POLITECNICO DI TORINO

Master of Science program in civil engineering

Master’s degree Thesis

Experimental investigation on asphalt mixtures containing plastic waste

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Abstract

We live in a world in which almost every single plastic piece created still exists because this material lasts for about four centuries. It became an environmental issue that could be contrasted with some actions in daily activities, personal and professional. That is a problem everyone should also face in the professional area. For that reason, this thesis describes how civil engineering can approach the previously formulated problem. It is possible to construct asphalt roads having a percentage of waste plastic treated in particular ways that improve the properties of the road, such as resistance, stability, and durability.

Nowadays, it is possible to find scientific research that analyzes how plastic waste influences the mixture with the aggregates and bitumen, and it is also possible to find implementations on rural roads in some countries, such as India and the United Kingdom. This document aims to prove if the local domestic waste from Turin, Italy, is usable to produce the asphalt for road construction. The plastic's usability will be evaluated experimentally in the Politecnico di Torino road materials laboratory in the DIATI department. For the experiments it will be used two types of plastic: the first one will be High-Density Polyethylene, and the second one will be a blend of domestic plastic waste composed of PET-1, LDPE-4, PP-5, and PS-6.

The first step focused on determining the geometrical properties and characterization of the aggregates available in the laboratory, where three different types of materials were provided, and sieve analysis and maximum density tests were performed on each type. Then, a mixture design was carried out by finding a fine aggregate gradation and optimal binder content that satisfied the requirements stipulated at the beginning of these activities. Once the optimal mixture design was selected, five different mixtures were prepared. Firstly, one mixture was prepared as a control sample without adding waste plastic. Secondly, three mixtures were made with the addition of shredded waste plastic polyethylene (PE) by varying the percentage of plastic by weight of aggregates in 0.27%, 1.5%, and 5%. Lastly, the other mixture was produced with an addition of shredded waste plastic with 1.5% by weight of aggregates using a mixture described previously. There were compacted six cylindrical specimens employing the gyratory shear compactor for each mixture mentioned before.

The volumetric properties of each mixture, maximum density, and bulk density were evaluated to find the air voids content of each of them since this is a parameter of such importance that it is related to many of the distresses that occur in the asphalt pavements. The results were compared with the control mixture without adding plastic to evaluate the influence of the addition of shredded plastic in a bituminous mixture. Finally, mechanical tests were performed on all cylindrical specimens of the five bituminous mixtures, for which half of the specimens were conditioned in water at elevated temperatures, and the rest were dry specimens. The performed tests were the indirect tensile stiffness modulus and indirect tensile strength. The second one determines the water sensitivity of each mixture through the indirect tensile strength ratio calculation. All the results were compared between them and the control sample to assess the behavior when adding shredding plastic in terms of stiffness and water resistance.

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Every accomplishment starts with the decision to try.

[GAIL DEVERS]

1 Introduction

Currently, our planet is experiencing significant environmental damage from water and air pollution, climate change, tons of industrial and domestic waste, and global warming. Those are daily issues that modern industries are dealing with timidly, but it is necessary to make a fundamental change in our consuming society. Many activities and materials can help improve all the environmental problems that each time are becoming more prominent and decisive. Nowadays, there are many ways to help the planet, but there should be more and better ways to do it. Hence, being an inhabitant of this planet is our duty to find valuable solutions that contribute to and promote the arrangement of this situation.

In the civil engineering sector, many processes contribute to the problems abovementioned. Particularly on road construction, the exploitation of petroleum is a crucial agent playing a role in environmental pollution. It is used to produce asphalt applied in the construction of pavements to improve specific properties, such as flexibility and viscosity. Those materials are used in a very high quantity and are necessary to the mix because they enhance strength, stability, resistance, and durability when used and dosed appropriately. It is necessary to transform those contributions from problems into solutions.

Outside the civil engineering sector, there is material all around the world that generates tons of trash and contamination because it takes a very long time to degrade. Its industry generates large quantities of pollution and waste since it is one of the most used materials in the world: plastic. This material has its provenience from very different sources; an example, the natural gas, plants, or oil that in a refining and heating process are converted into ethylene and propylene that are mixed to create polymer chains that compose the different types of plastics that exist.

In today's reality, it is challenging to think of a world without plastic because it is used all over the industries as a primary resource but also as a "single-use" material; medical supplies, food wrap, containers, shopping bags, bottles (water, juice, soda, tea and in general all the beverages), disposable dishes, cutlery, and straws. All this plastic is produced for single and fast use (often less than a minute), but it takes centuries to complete decompose process. For instance, a plastic bottle takes approximately 4 centuries to decompose, which is one of the reasons plastic can be considered a non-degradable material. Plastic could be beneficial if used intelligently and precisely, but the industry is taking advantage of its properties without thinking of the environmental damage they are causing. Sometimes the usage of plastic films and packages is avoidable. To illustrate, some fruits as bananas, have their peel that protects the edible content, so it is not necessary to use a plastic container or film to protect them.

During the last decades, sustainability has become a trend in industrial areas. Therefore, people have begun to worry about the environment and prefer products that guarantee green production and decomposition. This fact is excellent, but it should not be only a marketing matter that allows some industries to sell their products more. Industries are continuously searching how and where it could be possible to recycle waste, particularly plastic.

Taking advantage of plastic waste as a resource, several implementations are being generated to use waste plastic in many different sectors. The road construction industry has not been left behind, and until now, there have been numerous studies of the addition of waste plastic pieces in the mix design of asphalt pavements. These studies, experiments, and implementations have shown positive results in multiple features that talk about pavement quality and are reported as an essential advantage of reducing asphalt content, which is a bonus to reducing the environmental pollution.

Nowadays, there is a lot of scientific research and testing in which plastic materials are studied and implemented in industrial processes. One of these groups, RILEM, is researching the properties that recycled plastic can increment in the asphalt pavements. The RILEM group (International Union of laboratories and experts in construction materials, systems and structures) had important knowledge and papers that are being tested around the asphalt pavements containing plastic. A portion of the activities done for this thesis was part of that testing work that consolidated the data and helped the group to obtain some results for one of their investigations in progress. Their main contribution to the development of this thesis was the guideline of the activities to perform and the first type of plastic used for the first asphalt mixture.

Since the last decade, countries like India have implemented asphalt pavement with recycled plastic and have had documentation and studies that make the idea real. In India's government, the Ministry of Road Transport and Highways has the task of researching and implementing green solutions and eco-friendly products for its works inside its vast portfolio of responsibilities. That is why they have their own specifications, guidelines, and methods to recycle the plastic and use it not only for rural roads but also for urban ones (indeed, the plastic percentage for each kind of road is different, and the impact on the properties is not proportional). This idea is not a worldwide solution because each country or region has its own recycling laws, organizations, and processes that contribute in an important way to this kind of activity.

This report focuses on assessing specific types of plastic used in the mix design of bituminous mixtures and the comparison with a reference mixture without waste plastic. An essential part of the activities will consider the local most consumed products, meaning the domestic leftover plastic in Turin, Italy.

Additionally, a user manual for the UTM-30 machine located in the Politecnico di Torino DIATI department, specifically in the Road Materials laboratory, will be developed as a parallel activity. The 30 kN servo-hydraulic Universal Testing Machine (UTM-30) is used to test the mechanical properties of cylindrical compacted specimens created in laboratory or samples taken infield. This manual will contain a definition of the machines that compose the whole system, the procedures to turn it on and off, and precisely how to perform the most important tests for this thesis: Indirect Tensile Strength (ITS) and Indirect Tensile Stiffness Modulus (ITSM) that will be described in subsequent chapters.

2 Objectives

The environmental motivation of this report is one of the most significant objectives that push to perform the laboratory tests on the selected samples that will be explained in the following chapters. The objective is to reuse waste plastic in bituminous mixes to find the optimum mix and method to be used in Turin city. This aim will take advantage of plastic packaging and film plastic to be used in bituminous mixes to test its properties and find the best way of producing green pavement mix, helping the environment with this nonperishable and contaminant material.

In the civil engineering area, the main objective of this thesis is to evaluate the mechanical properties of an asphalt mix with different kinds of recycled plastics. On the one hand, plastic is treated industrially and composed of plastic-type PE. On the other hand, the second type of plastic has a domestic and manual process to make it worthwhile for the pavement mix. This material is a set of different plastics divided in a balanced way by their availability, in which are present the types 1 PET, 4 LDPE, 5 PP, and 6 PS.

For the mixtures, the first type of plastic (industrial treatment) is thicker than the second one (domestic), and the aim is to prove if the behavior of those materials inside the asphalt mix is similar. That has an internal second intention to analyze the results for the second compound that emulates the process that should be done, having as input local plastic domestic waste and performing a manual process that could be improved if the results are good enough and the hypothesis is proven.

Finally, this thesis aims to compare the resultant values of the mechanical properties of the previously mentioned asphalt mixtures between them and a reference bituminous mixture without plastic. The available literature shows that mixtures containing a certain amount of plastic will increase properties such as strength, water resistance, binding of the mix, and service life.

3 Asphalt pavement with waste plastic

Asphalt is a substance with some properties ideal for constructing pavements due to its strength, resistance, and waterproofing, improving its durability and efficiency. The Merriam-Webster dictionary gives two self-explanatory definitions: “a dark bituminous substance that is found in natural beds and is also obtained as a residue in petroleum refining and that consists chiefly of hydrocarbons” and “an asphaltic composition used for pavements and as a waterproof cement” (Merriam-Webster, 2022).

There are many ways in which an asphalt pavement can be created. Depending on the environmental and transit factors, a mixture is designed to increase some properties instead of others. For example, the asphalt used for a road in an arid and hot place rarely transited is not the same as the one used in a very humid and rainy place inside a big city. Each of them should have different amounts and types of materials to permit the pavement to be resistant to its climate context and to behave in the best way for the usage that will be given.

3.1 Plastic

The Science History Institute defines plastic as follows: “Plastics are a group of materials, either synthetic or naturally occurring, that may be shaped when soft and then hardened to retain the given shape. Plastics are polymers. A polymer is a substance made of many repeating units.” (Science History Institute, 2022).

Plastic materials can be classified into two main types depending on their physical properties:

a. Thermosetting plastic.
b. Thermoplastic.

“Thermoplastic materials can be formed into desired shapes under heat and pressure and become solids on cooling. On subjected to the same conditions of heat and pressure, they can be remolded. Thermosetting materials which once shaped cannot be softened/remolded by the application of heat.” (Research Design and Standards Organization, 2019). In this definition is evident that thermosetting polymer cannot be reshaped, which means that once it is shaped, it cannot be melted by applying heat and modeled as another object. That gives the material strength and heat resistance. On the other hand, thermoplastics are materials that can be modified by melting, reshaping, and solidified by cooling. That means that the second plastic type is ideal for recycling.

This kind of material is very useful for almost any activity, and today it is one of the most used ones in the world. The big problem with plastics arrives when their useful life ends, and it is discarded, becoming waste. It should be recycled as a non-degradable material because it will stand for approximately four centuries.

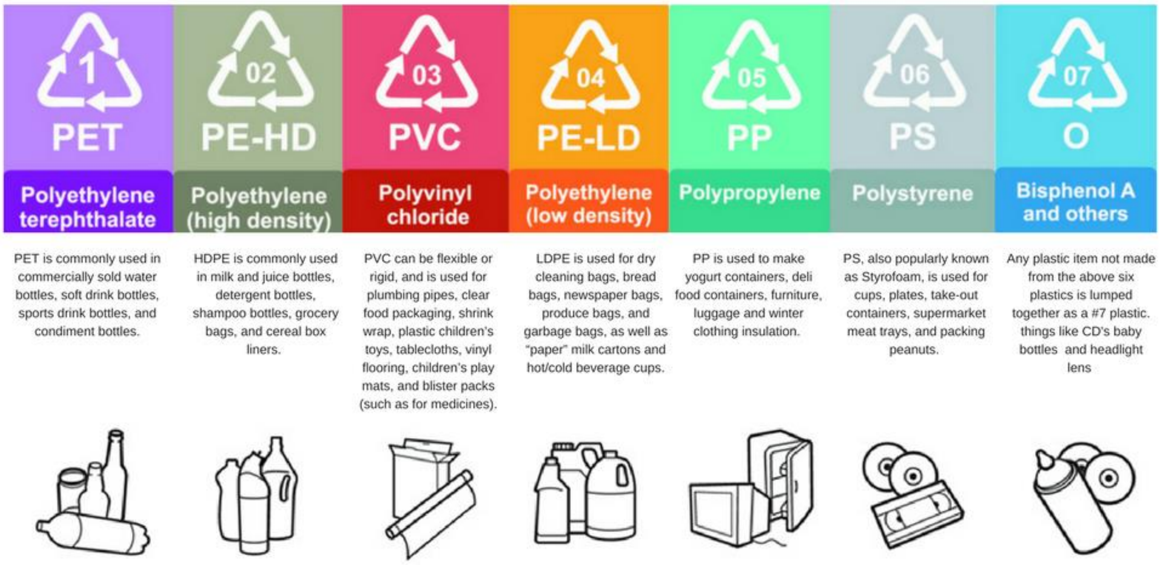

Figure 1: Plastic waste types

As it is possible to see in the "Plastic waste types" Figure (Hardin, 2021), there are seven different types of plastic waste. They are number coded to simplify their identification and classification in most of the world. Each is used in different products according to its strength, flexibility, or thickness properties.

3.2 Available technologies to produce asphalt mixtures containing waste plastic

The initial activities are related to the selection, cleaning, and shredding of the plastic waste to allow its usage in the mixture of elements that compose the asphalt (the details of this process will be illustrated in the following chapters). The idea of including plastic pieces into the asphalt mix is to reduce the bitumen quantity and to improve some of the resultant product properties. The plastic will be mixed with the heated aggregates to melt, creating a plastic cover layer around the compound. This process can be performed in two different ways:

a. Dry process: "the processed waste plastic is shredded and added to the hot aggregate. […] The Indian Road Congress (2013) and National Rural Roads Development Agency (2019) indicates that the shredded waste plastic size should preferably be 2-3 mm for better spread and coating on the aggregate. Dust and other impurities should not exceed 1%. The shredded waste plastic is then added to the aggregates that are heated to 170ºC. The shredded waste plastic softens and melts to form a coating around the aggregates […]. The bitumen is also heated to 160ºC and the plastic-coated aggregates are then mixed with bitumen and used for road construction." (Sasidharan, Eskandari Torbaghan, & Burrow, 2019).
b. Wet process: "the processed waste plastic in powder form is added to the hot bitumen […]. The powdered waste plastic is directly mixed with bitumen before adding them to the aggregates. It has to be ensured that there is an even mix of plastic and bitumen, and

> the temperature range for this method is 155ºC to 165ºC (Asare et al., 2019). Sahu and Singh (2016) and Asare et al. (2019) suggests a 6-8% of waste plastic powder within the bitumen mix." (Sasidharan, Eskandari Torbaghan, & Burrow, 2019)

In the precedent definitions, it became evident that the main difference between those processes is how the plastic waste is pre-processed and where it is added for optimal results. But that is not all, "The dry process is considered to be simple, economical and environmentally friendly, while the wet process requires more investment and machinery, and hence is not commonly used" (Mishra & Gupta, 2018).

The activities to elaborate this thesis were led by formal documents representing guidelines, standards, and a glimpse of the regulatory framework, containing the description and the technical basis of each process, to achieve the previously mentioned goals. The standards correspond to a series of documents published by The British Standards Institution that describe the processes to calculate the properties of the different materials and mixtures. The central part of the content will be described in the following sections when is appropriate.

Moreover, the guidelines for using plastic ways in road construction were an important part of the investigation because it was necessary to consider many variables that fit the initial requirements and expectations. For this reason, it was decided that the Indian guidelines, produced by the Ministry of Rural Development and elaborated by the National Rural Roads Development Agency, were the most suitable for this thesis. The title is "Guidelines for the use of Plastic Waste in Rural Roads Construction" and stand that "The present guidelines are based on the presentations made by Dr. Sangita, Sr. Scientist, Flexible Pavement Division, CRRI and the literature supplied by Dr. R. Vasudevan of Thiagarajar College of Engineering, (TCE), Madurai" (National Rural Roads Development Agency, India).

To better understand the following chapters, the essential parts of the guidelines will be extracted here. Firstly, it is important to specify the types of plastic that can be used and how it will be treated: "The following types of waste plastic can be used in the construction of rural roads:

- Films (Carry Bags, Cups) thickness up to 60micron (PE, PP and PS)
- Hard foams (PS) any thickness
- Soft Foams (PE and PP) any thickness.
- Laminated Plastics thickness up to 60 micron (Aluminum coated also) packing materials used for biscuits, chocolates, etc." (National Rural Roads Development Agency, India)

The guideline also highlights that "the size of the shredded plastic should normally be 2-3 mm for better spread and coating the aggregate." (National Rural Roads Development Agency, India), and that is an important thing because if the aggregate is not covered in a uniform and distributed way, the properties that should improve will be decreased, and the results fail. Related to that idea, the document stands that "we can adopt 8% as the optimum plastic content for blending the bitumen in the construction of plastic roads" (National Rural Roads Development Agency, India), which refers to the percentage of plastic by weight of bitumen.

The guideline specifies a small industrial process for the mixing and construction methods, so this part was partially considered for the laboratory process. It is referred to the previously described dry process in section 3.2 with additional information. For example, it explains that the plastic should be added to the aggregate in no more than thirty seconds for a correct melting and coating.

Additionally, the guideline document reports some of the evidence and results of the studies and implementations in Tamil Nadu, a southern Indian state where this process was implemented. “The performance studies carried out on the roads constructed in Tamil Nadu indicated satisfactory performance with good skid resistance, good texture value, stronger and less amount of progressive unevenness over a period of time. The experimentation carried out by CRRI also indicated better stability value, indicating higher strength, less flow and more air voids. […] It has been found that modification of bitumen with shredded waste plastic marginally increases the cost by about Rs. 2500 per tonne. However this marginal increase in the cost is compensated by increase in the volume of the total mix, thereby resulting in less overall bitumen content, better performance and environmental conservation with usage of waste plastic.” (National Rural Roads Development Agency, India)

Furthermore, the regulatory framework considers more legal and government considerations for the process that will be performed. This framework will be only mentioned because it should be an object of study during field application analysis and implementation time. “An adequate regulatory framework for the use of waste plastics in road construction, drawing on evidence-based standards, is important to establish the legal as well as technical basis for the use of this technology […]. Governments could consider providing the highways/road authorities with the mandate to oversee the use of waste plastics in road construction. The authorities could also be responsible for the technical monitoring involving the checking of temperature of the mix, quantity and type of waste plastic and bitumen and run quality assurance regimes.” (Sasidharan, Eskandari Torbaghan, & Burrow, 2019).

4 Experimental investigation

This thesis aims to evaluate the potential use of different types of plastic when added to a bituminous mixture. The experimental investigation was based on producing a traditional bituminous mixture without adding waste plastic and a series of mixtures containing different percentages of plastic added. These mixtures were tested and compared with the control mixture without plastic. Firstly, the characterization of the aggregates available in the laboratory was carried out by performing a granular size distribution test and finding the maximum density with the volumetric procedure. The first test was practical to obtain the aggregate gradation employed in the mix preparation. The second test was useful to obtain an estimated quantity of the bituminous mixture density.

This investigation employed two types of plastic to prepare two different bituminous mixtures. The first one was a plastic PE proportioned by the group RILEM, which is "the International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM, from the name in French – Réunion Internationale des Laboratoires et Experts des Matériaux, systèmes de construction et ouvrages) was founded in June 1947 in Paris, France, with the aim of promoting scientific cooperation and to stimulate new directions for research and applications, thus promoting excellence in construction worldwide" (International Union of Laboratories and Experts in Construction Materials, Systems and Structures, 2020). The first activity of this thesis is based on a plan for the joined interlaboratory testing (ILT) promoted by RILEM, which provided specifications on the materials and procedures. The second type of plastic was a mix of different types recycled and shredded domestically, composed of 1 PET, 4 LDPE, 5 PP, and 6 PS. The mixture preparation was performed following the dry method mentioned previously, and after finding the optimal bitumen content were prepared five mixtures as:

- One mixture without any plastic added.
- One mixture with 0,27% plastic-type one PE, added by weight of aggregates.
- One mixture with 1,5% plastic-type one PE, added by weight of aggregates.
- One mixture with 5% plastic-type one PE, added by weight of aggregates.
- One mixture with 1,5% plastic-type two, added by weight of aggregates

For each mixture was found the theoretical maximum density and were compacted six cylindrical specimens divided into two subsets of similar properties to be conditioned in a dry (three specimens) or wet (three specimens) manner for further testing comparison. The test performed to find the air voids content in each specimen was the bulk density by the saturated surface dry method. Finally, the mechanical test to which each specimen was subjected was the Indirect Tensile Stiffness Modulus test (ITSM) and the Indirect Tensile Test (ITS). Additionally, it was calculated the Indirect Tensile Strength Ratio (ITSR) that considers the results from the application of ITS on wet and dry subsets to obtain an estimation of the moisture resistance of the specimens.

All the results of bituminous mixtures containing plastic were compared with the reference control mixture without plastic.

Two similar expressions could deceive the reader in this text, so it is important to clarify. In the report, the expression “plastic-type 1 PET” is referred to the coded-numbered plastic-type corresponding to the Polyethylene terephthalate or PET. Furthermore, it could be found the expression “plastic-type one” (written alphabetically) that refers to the first plastic-type used in the activities that correspond to the thick PE (Polyethylene) plastic treated industrially. In the same way, should be differenced the expression “plastic-type 2 HDPE” (High-Density Polyethylene) from the “plastic-type two” (a balanced mix of different plastic types used for the second part of the activities).

4.1 Materials

This section describes the materials used in the laboratory activities, their properties, and their usage. The processes described in this chapter are only related to the initial phases in which the material is selected, classified, prepared, and measured.

4.1.1 Aggregates

For this thesis were supplied 3 different types of limestone virgin aggregates of different sizes:

Figure 2: Aggregate size 5/15

Figure 3: Aggregate size 3/8

Figure 4: Aggregate size 0/5

The filler used in this paper is a $CaCO_3$ material shown in the figure.

Figure 5:Filler $CaCO_3$

4.1.1.1 Preparation of soil sample

The first step with the aggregates from the field was spreading the material for air drying for one day, as shown in Figure 6.

Figure 6: Spreading material for air drying

Then, to obtain a representative sample of the material was followed the standard BS EN 932-2:1999 applying method B referred to quartering process, to reduce the large soil sample to an adequate size for sampling as follows:

a. Mix the material by turning over it and leaving it in a conical shape
b. Flat the surface of the cone until it reaches a uniform thickness and diameter
c. Divide the material into four equal parts

Figure 7:Quartered material for size reduction

d. Discard the opposite quarters and mix the other material
e. Quarter again until the sample is reduced to the desired size.

4.1.1.2 Aggregates size distribution

The aggregate size distribution for the three types of aggregates was performed through the sieve analysis following the standards BS EN 933-1:2012. Sieve analysis can be performed by washing or dry method, and is performed by putting in decreased sizes sieves of specific aperture to separate the material in different portions depending on their particle size to calculate the percentage of each particle size concerning the entire sample.

The first step is to select a representative soil sample, as shown in section 4.1.1.1. The minimum size of the test portion is selected depending on the maximum aggregate size, based on a table provided by the guidelines:

Aggregate size D (maximum) mm	**mass of aggregates** kg	**volume of lightweight aggregates (litres)**
90	80	-
32	10	2,1
16	2,6	1,7
8	0,6	0,8
≤ 4	0,2	0,3

Table 1. Minimum size of test portions (The British Standards Institution, 2012)

A portion higher than 2.6kg mass aggregates were taken for type 5/15, 0.6kg for type 3/8, and 0.2kg for type 0/5. These quantities of each material must be dried in an oven at 110±5°C, left cool down, and weight as 'm_1'.

This study performed the washing method that consists of cleaning the material over the sieve size 0.063mm until water passing the sieve becomes clear. The material retained in this sieve is dried at 110±5°C, and the final mass is recorded as 'm_2'. This procedure is performed to know the percentage of material smaller than 0.063mm to account for the particle size distribution graph.

Then is performed the sieving analysis by following the following steps:

a. As shown in the figure, fit the columns of sieves together and arrange them by decreasing aperture size from top to bottom.

Figure 8: Sieves column arrangement to granular size distribution test

The sieves used in this test are shown in Table 2. In the washing process are not removed all the particles lower than 0.063mm, so is also used the corresponding sieve to ensure the correct measurement of particles of this size.

Sieve aperture size [mm]
16
14
12.5
10
8
6.3
4
2
1
0.5
0.25
0.063

Table 2: Sieve aperture size for the arrangement of sieves column

b. The dried material previously washed is put into the sieving column, not overloading the sieves.

c. The sieving procedure can be realized by mechanical way or manually. This test was performed by shaking the sieve column mechanically for 10 minutes. After that, each sieve was manually shaken one by one, starting with the sieve of the largest aperture size. This procedure is performed until 1 minute of shaking, not more than 1% of the mass retained material change.
d. The mass of material retained per sieve is recorded as ‘Rn’ while the mass retained in the pan as ‘P’.

From the standards, “The percentage of fines f passing the 0,063 mm sieve is computed from the equation:

$$f = \frac{(M_1 - M_2) + P}{M_1}$$

where

$M1$ is the dried mass of the test portion, in kilograms;

$M2$ is the dried mass of the residue retained on the 0,063 mm sieve, in kilograms;

P is the mass of the screened material remaining in the pan, in kilograms.” (The British Standards Institution, 2012) BS EN 933-1:2012

The results obtained are shown in Table 3.

	Aggregate 0/5		**Aggregate 3/8**	
	Test 1	**Test 2**	**Test 1**	**Test 2**
Fines [%]	2,906	2,761	1,382	1,032

Table 3: Fines percentage in each type of aggregate

The accumulated percentage of retained aggregate on each sieve is computed with respect to the initial total mass of test samples M1 and then is transformed as a percentage passing each sieve as

$$\%Passing = 100 - \sum(100 \times \frac{R_i}{M_1})$$

A table that summarizes the test and shows the percentage passing of each sieve is presented.

	Aggregate 0/5		Aggregate 3/8		Aggregate 5/15		Filler
	Test 1	Test 2	Test 1	Test 2	Test 1	Test 2	-
Sieve [mm]	**P [%]**	**P [%]**	**P [%]**	**P [%]**	**P [%]**	**P [%]**	**P [%]**
16	100,0	100,0	100,0	100,0	99,7	99,7	100,0
14	100,0	100,0	100,0	100,0	97,3	97,6	100,0
12,5	100,0	100,0	100,0	100,0	91,1	88,5	100,0
10	100,0	100,0	100,0	100,0	67,7	62,3	100,0
8	100,0	100,0	98,8	98,3	40,1	35,4	100,0
6,3	98,8	99,4	81,3	73,2	18,8	13,8	100,0
4	85,7	85,0	37,4	22,1	6,7	4,4	100,0
2	56,9	56,5	15,8	5,7	3,6	2,4	100,0
1	34,1	33,0	6,5	2,6	2,1	1,4	99,7
0,5	19,0	17,9	3,3	1,8	1,3	0,9	99,5
0,25	9,6	8,8	2,1	1,4	0,9	0,6	98,5
0,063	3,0	2,8	1,4	1,1	0,2	0,1	91,1
pan	0,0	0,0	0,0	0,0	0,0	0,0	-

Table 4: Aggregate size distribution results for each type of aggregate and filler

The granular size distribution curve is obtained by making a graph of percentage passing versus diameter of each sieve aperture.

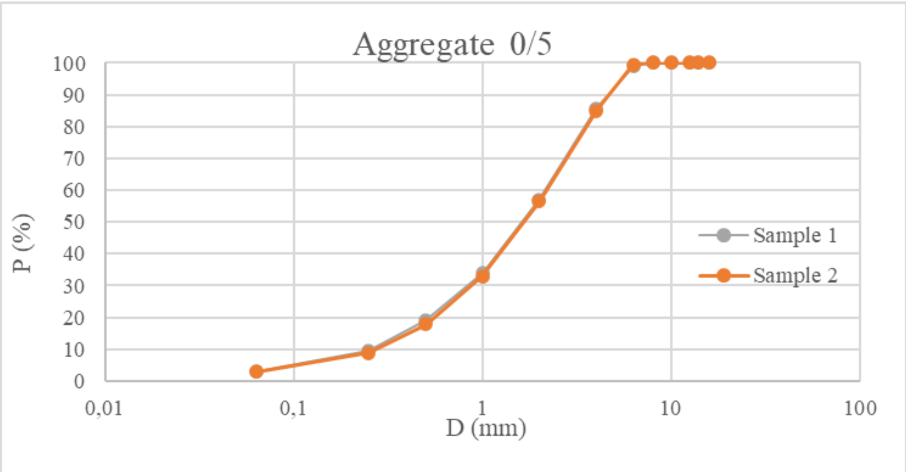

Figure 9:Granular size distribution graph, aggregate 0/5

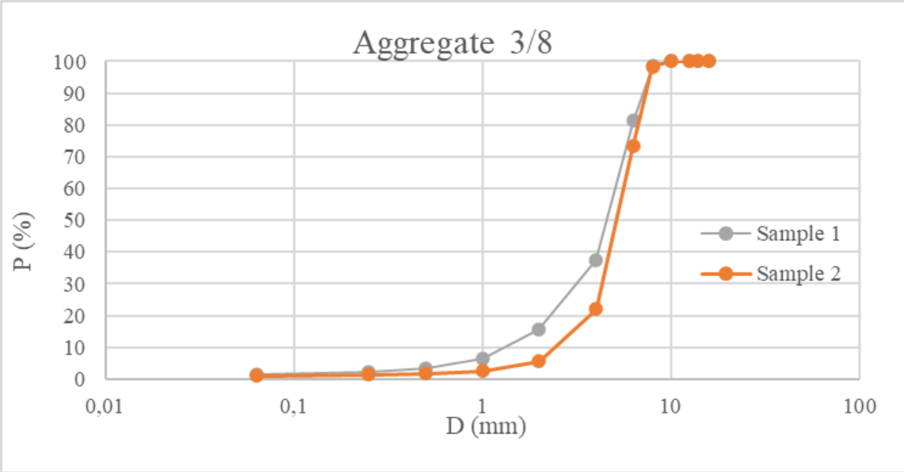

Figure 10: Granular size distribution graph, aggregate 3/8

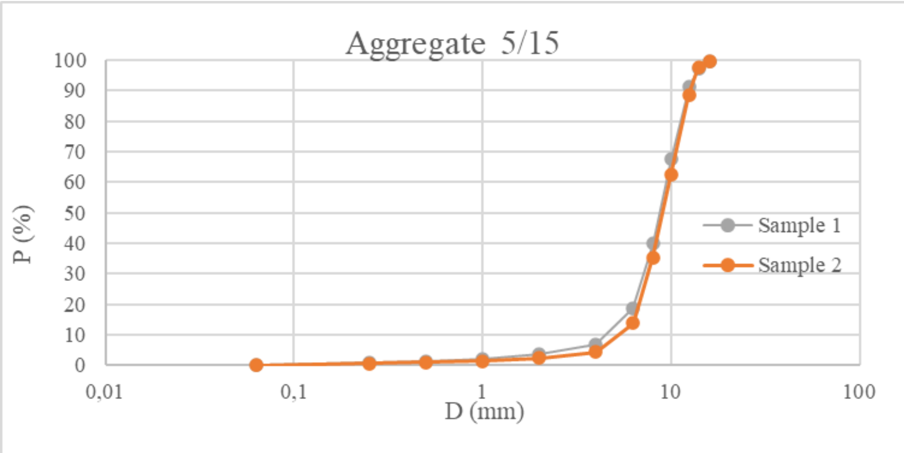

Figure 11: Granular size distribution graph, aggregate 5/15

The test is considered acceptable if the following condition is followed:

$$\frac{M_2 - (\sum R_i + P)}{M_2} \times 100 < 1\%$$

That means the difference between the final and initial test samples does not differ more than 1%; in other words, the percentage of mass loss during testing is lower than 1%. Otherwise, the test should be repeated.

4.1.1.3 Theoretical maximum density

To find the theoretical maximum density of aggregates was followed the standards BS EN 12697-5:2018. The standard presents different methods to compute this parameter, but this paper uses the volumetric procedure method employing pycnometers. This method calculates the material sample's density, neglecting their air voids content. This value is obtained by the test sample's mass and volume, which is obtained by the displacement of the mass volume of water on a container of a specific known volume calibrated previously (pycnometer). The following steps will be described and explained with images taken in the process:

a. Weight the pycnometer with its corresponding cap and record the mass as ‘m_1’.

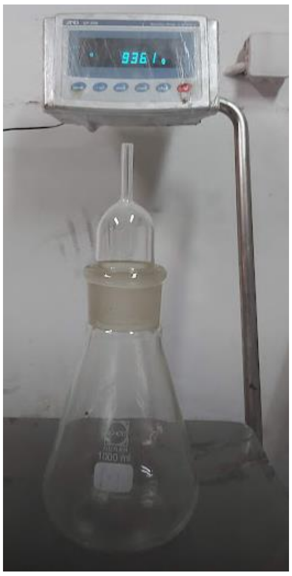

Figure 12: Weighting of empty pycnometer

b. Put into the pycnometer a representative dry soil sample to be tested. The mass of the soil sample must be “at least 50 times the numerical value of the nominal maximum particle size of the aggregates in millimeters (mm) (i.e., the largest specified sieve size of the mixture) with a minimum of 250 g” (The British Standards Institution, 2018) [BS EN 12697-5-2018]. Report the value of the mass of the pycnometer filled with material as ‘m_2’.

Figure 13: Reduction of a soil sample by quartering

Figure 14: Pycnometer with soil sample

c. Fill the pycnometer with de-aired demineralized water up to 30mm below the head joint and put the sample in a vacuum system to remove the air between sample particles and, as much as possible, the air voids in accessible pores for 15±1 minute. This process is facilitated by the shaking or vibration of the pycnometer during the process.

Figure 15: Pycnometer filled with a soil sample and water subjected to a vacuum system

d. Fit the cap of the pycnometer and fill it with water until the calibration mark. Record the weight of the pycnometer, soil sample, and water as ‘m_3’ and measure the temperature of the water.

Figure 16: Pycnometer with a cap filled with water

Figure 17: Measurement of water test temperature

From the BSI Standards Publication Part5: Determination of the maximum density (BS EN 12697-5:2018), the maximum density is obtained as: “

$$\rho_{mv} = \frac{m_2 - m_1}{10^6 \times V_p - (m_3 - m_2)/\rho_w}$$

where

ρ_{mv} is the maximum density of the bituminous mixture, as determined by the volumetric procedure, in megagrams per cubic meter (Mg/m3) to the nearest 0,001 Mg/m3;

m_1 is the mass of the pycnometer plus head piece and spring, if any, in grams (g);

m_2 is the mass of the pycnometer plus head piece, spring and test sample, in grams (g);

m_3 is the mass of the pycnometer plus head piece, spring, test sample and water or solvent, in grams (g);

V_P is the volume of the pycnometer, when filled up to the reference mark, in cubic meters (m3);

ρ_W is the density of the water in accordance with 10.1.2 or solvent at test temperature, in megagrams per cubic meter (Mg/m3) to the nearest 0,000 1 Mg/m3." (The British Standards Institution, 2018) [BS EN 12697-5:2018]

The formula given by the standard can calculate the density of the water at the test temperature: "

$$\rho_w = 1{,}00025205 + \left(\frac{7{,}59 \times t - 5{,}32 \times t^2}{10^6}\right)$$

where

ρ_w is the density of water at test temperature, in megagram per cubic meter (Mg/m3);

t is the temperature of the water in degrees Celsius (°C)." (The British Standards Institution, 2018) [BS EN 12697-5:2018]

The results are shown in the table below.

Sample	M_P (m_1)	M_{P+M} (m_2)	$M_{P+M+H2O}$ (m_3)	V_P	T	ρ_W	ρ_{mv}	Avg.	Gmm
[-]	[g]	[g]	[g]	[m^3]	[°C]	[kg/m3]	[kg/m3]	[kg/m3]	-
0/5	925,3	1750,9	2823,6	0,001370	18,7	998,6	2795	2794,9	2,795
	936,3	1868,4	2761,9	0,001358	18,7	998,6	2014		
3/8	936,3	1812,1	2846,3	0,001358	19,5	998,4	2721	2720,2	2,720
	937,8	1800,4	2813,0	0,001331	19,4	998,4	2719		
5/15	936,1	1671,5	2756,9	0,001358	20,9	998,1	2721	2718,0	2,718
	937,7	1744,9	2777,1	0,001331	20,7	998,2	2715		

Table 5: Theoretical maximum density results

For each type of aggregate, two repetitions were performed. The second repetition of aggregate 0/5 was discarded due to the diverse value obtained.

4.1.2 Bitumen

The bitumen used in this research was a 50/70 penetration grade, one of the most used for preparing hot mix asphalt used in roads, airports, and other pavemented areas construction and maintenance, specifically for bases and wearing courses. Depending on the penetration grade of bitumen, the asphalts behave diversely. This type of bitumen was selected for this thesis and as required by the research group RILEM.

Figure 18: Bitumen 50/70pen grade

4.1.3 Plastic

In the bituminous mixture, two types of plastics were used to perform the activities and understand if the pavement's properties were the same. Two types of plastic allow the analysis to have more data and make more objective conclusions, for example, what is the influence of the plastic selection in the mixture, the different properties that each one of them gives to the resultant asphalt pavement, and the comparison with a standard asphalt without plastic sample.

This section describes the two plastic materials and how they were treated and processed for final usage.

4.1.3.1 Plastic-type one

The plastic-type one included only High-Density PE that was already treated industrially by an external company with the technical support to do that process. The given plastic was shredded into small irregular pieces that should be sieved to select only those usable parts.

Figure 19: Shredded plastic-type one

The plastic material should be sieved, and those pieces passing the 11.5mm sieve must be selected, as shown in Figure 20.

Figure 20: Sieved plastic

The plastic used in the mix design must be reduced to a representative sample, as mentioned in section 4.1.1.1 Preparation of soil sample. The plastic sample is quartered, as shown in Figure 21.

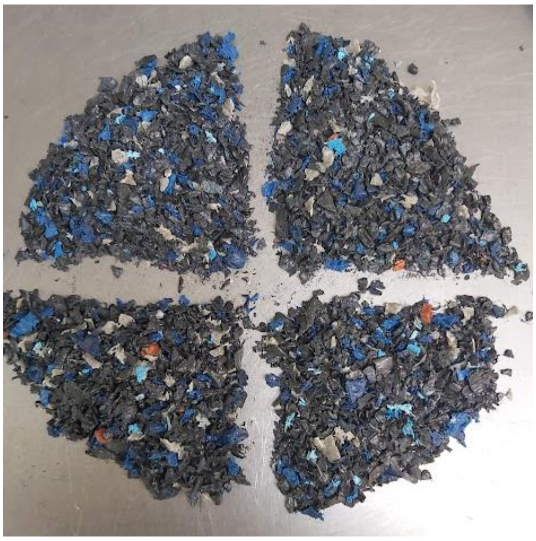

Figure 21: Quartered plastic to sample reduction

4.1.3.2 Plastic-type two

For the second part of the tests, domestic waste plastics were obtained from an ordinary house consumption of food and cleaning products. The selection process was influenced by the environment that was developed intentionally because the study of this plastic-type wanted to emulate the real conditions in which plastic waste is available. The following sections describe the selection, cleaning, and shredding process.

4.1.3.2.1 Selection of the waste plastic to be used

The selection process of the waste plastic had two main stages: the first phase was the analysis of the different types of plastic, considering the recycling process with heat that will be done for the tests. In this phase, two types of plastic were immediately discarded because some dangerous gases were produced in the melting process: plastic-type 3 PVC and plastic-type 7 OTHER.

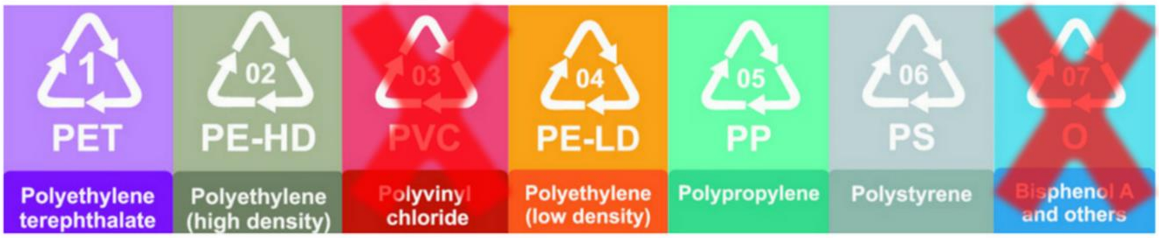

Figure 22: Discarded plastics

The second phase was the physical analysis of the waste plastic. Being a non-industrial process, without machinery that facilitates the cleaning and shredding of the elements, it was necessary to decide that the thickest, dirtiest, and most difficult elements to work with, should be discarded. In that way, the most significant part of the plastic waste useful for the process corresponds to the packaging of the most consumed products in Italy, such as pasta, coffee, and bread. It was an essential factor, considering that in the Italian industry, much plastic waste could be used and recycled in the asphalt pavement.

The collected plastic with each approximately density was the following:

a. PET (type 1) [1,350 g/cm3 amorphous - 1,455 g/cm3 crystalline]

Figure 23: Collected PET

b. HDPE (type 2) [0,93 to 0,97 g/cm3]

Figure 24: Collected HDPE

c. LDPE (type 4) [0,91 to 0,94 g/cm3]

Figure 25: Collected LDPE

d. PP (type 5) [0,855 g/cm3 amorphous - 0,946 g/cm3 crystalline]

Figure 26: Collected aluminum-coated PP

Figure 27: Collected transparent PP

e. PS (type 6) [1,050 g/cm3]

Figure 28: Collected PS

4.1.3.2.2 Sorting out, cleaning, and shredding waste plastic

The sorting process was long but easy because almost all the plastic waste had a numeric code that accelerated the selection. It was evident that some plastic types had much larger volumes, such as the plastic-type 5 PP and 1 PET. The plastic-type 2 HDPE was discarded in this phase because it had physical characteristics that do not allow the correct material sizing for the previously mentioned purposes.

Some of this waste was very clean because it contained dry and solid things that ease its cleaning, but others were complicated because they were dirty and had labels attached with powerful and viscous glue. Cleaning took about a couple of days to remove most of the non-plastic parts that should affect the process negatively.

The thickness of each selected plastic type was measured using the dynamic shear rheometer (DSR), as shown in Figure 29.

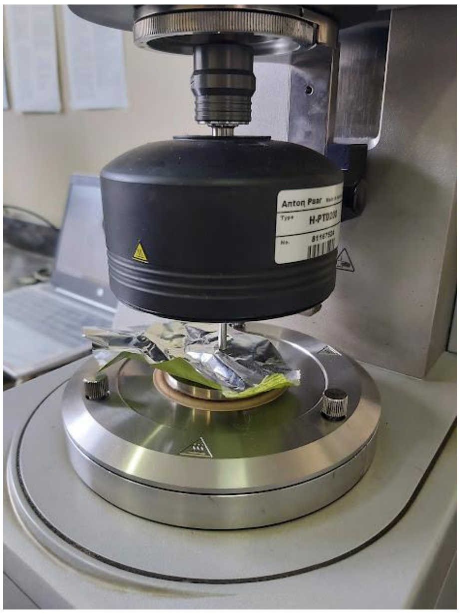

Figure 29: Dynamic Shear Rheometer used for thickness measurement of each plastic

Before starting the testing phase, it was necessary to shred all the selected plastic without any industrial machine that could make simple and efficient the process. It was imperative to cut the plastic elements into small pieces: according to the guidelines made in India, where this type of asphalt has been studied, tested, and produced, the “size of the shredded plastic should normally be 2-3 mm for better spread and coating the aggregate.” (National Rural Roads Development Agency, India). This process was manually done for some weeks with scissors and bistoury because there were no efficient machines that improved the shredding process to obtain the desired outcome. The resultant plastic divided by type and specifical provenience is illustrated in the following figures:

Figure 30: Plastic-type 1 PET (eggs package)

Figure 31: Plastic-type 4 LDPE (coffee internal package)

Figure 32: Plastic-type 4 LDPE (toilet paper wrap)

Figure 33: Plastic-type 5 PP (aluminum coated packaging)

Figure 34: Plastic-type 5 PP (outer coffee packaging)

Figure 35: Plastic-type 5 PP (pasta packaging)

Figure 36: Plastic-type 5 PP (rigid containers)

Figure 37: Plastic-type 6 PS (yogurt containers)

In Figure 38, it is possible to compare the dimension of the shredded plastic with a ten-cent euro coin to ensure that the plastic pieces are standard-compliant, which means that each piece size is between two and three millimeters.

Figure 38: Comparison of plastic and coin dimensions

Each type of shredded plastic was weighted, and the corresponding percentage was calculated to make a mix of them in correspondence with the values. That is how was calculated the amount of plastic necessary for a mix containing 6000g of aggregates and 1,5% of plastic. The results are shown in the following table:

Type		Thickness [mm]	Quantity [g]	[%]	1,5% plastic [g]
1	eggs package	0,18	48,65	12,47	11,23
4	coffee internal package	0,06	31,41	8,05	7,25
	toilet paper wrap	0,01	20,23	5,19	4,67
5	aluminum coated packaging	0,07	17,98	4,61	4,15
	pasta packaging	0,021	105,91	27,16	24,44
	outer coffee packaging	0,05	17,71	4,54	4,09
	rigid containers	0,16	93,36	23,94	21,54
6	yogurt containers	0,27	54,75	14,04	12,63
		TOTAL	390	TOTAL	90,00

Table 6: Quantity and thicknesses of each type of plastic

The plastic was weighted, as the proportional value illustrates, and mixed in a unique container to have a homogeneous material (the different densities of the plastic pieces allow only a certain kind of “mixture” of them) as shown in the figure:

Figure 39: Weighted and proportional plastic mix

4.2 Mix production

The following chapter describes the mixture design done for the specific requirements and testing for the objectives of this document. There are defined measurements, procedures, and techniques that are performed.

4.2.1 Aggregate gradation

Aggregate gradation should fall within the band described in Table 7 (AC16 mixture).

Sieve size [mm]	Lower Limit [% passing]	Upper Limit [% passing]
32	100	100
16	90	100
10	73	85
4	45	56
2	28	38
0.5	16	24
0.25	11	18
0.063	4	8
Bitumen content [% by weight of aggregates]	4-6	

Table 7: Aggregate gradation requirements

A fitting process with excel was performed to obtain a combination of aggregates that fall into the established limits curves.

Sieve	Lower Limit	Upper Limit	Central Curve	Project Curve		0/5	3/8	5/15	Filler
Diameter	**Passing Percentage**				**Diameter**	**Passing Percentage**			
[mm]	**[%]**				**[mm]**	**[%]**			
32	100,0	100,0	100,0	100,0	**20**	100,0	100,0	100,0	100,0
16	90,0	100,0	95,0	99,9	**16**	100,0	100,0	99,7	100,0
10	73,0	85,0	79,0	84,9	**10**	100,0	100,0	65,0	100,0
4	45,0	56,0	50,5	51,8	**4**	85,4	29,7	5,6	100,0
2	28,0	38,0	33,0	35,8	**2**	56,7	10,7	3,0	100,0
0,5	16,0	24,0	20,0	15,0	**0,5**	18,4	2,6	1,1	99,5
0,25	11,0	18,0	14,5	10,0	**0,25**	9,2	1,8	0,7	98,5
0,063	4,0	8,0	6,0	6,1	**0,063**	2,9	1,2	0,1	91,1
					alfa,i	0,52	0,00	0,43	0,05

Table 8: Fitting process for aggregate gradation

The previous table presents the percentage passing for the project curve (PC), which meets the previously specified limits. This curve is obtained by combining the different size aggregates through the coefficients of proportionality shown as alfa,i. The results are shown in the following graph. To fit the curve, removing the material 3/8 from the design became necessary.

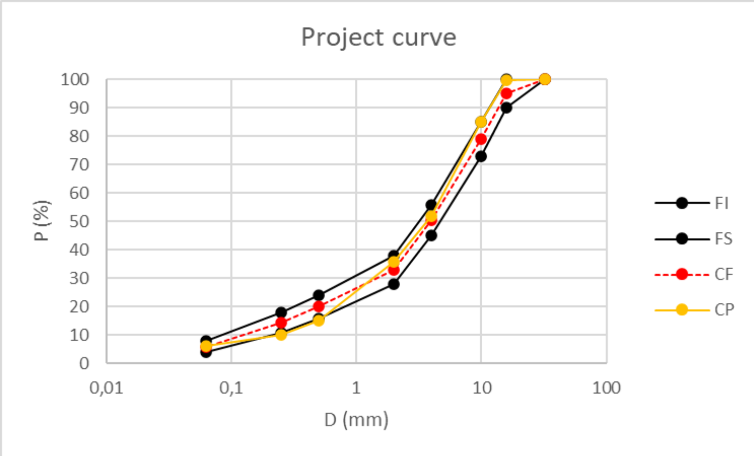

Figure 40:Project curve by the fitting process

4.2.2 Mixture preparation

The mix design of this thesis was produced by following the European standard EN12697-35 and the guidelines given by the research group RILEM. This guideline gives the procedure to prepare an asphalt mixture composed of aggregates, bitumen, filler, and, in this case, an amount of plastic with a variable percentage depending on the mix. This mixture is intended to create cylindrical specimens to be mechanically tested later.

An important parameter that must be defined before the mix is the compaction temperature. The standard provides data on compaction temperature depending on the bitumen penetration grade used, as shown in Table 9.

Paving grade of bitumen	Reference compaction temperature for: °C	
	Mixtures of types other than mastic asphalt	Mastic asphalt mixtures
10/20 to 20/30	180	230
30/45	175	220
35/50	165	210
40/60	155	200
50/70	150	-
70/100	145	-
100/150	140	-
160/220	135	-

Table 9: Reference compaction temperatures for mixtures with pavement grade (The British Standards Institution, 2016) BS EN 12697-35:2016

For the type of bitumen used in this thesis (50/70pen), the reference compaction temperature is 150°C. The standard presents the manner to select the laboratory mixing temperature as “The maximum laboratory mixing temperature reached shall not be more than 20 °C above the reference compaction temperature. The target laboratory mixing temperature shall be selected so that the mixture will have cooled to the reference compaction temperature ± 5 °C when compaction is due to commence but shall not be greater than the maximum laboratory mixing temperature” (The British Standards Institution, 2016) [BS EN 12697-35:2016]. The selected mixing laboratory temperature was 160°C.

The procedure followed is:

a. Preparation of the material: aggregates and filler to be used must be dried until constant mass in an oven at 110±5 °C. Afterward, weigh each aggregate and filler type according to the proportion found in section 4.2.1 Aggregate gradation. For a mix containing 3000g of aggregates, having the objective of making three cylindrical specimens, the proportion and amount of each material are shown in the table below

	0/5	**5/15**	**Filler**
alfa,i	0,52	0,43	0,05
mass [g]	1560	1290	150

Table 10:Proportional amount of each material

Figure 41: Mixed aggregates

Figure 42: Filler

The aggregate is mixed in a single container and put into an oven at the mixing temperature of 160 ± 5 °C. The filler is left at room temperature.

According to the percentage of plastic by weight of aggregates, the amount of plastic to be added is weighted. Specifically, for a mix of 3000g of aggregates, the weight of plastic is shown in Table 11.

Plastic by weight of aggregates [%]	0,00	0,27	1,50	5,00
Weight of plastic [g]	0,0	8,1	45,0	150,0

Table 11: Percentage and quantity of plastic for a mixture of 3000g of aggregates

All the previous quantities are given for an aggregate weight enough for three cylindrical specimens. This thesis aims to do six cylindrical specimens compacted on the same day, so for each percentage of plastic, two blends were prepared, as mentioned before.

b. Preparation of the bitumen: the amount of binder to be used is selected in accordance with section 4.2.3, where the optimal binder content is found. The binder content found for an optimal mix with target air void content between 4 and 6% results in 5,3% of bitumen by weight of aggregates that, in mass, for a mix design of 3000g of aggregates, is equivalent to 159g of bitumen. The bitumen is weighted and put in a metallic container in an oven at the laboratory mixing temperature of 160±5 °C. The bitumen is left in the oven until it reaches the mixing temperature for three to five hours, depending on the amount of binder.
c. All the apparatus and elements used for the mix preparation must be pre-heated at the mixing laboratory temperature of 160±5 °C, including the mixer bowl, the spatula for manual mixing, and the stirring and a steel stirring device to stir the hot binder before mixing.
d. Mixing: once all the materials are reached the mixing temperature, the mix starts. The first step is to put the hot aggregates into the mixer bowl. When plastic is added, is followed the procedure described in section 3.2 for the dry method of asphalt mixture with plastic added. In this case, the second step is adding the shredded plastic at room temperature into the mixer bowl with the hot aggregates and mixing the blend for one minute. If no plastic is to be added, the previous step is omitted. The third step is the addition of the binder by weighing the exact quantity mentioned before and mixing the blend for two minutes. Finally, the filler material is added at room temperature, and the blend is mixed for one minute. The procedure is shown in the above figures (Figure 43, Figure 44, Figure 45, and Figure 46)

Figure 43:Heated aggregates

Figure 44:Addition of plastic to the heated aggregates

Figure 45:Addition of bitumen to the heated aggregates

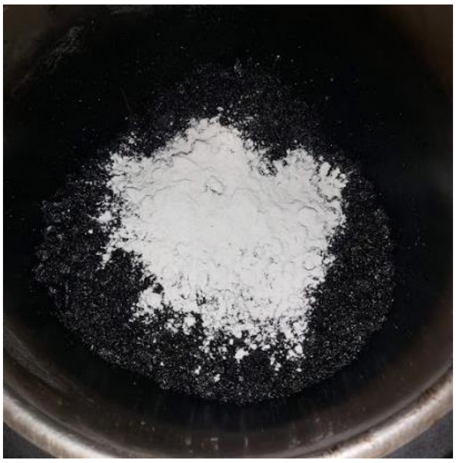

Figure 46:Addition of filler to the bituminous mixture

A picture of when the plastic of type two is added to the mix is shown in Figure 47.

Figure 47:Addition of plastic-type two to the heated aggregates

The mixing process should not exceed a certain temporary lapse given in the standards depending on the type of binder and the mixing method, as shown in Table 12: Maximum laboratory mixing times [BS EN 12697-35:2016].

Mixture type	Binder	Reclaimed asphalt	Mechanical mixing	Hand mixing
Stone mastic asphalt	Paving grade	Not included	4 min	5 min
		Included	5 min	As appropriate
	Modified	Included or not included	5 min	As appropriate
Other than stone mastic asphalt	Paving grade	Not included	3 min	5 min
		Included	5 min	As appropriate
	Modified	Included or not included	5 min	As appropriate

Table 12: Maximum laboratory mixing times (The British Standards Institution, 2016) BS EN 12697-35:2016

4.2.3 Finding the optimal mixture

As specified in Table 7: Aggregate gradation, the binder content must be within 4–6% limits. The mix design aims to obtain cylindrical specimens of 100mm diameter, and 50mm compacted employing a gyratory shear compactor with 100 gyrations, respecting these limits. The target air voids percentage for these cylindrical specimens must be between 4 and 6%.

For this purpose, were produced 5 different mixes by varying the binder content starting with 4,5% of binder by weight of aggregates. All these mixes are produced without adding plastic. The volumetric properties of the mixes are presented in the table below.

	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
B [%]	4,5	5,0	5,6	5,0	5,3
Gmm	2,526	2,521	2,498	2,514	2,512
Gmb	2,379	2,352	2,395	2,342	2,362
Mass [g]	1306,800	911,083	941,750	928,550	903,650
hm [mm]	71,050	50,608	51,350	51,575	49,863
v [%] geom.	7,300	9,081	6,535	8,800	8,144
v [%] real	5,845	6,714	4,122	6,851	5,744

Table 13: Draft mixtures to find the optimal mixture

From the previous table, the optimal percentage of binder by weight of aggregates is 5,3%, where specimens of height 49,8mm are obtained, which is very near to the desired value of 50mm height. These results are influenced by the mass added to the cylindrical molds and the number of gyrations. Further details will be explained in section 4.2.4.

The analyzed mixtures mentioned at the beginning of this chapter were produced with 5,3% of binder by weight of aggregates to obtain specimens of air voids content between 4% and 6%.

4.2.4 Compaction of specimens employing gyratory shear compactor

A gyratory shear compactor is a laboratory machine that allows users to compact soil, emulsion, asphalt, and concrete by the pressure done while the gyratory system is performing.

The technical and commercial page report this information: "An electromechanical system with integrated controls and angle of gyration measurement drives the G2. Users define compaction mode, specimen size, number of gyrations, target height, pressure, and angle of gyrations using the control panel. The G2 compacts material at a constant pressure and angle of gyration. It gyrates at a fixed speed. An integrated extruder conveniently expels specimens from molds. The enclosed compaction chamber keeps the user safe." (PINE test equipment, 2022)

The compaction employing the gyratory shear compactor (GSC) is performed following the European standards regulation BS EN 12697-31:2019.

The procedure followed is:

a. Put the bituminous mixture in an oven to bring it to the reference compaction temperature, which in this case is 150°C. The mixture must not be below 20°C below the compaction temperature and cannot be heated for a very long time because it can cause aging of the mixture. The mix prepared is enough for three cylindrical specimens. An intermediate step to reduce the probability of discrepancies between the specimens due to different aggregate gradation is done by dividing the mix into three containers with approximately a similar size of aggregates, as shown in Figure 48.

Figure 48:Separation of the bituminous mixture into homogeneous portions

b. All the apparatus and elements to be used must be pre-heated at the reference compaction temperature of 150±5 °C for at least two hours, including molds, inserts, funnel, and spatula.
c. Make the assemblage of the mould by putting the inserts and a paper filter at the base of the mould, then fill the mould with the help of a funnel and weigh the exact quantity of asphalt mixture to obtain the desired dimensions of the cylindrical specimen. The mass of mixture to be introduced in the mould as the BS EN 12697-31:2019 stand is: "

$$M = 10^{-3}\pi\frac{D^2}{4}h_{min}\,\rho_m$$

where

M is the mass of a dry mixture to be introduced in the mould, in grams (g);

D is the internal diameter of the mould, in millimeters (mm);

hmin is the minimum height of compacted specimen, corresponding to zero percent of voids, in millimeters (mm);

ρM is the maximum density of the mixture, in Megagrams per cubic metre (Mg/m3).

The ratio of hmin to the internal diameter of the mould D shall be in the interval 0,66 to 1,05." (The British Standards Institution, 2019) [BS EN 12697-31:2019]

With specimens of 100mm diameter, the minimum height introduced in the formula was 66mm.

For the initial mix design, the maximum density was estimated using the aggregate's (in section 4.1.1.3) and bitumen's maximum density (for a bitumen grade 50/70pen is 1,015g/cm3).

$$\rho_m = \frac{1}{\frac{\%B}{\rho_{bit}} + \frac{\%agg}{\rho_{agg}}}$$

The result of this formula is 2,512g/cm3, corresponding to the estimated maximum density of the asphalt mixture. This value is used in the formula of the mass to be introduced in the mould. The resultant mass was 1301g and was the mass used to prepare the first specimen made with the first mix design. For further preparations, after performing the maximum density and bulk density test on the mix design and specimens, the mass to be introduced in the mould was calculated by taking into account the maximum density of the mix and the percentage of air voids as: "

$$M = (1 - v\%)\rho_m \frac{\pi}{4} D^2 h$$

where

v% is the percentage of air voids content

h is the height of desired specimen" (The British Standards Institution, 2019) [BS EN 12697-31:2019], in this case, 50mm.

d. Replace the filled mould into an oven until the compaction temperature is reached again for between 30 minutes and two hours. The mixture's temperature in the mould should not exceed 5°C below the reference compaction temperature.

Figure 49:Oven for heating the moulds and bituminous mixture to specimen compaction

e. Once the mixture into the mould has the reference compaction temperature, put a filter paper and the upper insert, place the mould into the test device (the gyratory shear compactor) and start the test. The compaction should be completed within eight minutes after taking the mould from the oven. The test machine was set to stop after one hundred gyres were obtained.

Figure 50:Gyratory shear compactor machine

f. When the machine stops, the cylindrical specimen is extruded using a jack, as shown in the figure. The upper insert is removed from the top of the specimen. Then, the specimen is stored on a flat metal surface.

Figure 51:Extrusion of a cylindrical specimen from the mould

Below are the final extruded specimens for each type of designed asphalt mixture. For each asphalt mixture were compacted six cylindrical specimens the same day.

Figure 52:Cylindrical compacted specimens, control 0%PE

Figure 53:Cylindrical compacted specimens, 0,27%PE

Figure 54: Cylindrical compacted specimens, 1,5%PE

Figure 55: Cylindrical compacted specimens, 5%PE

With plastic-type two, only one bituminous mixture with 1,5% plastic by weight of aggregates was designed to perform the mechanical tests.

Figure 56: Cylindrical compacted specimens, 1,5% Plastic-type two

g. All cylindrical specimens were measured in diameter and height, as described in the standards BS EN 12697-29:2020. In it is described that the height and diameter should be measured four times to calculate an average dimension.

Figure 57:Measurement of the diameter of cylindrical compacted specimens

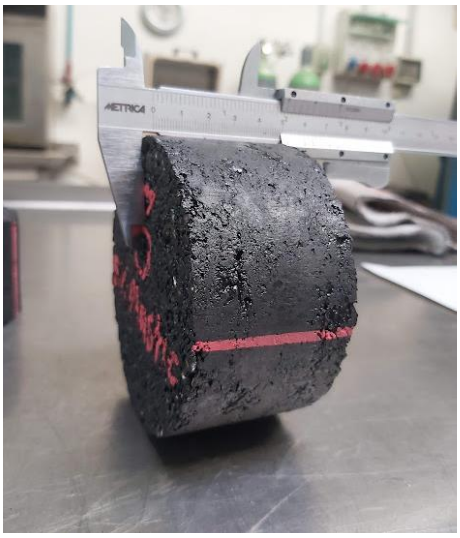

Figure 58: Measurement of the height of cylindrical compacted specimens

4.2.5 Temperature variation for the plastic-type two mix

Some anomalies were noticed during the mixture preparation with plastic-type two, although the previous mixture (plastic-type one PE) was not happening. When the plastic was added to the heated aggregates, some parts of the plastic material became viscous, and some lumps appeared. It started to glue to the mixer bowl walls, and the plastic was not melted uniformly to coat the aggregates.

After finishing the compaction procedure, the dimensions of the specimens were measured. These measurements were repeated the day after. The specimens showed an increment of about 1.5mm, and by performing the volumetric properties tests, high values of the percentage of air voids were obtained.

Due to the unexpected results mentioned, two trials were developed to understand and compare this behavior by making a mixture only for the compaction of one specimen (1000g of aggregates). One mixture was performed at the same laboratory mixing temperature as the first set of specimens (160°C), and the second mixture was produced with an increment of laboratory mixing temperature of 10°C.

Figure 59 shows the heated aggregates with the addition of plastic at 160°C, and is observed a similar behavior mentioned before for the first set of specimens mixed at the same temperature. In this case, the increment of height after one day of compaction was 0,5mm, and the percentage of air voids decreased from the previous one.

Figure 59:Trial mixture 1 at 160°C

Height the same day of compaction [mm]	51
Height after one day of compaction [mm]	51,5
Maximum density [kg/m^3]	2489
Bulk density [kg/m^3]	2327
Air voids content [%]	6,5

Table 14: Volumetric properties for trial mixture 1 at 160°C

Figure 60 presents the mixture preparation at 170°C, where the plastic was already introduced into the hot aggregates, and in this case, plastic melts more rapidly than in the previously prepared mixtures at lower temperatures leading to a better coating of the aggregates. The increment in height after one day of compaction was reduced significantly to only 0,05mm, leading to a very low percentage of air voids.

Figure 60:Trial mixture 2 at 170°C

Height the same day of compaction [mm]	57,6
Height after one day of compaction [mm]	57,65
Maximum density [kg/m^3]	2470
Bulk density [kg/m^3]	2388
Air voids content [%]	3,34

Table 15: Volumetric properties for trial mixture 1 at 170°C

After doing these trials, were created two other mixtures with the same percentage of plastic (1.5%) and at the same initial temperature (160°C). After this process, three different mixes with 1.5% plastic by weight of aggregates were done with plastic-type two. Then, there were compacted six cylindrical specimens for each one of them. That is performed to compare the differences in dimensions of the specimens immediately after compaction and the day after. In this way is found an equivalent increment in air voids content due to these increments.

The second mixture was designed under the same conditions as the first one, only for repeatability and comparison. For the third mixture, the plastic was added in small doses, each type of plastic separately, and mixed fastly. The stepping of the addition of plastic is shown below.

Figure 61: First plastic addition

Figure 62: Second plastic addition

Figure 63: Third plastic addition

The mechanical tests were only performed in the first mixture's six cylindrical specimens.

4.3 Evaluation of volumetric properties of the mixture

4.3.1 Theoretical maximum density

“The maximum density, together with the bulk density, is used to calculate the air voids content of a compacted sample and other volumetric-related properties of a compacted bituminous mixture. In the volumetric and hydrostatic procedures, the maximum density of bituminous mixture is determined from the volume of the sample without voids and from its dry mass." (The British Standards Institution, 2018) [BS EN 12697-5-2018]

The simple definition given by the same authors is: "mass per unit volume without air voids of the bituminous mixture" (The British Standards Institution, 2018) [BS EN 12697-5-2018]

The theoretical maximum density of the mix design is obtained with the volumetric method using the pycnometers as mentioned in section 4.1.1.3 following the standard BS EN 12697-5:2018. The process follows the steps:

a. Before starting this test, the bituminous mixture test portion should be prepared following the standards BS EN 12697-28:2020. If the sample is cold and presents difficulties to mix manually, the bituminous mixture should be heated in an oven until it is sufficiently soft to handily mix but should not be heated for more than 4 hours to minimize the loss of volatile constituents of the binder. The temperature at which the asphalt mixture is heated must be selected as given by the standards:

Nominal grade of binder in sample	Maximum temperature of oven °C
> 330 penetration at 25 °C	105
Above 60 up to 330 penetration at 25 °C	120
25 to 60 penetration at 25 °C	135
Less than 25 penetration at 25 °C	150

Table 16: Temperatures of the oven for reheating laboratory samples prior to sample reduction (The British Standards Institution, 2020) [BS EN 12697-28:2020]

Since it was used 50/70pen grade bitumen, the selected temperature was 135°C.

b. Place the material on a clean metallic surface and separate the material into particles and agglomeration lower than 6mm to obtain a loose material.
c. The sample is reduced to an adequate test portion by performing a quartering process mentioned in the standards BS EN 12697-28:2020: "mix the material thoroughly by heaping it into a cone and turning it over to form a new cone three times […] Flatten the third cone formed from the mixed sample […] Quarter the heap along two diameters that intersect at right angles. Combine one pair of diagonally opposite quarters and discard the remainder." (The British Standards Institution, 2020). This process is repeated until the desired sample size is obtained. The adequate sample size to be tested following the standards is:

Type of material	Maximum aggregate size, mm	Mass of test portion for each determination	
		Minimum (normative) g	Maximum (informative) g
Bituminous mixture	> 31,5	3 000	5 000
	> 22,4 ≤ 31,5	2 400	3 000
	> 16 ≤ 22,4	1 500	2 500
	> 10 ≤ 16	1 000	2 000
	> 6,3 ≤ 10	800	1 400
	> 4 ≤ 6,3	650	1 000
	≤ 4	450	600
Coated chippings	All sizes	2 000	3 000
NOTE Maximum masses are given for guidance only.			

Table 17: Mass of material for each determination (The British Standards Institution, 2020) BS EN 12697-28:2020

The procedure shown in section 4.1.1.3 Theoretical maximum density is followed, having the desired test portion. A summary of this test can be observed in the figures below.

Figure 64: Weight of empty pycnometer

Figure 65:Reduction of the bituminous mixture to be tested

Figure 66:Weight of pycnometer and sample

Figure 67:Vacuum application to the sample with water

Figure 68:Weight of pycnometer with water and sample

Figure 69:Test water temperature

4.3.2 Bulk density of the compacted specimen

Bulk density is a property that is derived from the mass and the total volume of a material. The standard stand that this property is the "mass per unit volume, including the air voids, of a specimen at known test temperature" (The British Standards Institution, 2020) [BS EN 12697-6:2020]

The bulk density of the mixture is obtained through the bulk density test following procedure B: Bulk density saturated surface dry (SSD) described in section 9.3 of the regulated standards BS EN 12697-6:2020. This test is performed in a compacted bituminous cylindrical specimen obtained as in section 4.2.4 and consists of finding the specimen's density, taking into account the air voids in them from their mass and volume. The procedure followed was

a. Weigh the dry specimen (in the air) and record the mass as ‘m_1’.
b. Place the specimen in a water bath for at least 30 minutes to allow the specimen saturates all the voids and the mass not to change.
c. Weigh the saturated specimen inside the water bath, ensuring no air bubbles adhere to the surface of the specimen, and record this mass as ‘m_2’.

Figure 70:Weight of saturated specimen in water

d. Take out from the water bath the specimen, and by using a damp chamois, dry the surface of the specimen from adhered water drops. That is how the condition of ‘saturated surface dry (SSD)’ is obtained.

Figure 71:Drying of the surface specimen

Figure 72:Drying of the surface specimen

e. Weigh the specimen in the air immediately after drying mentioned in the previous step, and record this mass as 'm_3'.

Figure 73:Weight of saturated surface dry specimen

f. Measure the water temperature to calculate water density at the test temperature further.

The bulk density of the specimen is computed, following the standard: "

$$\rho_{bssd} = \frac{m1}{m3 - m2} \times \rho_w$$

where

ρ_{bssd} is the bulk density (SSD), in megagram per cubic meter (Mg/m3);

m_1 is the mass of the dry specimen, in gram (g);

m_2 is the mass of the specimen in water, in gram (g);

m_3 is the mass of the saturated surface-dried specimen, in gram (g);

ρ_w is the density of the water at test temperature, in megagram per cubic meter (Mg/m3) computed as:

$$\rho_w = 1{,}00025205 + \left(\frac{7{,}59 \times t - 5{,}32 \times t^2}{10^6}\right)$$

Where t is the temperature of the water, in degrees Celsius (°C).” (The British Standards Institution, 2018) [BS EN 12697-6:2020.]

4.3.3 Air voids content

Air void content in a bituminous mixture is the total percentage of air spaces between the different components of the mixture regarding the total apparent volume. The standard assumes this property as the “volume of the air voids in a bituminous specimen, expressed as a percentage of the total volume of that specimen” (The British Standards Institution, 2018) [BS EN 12697-8:2018]

The air voids content is calculated for a compacted cylindrical specimen based on the maximum density of the asphalt mixture and its bulk density. To compute this result is followed the standard BS EN 12697-8:2018 that gives: “

$$V_a = \frac{\rho_m - \rho_b}{\rho_m} \cdot 100$$

where

V_a is the air voids content of the bituminous specimen, in 0,1 percent (by volume);

ρ_m is the maximum density of the mixture, in megagrams per cubic meter (Mg/m3);

ρ_b is the bulk density of the specimen, in megagrams per cubic meter (Mg/m3).” (The British Standards Institution, 2018) [BS EN 12697-8:2018]

4.4 Mechanical tests

4.4.1 Indirect tensile stiffness modulus (ITSM)

The stiffness is the property denoting the pavement's deformation due to a load. Precisely, the stiffness modulus is the “relationship between maximum applied stress and maximum measured strain response” (The British Standards Institution, 2018) BS EN 12697-26:2018

To obtain the stiffness modulus of a bituminous mixture is followed the standard BS EN 12697-26:2018. In this case, will be computed the indirect tensile stiffness modulus (ITSM) that is described in Annex C ‘Test applying indirect tension to cylindrical specimens (IT-CY)’ of the standard, as will be explained next.

Annex C of the standards describes the indirect tensile test that should be performed to obtain the ITSM for the cylindrical specimens obtained from the mixing and compaction process previously mentioned and is based on the calculation of this parameter through the stress and strain measured during a pulse load. The execution of this test is performed with the 30kN servo-hydraulic universal testing machine UTM-30 (exposed in Figure 74: 30kN servo-hydraulic universal testing machine (UTM-30)).

Figure 74: 30kN servo-hydraulic universal testing machine (UTM-30)[1]

[1] Image taken from the road materials laboratory of Politecnico di Torino at https://www.diati.polito.it/en/about/laboratories/road_materials

The procedure to be followed is:

a. Compaction of cylindrical specimens as described in section 4.2.4. The standards require specific dimensions of the specimens as follows:

Maximum grain size mm	**Specimen diameter** mm	**Specimen height** mm
≤ 16	100 ± 3 150 ± 3	40 to 60 ± 2
> 16 to < 32	150 ± 3	60 ± 2
≥ 32	150 ± 3	90 ± 2

Table 18: Specimen dimensions (The British Standards Institution, 2018)

Each specimen's dimensions were measured and satisfied the requirements for a maximum grain size lower than 16mm with a specimen diameter of 100mm and a specimen height of about 50mm. In each sample were marked two orthogonal diameter lines to guide further tests.

b. Conditioning of specimens at the selected test temperature, in this case, 25°C for at least 4 hours.
c. Then, the specimen is mounted between the lower and upper loading strips, having the specimen evenly centered. This configuration is loaded into the UTM-30 machine, and the transducers are plugged in to measure the specimen's strain deformations. This configuration is shown in Figure 75.

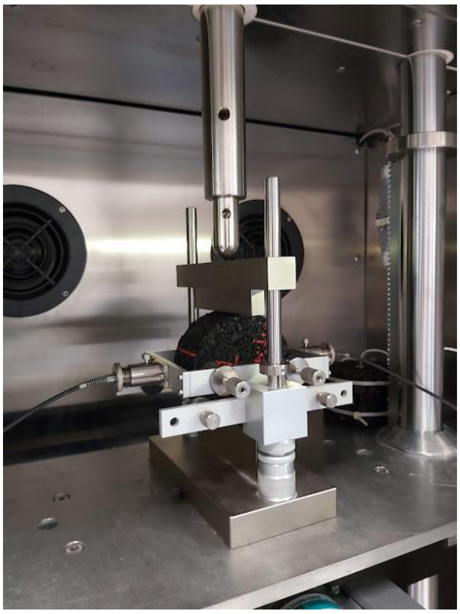

Figure 75:Configuration for the indirect tensile stiffness modulus test

d. Now, is applied the pulse loading. First are applied ten cycles of pulse loading only for the machine's conditioning to reach the desired load and deformation. Then, five cycles of pulse loading are applied, for which the corresponding load and deformation must be recorded. The last results are used to compute the stiffness modulus. The standards say that “The loading-time, measured from the start of the load pulse until it reaches the maximum value shall be in the range of 50 to 125 ms with an accuracy of ± 5 ms. […] The applied load shall be measured, using a load cell with capacity of 10 kN and an accuracy of 2 %. The pulse repetition period (see Figure C.2) shall be (3,0 ± 0,1) s.” (The British Standards Institution, 2018) [BS EN 12697-26:2018] For this thesis, the selected parameters were: loading time 124ms, pulse repetition period of 3000ms, and target horizontal deformation of 5µm.S

e. After the test’s conclusion, the upper strip is removed, and the cylindrical sample is rotated 90° to repeat the test along the other diameter. The final ITSM value is obtained as the average value between these two diameters.

The stiffness modulus of the bituminous mixture is then calculated by the formula presented in the standards: “

$$E = \frac{F \cdot (v + 0{,}27)}{(z \cdot h)}$$

where

z is the amplitude of the resilient horizontal deformation obtained during the load cycle, expressed in millimeters (mm);

v the Poisson’s ratio;

F the loading force, in newtons (N);

h the mean thickness of the specimen, in millimeters (mm)” (The British Standards Institution, 2018) [BS EN 12697-26:2018]

4.4.2 Indirect tensile strength (ITS)

The indirect tensile strength is referred to the strength of a material against a perpendicular external force. “Maximum tensile stress calculated from the peak load applied to a cylindrical specimen loaded diametrically until break at specified test conditions” (The British Standards Institution, 2017) [BS EN 12697-23:2017]

The indirect tensile strength property calculation is performed in the indirect tensile test following the standard BS EN 12597-23:2017. This test will be done for a total of six samples for each type of mixture, three in a wet conditioning state and the other in a dry state. The process will be described in the following section.

The sample preparation begins as the 4.2.4 Compaction of specimens employing gyratory shear compactor indicates for cylindrical specimen with height near to 50mm and diameter of 100mm. The dimensions measure was taken according to the BS EN 12697-29:2020 standard.

The conditioning process that will be considered is Storage, in which the regulation stands that the specimen, which in this case has a diameter of 100mm, should be stored in the water bath or air chamber for at least 2 hours. In this case, the air chamber was used to condition the samples. The chosen test temperature was 25°C. The specimen's behavior in the cracking process is compressive for higher temperatures, so it should be avoided.

Now will be described the test procedure:

a. The first step is placing a conditioned specimen in the testing head.
b. Then it is necessary to align the sample to the lower ribbon in a diametrical way (as shown in the figure below).

Figure 76:Configuration to the indirect tensile strength test

c. Begin the specimen's compression process, which will continuously apply a load. The deformation speed should be 50 ± 2 mm/minutes, and continue the test until the specimen reaches the peak load when the failure is evident or breaks. The test must be performed in less than two minutes since the conditioned specimen is taken.

Figure 77:Failure of the specimen during ITS test

d. Now it is necessary to open the broken specimen to inspect the surface aspect to find the aggregate's state.

The calculation of the ITS property is derived from the following formula: "

$$ITS = \frac{2P}{\pi\, D\, H} \cdot 1000 \qquad [kPa]$$

where

P is the peak load [N]

D is the diameter of the specimen [mm]

H is the height of the specimen [mm]" (The British Standards Institution, 2017) BS EN 12597-23:2017

4.4.3 Determination of the water sensitivity (ITSR)

ITSR refers to the ratio of results of an indirect tensile strength test performed in a cylindrical compacted specimen in dry conditions and another subjected to a water conditioning process. The description of this chapter is based on the standards chapter 5 method A of the BS EN 12697-12:2018.

To calculate the result, six cylindrical specimens are compacted on the same day, as described in section 5.4. This sample must be separated into two subsets of similar average properties (referring to air voids content, height, and bulk density) to test three cylindrical specimens in dry conditions and three cylindrical specimens subjected to wet conditioning and obtain comparable results. The standards say, "The difference of the average heights shall not exceed

5 mm. The difference of the average bulk densities shall not exceed 0,015 Mg/m3" (The British Standards Institution, 2018) [BS EN 12697-12:2018]

4.4.3.1 Conditioning of specimens

4.4.3.1.1 Dry specimens

The cylindrical specimens shall be on a controlled ambient dry air temperature at 20 ± 5°C on a flat surface.

4.4.3.1.2 Wet specimens

The specimen is introduced in a container filled with water at ambient temperature (20°), with the water level above the specimen about 20mm.

Figure 78:Container with specimen and water for the conditioning process

The container is filled with water. The cylindrical specimen is connected to a vacuum system that progressively (within 10min) reduces the pressure until having a 6,7 ± 0,3 kPa. It is maintained for 30 minutes.

Figure 79:Vacuum system to the water conditioning process

After the 30 minutes, the pressure must be decreased progressively (also within 10 minutes) until it reaches the atmospheric pressure again, and the specimen is maintained submerged in water for 30 minutes.

Figure 80:Cylindrical specimen in water

The specimen is removed from the water bath, and its dimensions are re-measured, following the standards BS EN 12697-29 mentioned in section 5.4, to check if any specimen shows an increase of volume higher than 2%.

Figure 81: Dimensions measurement to control the possible increase in volume

Finally, the specimens are placed in a controlled temperature water bath at 40 ± 2 °C for 72 hours.

Figure 82:Water conditioning at 40°C for 72 hours

4.4.3.2 Test procedure

After the conditioning process, the samples are removed from their ambient. After 30 minutes, the measurements are retaken to record if any increment in volume occurs. After that, the wet subset is stored in a water chamber and the dry subset in an air chamber, both at the test temperature selected of 25°C for at least four hours. After this period, the indirect tensile strength test can be performed, as mentioned in section 4.4.2, to find the ITS value for dry and wet subsets.

The ITSR, as given by the standard BS EN 12697-12, is: “

$$ITSR = 100 \times \frac{ITS_w}{ITS_d}$$

where

ITSR is the indirect tensile strength ratio, in percent (%);

ITS_w is the average indirect tensile strength of the wet group, in kilopascals (kPa);

ITS_d is the average indirect tensile strength of the dry group, in kilopascals (kPa)." (The British Standards Institution, 2018) [BS EN 12697-12:2018]

5 Results

This chapter presents the average results of each mixture obtained by applying the volumetric and mechanical tests to each cylindrical specimen belonging to the mixture. These results are exposed separately for the effect of adding plastic-type one and plastic-type two, comparing each with the results obtained for the control mixture without plastic, which are also shown in each section.

Table 19 presents the proportional amount of each component of the mix with respect to a hundred grams of aggregates and, in addition, is expressed the percentage of plastic by weight of bitumen as can be found in other documented specifications on this topic.

The mixture without plastic was the first mix design prepared to verify the required specifications of height and air voids content of 50mm and 4-6%, respectively. As the obtained results were satisfactory, the subsequent mixtures were designed with the same percentage of bitumen by weight of aggregates (5,3%) as the previous one.

	AC 16 Control	**AC 16 0.27%PE**	**AC 16 1.5%PE**	**AC 16 5.0%PE**
weight of aggregates [g]	100	100	100	100
Bitumen dosage by weight of aggregates [%]	5,3	5,3	5,3	5,3
mass of bitumen [g]	5,3	5,3	5,3	5,3
PE dosage by weight of aggregates [%]	0,00	0,27	1,50	5,00
PE dosage by weight of bitumen [%]	0,00	5,09	28,30	94,34
weight of plastic [g]	0,00	0,27	1,50	5,00
wight of the total mix [g]	105,30	105,57	106,80	110,30

Table 19:Design mixture components

The quantities in the previous table are expressed when using plastic-type one, but the same percentage of the components are used for the mixture preparation with plastic-type two as shown for AC 16 1.5%PE.

5.1 Effects on plastic-type one addition

As mentioned previously, were designed four bituminous mixtures which one of them was made without the use of plastic to control and comparative purposes. The other three mixes were made with 0.27%, 1.5%, and 5.0% of plastic PE by weight of aggregates. Below are shown the results for these four mixes for the volumetric properties and mechanical tests.

A picture after compaction of the specimen containing 5%PE is shown below. It is observed that during compaction, the plastic tended to go to the cylinder edges, and when the extrusion was made, some pieces of plastic were visible outside the surface of the cylinder, generating some plastic ridges.

Figure 83: Extruded specimen, mixture with 5%PE

The excessive addition of plastic into the bituminous mixture shows a non-total melt of the plastic, leading to phase separation and not a good covering of aggregates by the plastic film.

Below are shown the results obtained by the compaction of cylindrical specimens employing the gyratory shear compactor as explained in section 4.2.4 with an applied pressure of 600kPa and angle of gyration of 1,25° where six specimens of diameter 100mm were compacted for the four asphalts mixtures.

CONTROL					
Sample	**Gmb [kg/m^3]**	**Gmm [kg/m^3]**	**Air Voids [%]**	**#Gyrations**	**CDI**
AC 16 Control 1	2372	2512,0	5,6%	100	122,94
AC 16 Control 2	2371	2512,0	5,6%	100	155,60
AC 16 Control 3	2334	2512,0	7,1%	100	313,39
AC 16 Control 4	2383	2512,0	5,1%	100	99,60
AC 16 Control 5	2351	2512,0	6,4%	100	189,03
AC 16 Control 6	2362	2512,0	6,0%	100	162,73
AC 16 Control (average)	2362	2512,0	6,0%	100	173,88
Standard deviation	16,0		0,6%	0,0	68,63

Table 20:Volumetric properties from GSC results, Control mixture (0%PE)

0,27% PE					
Sample	**Gmb [kg/m^3]**	**Gmm [kg/m^3]**	**Air Voids [%]**	**#Gyrations**	**CDI**
AC 16 0.27%PE 1	2343	2510,0	6,6%	100	256,85
AC 16 0.27%PE 2	2365	2510,0	5,8%	100	129,28
AC 16 0.27%PE 3	2344	2510,0	6,6%	64	113,58
AC 16 0.27%PE 4	2387	2510,0	4,9%	143	185,36
AC 16 0.27%PE 5	2386	2510,0	5,0%	100	113,08
AC 16 0.27%PE 6	2361	2510,0	5,9%	100	113,08
AC 16 0.27%PE (average)	2364,3	2510,0	5,8%	101,2	151,87
Standard deviation	17,4		0,7%	22,9	53,43

Table 21: Volumetric properties from GSC results, mixture 0,27%PE

1,5% PE					
Sample	**Gmb [kg/m^3]**	**Gmm [kg/m^3]**	**Air Voids [%]**	**#Gyrations**	**CDI**
AC 16 1.5%PE 1	2335	2450,0	4,7%	100	67,96
AC 16 1.5%PE 2	2316	2450,0	5,5%	164	237,82
AC 16 1.5%PE 3	2309	2450,0	5,8%	100	155,06
AC 16 1.5%PE 4	2346	2450,0	4,3%	100	64,50
AC 16 1.5%PE 5	2347	2450,0	4,2%	100	63,47
AC 16 1.5%PE 6	2354	2450,0	3,9%	100	60,91
AC 16 1.5%PE (average)	2334,4	2450,0	4,7%	110,7	108,29
Standard deviation	16,7		0,7%	23,9	66,79

Table 22: Volumetric properties from GSC results, mixture 1,5%PE

5% PE					
Sample	**Gmb [kg/m³]**	**Gmm [kg/m³]**	**Air Voids [%]**	**#Gyrations**	**CDI**
AC 16 5%PE 1	2285	2346,0	2,6%	100	7,85
AC 16 5%PE 2	2293	2346,0	2,2%	100	10,21
AC 16 5%PE 3	2284	2346,0	2,6%	100	10,14
AC 16 5%PE 4	2293	2346,0	2,3%	100	8,29
AC 16 5%PE 5	2263	2346,0	3,5%	100	5,65
AC 16 5%PE 6	2273	2346,0	3,1%	100	3,31
AC 16 5%PE (average)	2282	2346,0	2,7%	100	7,58
Standard deviation	10,7		0,5%	0,0	2,45

Table 23: Volumetric properties from GSC results, mixture 5%PE

In each table were presented the average bulk density (Gmb), maximum density (Gmm), percentage of air voids, the construction densification index (CDI), and the corresponding standard deviation.

As described by the International Journal of Pavement Research and Technology, "Considering the Construction Densification Index CDI, (the area that is under the densification curve ranges from density at eight gyrations to a density of 92 % of the theoretical maximum specific gravity), that stands for work validation through the period of construction to achieve the percentage of air void of about 8 %" (Fattah, Hilal, & Flyeh, 2019) the CDI value was obtained for each mixture. The graphical representation of this definition only for the CDI value of the mixture without plastic (AC 16 control) is shown in Figure 84.

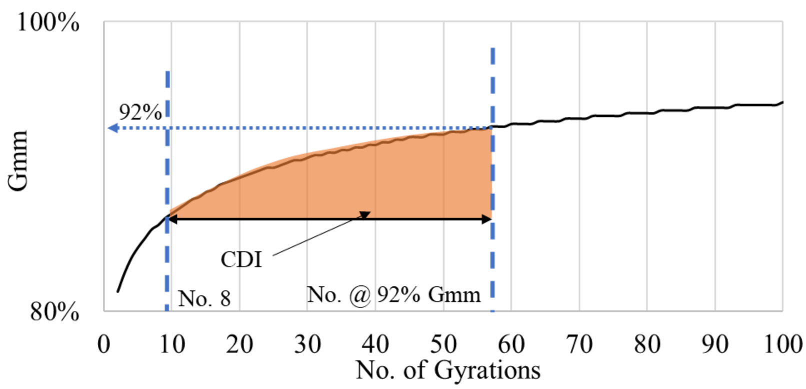

Figure 84:Control mixture, graphical representation of CDI value

Figure 85 shows the average CDI value for all the mixtures and exposes a decrement of the CDI as the percentage of plastic PE increases. This value represents a mixture's compactibility regarding volumetric properties and the energy required for compaction in field applications. Hence, a considerable value of CDI means that the mixture needs higher energy to densify and obtain the desired volumetric properties, leading to longer times and higher costs during the construction phase of these pavements with asphalt mixture with high CDI. These results show acceptable behavior when adding plastic PE to the asphalt mixture. It is important to also consider the consequent phase after construction when the traffic load comes into play and the densification of the pavement is not desired in a higher percentage.

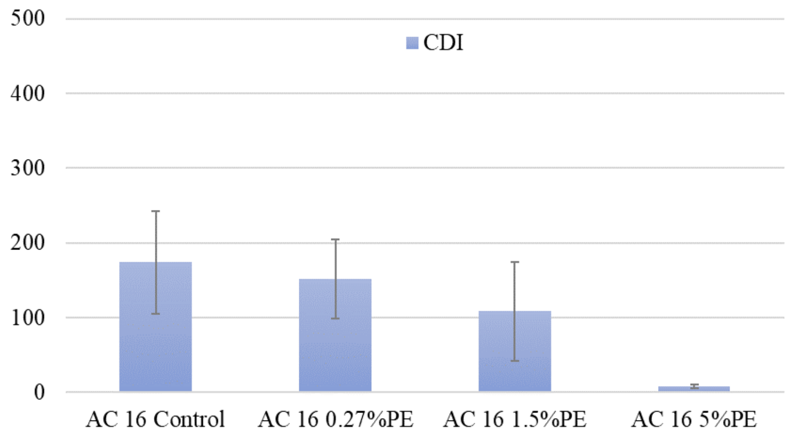

Figure 85:Construction densification index (CDI) results

Results shown in Table 24 are obtained by applying the standard test described in chapter 4.3. The maximum density exhibits a decrement behavior as the percentage of plastic increases, directly affecting the percentage of air voids content, leading to a progressively decrement. As well known, the air voids content in an asphalt mixture must be well controlled because large or too low values of it are the principal generator of distresses and degradation of the pavements. The void percentage decrement is favorable only if it is not excessive. Therefore, it is possible to affirm that a mix having until 1.5% PE plastic having 4.7% voids is acceptable. That means that the results of the mix with 5% of PE plastic show a very low percentage of voids (2.7%) that is excessive and could contribute to the impairment of the pavement characteristic because there enter into consideration another type of distresses.

	AC 16 Control	**AC 16 0.27%PE**	**AC 16 1.5%PE**	**AC 16 5.0%PE**
Maximum density [g/cm^3]	2512	2510	2450	2346
Avg. bulk density [g/cm^3]	2362	2364	2334	2282
Avg. air voids content [%]	6,0	5,8	4,7	2,7

Table 24:Volumetric properties of the mixtures by volumetric tests

The percentage of air voids and the maximum density in bituminous mixtures show a significant reduction when plastic-type one (PE) was added to the mix. Compared with the mixture without the addition of plastic, the decrement in air voids content shown by the mixture with 0.27% PE, 1.5% PE, and 5% PE were 3.33%, 21.67%, and 55.00%, respectively. The reduction in air voids content is favorable because it can help reduce bitumen content used in a bituminous mixture contributing to environmental issues (climate change) and diminution of considerable distresses generated in asphalt pavement due to high values of air voids thanks to the better compactibility and increasing resistance. On the other hand, a reduction of 55% in air voids content corresponding to a value of 2,7% of air voids for a mixture with 5% PE is an excessive reduction for this value, not acceptable in much literature because it leads to another type of distresses as rutting.

The result obtained in this section is remarkably concordant with the previous investigation presented in section 3.2. The state that manifests that the optimal solution is around 8% plastic by bitumen weight (approximately 0.43% by the aggregates weight) is ideal, even if the 28.3% (1.5% by the aggregates weight) is still acceptable according to the previously presented results.

The results obtained by applying the Indirect Tensile Stiffness Modulus (ITSM) test, as described in section 7.1, are shown below. The stiffness modulus for dry and wet subsets is presented for all four mixtures.

	AC 16 Control	**AC 16 0.27%PE**	**AC 16 1.5%PE**	**AC 16 5.0%PE**
ITSM dry [MPa]	3485	4678	5613	5549
ITSM wet [MPa]	3498	4027	4495	5871

Table 25:Dynamic stiffness modulus results

An evident increase in the stiffness modulus can be observed by the increment in the addition of plastic PE for both dry and wet subsets. That is a meaningful result from which it is possible to say that for this specific type of plastic PE an increment of properties related to stiffness is obtained.

By comparing the stiffness modulus obtained for a dry and wet subset on the same mixture, it is observed that there is not a significant change for the control mixture (0%PE). On the other hand, the mixtures with 0.27% and 1.5%PE exhibit a significant decrement in the stiffness modulus, making evident their reduction in properties related to the stiffness of the mixture when subjected to a conditioning process in water. On the contrary, the mixture with 5%PE shows an increase in the stiffness modulus when subjected to water conditioning.

A linear relationship was assumed between ITSM and air voids. In this manner, the results shown before were estimated at the average air voids content shown in Table 24 by means of the slope and intercept of the lines in the graphs below.

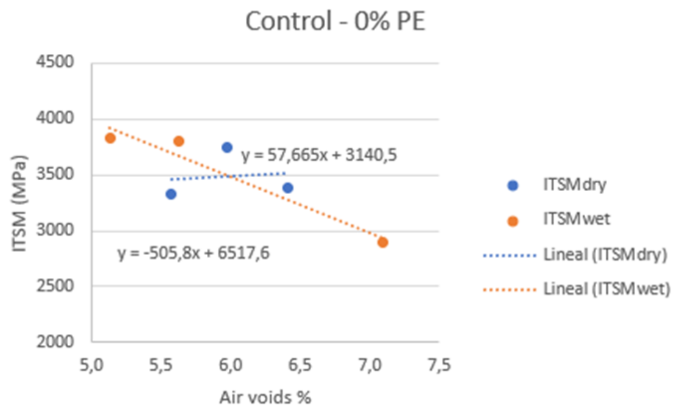

Figure 86: ITSM result 0% PE

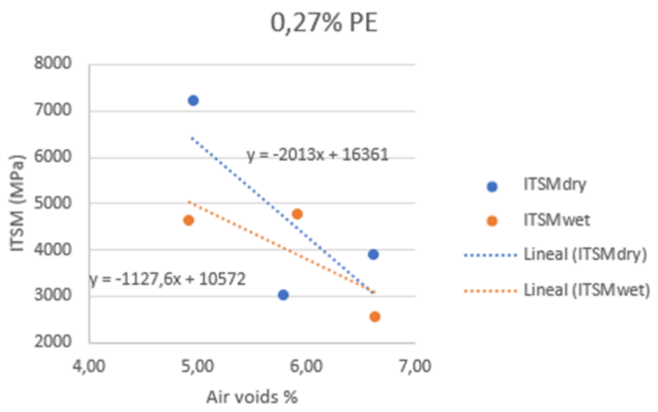

Figure 87: ITSM result 0,27% PE

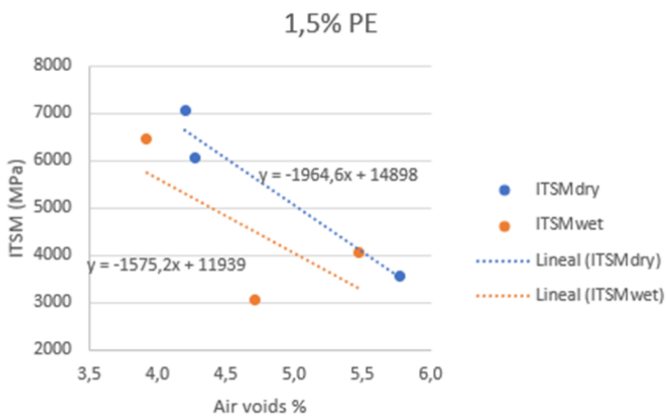

Figure 88: ITSM result 1,5% PE

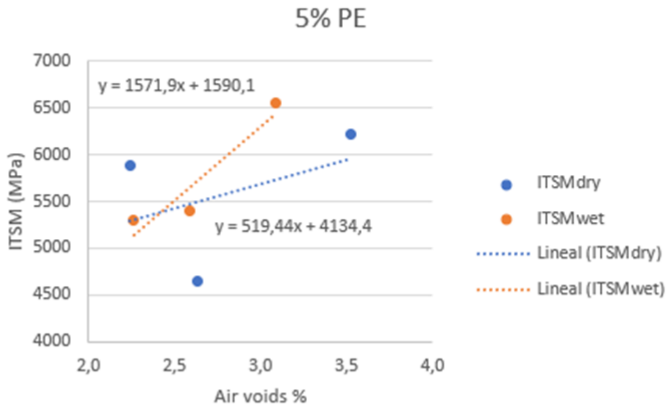

Figure 89: ITSM result 5% PE

The linear relationship graphs regarding the control mix (0%PE), 0.27%PE, and 1.5%PE show a negative trend of the ITSM value when the percentage of air voids increases for both wet and dry subsets. The behavior of the mixture with 5%PE, regarding the air voids content, also exhibits a contrary behavior to the previous mixtures, with a positive trend of the ITSM value with the increase of air voids content.

The stiffness modulus of the mixtures computed from the indirect tensile stiffness modulus test (ITSM) on mixtures with plastic-type one shows an increment as the percentage of added plastic increases. These results are related to the decrement in air voids content mentioned before, leading to stiffer mixtures where the compaction reaches better results; the aggregates fill as much of the voids of the cylindrical specimens resulting in higher resistance. It is a good result regarding the stress-strain response of a pavement subjected to the traffic load. An increment of 61% of ITSM was found when adding 1.5% PE, but for higher quantities of plastic (5% PE), the ITSM value started to reduce.

The following paragraph will describe the results obtained from applying the standards described in sections 4.4.2 and 4.4.3. Table 26 shows the average indirect tensile strength for dry and wet subsets and their corresponding indirect tensile strength ratio for all four bituminous mixtures.

	AC 16 Control	AC 16 0.27%PE	AC 16 1.5%PE	AC 16 5.0%PE
ITS dry [kPa]	1030	1118	1446	1887
ITS wet [kPa]	1070	1148	1419	1724
ITSR	103,9	102,7	98,1	91,4

Table 26: ITS results for dry and wet subsets and ITSR value

The previous results are obtained from the dimensions of each cylindrical compacted specimen and the peak load obtained during testing. The results show that the ITS value increases with the increment in the percentage of plastic PE. The mixture with no plastic and 0.27%PE present an increment in the ITS of wet conditioning specimens compared to the dry specimens; instead, for the mixtures with 1.5%PE and 5%PE, the ITS value for wet conditioning specimens is lower with respect to the dry specimens. On the other hand, the ITSR always shows an increment when the percentage of plastic increases.

The following graph will present the curves of axial force applied versus the measured deformation at each time for all the six cylindrical specimens of all the bituminous mixtures. The results of the dry and wet subsets are reported in different graphs.

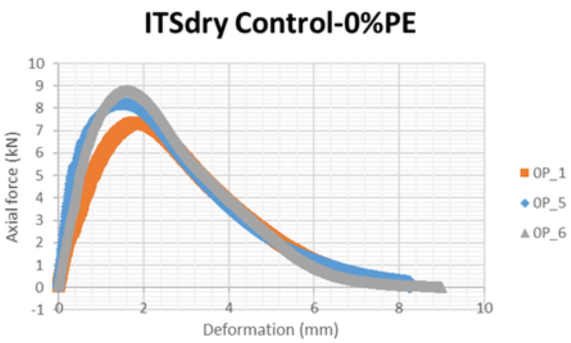

Figure 90: ITS dry AC 16 Control

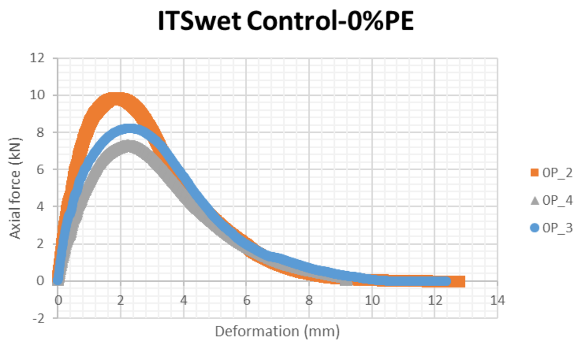

Figure 91: ITS wet AC 16 control

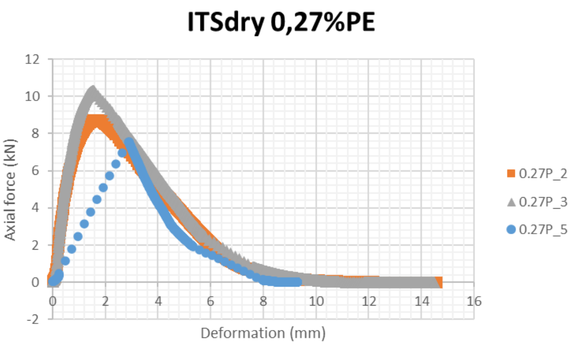

Figure 92: ITS dry 0,27%PE

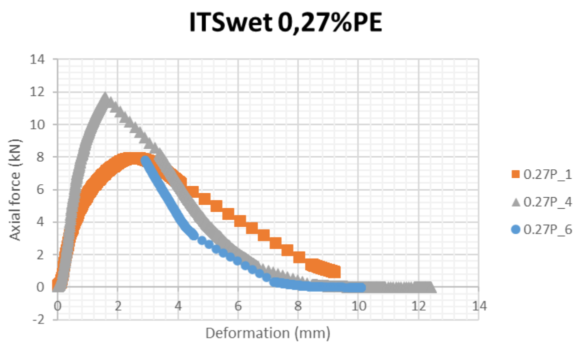

Figure 93: ITS wet 0,27%PE

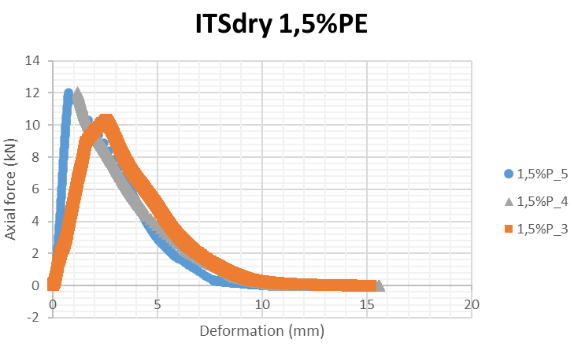

Figure 94: ITS dry 1,5%PE

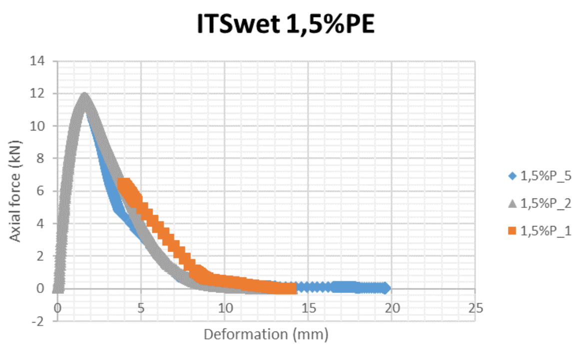

Figure 95: ITS wet 1,5%PE

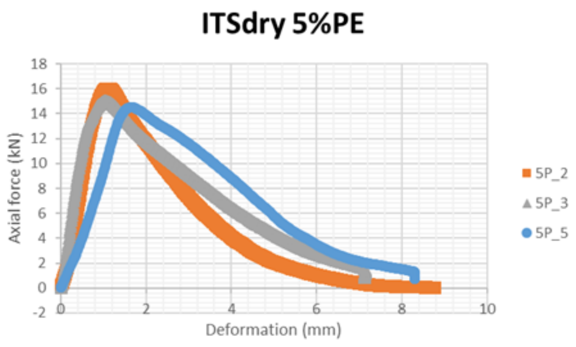

Figure 96: ITS dry 5%PE

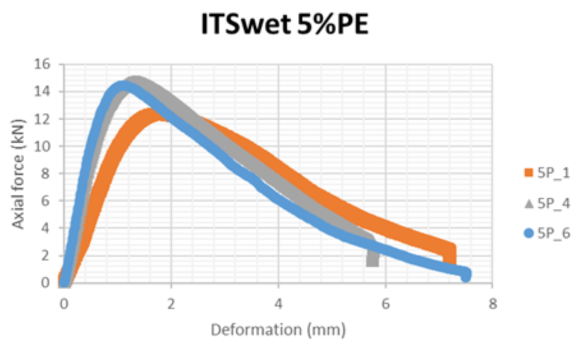

Figure 97: ITS wet 5%PE

From the indirect tensile strength results (ITS) of mixtures with plastic-type one, a behavior with a positive trend is obtained when adding plastic. This result means that adding plastic to a bituminous mixture increases the resistance to deformation of the pavement under stress application, so a cylindrical specimen containing more plastic need of higher load to break. From this test, the adherence between aggregates and bitumen can also be seen where the plastic plays a role in improving this characteristic when melted and covering the aggregates uniformly. The highest increment with respect to the mixture without plastic was about 83% for the bituminous mixture with 5% PE.

The indirect tensile strength ratio (ITSR) gives sensitivity to the water of each mixture. The higher ITSR, the higher the moisture resistance. ITSR is regulated at around 80% minimum, depending on the country. The increasing addition of plastic-type one PE leads to lower values of ITSR, indicating that the higher the percentage of plastic, the lower the moisture resistance leading to distresses as stripping where the adhesion of aggregates-bitumen is weakened due to penetration of moisture. For mixtures with 0% PE and 0.27% PE, the ITS of the wet subset was higher than the dry subset. On the other hand, for mixtures with 1.5% and 5% PE, the opposite happened.

Below are shown the failed specimens, one for the control mixture of 0% PE and one for the mixture containing 5% PE. Any of them exhibit a clear tensile break line but a combination with some deformation near the loading strip.

Figure 98: Failed specimen, control 0%PE

Figure 99:Failed specimen, 5%PE

A visual inspection of the specimens after failure was done, and the corresponding pictures are shown below. Figure 100 shows a broken specimen of the control mixture with 0% PE where the aggregate seems to be intact, but some of them with a loss of bitumen film.

Figure 100: Visual inspection of the broken specimen, Control 0%PE

Figure 101: Visual inspection of the broken specimen, 1,5%PE

Figure 102: Visual inspection of the broken specimen, 5%PE

From Figure 101 and Figure 102, the results from the mixture can be compared when 1.5% PE and 5% PE are added. The specimen with 5% PE shows a more significant amount of aggregates with loss of bitumen film than the one with 1.5%PE. In both cases, the surface doesn't present broken aggregates. From the visual inspection, the specimens with a higher percentage of plastic exhibit a greater quantity of aggregates with a loss of bitumen film, thus contributing to the fact that the plastic acts not like a bond but, on the contrary, acts as a separating barrier between aggregates and bitumen.

5.2 Effects on plastic-type two addition

Next, the results of the plastic-type two bituminous mixture with 1.5% of plastic by weight of aggregates will be shown, for which were performed the mechanical tests. The volumetric properties and the results obtained by applying the mechanical test mentioned before are shown in the below tables, and for comparative purposes, the results are presented for the control mixture without plastic.

Below are shown the results obtained by the compaction of cylindrical specimens employing the gyratory shear compactor as explained in section 4.2.4 with an applied pressure of 600kPa and angle of gyration of 1,25° where six specimens of diameter 100mm were compacted for the 1.5%Plastic-type two mixture.

1,5% Plastic-type two					
Sample	**Gmb [kg/m³]**	**Gmm [kg/m³]**	**Air Voids [%]**	**#Gyrations**	**CDI**
AC 16 1.5% 1	2170	2475,0	12,3%	100	454,88
AC 16 1.5% 2	2181	2475,0	11,9%	100	450,43
AC 16 1.5% 3	2199	2475,0	11,1%	100	453,68
AC 16 1.5% 4	2157	2475,0	12,8%	100	487,50
AC 16 1.5% 5	2155	2475,0	12,9%	100	430,89
AC 16 1.5% 6	2177	2475,0	12%	100	474,14
AC 16 1.5% (average)	2173	2475,0	12,2%	100	458,25
Standard deviation	15,0		0,6%		17,75

Table 27: Volumetric properties from GSC results, mixture 1,5% Plastic-type two

Figure 103 shows the average CDI value for all the mixtures and exposes a significant increment of the CDI as plastic-type two is added. This result is non-favorable, indicating that the mixture containing this type of plastic needs very high energy to densify and obtain the desired percentage of compaction.

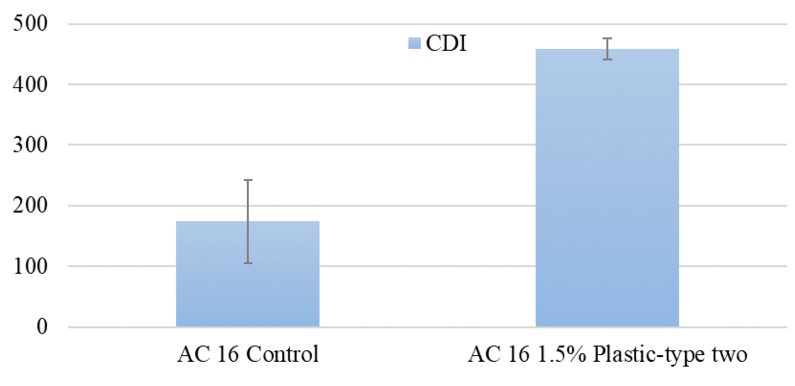

Figure 103 :Construction densification index (CDI) results

Results shown in Table 28 are obtained by applying the standard test described in chapter 4.3.

	AC 16 Control	Plastic-type two
Maximum density [g/cm3]	2512	2475
Average Bulk density [g/cm3]	2362	2173
Average air voids content [%]	6,0	12,2

Table 28: Plastic-type two volumetric properties results

The results presented before showed a significative increment in the air voids content when using 1.5% plastic-type two (mix of plastics as explained in section 4.3.2) by weight of aggregates, around the double respect the mixture without adding plastic. This increment in air voids content is reflected in the mixture's mechanical properties, giving very low values of stiffness modulus and indirect tensile strength compared with the mixture without plastic.

	AC 16 Control	Plastic-type two
ITSM dry [MPa]	3485	2280
ITSM wet [MPa]	3498	1750

Table 29: Plastic-type two ITSM results

	AC 16 Control	Plastic-type two
ITS dry [kPa]	1030	725
ITS wet [kPa]	1070	607
ITSR	103,9	84,0

Table 30: Plastic-type two ITS results

The stiffness modulus and the ITS with 1.5% plastic showed a higher value in dry specimens than the wet conditioning specimens. The results from the bituminous mixture with 1.5% plastic-type two were compared with the 0% plastic mixture. The results show poor behavior of volumetric and mechanical properties when adding this type of plastic. The maximum density decreased only by 1.5% with respect to the mixture without plastic. On the other hand, the percentage of air voids increased by more than 100%, which relates to the expansion behavior described before. The stiffness modulus and indirect tensile strength in wet and dry subsets significantly decrease by about 35% and 30% when adding plastic, respectively. The resultant ITSR decreases by 19%, having a value of 84. This result was very near the limit values found in each country's regulations, indicating lower resistance to moisture damage.

The ITSR value is lower for bituminous mixture with the addition of finely shredded plastic, as is the plastic-type two in comparison with the plastic-type one belonging to thicker pieces of plastic. This result is significantly related to the fact that the percentage of air voids content in the mixture with plastic-type two is much larger than in the mixture with plastic-type one. In the beginning, the activity aim was to compare the results obtained with plastic-type one and plastic-type two, but this could not be done due to the high difference in the result of the percentage of air voids.

As in the case of mixtures using the plastic-type one (PE), was assumed a linear relationship between ITSM value and the air voids content of the specimen. Figure 104 shows the results for both dry and wet subsets, and the ITSM value is calculated at the average air voids content from the slope and intercept of each curve.

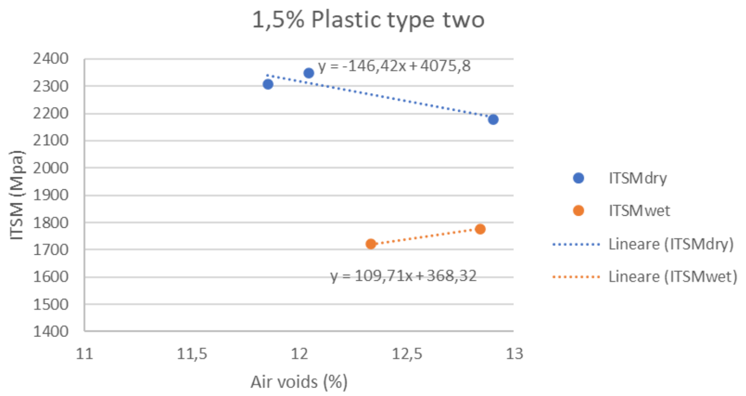

Figure 104:Plastic-type two, linear relationship between ITSM and air voids content

Below are shown the graphs of axial force versus the measured deformation used for calculating the indirect tensile strength (ITS).

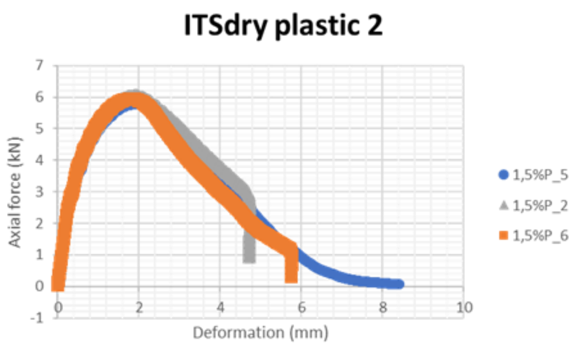

Figure 105:ITS dry plastic-type two

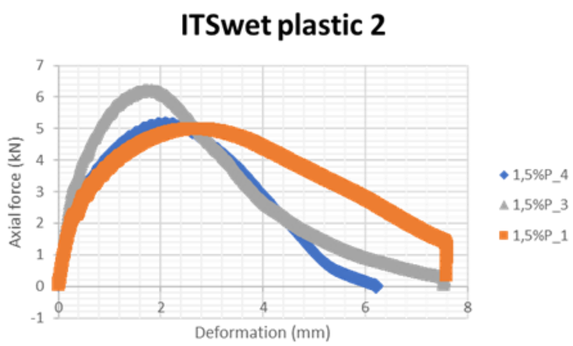

Figure 106: ITS wet plastic-type two

After reaching the peak load and the failure of the specimen occurs, some pictures were taken to record the type of failure. Most of the specimens present the failure shown in Figure 107, where a not clear tensile break line is presented and can be seen as an important deformation along the loading strip. On the other hand, Figure 108 shows a failed specimen belonging to the wet subset in which a tensile break line is presented clearer.

Figure 107: Type of failure 1 of a specimen with 1.5% of plastic

Figure 108: Type of failure 1 of a specimen with 1.5% of plastic

Below are shown the pictures of broken specimens subjected to an indirect tensile test corresponding to the mixture with 1.5% plastic-type two. In this case, some of the aggregates are broken, and the surface does not present a considerable bitumen film loss.

Figure 109: Visual inspection of broken specimens, a mixture containing 1.5% plastic-type two

As mentioned in section 4.2.5 Temperature variation for the plastic-type two mix, were done two additional mixtures to verify the behavior observed in the first one, where the cylindrical samples present an expansion of their dimensions. The dimensions of the six cylindrical specimens derived from the three mixtures were measured on the compaction day and the day after. The average differences (Δ) for height and diameter were calculated with these results. Correspondingly, an increment of the air voids percentage was calculated. The results are shown in the table below. Additionally, is shown for each mix, the average air voids content.

	Mix 1		Mix 2		Mix 3	
	height	**Diameter**	**height**	**Diameter**	**height**	**Diameter**
Δ [mm]	1,247	0,548	1,004	0,533	0,735	0,358
Δ air voids [%]	3,18	1,94	2,75	1,91	2,27	1,59
Avg. air voids [%]	12,20		10,98		9,84	

Table 31: Dimensions and equivalent air void content increment

The bituminous mixtures with the plastic-type two showed an expansion of dimension of cylindrical specimens after compaction. This expansion was reduced when the plastic was added by steps, for it is possible to assume that the characteristics of each type of plastic used for this plastic mix, like density or melting point, influence the behavior of the bituminous mixture.

6 Conclusions

This thesis aimed to evaluate the potential use of two different types of waste plastic by performing an experimental investigation evaluating the volumetric and mechanical properties compared with a mixture without any addition. From the abovementioned results, it is possible to conclude that:

1. A bituminous mixture with the addition of plastic-type one increases its volumetric and mechanical properties; specifically, the air voids content is reduced and their stiffness and strength increase, making the bituminous mixture more resistant as the percentage of waste plastic increases. The resistance to moisture given by ITSR value was reduced moderately but acceptable to have good resistance, compared with the mixture without plastic.
2. A bituminous mixture with the addition of plastic-type two decreases their volumetric and mechanical properties; specifically, the air voids content is increased, and their stiffness and strength decrease, making more unresistant the bituminous mixture when the plastic is added. The resistance to moisture given by the ITSR value was reduced significantly compared with the mixture without plastic.

When using plastic-type one in large proportions, as 5%PE, some non-uniformity in the cylindrical specimen was observed, showing a non-total melt of the plastic, leading to phase separation and not good covering of aggregates by the plastic film. Additionally, with this percentage of plastic, the air voids content is reduced below 3%, being this non-favorable and must be avoided. So, bituminous mixtures with plastic-type one are promising and feasible until 1,5% PE of added plastic. The previous idea suggests that when 5%PE is added to the mix, the plastic tends to behave as a binder leading to low values of air voids. A possible solution could be to reduce the percentage of bitumen used in the mixture, decreasing the cost and pollution from petroleum derivatives. It is suggested, for further research, to reduce the bitumen percentage while maintaining the same plastic portion to evaluate the mix behavior to obtain acceptable air void values and improve the stiffness and strength.

When using plastic-type two was observed that the dimensions of cylindrical specimens increase after one day of compaction; therefore, a large percentage of air voids content and low mechanical properties. This issue leads to say that bituminous mixtures with plastic-type two are not promising. The variation in the preparation of the mixture by adding the plastic in multi-steps gives good results leading to lower values of air voids compared with the traditional process, so the mixing process can be worked to improve the results obtained with plastic-type two. The composition of plastic-type two by different types of plastic is another fact that plays a role in the obtained results due to the different properties and parameters of each type of plastic, such as melting point or density, and this must be studied and taken into account deeply. It could be recommended to vary the mixing temperature to study the different plastic type's melting process to avoid the compacted specimen's expansion. Furthermore, the investigation of the melting point of each plastic should determine when and how each one should be added during the mixing process.

In conclusion, everyone can help reduce the environmental impact our modern consumer society produces on the earth. Specifically, in the civil engineering area, counting on the results of this thesis, it is very recommended to persist in the investigation of the usage of plastic materials to produce asphalt mixes for road constructions. For future investigations could be interesting to try different methods and configurations to make the most of the local plastic waste in the mix, evaluating the contribution each type of the selected plastics could give and how are the interactions between them and the aggregates when melted.

7 Bibliography

Fattah, M. Y., Hilal, M. M., & Flyeh, H. B. (2019). Evaluation of the mechanical stability of asphalt mixture using the gyratory compactor. *International Journal of Pavement Research and Technology*.

Hardin, T. (2021, 02 23). *Plastic: It's Not All the Same.* Retrieved from Plastic Oceans: https://plasticoceans.org/7-types-of-plastic

International Union of Laboratories and Experts in Construction Materials, Systems and Structures. (2020). *2020 2021 Technical Report.* Retrieved from RILEM: https://www.rilem.net/global/gene/link.php?doc_id=6261&fg=1

Merriam-Webster. (2022). *Dictionary: Asphalt.* Retrieved from Merriam Webster: https://www.merriam-webster.com/dictionary/asphalt

Mishra, B., & Gupta, M. (2018). *Use of plastic waste in bituminous mixes by wet and dry methods.* Municipal Engineer.

National Rural Roads Development Agency, India. (n.d.). *Guidelines for the use of Plastic Waste in Rural Roads Construction.* New Delhi: Ministry of Rural Development, India.

PINE test equipment. (2022). *G2 Superpave Gyratory Compactor (Part # AFG2)*. Retrieved from PINE test equipment: https://www.pinetestequipment.com/product/g2-superpave-gyratory-compactor/

Research Design and Standards Organization. (2019). *Guidelines on use of Plastic Waste in Road Construction (Provisional).* Lucknow: GOVERNMENT OF INDIA - MINISTRY OF RAILWAYS.

Sasidharan, M., Eskandari Torbaghan, M., & Burrow, M. (2019). *Using waste plastics in road.* Birmingham: University of Birmingham.

Science History Institute. (2022). *Science of Plastics*. Retrieved from Science matters: https://www.sciencehistory.org/science-of-plastics

The British Standards Institution. (1999). BSI Standards Publication - Tests for general properties of aggregates (BS EN 932-2:1999). *Part 2: Methods for reducing laboratory samples*. United Kingdom: BSI Standards Limited.

The British Standards Institution. (2012). BSI Standards Publication - Tests for geometrical (BS EN 933-1:2012). *Part 1: Determination of particle*. United Kingdom: BSI Standards Limited.

The British Standards Institution. (2016). BSI Standards Publication - Bituminous mixtures - Test methods (BS EN 12697-35:2016). *Part 35: Laboratory mixing*. United Kingdom: BSI Standards Limited.

The British Standards Institution. (2017). BSI Standards Publication - Bituminous mixtures - Test methods (BS EN 12697-23:2017). *Part 23: Determination of the indirect tensile strength of bituminous specimens*. United Kingdom: BSI Standards Limited.

The British Standards Institution. (2018). BSI Standards Publication - Bituminous mixtures - Test methods (BS EN 12697-12:2018). *Part 12: Determination of the water sensitivity of bituminous specimens*. United Kingdom: BSI Standards Limited.

The British Standards Institution. (2018). BSI Standards Publication - Bituminous mixtures - Test methods (BS EN 12697-26:2018). *Part 26: Stiffness*. United Kingdom: BSI Standards Limited.

The British Standards Institution. (2018). BSI Standards Publication - Bituminous mixtures - Test methods (BS EN 12697-5:2018). *Part 5: Determination of the maximum density*. United Kingdom: BSI Standards Limited.

The British Standards Institution. (2018). BSI Standards Publication - Bituminous mixtures - Test methods (BS EN 12697-8:2018). *Part 8: Determination of void characteristics of bituminous specimens*. United Kingdom: BSI Standards Limited.

The British Standards Institution. (2019). BSI Standards Publication - Bituminous mixtures - Test methods (BS EN 12697-31:2019). *Part 31: Specimen preparation by gyratory compactor*. United Kingdom: BSI Standards Limited.

The British Standards Institution. (2020). BSI Standards Publication - Bituminous mixtures – Test methods (BS EN 12697-28:2020). *Part 28: Preparation of samples for determining binder content, water content and grading*. United Kingdom: BSI Standards Limited.

The British Standards Institution. (2020). BSI Standards Publication - Bituminous mixtures - Test methods (BS EN 12697-29:2020). *Part 26: Determination of the dimensions of a bituminous specimen*. United Kingdom: BSI Standards Limited.

The British Standards Institution. (2020). BSI Standards Publication - Bituminous mixtures - Test methods (BS EN 12697-6:2020). *Part 6: Determination of bulk density of bituminous specimens*. United Kingdom: BSI Standards Limited.

8 APPENDIX

UTM-30 User Manual