et al., 2010).

2.2.1 Disposal of Plastic Waste

The Canadian Plastic Industry Association (2018) stated that a total of 325 million kilograms of postconsumer plastic was collected for recycling in 2016, and 36% of the total sum represents PET plastics. Disposal of plastic material like any other consumer material contributes to the growth of municipal waste and urban litter. These wastes consist of large quantities of discarded materials, including thermoplastic products that make up more than 90% of the articles found on the sea beaches (Andrady & Neal, 2009; Salman, 2013). Due to the incapability of plastics to decompose naturally, alternative methods to recycle plastic material needs to be implemented. Recovering plastic from the waste stream for recycling or combustion for the generation of energy has the potential to minimize these problems. Burning plastic for energy requires air emissions controls and produces hazardous ash which is an inefficient way to dispose of the material. Some attractive qualities of plastic such as its versatility, flexibility, moisture resistance, strength, and its relatively inexpensive price, have led to such over-consumption of plastic goods.

Utilizing wastes materials by incorporating them into construction is becoming a worldwide trend as it helps in easing landfill pressures, reducing the need for extraction, protecting the environment and minimizing the consumption of original resources (Essawy et al., 2013). Countries such as Denmark, The Netherlands, USA, and India have made recycling of wastes in construction a national priority (Miller & Bahia, 2009; Wahlström et al., 2014) and there is still ongoing research and field studies investigating for better utilization of these recycled materials.

2.2.2 Recycling of PET

Recycling plastic involves recovering waste or scrap plastic and reprocessing the material into functional and useful products, sometimes in entirely different forms from their previous state (LeBlanc, 2016). Recycling and reuse of plastics are gaining importance as a sustainable method for plastic waste disposal. Unfortunately, plastic is much more difficult to recycle than materials like glass, aluminum, or paper. A communal problem with recycling plastics is that plastics are often made up of more than one kind of polymer, or there may be some sort of fiber added to the plastic. Plastic polymers require greater processing to be recycled as each type melts at different temperatures and has different properties, so careful separation is necessary. Moreover, most plastics are not highly compatible with one another. Apart from familiar applications like recycling bottles and industrial packaging film, there are also new developments, e.g. the Recovinyl initiative of the PVC industry (covering pipes, window frames, roofing membranes, and flooring). In contrast, recycling of polyvinyl chloride (PVC) bottles and other materials are limited. A major problem in the recycling of PVC is the high chlorine content in raw PVC (around 56 percent of the polymer's weight), and the elevated levels of hazardous additives added to the polymer to achieve the desired material quality.

Polyethylene terephthalate (PET) and high-density polyethylene (HDPE) bottles are taken by most curbside and drop-off recycling programs and have the potential to be mechanically recycled (Rebeiz & Craft, 1995). The growth of bottle recycling has been facilitated by the development of processing technologies that increase product purities and reduce operational costs. Hopewell et al. (2009) stated that the postconsumer process of recycling PET comprises of several stages:

1. Collection: Plastics come in different forms such as plastic containers, jars, bottles, plastic bags, packaging plastic and so on. People have ventured into the business of collecting plastics due to its availability. Tons of waste plastic are collected and then taken to a recycling facility for sorting.
2. Separating: The entire plastic recycling process begins with separating different plastic items with the use of a Trommel (Figure 2). This a specially designed perforated spinning drum used to separate plastic bottle from all non-recyclable materials. This is carried out to eliminate all forms of contamination during the recycling process.

Figure 2. Trommel Screen (CP Manufacturig, 2012)

3. Shredding and melting: After separation, the plastics are cut into small pieces which are then washed again to remove any remaining impurities such as the remainder

of paper label. After washing, the shredded plastic is then dried up and melted under regulated temperatures using specialized equipment designed to melt down plastic without destroying them.

4. Flaking: This involves transforming the melted plastic into flakes (Figure 3) or pellets (Figure 4) as it cools, such that they are transported to plastic manufacturing companies who reused or redesigned them into new plastic products. Recycled plastic is hardly transformed into its previous form based on the process involved in recycling.

Figure 3. Plastic Flakes (Plastrec, 2016)

Figure 4. Plastic Pellets (Plastrec, 2016)

This process of recycling plastics plays a significant role in reducing the amount of wasted plastic in the surrounding such that after the entire process of recycling, the PET flakes are clean, contaminant-free, and ready for use in the manufacturing of different recycled products.

2.3 Incorporation of Plastic Waste in Concrete

As concluded by several studies, incorporation of plastic waste as partial replacement of materials in concrete has proven to affect various properties of the concrete some of which include: compressive strength, permeability, workability, modulus of elasticity and tensile strength. Polyester concrete (PC) products can also be used for the long-term disposal of PET waste (Rebeiz & Craft, 1995).

Rahmani et al. (2013) reported the effects of adding PET particles on the mechanical properties of concrete. In this case, when 5% of the fine aggregates were replaced with PET particles, the compressive strength increased by 8.86% and 11.97% in relation to the control concrete mix with water cement ratio of 0.42 and 0.52, respectively. Al-Hadithi (2013) studied the fresh properties of self-compacting concrete with plastic waste as partial replacement of sand, using plastic bottle wastes with different percentages (0.5%, 1.0%, and 1.5%) of concrete volumes. Test results showed an improvement in both compressive and splitting tensile strengths of concretes. The improvement in splitting tensile strength appeared more clearly. Hama & Hilal (2017) studied the effect of both content and sizes of plastic wastes on the fresh properties and compressive strength of Self Compacting Concrete (SCC). Three varied sizes of plastic wastes (Fine, Coarse, and Mixed Plastic wastes) were used as partial replacement of natural sand at six different contents of 0, 2.5, 5, 7.5, 10, and 12.5% by volume. Test results showed using plastic waste as partial replacement of fine aggregate increased both T_{50} slump flow and V-funnel flow times.

Al-Tulaian et al. (2016) investigated the effects of recycled plastic waste fibers on the flexural behavior and plastic shrinkage of Portland cement mortar. Two different lengths of fibers (20 mm and 50 mm) and three different fiber volume fractions of 0.5%, 1.0%, and 1.5% were used. An enhancement in performance was noted after the incorporation of PET fibers in concrete due to the improvement in the flexural toughness and the reduction in plastic shrinking cracking of the concrete slabs. It was observed that the fiber reinforced concrete specimen containing 1.5% of 50 mm long recycled plastic fibers showed a substantial increase in flexural toughness of up to 61 times and an increase in flexural strength by 84% compared to the control mortar specimen without fibers. The rate of surface moisture loss at which plastic shrinkage cracks started appearing on the surfaces of mortar slabs cast in this investigation was 0.97 kg/hr/m^2. Plastic shrinkage cracking was minimized by increasing the fiber volume fraction from 1.0% to 1.5% for a fiber length of 50 mm.

2.4 Incorporation of Plastic Waste in Road construction

Recycling of waste as partial replacement of pavement material has been in practice with varying degrees of success around the world. Few countries have formulated rules, regulations, suggestions, and restrictions which permit the corresponding transportation departments to utilize the locally available waste as there are limited ways to dispose of this waste (Basha et al., 2005). Many other countries still show concerns over the use of recycled materials in pavement construction due to doubt of quality variations in the wastes, insufficient information as regards the properties of the recycled material during production, absence of technical standard that govern the use of recycled material in new construction, and lack of awareness regarding the promotion of recycled waste (Vieira & Pereira, 2015; Wahlström et al., 2014). Several studies have been conducted on the use of plastics as a modifier for asphalt cement or as an additive to aggregates blends in hot mix asphalt pavement.

Mohammed & Hussein (2014) evaluated the use of PET as asphalt modifier in asphalt concrete mix, and results showed that the optimum polymer content of PET was 4%. Addition of this percentage of polymer increased the Marshall stability by 39.09% for PET modified asphalt. There was also an improvement in the durability and resistance of asphalt mixture to moisture damage. A study on the effect of Polyethylene on the modified asphalt properties was conducted by Fuentes-Audén et al. (2008), whereby it was concluded that if more than 5% of Polyethylene were incorporated in the asphalt, the resulting viscosity would reduce the processability of the mixture. It was also stated that the addition of recycled Polyethylene promotes better resistance to rutting, cracking and thermal fatigue.

Rahman & Wahab (2013) carried out research to determine the optimum quality and the effect of utilizing recycled PET as a partial fine aggregate replacement in modified asphalt mixture by determining the permanent deformation and stiffness behavior. It was stated that modified asphalt mixtures were produced from a content concentrate of recycled PET pellets. These mixtures ranged between 5 and 25% of the mass of asphalt mixture with sieve size from 2.36mm to 1.18mm and 5% weight of bitumen content in accordance with the hot mix asphalt wearing course 14 (ACW14) in Standard Specification of Road Work in Malaysia. The Repeated Load Axial Test (RLAT) loading was carried out on the samples for 1800 cycles, and an axial load of 100 kN was applied to determine permanent deformation of the modified asphalt mixture. To evaluate the stiffness of the modified asphalt sample, the Indirect Tensile Stiffness Modulus Test (ITSM) was carried out at 25 degrees Celsius. Results from the lab revealed that maximum permanent deformation of the modified asphalt mixture occurred when the asphalt mixture was replaced with 20% recycled PET. However, the stiffness of PET modified asphalt mixtures has the tendency to decrease compared to the unmodified asphalt mixture. The finding indicates that PET has the ability to improve permanent deformation properties of asphalt mixtures and considering the environmental and economic aspects, the PET modified asphalt mixture was found to be suitable for road pavements.

Leng et al. (2018) carried out a study on ways to improve the performance of mixtures containing RAP with the use of polymeric additives made from chemically recycled PET waste. When the synthesized PET was combined with asphalt binders containing RAP, better performance was achieved against the virgin binder without any additive. Several tests were conducted for this study to determine the effect of partially adding the additive. In accordance with the anti-stripping tests, it was observed that the stripping properties of the RAP binder reduced when the PET additive was added into high RAP mixes. It was also observed that the low temperature of the modified binders with RAP improved after adding the PET additive.

Mishra & Gupta (2018) based their research on the effect caused by the addition of recycled polyethylene terephthalate (PET) fibers combined with fly ash as partial replacement of the subgrade soil. The tests carried out for this report were shear strength, shear modulus, California Bearing Ratio (CBR), indirect tensile strength and Atterberg limits. It was observed that the optimum quantity was at 1.2% addition of PET fiber and 15% addition of fly ash. With this inclusion, the shear strength became 1.45 times the shear strength of the unreinforced soil. There was a decrease in optimum moisture content and maximum dry density with an increase in PET fiber which is because of the elastic nature of PET fibers.

A report published by Saini (2015) stated the concept developed by VolkerWessels, a Dutch construction company, called Plastic Road. The focal idea of this concept is to build roads completely from recycled plastics recovered from oceans and burnt plants. VolkerWessels proposed that segments of the road would be manufactured in a factory and assembled Lego-like at the construction site. With this approach, grooves for traffic sensors and light poles would be worked in before each segment leaves the factory. Also, there would be an allowance for hollow space below the surface which would make it easier to lay cables and pipeline for future purposes as shown in Figure 5. According to VolkerWessels, the road would last three times longer than a normal pavement road and would survive severe weather conditions as low as -40 degrees and as high as 80 degrees Celsius.

Figure 5. Plastic Roads (Plastic Road, 2018)

2.5 Utilization of Waste Materials in the Granular Base of Pavements

The exploration of advanced methods to which waste materials can be used is growing such that many research institutions, highway agencies, and private organization are either in the process of commencing, completing or have completed a variety of studies on the possibility, environmental sustainability, and performance of incorporating recycled waste material in road construction. Some of such materials include reclaimed concrete pavement, reclaimed asphalt pavement, recycled concrete aggregate, roofing shingle, scrap tires, plastics, steel slag, waste rock and many more (Schroeder, 1994).

For instance, Melbouci (2009) studied the compaction and shearing behavior of recycled aggregates, using several test methods, one of which is the CBR (California Bearing Ratio) test. The purpose of this test was to determine the granular material (recycled concrete aggregates) bearing pressure intended to be used in bases of roadways. The bearing pressure of this material depends considerably on its own state characteristics. Two characteristics were determined: the immediate CBR index and CBR index after immersion. Due to the improvement of grain size distribution during the compaction, good resistance was obtained from the bearing pressure of the granular mixture (concrete aggregates + cement), which resulted in high values of immediate and after immersion CBR indices. However, CBR indices obtained after immersion on mixtures with sand and brick are lower than those of the concrete aggregates.

In another example, Saha & Mandal (2017) conducted a laboratory investigation on Reclaimed Asphalt Pavement (RAP) for use as the base course of flexible pavement. CBR tests were conducted on RAP, a mixture of RAP and crushed stone aggregates and on a mixture of RAP and crushed stone aggregates, stabilized with various percentages of cement. They observed a significant increase in the soaked CBR value of RAP mixed with crushed stone and stabilized with cement. The soaked CBR value of RAP increases from 20% to more than 100% when it was mixed with 25%, 50%, and 75% crushed stone aggregates and stabilized with 1%, 2% and 3% of cement, thereby making it suitable for using it as subbase/base of flexible pavement.

Last but not the least, research conducted in Spain by Silvestre et al. (2013) involved the utilization of Recycled Ceramic Aggregates (RCA) obtained from tile industry to design open graded wearing course on both laboratory and in situ basis. Various characterization tests such as sieve analysis, the specific gravity of fine, filler and coarse aggregates, water absorption, sand equivalent, bulk density in toluene, flakiness index, and Los Angeles abrasion value test were carried out. The RCAs had a lower specific gravity and bulk density compared to the natural aggregates, related to higher air void content. RCA had adequate toughness and abrasion resistance for using in medium traffic volumes (below the L.A. abrasion value of maximum 25% established at specifications). Conclusion of this paper technically considered recycled ceramic wastes feasible to be incorporated as aggregates into asphalt concrete mixtures for open-graded wearing courses. With 30% of aggregates weight replaced with recycled ceramic aggregates, the mixture met most of the mechanical and superficial characteristics within the Spanish specifications used as road surface layer for medium-low traffic volumes.

2.6 Summary

In this chapter, an overview of pavement, plastics, incorporation of recycled plastic in civil structures such as concrete and asphalt was carried out. From the review, plastic fibers were mostly used as a replacement of fine aggregate in concrete such that it was concluded that the compressive strength, permeability, workability, and flexural toughness of the concrete were enhanced. Furthermore, the use of recycled plastic as a binder in asphalt was also reviewed, and various properties such as Marshall Stability, resistance to rutting and cracking, permanent deformation, and Shear strength was also noted to be enhanced due to the addition of the recycled plastics. In view to explore more ways to which recycled plastic can be incorporated into road construction and improve various properties after the incorporation of recycled plastics in fine aggregate of pavement, the need to explore the feasibility of incorporating recycled plastic shreds into the granular layer of pavement became necessary as there is no research on this effect.

3 Preliminary Investigation

A study was designed and conducted to determine the feasibility of using plastic shreds as partial replacement of aggregate in the granular base of pavements. The preliminary investigation consisted of three phases. In the first phase, the required standard specifications that a blend of aggregates and plastics for a granular base should meet were investigated. In the second phase, potential sources of materials were identified. Phase three consisted of the laboratory testing. Details of the test standards, test specimens, test set-up, and test procedure are presented in this section of the study.

3.1 Standard Specifications

Standards and specifications for materials used in pavement construction differ by province. New Brunswick Department of Transportation and Infrastructure (NBDTI) Standard is a guide used by the New Brunswick Department of Transportation and Infrastructure for setting standard specifications for highway construction. For the utilization of recycled materials during construction, the recycled material intended for use during construction should be subjected to property test like that of conventional material. The product obtained using the waste material (used either as a partial or full replacement of virgin material) should meet the standards requirement regarding minimum strength, stability, durability and other required specifications (Gautam et al., 2018). Bid items in the standard specifications are intended to be comprehensive elements of work and clearly state the scope, material requirements and specific construction provisions to produce the specified product.

Physical requirement of gravel aggregate in the standard states that aggregate should be composed of clean, hard, sound, durable, uncoated particles that do not contain toxic materials that would make the aggregates prone to decomposition, disintegration or present any environmental hazards when exposed to the natural elements after placement in the work. Aggregates must also meet the requirements of Table 2 which shows the maximum allowable values after conducting these tests.

Table 2. Properties of Gravel Aggregate (Government of New Brunswick, 2011)

Test and Method	**Aggregate Type**	**Max. Allowable (%)**
Micro-Deval (MTO LS - 618)	Cover Material	22
	Aggregate Base	25
	Aggregate Subbase and Shoulder Material	30
Micro-Deval (MTO LS - 619)	Blending Material (Aggregate Base)	25
	Blending Material (Aggregate Subbase and Shoulder Material)	30
Freeze Thaw (MTO LS - 614)	All Highway Aggregate	20
Flat & Elongated Particles @ 4:1 (MTO LS - 608)	Crushed Rock Aggregate	35
Plasticity Index (AASHTO T89 and T90)	Aggregate Base and Blending Material	3
	Aggregate Subbase and Blending Material	5

Specification for crushed gravel states that the material used as a base/subbase for a project shall be produced by the crushing and processing of gravel to conform to the grading limits of Table 3. It also specifies that gravel base must have a minimum of 40% of the particles by mass having a fractured face when tested in accordance with ASTM D5821.

Table 3. Grading Limits Crushed Gravel Base (Government of New Brunswick, 2011)

ASTM Sieve Size	Aggregate Base		Aggregate Subbase		
	25 mm % passing	31.5 mm % passing	50 mm % passing	75 mm % passing	100 mm % passing
100.0 mm					100
90.0 mm				100	95 - 100
75.0 mm				95 - 100	80 - 100
63.0 mm			100	86 - 100	
50.0 mm			95 - 100	75 - 95	60 - 87
37.5 mm		100	79 - 100	61 - 87	50 - 81
31.5 mm	100	95 - 100			
25.0 mm	95 - 100	83 - 100	63 - 85		
19.0 mm	75 - 100	70 - 90	53 - 78	38 - 70	34 - 68
12.5 mm	60 - 82	55 - 78			
9.5 mm	52 - 75	45 - 72	35 - 62	28 - 56	25 - 58
4.75 mm	36 - 61	30 - 57	24 - 51	19 - 46	17 - 48
2.36 mm	25 - 48	20 - 46	17 - 42	13 - 37	13 - 39
1.18 mm	16 - 36	14 - 35	12 - 33	9 - 30	9 - 30
300 μm	5 - 16	5 - 19	5 - 18	4 - 16	4 - 17
75 μm	0 - 6	0 - 6	0 - 6	0 - 7	0 - 7

Sometimes, a single type of aggregate does not meet the standard specifications, in that case, the specification allows to blend several types of aggregates (i.e., crushed vs. natural gravels or sands) to achieve the required properties. For that purpose, the specification suggests the following considerations:

- The blending of aggregates shall be permitted to meet the grading requirements, increase the percentage of crushed particles, or decrease the percentage of flat and elongated particles.
- Blending shall not be permitted if required solely to improve the results of material quality tests (micro-Deval, freeze-thaw and plasticity index)
- Blending shall be permitted only at the crusher, and the method and location of introducing the blending material into the crushing process shall be submitted in writing to the engineer for approval, prior to production of any blended product.

- The blending material shall be added such that the rate of blending is controlled and measurable
- Blending material shall be granular materials having a dust content not exceeding 20% when tested in accordance with ASTM C117
- The blending material shall individually meet the micro-deval and plasticity index requirements of the properties of gravel aggregate.
- Natural sand or gravel used as blending materials in the production of the crushed rock aggregates shall not exceed 20% by mass of the blended aggregate produced
- The blending of aggregate shall produce a consistently graded product.

The following paragraphs describe the efforts made to find a potential provider of recycled plastic. Also, a brief description of the virgin aggregates is provided.

3.1.1 Recycled Plastic

It was discovered that several companies across Canada are not into plastic shredding but are majorly into compiling the plastics into bales. The Canadian Plastics Buyer's Guide (Canadian Plastics Industry Association - Waste Management, 2017) was used to identify potential providers of recycled plastics. No plastic recycling companies were found in New Brunswick. The companies that recycle plastics (Table 4) were contacted through phone calls and emails. Fourteen companies were contacted in total, and only 4 of these companies responded. Plastrec and Exxel Polymer stated that they would not be able to deliver the plastics at the standard size of 2.36mm required for the project and can only deliver in large quantities. Plast-Ex stated that they do not shred the waste plastics but recycle them into new materials. However, Kal-polymers from Ontario offered to provide recycled postindustrial plastic, clear on mixed color with a standard grind size of 3/8 in (2.36 mm). The price for mix color was about USD$0.38/lb pick up and for clear was about USD$0.60/lb pick up.

Table 4: Contacted Companies into Plastic Recycling

Company	Location	Services	Response
BMP Recycling/Ice River Springs	Ontario	Plastic recycling	No Response
EFS-Plastics Inc.	Ontario	Process recycled plastic	No Response
Enviroplast Inc.	Quebec	Plastic recycling	No Response
GreenMantra Technologies	Ontario	Process recycled plastic	No Response
Kal-Polymers	Ontario	Plastic recycling	Responded
Nam Polymers Inc.	Ontario	Supplies PET resin	No Response
Plastrec	Quebec	Plastic recycling	Responded
Exxel Polymer	Quebec	Plastic recycling	Responded
Norwich Plastics	Ontario	Reprocessing of plastic	No Response
Pyrowave Inc.	Quebec	Plastic recycling	No Response
Plast-Ex	Ontario	Process recycled plastic	Responded
Target Recycling Services Inc.	Ontario	Plastic recycling	No Response
Scotia Recycling Ltd.	Nova Scotia	Plastic recycling	No Response
Urban Polymers	Ontario	Plastic recycling	No Response

The second alternative evaluated was to process the plastic in house. Plastic soda bottles were used. The labels were removed, the bottles were washed, and the neck and bottom were cut. The remaining plastic was cut into pieces of approximately 50mm long by 50mm wide. The plastics were frozen with dry ice to make them brittle and then later crushed after 24 hours using a food processor. This process was not as effective since the food processor did not shred all the plastic, and only an insignificant amount of fine particles were produced. The plastics were then put back into the dry ice for another 24 hours with the idea of making them more brittle, but instead, the process was not forthcoming. A paper shredder was also used unsuccessfully, since the plastic stretch and jams the mechanism. After this trial phase, the plastics were discarded which resulted in finding other means of getting the shredded plastic. Figure 6, Figure 7, and Figure 8 show pictures of the cut plastic and the dry ice sample used.

Figure 6. Cut Pieces of Plastic

Figure 7. Sample of Dry Ice

Figure 8. Plastic Pieces in Dry Ice

During the 2018 Canadian Society for Civil Engineering (CSCE) annual conference in Fredericton, Professor Leonard Lye presented a paper on the use of post-consumer plastic in concrete. In the paper, it was stated that a plastic shredder was built due to the difficulty in sourcing for shredded plastic. It was also noted that even though the shredder met its purpose for the research, the machine still required further refinements as obtaining the shredded plastic was time-consuming and required large volumes of empty bottles. Professor Leonard Lye offered to send about 923.6g of the processed plastics, which represented leftover of what was used to conduct the research by Vivas et al. (2018) on the incorporation of waste polyethylene terephthalate (PET) into concrete using statistical mixture design. The plastics were categorized into two types (Table 5). Type 1 consisted of spring water bottles and type 2 consisted of soft drink bottles. Vivas et al. (2018) stated the waste PET were obtained from the waste stream at the St. John's recycling centre, and most of it being water and soft drink bottles. The bottles were not washed and separated by colour, but the labels and the lids were manually removed before shredding.

Table 5. Classification of Bottles (Vivas et al., 2018)

Type	**Volume (ml)**	**Thickness (mm)**	**Typical Use**
1	500	0.1	Spring Water
2	2000	0.25	Soft Drink

3.1.2 Natural Aggregates

Two types of natural aggregates were investigated:

1. Crushed gravel from New Brunswick with a maximum nominal size of 31.5mm meeting the average gradation shown in Table 2.
2. Crushed rock sources by the province of Prince Edward Island with a known particle size distribution.

4 Laboratory Testing

4.1 Size Distribution

The sieve analysis test was carried out using the ASTM C136 / C136M - 14 to determine the grading of materials proposed for use as aggregates. Results of gradation are used to check compliance of the particle size distribution with applicable specification requirements. It also provides data for control of the production of various aggregate products and mixtures containing aggregates. A vibrating machine (Figure 9) was used to shake the materials in the sieve.

Figure 9. Laboratory Vibrating Sieve Machine

4.2 Compaction Test

The compaction test was used to determine the relationship between water content, dry unit weight, and total unit weight of the granular material partially replaced with 5% shredded plastic. The material shall be compacted to a minimum of 95% of the maximum dry density in accordance with NBDTI standards, using the standard method of test for moisture-density relations of soil using a 2.5kg (5.5-lb) rammer and a 305mm (12 in) drop AASHTO T 99-18. Samples were compacted in a mold having a 4-in (101.6mm) average inside diameter, a height of 4.584-in (116.4mm) and a volume of 0.0333ft^3 (943cm^3). A 5.5-lbf. (24.47N) rammer was dropped repeatedly 25 times from a height of 12-in. (304.8 mm) subjecting the soil to a compactive effort of 12,400 ft-lbf/ft^3 (600 kN-m/m^3). Image of the equipment used is shown in Figure 10. The equation used is as follow:

$$\text{Moisture Content \%} = \frac{\text{Weight of water (g) x 100}}{\text{Weight of dry soil (g)}} \dots\dots\dots\ (1)$$

$$W_1 = \frac{A - B}{V} \dots\dots\dots\ (2)$$

Where:

W_1 = Wet density in kg/m^3 (lb/ft^3) of compacted soil

A = Mass of the mold, base plate, and wet soil

B = Mass of the mold, and base plate

V = Mold volume.

$$W = \frac{W_1}{w + 100} * 100 \ldots\ldots\ldots (3)$$

Where:

W = Dry density, in kg/m^3 (lb/ft^3) of compacted soil

W_1 = Wet density in kg/m^3 (lb/ft^3) of compacted soil

w = moisture content (percent) of the specimen

Figure 10. Compacting Machine with Rammer and Mold

5 Results and Discussion

This chapter summarizes the major findings from the study carried out.

5.1 Theoretical Design

A design is conducted to estimate the required proportions of the different components in the aggregate mix to meet the standard specification. This design is based solely on the particle size distribution. For this report, three trials of grain size distribution were conducted as described in the following sections.

5.1.1 Trial 1

The first trial involved the use of shredded postindustrial plastic which was assumed to be retained on the 2.36mm sieve. For the natural aggregate, it was assumed that the aggregate distribution would follow the average gradation of crushed gravel as required for the New Brunswick standard specifications. It was obtained that the crushed gravel could be partially replaced with a maximum of 18% post industrial plastic. Table 6 and Figure 11 shows the maximum allowable shredded postindustrial plastic and the gradation curve.

Table 6. Maximum Allowable Postindustrial Recycled Plastic

ASTM Sieve size (mm)	% Passing Average NB Crushed gravel	% Passing Recycled plastic	% Passing Combined material (82% crushed gravel & 18% plastic)
31.5	100	100	100.0
25	97.5	100	98.0
19	87.5	100	89.8
12.5	71	100	76.2
9.5	63.5	100	70.1
4.75	48.5	100	57.8
2.36	36.5	0	47.9
1.18	26	0	21.3
0.3	10.5	0	8.6
0.075	3	0	2.5

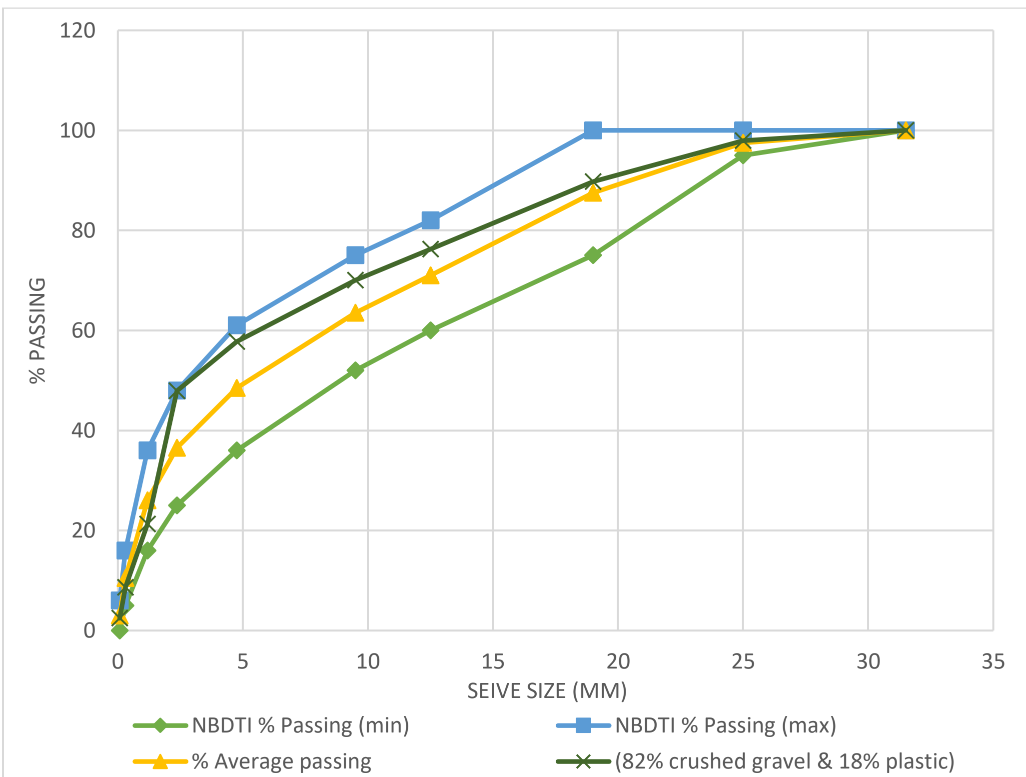

Figure 11. Gradation Curve for Maximum Replaceable Postindustrial Plastic

5.1.2 Trial 2

For the second trial, the size distribution of the shredded postconsumer plastic used in the research carried out by Vivas et al. (2018) was used. In their research, the collected waste PET were typically water and soft drink bottles which they classified into three main types based on the volume of the bottles. The labels and lids were manually removed before shredding the bottles which were neither washed nor separated by colors. It was noted that crushed gravel could be partially replaced with a maximum of 30% postconsumer plastic to meet the requirements of the grain size distribution with respect to NBDTI standards. Table 7 and Figure 12 shows the maximum allowable shredded postconsumer plastic and the corresponding gradation curve.

Table 7. Maximum Allowable Postconsumer Shredded Plastic

ASTM Sieve size (mm)	% Passing Average NB crushed gravel	% Passing Recycled plastic	% Passing Combined material (70% crushed gravel & 30% plastic)
31.5	100	100	100.0
25	97.5	100	98.3
19	87.5	100	91.3
12.5	71	100	79.7
9.5	63.5	100	74.5
4.75	48.5	90	61.0
2.36	36.5	13	29.5
1.18	26	2	18.8
0.3	10.5	0	7.4
0.075	3	0	2.1

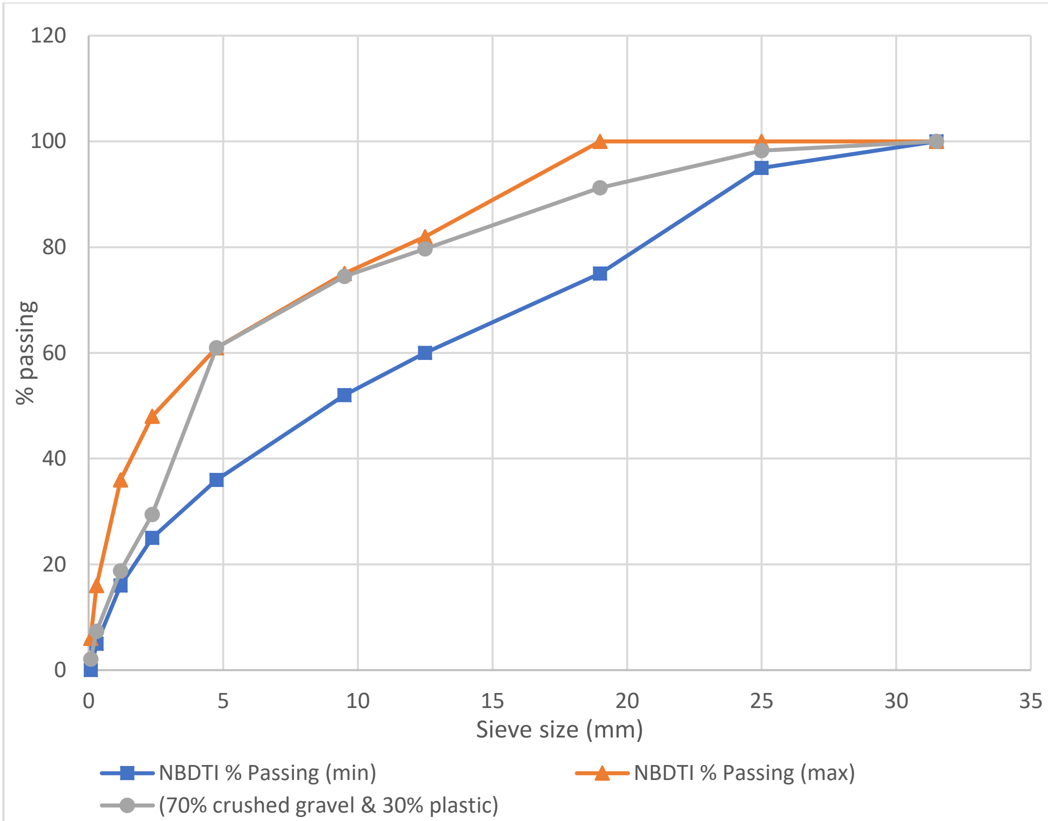

Figure 12. Gradation Curve for Maximum Replaceable Postconsumer Plastic

5.1.3 Trial 3

This trial used the crushed rock for granular base available from the research project conducted by another research student which met the Prince Edward Island Department of Transportation and Public Works standard specification. For the recycled plastic, the material provided by Professor Leonard Lye was considered. The materials were provided separated, in total 400.2 g of type 1 (spring water bottles) and 523.4 g of type 2 (soft drink bottles) were received. After conducting the size distribution test on the PET received (Appendix A), it was observed that the gradation of both types was similar, and to optimize the use it was decided to mix them. It is observed that most of the particles were retained on the 2.36mm (Table 8).

Table 8. Sieve Analysis Shredded Plastic

Sieve Size (mm)	Percent Passing		
	Type 1	Type 2	Combined
9.5	100	100	100
4.75	69.3	73.0	71.4
2.36	18.2	15.2	16.5
1.18	3.7	2.5	3.0
0.6	0.6	0.4	0.5
0.3	0.1	0.1	0.1
0.15	0.0	0.0	0.0

It was obtained that the crushed rock can be partially replaced with a maximum of 20% postconsumer plastic to meet the requirements of the grain size distribution in accordance with the PEI standards. Table 9 and Figure 13 shows the gradation curve of PEI standard for crushed rock and the maximum allowable for partial replacement of the virgin material with the shredded plastic provided by Memorial University.

Table 9. Maximum Allowable Postconsumer Shredded PET

ASTM Sieve size (mm)	% Passing PEI crushed rock	% Passing Combined plastic	% Passing Combined material (80% crushed rock & 20% plastic)
31.5	100	100	100.0
25	96.4	100	99.3
12.5	66.2	100	74.9
4.75	41.9	71.4	49.8
1.18	18.8	3.0	17.1
0.6	13.6	0.5	12.3
0.3	9.8	0.09	9.0
0.075	4.9	0	4.0

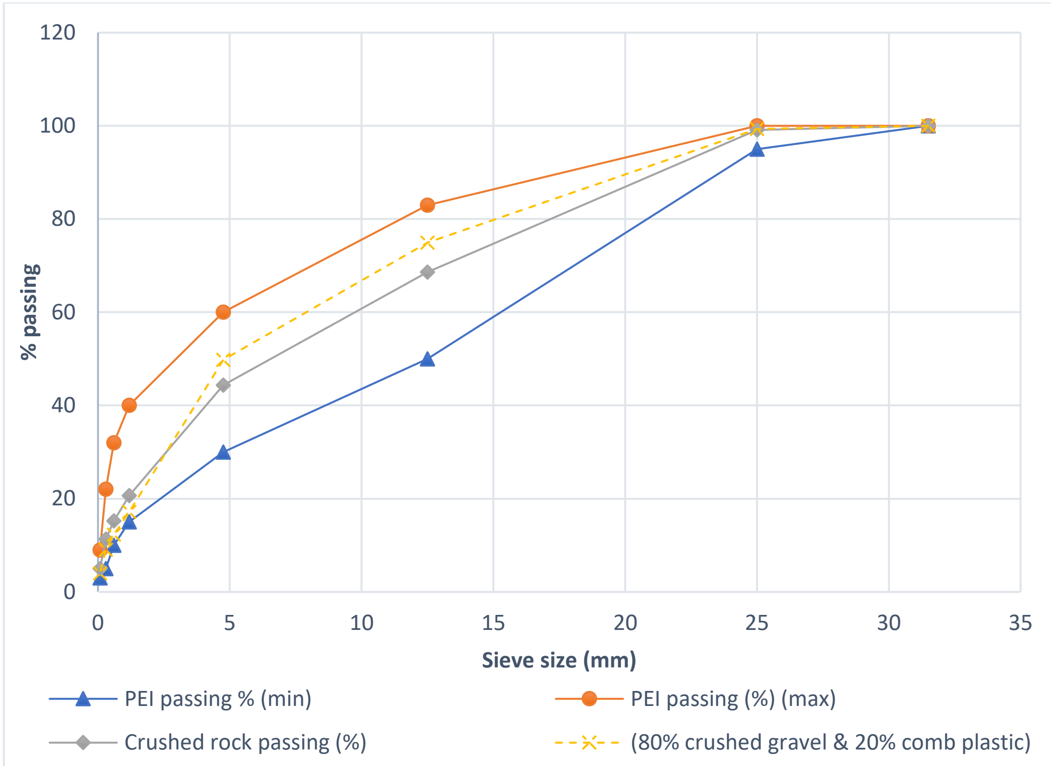

Figure 13. Gradation Curve for Maximum Replaceable Shredded PET

5.2 Standard Proctor Test

Since the sample of shredded PET received was approximately 1 kg, it was decided to prepare a mix with 5% recycled plastic only. In the research conducted by Matt MacEachern at the University of New Brunswick on the virgin material, the Standard proctor compaction test (AASHTO T 99-15) was conducted on 100% crushed rock with a batch size of 3000g. For this study, a mixture of crushed rock and shredded plastic with a batch size of 2000g was used. This amount is below the recommended 3000g because of insufficient shredded plastic and given that method A only uses the particles passing the 4.75mm sieve. Appendix B shows the complete test preparation summary and test results obtained for 100% crushed rock. As noted earlier, these results were obtained by another graduate student, and are included for comparison since the same virgin material was used for this study. Appendix B also shows the complete test preparation summary and test results obtained for 95% crushed rock mixed with 5% PET.

Figure 14 and Figure 15 shows the crushed rock sample retained in the 4.75mm sieve and shredded plastic sample retained in the 2.36mm sieve before and after mix, respectively. Figure 16 shows the preparation of the sample in the mold while Figure 17 shows how the sample is rammed at different layers till mold is full.

Figure 14. Shredded Plastic and Crushed Rock

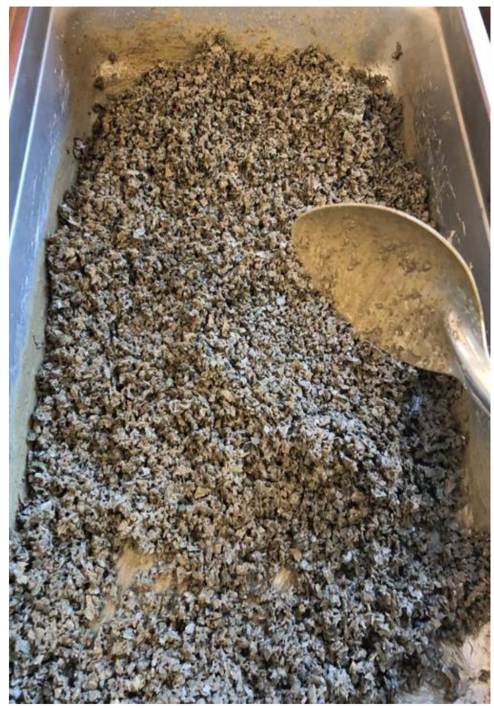

Figure 15. Sample Mixed with Water

Figure 16. Sample in Mold

Figure 17. Sample being Rammed

The maximum dry density (MDD) and optimum moisture content (OMC) obtained are illustrated in Table 10. It was observed that the Optimum moisture content of the natural aggregates was 9.9% and a maximum dry density of 20kN/m^3. On the other hand, at 95% crushed rock and 5% shredded plastic, there was a 20% drop in Optimum moisture content from 9.9% to 7.9% and a 22% drop in maximum density from 20kN/m^3 to 15kN/m^3(Figure 18). The results obtained indicate that less water is needed to attain maximum density when granular material is partially replaced with 5% plastic shreds. It was also observed that the density of the 5% PET replaced material would not have a significant change with moisture contents above 10%. The addition of shredded PET could make the material more permeable such that it would allow the infiltration of water through the material. This would prevent moisture accumulation in the base layer thereby preventing a reduction in the material's resistance to shear. However, further research is required to prove this hypothesis.

Table 10. Compaction Test Result

Materials	Optimum Moisture Content (%)	Maximum Dry Density (kN/m^3)
100% Crushed rock	9.9	19.95
95% crushed rock 5% shredded plastic	7.9	15.7

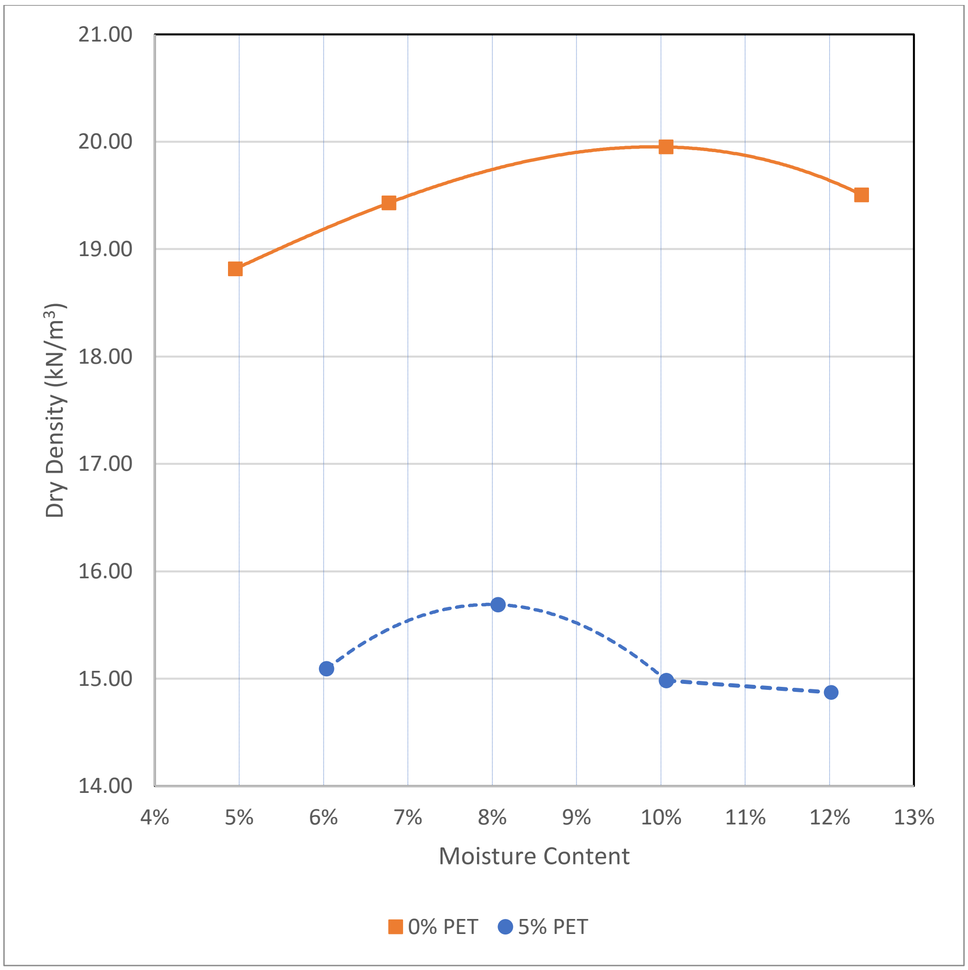

Figure 18. Proctor Curves at 100% and 95% Crushed Rock (Uncorrected)

5.3 Potential Future Test Program

Since there was not enough material to conduct a more comprehensive characterization, some recommendations for future research are provided. Table 11 and Table 12 shows the necessary parameters used to identify the suitability of materials used during the construction of flexible pavement.

Table 11. Property Analysis for Soil Subgrade

Test Name	**Property**	**Code**
Liquid limit, Plastic limit, and Plasticity Index of soil	Plasticity	ASTM D4318 - 17
Gradation of soil using Sieve analysis	Particle size distribution	ASTM D6913 / D6913M - 17
Specific Gravity of soil specimen (using pycnometer)	Density of soil specimen	ASTM D854 - 14
California Bearing Ratio (CBR)	Strength of soil	ASTM D1883 - 16

Table 12. Physical Properties Tests for Aggregates

Test Name	**Property**	**Code**
Los Angeles Abrasion loss	Toughness	ASTM C131 - 01
Water Absorption Test	Water Absorption	ASTM D7172
Flakiness and Elongation Index	Particle Shape	ASTM D4791 - 10
Soundness Test	Durability	ASTM C88 / C88M - 18
Specific Gravity	Density of aggregates	ASTM C127 - 15

It was noted that Los Angeles Abrasion, flakiness and elongation, and soundness apply for coarse aggregates (size bigger than 4.75mm) since the studied plastic is mostly retained the

2.36mm sieve, it is expected that those properties would not be affected significantly. After determining the potential tests required, a preliminary estimation was made to determine the quantities of material that would be needed after 5% partial replacement of granular material with plastic shreds. Table 13 shows an estimation of the total quantities of material needed for the project multiplied by a safety factor of 1.5 which accounts for the loss of material during transportation, mixing and at any other process at which materials could be wasted. The recommended Abrasion test for the combined material is the Standard Test Method for Resistance of Fine Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus ASTM D7428-15.

Table 13. Estimation of Total Materials Needed for Tests

Test	Mix	Replicas	Volume (g)	Aggregate (g)	Plastic (g)	Total Vol (g)
Proctor	(95%+5%)	3	3000	8550	450	9000
CBR	(95%+5%)	3	5179	14760	777	15537
Abrasion	(95%+5%)	3	725	2066	109	2175
Specific gravity	(95%+5%)	3	1000	2850	150	3000
Water Absorption	(95%+5%)	3	505	1439	76	1515
Total				29666	1561	31227
Total after Safety factor of 1.5				44498	2342	46841

The California Bearing Ratio (CBR) is one of the vital parameters used in the evaluation of soil sub grades for both rigid and flexible pavements design. This test method in accordance with ASTM D1883 – 16, is used as an aid for pavement design by evaluating subgrade, subbase and base materials having a maximum particle size less than $^{3}/_{4}$ in. (19 mm). By tradition, this preparation method of the specimen has been used to avoid the constant error in testing materials comprising of large particles in the CBR test apparatus; the modified material is likely to have a significant difference in strength compared to the original material. Using this test method, a substantial database has been developed such that the materials have been modified and suitable design methods are used in accordance with the results obtained from using this procedure.

6 Conclusion and Recommendations

6.1 Conclusion

The goal of this study was to assess the feasibility of partially replacing aggregates material of base in the pavement with recycled plastics. To achieve this, several literature studies were reviewed on the utilization of waste materials as a partial replacement of granular materials with more emphasis placed on recycled plastic waste. Materials such as Recycled Concrete Aggregate, Reclaimed Asphalt Pavement (RAP), and Recycled Ceramic Aggregates among others were identified to be the more suitable materials that can be used in granular material. Reports on these materials have shown positive signs towards improving the quality of pavement in general, although it was noted that incorporation of such waste in large quantity could be harmful to the structural capacity of the pavement. The use of plastics has not been fully considered as a replacement for granular materials but is prominent to be used as a replacement for fine aggregates. Polyethylene Terephthalate (PET) plastic was identified as the most available type of plastic for recycling purposes as it is typically used to store liquids such as water, soft drinks, motor oil, cooking oil, medicine, shampoo, and milk. An extensive study was conducted on the incorporation of plastic waste in civil construction such as concrete and asphalt mixture; it was concluded that the utilization of this kind of waste increased the compressive strength of the concrete when recycled plastic is partially replaced with fine aggregate. It was also noted that the incorporation of plastic waste as partial replacement of bituminous material helps to improve the permanent deformation properties of the asphalt mixture, promotes better resistance to rutting, cracking and thermal fatigue and helps alleviate the challenge of disposing of plastics.

After conducting a theoretical design in accordance with the PEI standards, it was noted that a maximum of 20% granular material can be replaced with plastic shreds and still meet the gradation specification. When 5% of the granular material was replaced with recycled plastic, it was observed that less water was required to achieve optimum moisture content compared to the control mix of only virgin material. A drop in maximum dry density was recorded when the granular material was partially replaced. Based on the initial test carried out, it is possible to mix the aggregates for the granular base with shredded plastic with a maximum nominal size of 4.75mm, and it was observed that the incorporation of recycled plastic shreds would provide a lighter fill material, i.e. lower specific gravity. However, this information is not enough to conclude that the incorporation of recycled plastic into the base layer of pavement is not feasible, as further extensive tests were not carried out.

6.2 Recommendation

A more comprehensive research which involves carrying out extensive tests such as CBR test, Abrasion test, Specific gravity test and Water absorption test, will help further validate the feasibility of partially replacing granular material of pavement base with shredded PET plastics which would ease the demand on virgin material and at the same time alleviate the issue of plastic disposal. Future studies should derive a more efficient method to get shredded plastics, as the main challenge of this report was getting a company that would supply shredded PET that can be retained in the 2.36mm sieve. It was observed during the study that most plastic recycling companies in Canada do not engage in the shredding of plastics but rather just compile these waste plastics into bales and sell them. It is therefore advisable that companies should engage in the entire process of plastic recycling as well as shredding rather than just compiling them for sale as the outcome of recycling or shredding can be used for several purposes, one of which is incorporating PET into the base of pavement.

7 References

AASHTO T 99-18. (2018). AASHTO T 99-18. Retrieved December 4, 2018, from https://www.techstreet.com/standards/aashto-t-99-18?product_id=2024290

Abukhettala, M. (2016, May). Use of Recycled Materials in Road Construction | Request PDF. Retrieved November 27, 2018, from https://www.researchgate.net/publication/302805749_Use_of_Recycled_Materials_in_Road_Construction

Al-Hadithi, A. (2013). Improving Impact and Mechanical Properties of Gap-Graded Concrete by Adding Waste Plastic Fibers (PDF Download Available). Retrieved July 7, 2017, from https://www.researchgate.net/publication/249010093_Improving_Impact_and_Mechanical_Properties_of_Gap-Graded_Concrete_by_Adding_Waste_Plastic_Fibers

Al-Tulaian, B. S., Al-Shannag, M. J., & Al-Hozaimy, A. R. (2016). Recycled plastic waste fibers for reinforcing Portland cement mortar. *Construction and Building Materials*, *127*, 102–110. https://doi.org/10.1016/j.conbuildmat.2016.09.131

Andrady, A. L., & Neal, M. A. (2009). Applications and societal benefits of plastics. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1526), 1977–1984. https://doi.org/10.1098/rstb.2008.0304

Arshad, M., & Ahmed, M. F. (2017). Potential use of reclaimed asphalt pavement and recycled concrete aggregate in base/subbase layers of flexible pavements. *Construction and Building Materials*, *151*(Supplement C), 83–97. https://doi.org/10.1016/j.conbuildmat.2017.06.028

ASTM C88 / C88M - 18. (2018). ASTM C88 / C88M - 18 Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate. Retrieved December 4, 2018, from https://www.astm.org/Standards/C88

ASTM C117. (n.d.). ASTM C117 | Testing Services | Standard Test Method for Materials Finer than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing. Retrieved December 4, 2018, from https://www.geocomp.com/GeoTesting/Details/15

ASTM C127 - 15. (2015). ASTM C127 - 15 Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate. Retrieved December 4, 2018, from https://www.astm.org/Standards/C127

ASTM C131 - 01. (2016). ASTM C131 - 01 Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine. Retrieved December 4, 2018, from https://www.astm.org/DATABASE.CART/HISTORICAL/C131-01.htm

ASTM C136 / C136M - 14. (n.d.). ASTM C136 / C136M - 14 Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. Retrieved December 4, 2018, from https://www.astm.org/Standards/C136

ASTM D854 - 14. (2014). ASTM D854 - 14 Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer. Retrieved December 4, 2018, from https://www.astm.org/Standards/D854

ASTM D1883 - 16. (2016). ASTM D1883 - 16 Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils. Retrieved December 4, 2018, from https://www.astm.org/Standards/D1883

ASTM D4318 - 17. (2018). ASTM D4318 - 17e1 Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. Retrieved December 4, 2018, from https://www.astm.org/Standards/D4318

ASTM D4791 - 10. (2010). ASTM D4791 - 10 Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate. Retrieved December 4, 2018, from https://www.astm.org/Standards/D4791

ASTM D5821. (2017). ASTM D5821 - 13(2017) Standard Test Method for Determining the Percentage of Fractured Particles in Coarse Aggregate. Retrieved December 4, 2018, from https://www.astm.org/Standards/D5821

ASTM D6913 / D6913M - 17. (2017). ASTM International - Standard References for ASTM D6913 / D6913M - 17. Retrieved December 4, 2018, from https://www.astm.org/DATABASE.CART/STD_REFERENCE/D6913.htm

ASTM D7172. (2014). ASTM D7172 - 14 Standard Test Method for Determining the Relative Density (Specific Gravity) and Absorption of Fine Aggregates Using Infrared. Retrieved December 4, 2018, from https://www.astm.org/Standards/D7172.htm

Athanasopoulou, A., & Kollaros, G. (2015). Fly ash exploited in pavement layers in environmentally friendly ways. *Toxicological & Environmental Chemistry*, *97*(1), 43–50. https://doi.org/10.1080/02772248.2015.1005090

Awaja, F., & Pavel, D. (2005). Recycling of PET. *European Polymer Journal*, *41*, 1453–1477. https://doi.org/10.1016/j.eurpolymj.2005.02.005

Basha, E. A., Hashim, R., Mahmud, H. B., & Muntohar, A. S. (2005). Stabilization of residual soil with rice husk ash and cement. *Construction and Building Materials*, *19*(6), 448–453. https://doi.org/10.1016/j.conbuildmat.2004.08.001

Canadian Plastic Industry Association. (2018). Canadian Plastics Industry Association - Reports, Studies, & Best Practices. Retrieved December 1, 2018, from https://www.plastics.ca/PlasticTopics/RecyclingPlastics/BestPracticesCaseStudies

Canadian Plastics Industry Association - Waste Management. (n.d.). Retrieved June 17, 2017, from https://www.plastics.ca/PlasticTopics/EnvironmentalSustainability/WasteManagement

Chesner, W. H., Collins, R. J., & MacKay, M. H. (1998). User guidelines for waste and by-product materials in pavement construction. Retrieved from https://trid.trb.org/view/483842

CP Manufacturig. (2012). Trommel Screens | CP Manufacturing. Retrieved December 4, 2018, from http://www.cpmfg.com/recycling-equipment/recycling-sorting-equipment/trommel-screens-2/

Essawy, A. I., Saleh, A. M. M., Zaky, M. T., Farag, R. K., & Ragab, A. A. (2013). Environmentally friendly road construction. *Egyptian Journal of Petroleum*, *22*(1), 189–198. https://doi.org/10.1016/j.ejpe.2012.09.010

Fuentes-Audén, C., Sandoval, J. A., Jerez, A., Navarro, F. J., Martínez-Boza, F. J., Partal, P., & Gallegos, C. (2008). Evaluation of thermal and mechanical properties of recycled polyethylene modified bitumen. *Polymer Testing*, *27*(8), 1005–1012. https://doi.org/10.1016/j.polymertesting.2008.09.006

Gautam, P. K., Kalla, P., Jethoo, A. S., Agrawal, R., & Singh, H. (2018). Sustainable use of waste in flexible pavement: A review. *Construction and Building Materials*, *180*, 239–253. https://doi.org/10.1016/j.conbuildmat.2018.04.067

Gourmelon, G. (2015). Global Plastic Production Rises, Recycling Lags | Worldwatch Institute. Retrieved April 6, 2017, from http://www.worldwatch.org/global-plastic-production-rises-recycling-lags-0

Government of New Brunswick, C. (2011, September 27). 2015 Standard Specifications for Highway Construction. Retrieved September 27, 2018, from https://www2.gnb.ca/content/gnb/en/departments/dti/tenders_contracts/content/2015_standard_specifications.html

Hama, S. M., & Hilal, N. N. (2017). Fresh properties of self-compacting concrete with plastic waste as partial replacement of sand. *International Journal of Sustainable Built Environment*. https://doi.org/10.1016/j.ijsbe.2017.01.001

Hopewell, J., Dvorak, R., & Kosior, E. (2009). Plastics recycling: challenges and opportunities. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1526), 2115–2126. https://doi.org/10.1098/rstb.2008.0311

Le Guern, C. (2018, March). Plastic Pollution. Retrieved November 28, 2018, from http://plastic-pollution.org/

LeBlanc, R. (2016). An Introduction to Plastic Recycling. Retrieved June 6, 2017, from https://www.thebalance.com/an-overview-of-plastic-recycling-4018761

Leng, Z., Sreeram, A., Padhan, R. K., & Tan, Z. (2018). Value-added application of waste PET based additives in bituminous mixtures containing high percentage of reclaimed asphalt pavement (RAP). *Journal of Cleaner Production*, *196*, 615–625. https://doi.org/10.1016/j.jclepro.2018.06.119

Melbouci, B. (2009). Compaction and shearing behaviour study of recycled aggregates. *Construction and Building Materials*, *23*(8), 2723–2730. https://doi.org/10.1016/j.conbuildmat.2009.03.004

Miller, T., & Bahia, H. U. (2009, February). Sustainable Asphalt Pavements: Technologies, Knowledge Gaps and Opportunities - PDF. Retrieved November 28, 2018, from https://docplayer.net/43164829-Sustainable-asphalt-pavements-technologies-knowledge-gaps-and-opportunities.html

Mishra, B., & Gupta, M. (2018). Use of randomly oriented polyethylene terephthalate (PET) fiber in combination with fly ash in subgrade of flexible pavement. *Construction and Building Materials*, *190*, 95–107. https://doi.org/10.1016/j.conbuildmat.2018.09.074

Mohammed, D. T., & Hussein, Z. H. (2014). Evaluation of Pyrolisis PET Utilization in Asphalt Binder. *International Journal of Enhanced Research in Science Technology & Engineering*, *3*(9), 114–121.

Muench, S. T., Mahoney, J. P., & Pierce, L. M. (2003). WSDOT pavement guide interactive. *Washington State Department of Transportation Engineering Publications*.

Oyake-Ombis, L., van Vliet, B. J. M., & Mol, A. P. J. (2015). Managing plastic waste in East Africa: Niche innovations in plastic production and solid waste. *Habitat International*, *48*, 188–197. https://doi.org/10.1016/j.habitatint.2015.03.019

Plastic Road. (2018). Plastic Road - A revolution in building roads. Retrieved December 3, 2018, from https://www.plasticroad.eu/en/

Plastrec. (2016, October 18). Products. Retrieved December 3, 2018, from https://plastrec.ca/en/products

Rahman, W. M. N. W. A., & Wahab, A. F. A. (2013). Green Pavement using Recycled Polyethylene Terephthalate (PET) as Partial Fine Aggregate Replacement in Modified Asphalt. *Procedia Engineering, 53*, 124–128. https://doi.org/10.1016/j.proeng.2013.02.018

Rahmani, E., Dehestani, M., Beygi, M. H. A., Allahyari, H., & Nikbin, I. M. (2013). On the mechanical properties of concrete containing waste PET particles. *Construction and Building Materials*, *47*, 1302–1308. https://doi.org/10.1016/j.conbuildmat.2013.06.041

Rebeiz, K. S., & Craft, A. P. (1995). Plastic waste management in construction: technological and institutional issues. *Resources, Conservation and Recycling*, *15*(3), 245–257. https://doi.org/10.1016/0921-3449(95)00034-8

Saha, D. C., & Mandal, J. N. (2017). Laboratory Investigations on Reclaimed Asphalt Pavement (RAP) for using it as Base Course of Flexible Pavement. *Procedia Engineering*, *189*, 434–439. https://doi.org/10.1016/j.proeng.2017.05.069

Saini, S. (2015). A Dutch city has come up with a genius plan that could eventually eliminate asphalt roads. Retrieved April 24, 2018, from http://www.businessinsider.com/a-dutch-city-is-planning-to-build-roads-from-recycled-plastic-2015-7

Salman, Z. (2013). A Glance at Plastics Recycling. Retrieved June 17, 2017, from http://www.ecomena.org/tag/plastic-waste-disposal/

Schroeder, R. (1994). Public Roads - The Use of Recycled Materials in Highway Construction , Autumn 1994 -. Retrieved November 30, 2018, from https://www.fhwa.dot.gov/publications/publicroads/94fall/p94au32.cfm

Seaman, G. (2012). Plastics by the Numbers. Retrieved September 3, 2018, from https://learn.eartheasy.com/articles/plastics-by-the-numbers/

Shanmukha, R. (2016, December 13). Flexible Pavement Definition. Retrieved September 25, 2018, from https://knowledge4civil.wordpress.com/2016/12/13/flexible-pavement-definition/

Silvestre, R., Medel, E., García, A., & Navas, J. (2013). Utilizing recycled ceramic aggregates obtained from tile industry in the design of open graded wearing course on both laboratory and in situ basis. *Materials & Design*, *50*, 471–478. https://doi.org/10.1016/j.matdes.2013.03.041

Sinha, K., Patel, M. R., & Patel, J. (2010, October). Pet Waste Management by Chemical Recycling: A Review. http://dx.doi.org/10.1007/s10924-008-0106-7

Vieira, C. S., & Pereira, P. M. (2015). Damage induced by recycled Construction and Demolition Wastes on the short-term tensile behaviour of two geosynthetics. *Transportation Geotechnics*, *4*, 64–75. https://doi.org/10.1016/j.trgeo.2015.07.002

Vivas, N., Lye, L. M., & Zhang, B. (2018). Design and Formulation of Concrete with Polyethylene Terephthalate (PET) using Statistical mixture design. *Building Tomorrow's Society*, 10.

Wahlström, M., Laine-Yliijoki, J., Järnström, helena, Kaartinen, T., Erlandsson, M., Palm Cousins, A., … Jørgensen, A. (2014). *Environmentally Sustainable Construction Products and Materials – Assessment of release* (Report No. 978-82-8277- 059– 0). Nordic Innovation.

Webb, H. K., Arnott, J., Crawford, R., & Ivanova, E. P. (2012, March). Plastic Degradation and Its Environmental Implications with Special Reference to Poly(ethylene terephthalate). http://dx.doi.org/10.3390/polym5010001

Yoder, E. J., & Witczak, M. W. (1975). *Principles of Pavement Design*. John Wiley & Sons.

Zoorob, S. E., & Suparma, L. B. (2000). Laboratory design and investigation of the properties of continuously graded Asphaltic concrete containing recycled plastics aggregate replacement (Plastiphalt). Retrieved April 8, 2017, from http://wenku.baidu.com/view/04075d3c0912a21614792960.html

Appendix A – Sieve Analyses

Table 14. Gradation of Shredded Spring Water Plastic Bottles (Type 1)

Sieve Size (mm)	Weight retained on each sieve (g)	Cumulative retained weight (g)	Weight (g)	(%) passing	% Retained
9.5	0	0	400.2	100	0
4.75	123.00	123.00	277.20	69.27	30.73
2.36	204.30	327.30	72.90	18.22	51.05
1.18	58.20	385.50	14.70	3.67	14.54
0.6	12.40	397.90	2.30	0.57	3.10
0.3	1.80	399.70	0.50	0.12	0.45
0.15	0.50	400.20	0.00	0.00	0.12
Total	400.20				100.00

Table 15. Gradation of Shredded Soft Drink Plastic Bottles (Type 2)

Sieve Size (mm)	Weight retained on each sieve (g)	Cumulative retained weight (g)	Weight (g)	(%) passing	% Retained
9.5	0	0	523.4	100	0
4.75	141.30	141.30	382.10	73.00	27.00
2.36	302.50	443.80	79.60	15.21	57.80
1.18	66.40	510.20	13.20	2.52	12.69
0.6	11.20	521.40	2.00	0.38	2.14
0.3	1.70	523.10	0.30	0.06	0.32
0.15	0.30	523.40	0.00	0.00	0.06
Total	523.4				100.00

Table 16. Gradation of Combined Plastic

Sieve Size (mm)	Weight retained on each sieve (g)	Cumulative retained weight (g)	Weight (g)	(%) passing	% Retained
9.5	0	0	923.6	100	0
4.75	264.30	264.30	659.30	71.38	28.62
2.36	506.80	771.10	152.50	16.51	54.87
1.18	124.60	895.70	27.90	3.02	13.49
0.6	23.60	919.30	4.30	0.47	2.56
0.3	3.50	922.80	0.80	0.09	0.38
0.15	0.80	923.60	0.00	0.00	0.09
Total	923.6				100.00

Appendix B. Standard Proctor Test

Table 17. Mix design for 100% crushed rock

Sieve Size	**Retained Percent (%)**	**Mass of each (kg)**	**Mass (g)**	**Trial 1 (g)**	**Trial 2 (g)**	**Trial 3 (g)**	**Trial 4 (g)**
25mm	3.52	0.25	251.05	NA	NA	NA	NA
19mm	12.25	0.87	872.78	NA	NA	NA	NA
12.5mm	18.03	1.28	1284.41	NA	NA	NA	
9.5mm	8.22	0.59	585.91	NA	NA	NA	
4.75mm	16.06	1.14	1144.41	NA	NA	NA	
PAN	41.91	2.99	2985.45	3000.13	3000.25	3000.03	3000.09
TOTAL	100.00	7.124	7124.00	3000.13	3000.25	3000.03	3000.09

Table 18. Mold Volume Calculation for 100% Crushed Rock

	1	2	3	4	5	Average
Mold Depth (m)	0.116	0.117	0.117	0.117	0.117	0.117
Mold Diameter (m)	0.101	0.101	0.101	0.101	0.101	0.101
Avg Volume					9.40E-04	m^3

Table 19. Initial Trial Water Content at 100% Crushed Rock

Trial #	Initial Water Content	Volume of Water (mL)
1	5%	150.01
2	7%	210.02
3	11%	330.00
4	14%	420.01

Table 20. Standard Proctor Test Results for 100% Crushed Rock

Trial #	Mass Mix + Mold (kg)	Mass of Mold (kg)	Mass of Mix (kg)	Wet Density (kN/m^3)
1	6.12	4.22	1.89	19.75
2	6.21	4.22	1.99	20.75
3	6.33	4.22	2.10	21.96
4	6.32	4.22	2.10	21.92

Table 21. Moisture Content and Dry Density for 100% Crushed Rock

Trial #	**Can #**	**Can + Wet Mix (kg)**	**Can + Dry Mix (kg)**	**Water (kg)**	**Mass of Can (kg)**	**Mass of Dry Mix (kg)**	**Moisture Content (%)**	**Dry Density (kN/m^3)**
1	18408	2.28	2.19	0.09	0.38	1.80	5	18.82
2	1404	2.24	2.11	0.13	0.25	1.86	7	19.43
3	1405	2.35	2.16	0.19	0.25	1.90	10	19.95
4	1416	2.33	2.10	0.23	0.25	1.85	12	19.51

Table 22. Mix Design for 95% Crushed Rock and 5% PET

Sieve Size	Gran A Percent Ret.	PET Percent Ret.	Gran A Required Sample	PET Required Sample	Trial 1		Trial 2		Trial 3		Trial 4	
					Gran A	PET	Gran A	PET	Gran A	PET	Gran A	PET
25mm	3.52	0	154.35	0.00	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
19mm	12.25	0	536.58	0.00	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12.5mm	18.03	0	789.66	0.00	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
9.5mm	8.22	0	360.22	0.00	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
4.75mm	16.06	28.62	703.58	65.97	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
PAN	41.91	71.38	1835.46	164.54	1835.4	164.5	1835.4	164.6	1835.5	164.30	1835.6	164.40
TOTAL	100	100	4379.84	230.52	1835.4	164.5	1835.4	164.6	1835.5	164	1835.6	164
PAN TOTAL					1999.9		2000		1999.8		2000	

Table 23. Mold Volume Calculation for 95% Crushed Rock and 5% PET

	1	2	3	4	Average
Mold Depth	0.117	0.117	0.117	0.117	0.117
Mold Diameter	0.101	0.101	0.101	0.101	0.101
Avg Volume				9.39E-04	m^3

Table 24. Initial Trial Water Content at 95% Crushed Rock and 5% PET

Trial #	**Initial Water Content**	**Volume of Water (mL)**
1	6%	120.00
2	8%	159.99
3	10%	200.00
4	12%	239.98

Table 25. Standard Proctor Test Results for 95% Crushed Rock and 5% PET

Trial #	**Mass Mix + Mold (kg)**	**Mass of Mold (kg)**	**Mass of Mix (kg)**	**Wet Density (kN/m^3)**
1	5.84	4.31	1.53	16.00
2	5.94	4.31	1.62	16.95
3	5.89	4.31	1.58	16.49
4	5.91	4.31	1.59	16.66

Table 26. Moisture Content and Dry Density for 95% Crushed Rock & 5% PET

Trial #	Can #	Can + Wet Mix (kg)	Can + Dry Mix (kg)	Water (kg)	Mass of Can (kg)	Mass of Dry Mix (kg)	Moisture Content (%)	Dry Density (kN/m^3)
1	A6	2.18	2.09	0.09	0.65	1.44	6	15.09
2	1911	1.87	1.75	0.12	0.25	1.50	8	15.69
3	1308	1.82	1.68	0.14	0.27	1.42	10	14.98
4	B7	1.99	1.82	0.17	0.40	1.42	12	14.87

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