Universidade de Aveiro Departamento de Engenharia Civil
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INTERNSHIP IN PAVEMENT CONSTRUCTION: ANALYZATION OF HOT BITUMINOUS MIXTURES DESIGN, FORMULATION, PLACEMENT AND QUALITY CONTROL.

ESTÁGIO NA CONSTRUÇÃO DE PAVIMENTOS: TECNOLOGIAS DE FABRICO E APLICAÇÃO.

Internship Report

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Internship Report presented to the University of Aveiro to fulfill the necessary requirements of obtaining the Master's Degree in Civil Engineering, held under the supervision of Dr. Agostinho António Rocha Correia e Almeida da Benta, Assistant Professor, Department of Civil Engineering, University of Aveiro.

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Author

Ihssan Khalifeh.

palavras-chave

construção de pavimento, misturas betuminosas a quente, design, formulação, betão betuminoso, controlo de qualidade.

resumo

Este trabalho prático baseia-se em observações realizadas sobre a execução de pavimentos rodoviários, a realizar por uma das empresas portuguesas especializadas nesta área de construção. O trabalho inclui três fases essenciais da indústria rodoviária, nomeadamente: design e produção de misturas betuminosas a quente, aplicação de misturas (construção de pavimentos) e controlo de qualidade. Cada fase é discutida em detalhe para fornecer o melhor entendimento possível sobre este tópico de acordo com a inspeção do local. Assim, permite dar uma boa compreensão sobre o trabalho, que estuda em detalhes todos os aspectos relacionados com a fabricação de misturas betuminosas a quente, bem como a sua aplicação em pavimentos rodoviários de acordo com uma série de circunstâncias impostas pela situação prática da obra, além de garantia de controle de qualidade.

keywords

road construction, hot bituminous mixtures, design, formulation, asphalt concrete, quality control.

abstract

This practical work is based on observations conducted over the execution of road pavements, to be held by one of the specialized Portuguese companies in this area of construction. The work includes three crucial phases of the road industry, namely: hot bituminous mixtures design and production, mixture application (pavement construction) and quality control. Each phase is discussed in detail to provide the best possible understanding over this topic in accordance with the site inspection.Thus, it aims to provide a good comprehension about the work, which studies in detail every aspect related to the fabrication of hot bituminous mixtures, as well as its application in road pavements according to a number of circumstances imposed by the practical situation of the construction site in addition to quality control assurance.

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1 INTRODUCTION

In this chapter, it is intended to make a short presentation of the participants: Trainee, the host company. In addition, the work carried out by the trainee over an eight-month period related to the training provided is discussed.

The objectives initially defined for the internship are described and a characterization of the internship is presented along with a summary of the work developed.

1.1 Company background

MOTA-ENGIL

With an experience of more than 70 years, and being a national leader and an international reference, Mota-Engil brings together technical expertise of excellence in the areas of Engineering and Construction, Environment and Services, Infrastructure Concessions for Transport and Mining.

Present in 19 countries and 3 continents, Mota-Engil concentrates its operations in four geographic centers - Portugal, Africa, Central Europe and Latin America - guaranteeing in each market the same standard of quality, capacity of execution and rigor that made the Group Mota-Engil a leader in Portugal and a reference at European level in these areas.

In Portugal, Mota-Engil is the leader in most business areas in which it operates, such as the construction and public works sectors, waste management, port operations and municipal water concessions, representing, overall, a significant level of activity in a diversified business model that has tried to replicate in the other geographies.

In a journey of permanent investment, innovation and recognized management capacity, the Portuguese market has represented an important and significant support to the process of internationalization and diversification of Mota-Engil's activities to other geographies.

Africa is a natural market for Mota-Engil Group, given its presence in Angola for more than 66 years, which allows Mota-Engil Angola to have a benchmark in this market.

With a very representative activity in markets such as Moçambique and Malawi, and other expanding markets such as South Africa, Cabo Verde, São Tomé e Principe, Zimbabwe and Zambia, Mota-Engil is increasingly active in Southern Africa.

Mota-Engil Group has been geographically expanding its activity in Africa, evaluating new markets and diversifying into new business areas, establishing a commitment to the development of these high potential economies.

Investment in mining is the latest example of this commitment to Africa.

In the process of building Europe and bringing the countries of Central and Eastern Europe closer to the rest of the European Union, infrastructure development is a determining factor.

To this end, Mota-Engil Group sought to position itself in the region in due course by centralizing operations in Poland as the main market for action.

Through Mota-Engil Central Europe, with a solid track of fifteen years and a position among the ten largest Polish companies in the construction sector, Mota-Engil Group is prepared to respond to projects in Poland, the Czech Republic, Slovakia and Hungary.

The presence of Mota-Engil Group in Latin America began in 1998 in Peru, and made a continuous investment in strengthening the execution capacity and in the development of technical skills to make Mota-Engil Peru a diversified company in the area of engineering and other business areas.

More recently, Mota-Engil Group has decided to enter new markets in the region such as Mexico, Brazil and Colombia, reinforcing growth and diversification in many areas, namely: road construction, mining works, port management and motorway concession projects.

Group Structure

Mota-Engil develops a wide range of activities related to Engineering and Construction, Environment and Services, Infrastructure Concessions of Transport and Mining.

Commitment to quality and established objectives, growing international commitment and the diversity of services ensured through the technical expertise shown in each project, has enabled Mota-Engil to build and maintain a reputation for excellence in each market where it operates.

The main mission of Mota-Engil Group is to ensure the capacity to respond to each new challenge, ensuring a permanent competitiveness and innovation in the solutions presented, reinforcing the international positioning through complementary strategic partnerships, projecting its businesses to the measure of each market in order to build a solid and sustainable economic future.

Business Areas

I. **Engineering and Construction**: The group has distinguished itself in the construction of various infrastructures such as roads, highways, airports, ports, dams, buildings, railways, electromechanical works, foundations, and geotechnical projects, among other specialties.

II. **Transport Concessions**

- Highways
- Motorways
- Bridges
- Railways
- Underground

III. **Mining**

- Prospecting
- Extracting
- Exploration

IV. **Waste Management**

- Collection of municipal and industrial waste
- Urban cleaning
- Biological and mechanical treatment of waste
- Energy and Organic recovery of waste
- Environmental Education

V. Logistics

- Operation of railway freight transport

VI. Multi-services

- Maintenance of Buildings and facilities
- Rehabilitation of pipelines
- Landscape architecture
- Design, construction and maintenance of green spaces and golf course

The group has 70 years of experience in the development of ambitious projects, based on versatility and pioneering in construction techniques, associated with a strong investment capacity in the training of human resources, equipment and new technologies.

Mota-Engil Ambiente e Serviços encompasses a diverse portfolio of activities and businesses.

In the environmental field, Mota-Engil Ambiente e Serviços develops activities in the waste and urban cleaning sector, it also leads the privatized market in solid urban waste management in Portugal. In addition, it generates a number of holdings in the water sector.

In the logistics and port sector, Mota-Engil Ambiente e Serviços leads the port operations market, offering comprehensive logistic integration solutions. Moreover, it is the first private Portuguese rail freight operator.

The Multi-Services component integrates businesses in the fields of building and facilities maintenance, conduit rehabilitation, landscape architecture, construction and maintenance of green spaces, car parks, electronic markets and direct mailing.

1.2 Objectives and duration of the internship

The internship goal is to understand the site management processes, having the possibility of experiencing day to day practical activities implemented in site, which is significant to develop the necessary autonomy at the organizational level.

The study of the construction stages and work planning are also defined as the main objectives, through monitoring and taking part in the production processes as an assistant to the site director.

The internship duration was eight months, in which I got introduced to read and analyze both the written and drawn project design details provided by the owner, Brisa Concessões, to serve as a work base, divided in chapters according to different work areas, namely: pavements, structural works, drainage, illumination, telecommunications, fencing, safety guards, etc.

In addition, it was really important to understand the specifications manual "Caderno de Encargos", supplied by the owner as the main work reference, consisting of two parts, the general clauses defined for all road projects, as well as the special technical clauses defining the conditions needed to be met for this project in particular.

It is worth stating the importance of accompanying other site areas such as topography, quantity surveying, safety, environment, and quality assurance, executing assignments in each field of the previously stated with the supervision of the site director, in addition to participating in the production reunions in order to prepare the weekly plan, an element that significantly enforced the planning capability by learning how to manage the appropriate activities sequence within the required timeframe and available manpower.

The following figure presents an example of the weekly plan prepared each Friday after the production meeting attendance.

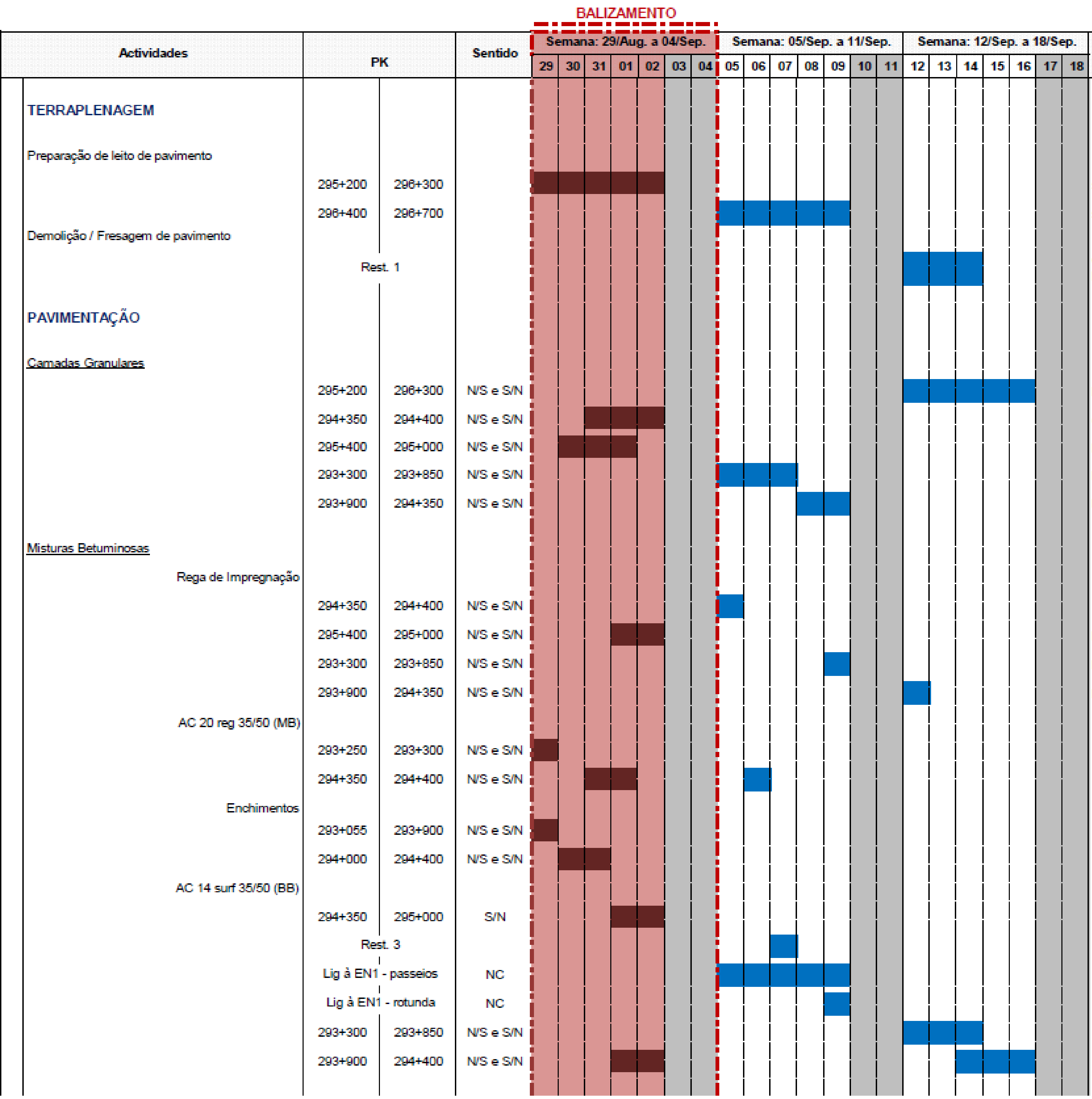


Figure 1.1 – Weekly Production Plan

However, the main objective was concentrating more profoundly on paving works using Hot Mix Asphalt (HMA), throughout a process conducted with the following sequence:

1. Overview of the pavement design
2. Hot bituminous mixtures formulation
3. Hot mixtures fabrication and site application
4. Quality control and laboratory tests

The previous four steps constitute the body of this report, in order to cover the practical process of HMA implementation in highway pavement construction.

1.3 Project background

The project has the following designation "enlargement and reformation of subsection Carvalhos/Stº Ovídio of the Highway A1, north Portugal", owned by Brisa Concessions (Figure 1.2).

The enlargement and reformation activities start at km 293+050 and finish at km 296+950, within a segment of 3900 m. The project includes the reformulation of the access ways leading to the service area of Gaia as well as those of the Jaca Node (Node with A29) and those of Stº Ovídio Node.

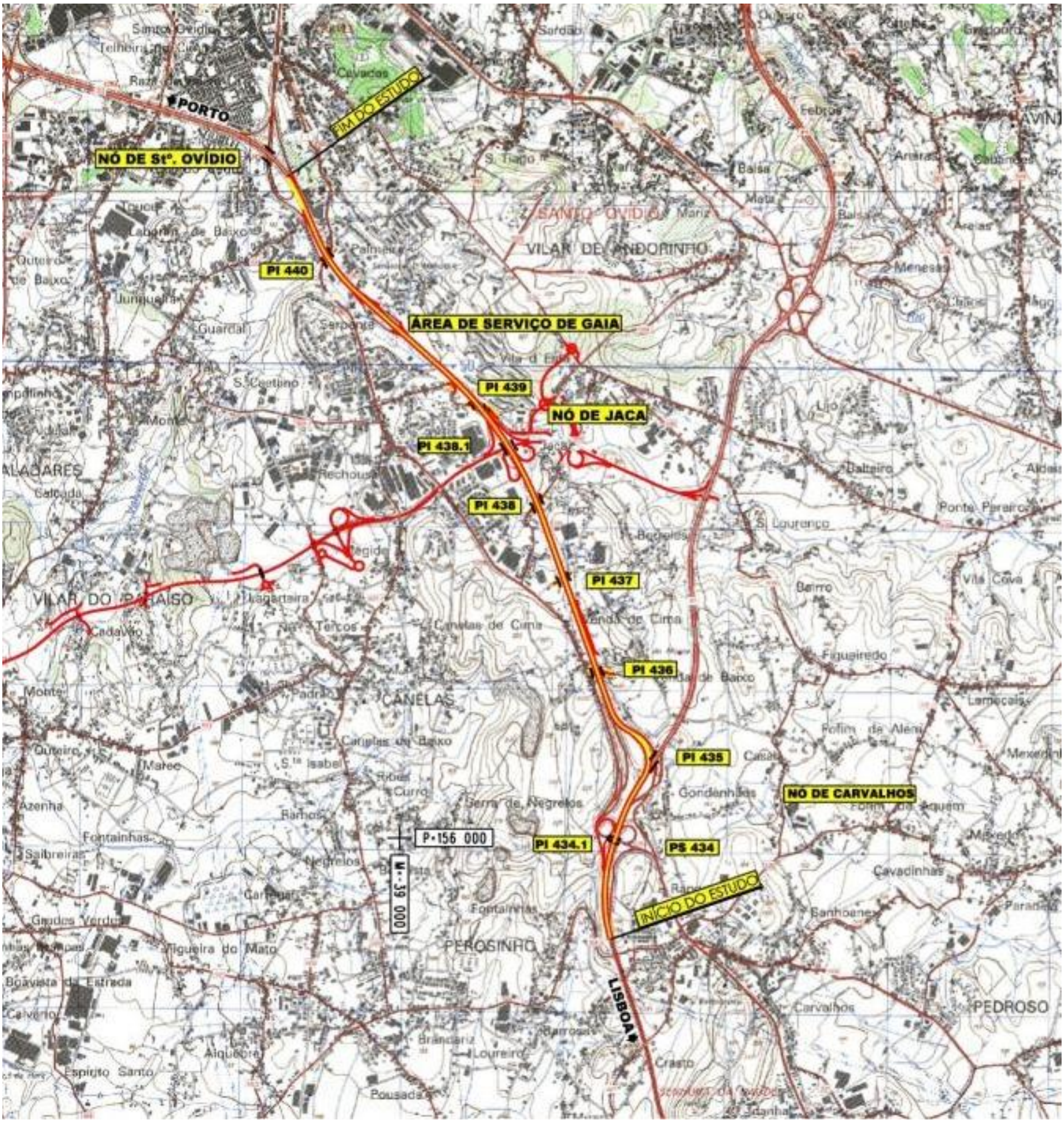


Figure 1.2 – Project Map

The cross section of the subsection's main way will consist of existent circulation lanes (2x2 lanes), provided that a third lane is added, in both directions, and obtained by enlarging the existing platform to the external side.

The pavements design takes into consideration a project life of 20 years, with the reinforcement / reformation measures of the existing pavement were defined based on emerging information related to the characterization of the existing situation.

Moreover, the project consists of the widening of 5 underpasses by destructing their existing decks and walls, and reforming their structure to reach the new design width, according the following sequence:

- Piles and foundation construction
- New walls and deck construction

In terms of the urban area where the layout is inserted and in order to minimize the land possession, as well as to protect the existing buildings and streets, 14 retaining walls are constructed, 11 of them are situated along the current section of the highway and the other 3 are located in the zone of the Carvalhos node.

In general, the work involves the execution of earthworks, pavement, transverse and longitudinal drainage, landscape integration, fences, security guards, horizontal and vertical signaling, telecommunications infrastructures, road lighting, underpasses demolition and reconstruction, containment structures construction, restoration of affected services, temporary signaling and safety guarantee which is necessary for traffic management and work execution.

The project is basically divided in two phases, as shown in the following figures, the first phase is in which the new lane is constructed including the extension of the 5 underpasses. In the second phase, all the pavement rehabilitation works in addition to the underpasses widening processes are done while the traffic is detoured to the newly constructed third lane.

Figure 1.3 – Project´s First Phase

Figure 1.4 – Project´s Second Phase

2 OVERVIEW OF THE PAVEMENT DESIGN

2.1 New pavements

2.1.1 METHODOLOGY

The design was performed based on the rational method, which uses the calculation of stress and strain induced in the pavement structure and its foundation, considering the number of axes of heavy vehicles.

The stress and strain are determined assuming a behavior model in which the pavement is treated as a set of overlapping layers, undefined in the horizontal plane, supported by the respective foundation, knowing that it's being considered as an infinite layer in terms of depth.

It is assumed that the materials constituting the layers have a linear and isotropic elastic behavior, with their mechanical characteristics being set according to the type of materials.

The action of heavy vehicles axes during the project lifetime is expressed in terms of an equivalent number of standard axis passages. For this axis, there were assumed dual wheels with 37.5 cm of spacing, and the circular tire print area of 12.5 cm radius.

The design verification was performed using an automatic calculation program "BISAR" of Shell method, from which are determined the extensions and the stresses induced by the application of a standard axis of 130 kN on the pavement structures.

The calculation process consists of a continuous optimization of the structural models considered, in order to obtain paving solutions that ensure, during the useful life of the structures, the full compliance with the conditions represented by the adopted ruin criteria.

2.1.2 TRAFFIC

Traffic Forecasts for the Subsection Carvalhos/Sto Ovídio

The heavy traffic demand was evaluated based on the traffic forecasts for this sub-section of A1, provided by the owner.

According to the information provided, considering a 20 years' project life and that the subsection's opening to traffic after the enlargement and reformation works will be done, will have the following values of Average Annual Daily Traffic (AADT or TMD in Portuguese) of motorized and heavy vehicles in both directions, until the end of the project life in 2032.

Table 2.1.2.1 – Average Annual Daily Traffic of Motorized and Heavy Vehicles

Year		2012	2017	2022	2027	2032
AADT	Motorized	56950	60288	65251	68856	70091
	Heavy	2916	3087	3341	3525	3589
T - Heavy vehicle growth rate (%)		1.07				

2.1.3 RECOMMENDED PAVEMENT STRUCTURES AND STRUCTURAL VERIFICATION

2.1.3.1 General Considerations

In order to analytically verify the selected structural models, it was applied a unit load of 6.5 t, transmitted by a dual wheel tire pressure equal to 0.662 MPa.

Thus, there were determined both the tensile deformation in the most critical interface, as well as the compressive vertical deflection in the pavement bed with the aid of an automatic calculation program.

The obtained results were compared with the maximum admissible deflections, in accordance with the number of expected load recurrences for the design period considered (20 years).

2.1.3.2 Structure of the Main Track

After analyzing the several structural models, the following pavement structure was considered adequate for the new 3rd lane and for the acceleration and deceleration lanes, resulting from the enlargement of this subsection of A1.

Table 2.1.4.1 – Recommended Pavement Structure for the Main Track Enlargement

Layer	Thickness	Properties
Surface Layer of Permeable Asphalt (PA 12,5 surf 50/70 (BBd))	4 cm*	E=5600 MPa; υ=0,35
Regularization Layer of Asphalt Concrete (AC 14 bin 35/50 (BB))	5 cm	E=5600 MPa; υ=0,35
Base Layer of Bit. Macadam (AC 20 base 35/50 (MB))	7 cm	E=5800 MPa; υ=0,35
Base Layer of a High Modulus Bituminous Mix (AC 20 base 10/20 (MBAM))	8 cm	E=10000 MPa; υ=0,35
Base Layer of Crushed Aggregates with a Continuous Particle Size Distribution	20 cm	E=250 MPa; υ=0,40
Sub-Base Layer of Crushed Aggregates with a Continuous Particle Size Distribution	20 cm	E=130 MPa; υ=0,40
Pavement Foundation		E=60 MPa; υ=0,45

**For design purposes, it was only considered the contribution of half the thickness of surface layer consisted of permeable asphalt concrete.*

2.1.3.3 Adopted mixtures designation according to NP EN 13108-1

The previous figure illustrates the bituminous mixtures considered to form the pavement structure, with the position of each in accordance with the required function defined by the designer.

Since each mixture has a specific designation defined by the Eurocode, a brief explanation is given below to explain what every one of these designations stands for:

- ***High Modulus Bituminous Mixture of the Base Layer of 8 cm thickness – AC 20 base 10/20 (MBAM)***
- ***Bituminous Macadam of the Base Layer of 7 cm thickness – AC 20 base 35/50 (MB)***
- ***Asphalt Concrete of the regularization Layer of 5 cm thickness – AC 14 reg 35/50 (BBsb)***
- ***Permeable Asphalt Concrete of the Surface Layer of 4 cm thickness – PA 12.5 surf 50/70 (BBd)***

Where:

AC – Refers to Asphalt Concrete

PA – Permeable Asphalt

20 – Maximum aggregate dimension (mm)

Base/Reg/Surf – Layer position/function

10/20 – Bitumen penetration grade (mm)

MBAM – "Mistura Betuminosa de Alto Módulo"

MB – "Macadame Betuminoso"

BBsb – "Betão Betuminoso subjacente"

BBd – "Betão Betuminoso drenante"

2.2 Reinforcement of the existing pavement

2.2.1 Methodology

To evaluate the load capacity of the existing pavement and subsequently define adequate rehabilitation solutions, it is necessary having a representative calculation model of the pavement structural behavior, when subjected to the heavy vehicles wheel action.

The definition of this model requires knowledge of the existing pavement structure constitution, as well as the deformability moduli of the various layers including foundation.

2.2.2 Traffic

To calculate the cumulative number of heavy vehicles on the reinforced lanes, it was supposed that only 30% of the total heavy vehicles will circulate using those lanes.

Thus, the cumulative number of heavy vehicles in the final design year is shown in Table 2.2.2.1.

Table 2.2.2.1 – Cumulative Heavy Traffic in Reinforced Lanes

Periods			
2012 - 2017	**2012 - 2022**	**2012 - 2027**	**2012 - 2032**
0,98 x 10^6	1,9 x 10^6	2,8 x 10^6	3,8 x 10^6

To calculate the corresponding cumulative numbers of standard axes, an equivalence factor of 1.0 is considered for standard axes of 130 kN.

Table 2.2.2.2 – Cumulative Number of Standard Axes of 130 kN in Reinforced Lanes

Periods			
2012 - 2017	**2012 - 2022**	**2012 - 2027**	**2012 - 2032**
0,98 x 10^6	1,9 x 10^6	2,8 x 10^6	3,8 x 10^6

2.2.3 Pavement reinforcement design

Proposed Solution

In general, the reinforcement is carried out with two bituminous layers: a regularization layer of asphalt concrete with 0.05 m thickness, underlying a new surface layer of permeable asphalt concrete with 0.04 m thickness, to minimize the hydroplaning phenomena.

Under these two layers, there will be a third layer of profiling, consisted of a dense bituminous mix or bituminous macadam, depending on the thicknesses involved, which will correct the existing super elevations.

2.2.4 Reinforcing Bituminous Mixtures

- ***Reinforcing Layer of Permeable Asphalt Concrete (Surface Layer) of 4 cm thickness – PA 12,5 surf 50/70 (BBd)***

It is foreseen to use permeable asphalt concrete 0/12.5, having bitumen of 50/70 penetration modified with polymers.

For structural calculation purposes, it was considered the contribution of half the permeable asphalt thickness, with a deformability modulus equal to that of the regularization subsurface asphalt (5600 MPa). For Poisson's ratio, it was considered the value of 0.35, the usual one for these mixtures.

- ***Reinforcing Layer of Asphalt Concrete (Subsurface Layer) of 5 cm thickness – AC 14 reg 35/50 (BBsb)***

For this layer, an asphalt concrete 0/14 of 35/50 penetration bitumen is used.

For structural calculation purposes, it was considered a deformability modulus of 5600 MPa. For Poisson's ratio, it was considered the value of 0.35 as well, the usual one for these mixtures.

- ***Profiling Layer of Dense Bituminous Mixture of variable thickness – AC 20 reg 35/50 (MBD)***

The correction of existing super elevation in this subsection of A1 requires executing a profiling layer with bituminous mixtures.

The high variability of necessary profiling thicknesses forced to adopt different bituminous mixtures, depending on the filling thicknesses involved.

Thus, when executing the filling layer with thicknesses equal to or less than 0.06 m, it is foreseen using a dense bituminous mix (0/20), which has a 35/50 penetration bitumen as a binder.

Since this layer always presents variable thickness according to the work levels, it was decided not to consider it in the structural analysis of the reinforced pavement, being on the safe side therefore.

- ***Profiling Layer of Bituminous Macadam of variable thickness – AC 20 reg 35/50 (MB)***

The filling layer execution with thicknesses over 0.06 m will require a bituminous macadam mixture (0/20), which has a 35/50 penetration bitumen as a binder.

Likewise, this layer wasn’t considered in the structural analysis of the reinforced pavement, being on the safe side therefore.

3 HOT BITUMINOUS MIXTURES FORMULATION

3.1 Methodology

The formulation process defines each mixture's composition taking the Marshall method as a base, the mix components' sources are also defined with lab tests conducted in order to check their compatibility with the specifications required by the project owner, taking the following steps:

- Defining the required specifications for the mixture and for each of its compositions.
- Adopting specific sources for aggregates and bitumen supply.
- Conducting lab tests over the aggregates of various sizes to check their compliance with the specifications.
- Choosing the aggregate percentages in compliance with the specified particle size distribution. `
- Finding out the optimum bitumen content.
- Conducting lab tests over the mixture to verify its compatibility.
- Listing final percentage of each composition, as well as its source.

The Marshall method of mix design is intended both for laboratory design and field control of bituminous hot-mix dense-graded paving mixtures.
There are some frequently used terms that should be explained such as:

- **VMA percentage in compacted paving mixture**

The voids in the mineral aggregate, VMA, are defined as the intergranular void space between the aggregate particles in a compacted paving mixture that includes the air voids and the effective bitumen content, expressed as a percentage of the total volume (Fig. 3.1.1).

The VMA is calculated based on the bulk specific gravity of the aggregate Gsb and is expressed as a percentage of the bulk volume of the compacted paving mixture.

Therefore, the VMA can be calculated by subtracting the volume of the aggregate determined by its bulk specific gravity from the bulk volume of the compacted paving mixture. If the mix composition is determined as a percentage by total mass of mixture:

$$VMA = 100 - \frac{G_{mb} P_s}{G_{sb}}$$

Where VMA =voids in mineral aggregate, percentage of bulk volume; Gsb =bulk specific gravity of total aggregate; Gmb =bulk specific gravity of compacted mixture; and Ps =aggregate content, percentage by total mass of mixture.

Or, if the mix composition is determined as a percentage by mass of aggregate:

$$VMA = 100 - \frac{G_{mb}}{G_{sb}} \times \frac{100}{100 + P_b} 100$$

Where Pb =bitumen content, percentage by mass of aggregate.

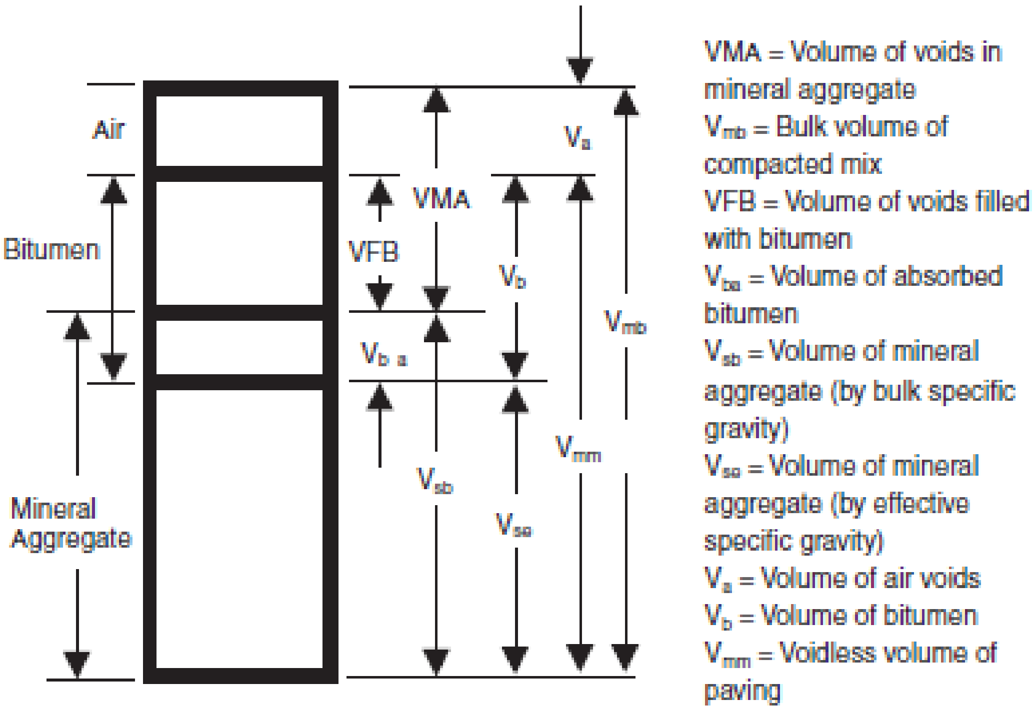


Figure 3.1.1 - Representation of volumes in a compacted bituminous mix

- **Air voids percentage in the compacted mixture**

The air voids, Va, is the total volume of the small spaces of air between the coated aggregate particles throughout a compacted paving mixture, expressed as a percentage of the bulk volume of the compacted paving mixture (Fig. 3.1.1). The volume percentage of air voids in a compacted mixture can be determined using:

$$V_a = 100 \times \frac{G_{mm} - G_{mb}}{G_{mm}}$$

Where Va =air voids in compacted mixture, percentage of total volume; Gmm =maximum specific gravity of paving mixture; and Gmb =bulk specific gravity of compacted mixture.

- **VFB percentage in the compacted mixture**

The voids filled with bitumen, VFB, is the percentage of the intergranular void space between the aggregate particles (VMA) that are filled with bitumen (Fig. 3.1.1).

The VFB, which does not include the absorbed bitumen, is determined using:

$$VFB = \frac{100(VMA - V_a)}{VMA}$$

Where VFB=voids filled with bitumen, percentage of VMA; VMA=voids in mineral aggregate, percentage of bulk volume; and Va =air voids in compacted mixture, percentage of total volume.

3.2 Formulation process

The Marshall method uses standard cylindrical test specimens that are 64 mm high by 102 mm diameter. These are prepared using a specified procedure for heating, mixing and compacting the bitumen–aggregate mixture. The two principal features of the Marshall method of mix design are a density voids analysis and a stability-flow test of the compacted test specimens.

The stability of the test specimens is the maximum load resistance, in Newtons, that the standard test specimen will develop at 60°C when tested. The flow value is the total displacement, in units of 0.25 mm, occurring in the specimen between no load and the point of maximum load during the stability test.

<u>Preparation of test specimens</u>

The aggregates are first dried to a constant weight at 105 to 110°C and then separated, by dry sieving, into the desired size fractions. The amount of each size fraction required to produce a batch that will give a compacted specimen of 63.5 mm thickness is then weighed in a separate pan for each test specimen, this is normally about 1.2 kg of dry aggregates. At least three specimens must be prepared for each combination of aggregates and bitumen. The pans are then placed in an oven until the dry aggregates achieve the required mixing temperature. When the batched aggregates have reached the mixing temperature, a mixing bowl is supplied with the heated aggregates, the required quantity of bitumen is added, and mixing is carried out until all the aggregate particles are fully coated.

If the viscosity of the bitumen is too high during mixing, the aggregate will not be properly coated and if the viscosity is too low, the bitumen will coat the aggregate easily but may subsequently drain off the stone during storage or transportation, thus, for satisfactory coating the dynamic viscosity should be about 0.2 Pa.s.

During compaction, if the viscosity is too low, the mix will be excessively soft, and resulting in pushing of the material in front of the roller, and high viscosities will significantly reduce the workability of the mix and little compaction will be achieved. The optimal bitumen viscosity for compaction should fall between 2 Pa.s and 20 Pa.s.

Compaction of specimens

Depending on the design traffic category (light, medium or heavy) that the compacted mix is expected to withstand, 35, 50 or 75 blows are applied, respectively, with the compaction hammer to each end of the specimen, therefore, 75 blows are applied in this case where heavy traffic is considered.

After compaction, the specimens are allowed to cool in air at room temperature until no deformation results when removing each from the mold.

Test procedure

In the Marshall method, each compacted test specimen is subjected to the following tests and analysis in the following order:

(a) bulk specific gravity test, (b) stability and flow test, and (c) density and voids analysis. The bulk specific gravity test may be performed as soon as the freshly compacted specimens have cooled to room temperature, after which the stability and flow tests are performed.

Prior to the stability and flow testing, the specimens are immersed in a water bath at 60°C for 30 to 40 minutes. The Marshall testing machine, a compression testing device, is designed to apply loads to test specimens through cylindrical segment testing heads at a constant rate of vertical strain of 51 mm per minute (Fig. 3.2.1). Loading is applied until specimen failure occurs. The Marshall testing machine is equipped with a calibrated proving ring for determining the applied testing load.

The force in Newtons required to produce failure of the test specimen is recorded as its Marshall stability value and the magnitude of deformation of the specimen at the point of failure is recorded as the flow value. The point of failure is defined by the maximum load reading obtained.

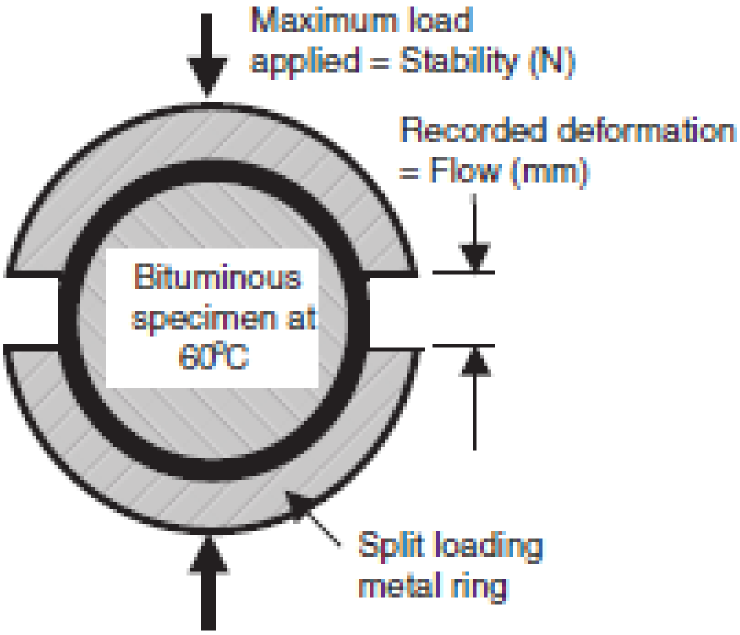


Figure 3.2.1 - The Marshall Stability Test

Preparation of test data

Measured stability values for specimens taken from the standard 63.5 mm thickness have to be converted to a correlated value by multiplying with the respective ratio obtained from Table 3.2.1 below.

Table 3.2.1 - Stability correlation ratios

Specimen volume (cm^3)	Approx. specimen thickness (mm)	Correlation ratio	Specimen volume (cm^3)	Approx. specimen thickness (mm)	Correlation ratio
277–289	34.9	3.33	457–470	57.2	1.19
290–301	36.5	3.03	471–482	58.7	1.14
302–316	38.1	2.78	483–495	60.3	1.09
317–328	39.7	2.50	496–508	61.9	1.04
329–340	41.3	2.27	509–522	63.5	1.00
341–353	42.9	2.08	523–535	65.1	0.96
354–367	44.4	1.92	536–546	66.7	0.93
368–379	46.0	1.79	547–559	68.3	0.89
380–392	47.6	1.67	560–573	69.8	0.86
393–405	49.2	1.56	574–585	71.4	0.83
406–420	50.8	1.47	586–598	73.0	0.81
421–431	52.4	1.39	599–610	74.6	0.78
432–443	54.0	1.32	611–625	76.2	0.76
444–456	55.6	1.25			

The conversion factor may be applied based on either measured thickness or measured volume. The flow values and the converted stability values for all specimens at a given bitumen content are then averaged.

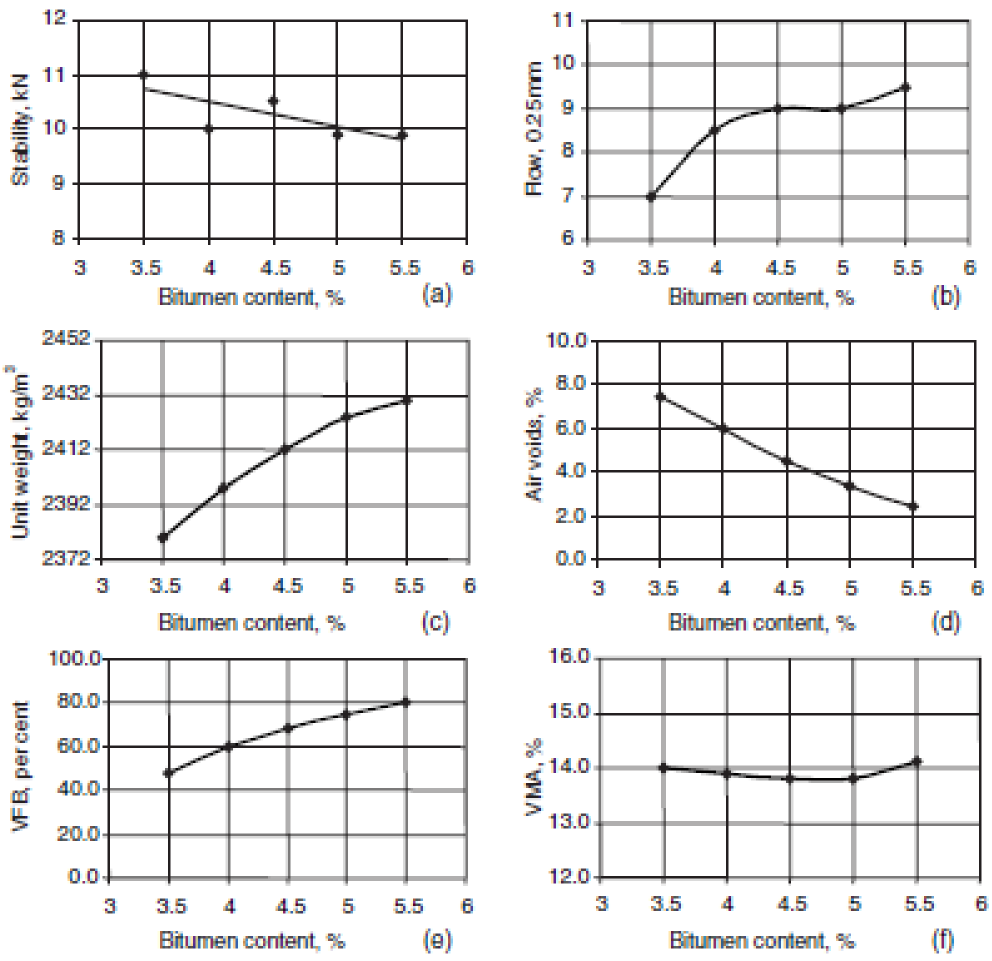


Figure 3.2.2 - Test property curves for hot mix design data by the Marshall method

As indicated in Fig. 3.2.2, a 'best fit' curve is plotted for each of the following relationships:

- Stability vs bitumen content
- Flow vs bitumen content
- Unit weight of total mix vs bitumen content
- Percentage air voids (Va) vs bitumen content
- Percentage voids filled with bitumen (VFB) vs bitumen content
- Percentage voids in mineral aggregate (VMA) vs bitumen content.

These graphs are used to determine the design bitumen content of the mix.

Analyzation of test data

The sensitivity of the mixture to bitumen content can be gained by examining the test property curves information.
Cases generally noted are:

(a) The stability value increases with increasing bitumen content up to a maximum after which the stability decreases.

(b) The flow value consistently increases with increasing bitumen content.

(c) The curve for unit weight of total mix follows the case of the stability curve, except that the maximum unit weight occurs at a little higher bitumen content than the maximum stability.

(d) The percentage air voids, Va, steadily decreases with increasing bitumen content, ultimately approaching a minimum void content.

(e) The percentage voids in the mineral aggregate, VMA, generally decreases to a minimum value then increases with increasing bitumen content.

(f) The percentage voids filled with bitumen, VFB, steadily increases with increasing bitumen content, due to the VMA being filled with bitumen.

Selection of final mix

The selected mix design is usually the most economical one that will satisfactorily meet all the established design criteria. However, this mix should not be designed to optimize one particular property. For instance, mixes with extremely high values of stability are often less desirable because pavements with such materials tend to be less durable, and may crack prematurely, under heavy volumes of traffic. This situation is especially critical if the subbase and subgrade materials beneath the pavement are weak and permit moderate to relatively high deflections under the actual traffic.

The design bitumen content should be selected to balance all the mix properties. The mix design criteria will normally produce a narrow range of acceptable bitumen contents that pass all the guidelines (Fig. 3.2.3), and the bitumen content selection is then adjusted within this narrow range to achieve a mix property that will satisfy the needs of the project.

Different properties are more critical for different circumstances, depending on traffic loading and volume, pavement structure, climate, construction equipment, and other factors.

In many cases, the most difficult mix design property to achieve is the minimum amount of voids in the mineral aggregate. The target is to provide enough space for the bitumen so it can provide adequate adhesion to bind the aggregate particles, but without bleeding when temperatures rise and the bitumen expands. Normally, the curve exhibits a U-shape, decreasing to a minimum value and then increasing with increasing bitumen content, as shown in Fig. 3.2.4(a).

The total volume changes across the range of bitumen contents. With the increase in bitumen, the mix becomes more workable and compacts more easily and, up to a specific point, the bulk density of the mix increases and the VMA decreases.

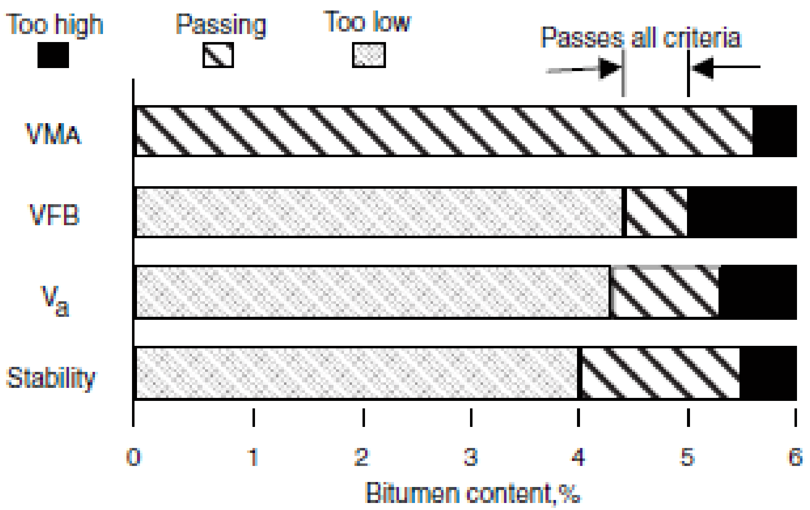


Figure 3.2.3 - An example of the narrow range of acceptable bitumen contents arising from the Marshall test

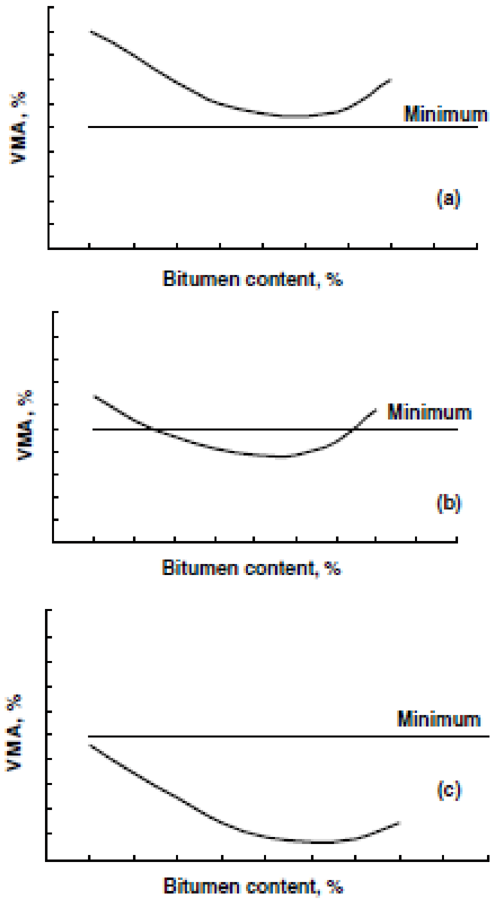


Figure 3.2.4 - Relationship between VMA and the specification limit

At some point as the bitumen content increases (the bottom of the U-shaped curve), the VMA begins to increase because the denser material (aggregate) is displaced and pushed apart by the less dense material (bitumen).

Ideally, the design bitumen content should be selected slightly to the left of the low point of the VMA curve in Fig. 3.2.4(a), provided none of the other mixture criteria are violated.

In some mixes, the bottom of the U-shaped VMA curve is very flat, meaning that the compacted mixture is not very sensitive to bitumen content in this range.

In the normal range of bitumen contents, compaction ability is more influenced by aggregate properties. However, at some point the quantity of bitumen will become critical to the behavior of the mix, and the effect of bitumen will dominate as the VMA increases noticeably.

If the bottom of the U-shaped VMA curve falls below the minimum criteria level required for the nominal maximum aggregate size of the mix in Fig. 3.2.4(b), it is an indication that changes to the job mix formula are necessary and that the aggregate grading should be modified to provide additional VMA. The design bitumen content shouldn't be selected at the extremes of the acceptable range, even if the minimum criteria are met. On the left-hand side the mix would be too dry, susceptible to segregation and, probably, with a high air voids percentage.

On the right-hand side, the mix could be expected to rut. If the minimum VMA criteria are completely violated over the entire bitumen content range, for instance, if the curve is completely below minimum in Fig. 3.2.4(c), a significant change in materials sources is recommended. It should be noted that the desired range of air voids (3 to 5 percent) is the level desired after several years of traffic and that this range does not vary with traffic.

This air void range will normally be achieved if the mixture is designed at the correct compaction effort, which is a function of the traffic load, and if the percentage air voids immediately after construction is about 8 percent, as some consolidation can be expected under traffic.

It's been proven that asphalt concrete mixtures which ultimately consolidate to less than 3 percent air voids are more likely to rut and shove if placed in heavy traffic locations. Several factors may contribute to this occurrence, like an accidental increase in bitumen content at the mixing facility or an increased amount of fine particles passing the 75 µm sieve which acts as a bitumen extender.

Problems can also occur if the final air void content is above 5 percent or if the pavement is constructed with over 8 percent air void initially, therefore, brittleness or premature cracking are possible results under these conditions.

The VFB, VMA and Va are all interrelated, and only two of the values are necessary to calculate the third. The main effect of the VFB criteria is to limit maximum levels of VMA, and, subsequently, maximum levels of bitumen content.

VFB also restricts the allowable air void content for mixes that are near the minimum VMA criteria.

Mixes designed for lower traffic volumes will not pass the VFB criteria with a relatively high percentage of air voids (5%) even though the air void criteria range are met.
This ensures that less durable mixes are avoided in light traffic situations.
Mixtures designed for heavy traffic will not pass the VFB criteria with relatively low percentage air voids (less than 3.5 percent), even though the amount of air voids falls within the acceptable range.

Because low air void content can be very critical in terms of permanent deformation, the VFB criteria helps to avoid those mixes that would be susceptible to rutting in heavy traffic situations.

3.2.1 Asphalt Concrete of the Sub-Surface Layer - AC 14 reg 35/50 (BBsb)

3.2.1.1 Specifications Required

- **Characteristics of Aggregates**

The aggregates of this mixture should meet the following parameters:

Table 3.2.1.1 – Specified Aggregate Characteristics

Characteristic	Specified Value
Gross Aggregate Shape - Flattening Index	FI_{20}
Stretching Index	25
Sand Equivalent of Fraction 0/2 mm	SE_{55}
Methylene Blue Value of Fraction 0/2 mm	MB_2
Methylene Blue Value of Fraction 0/0.125 mm	MB_f10
Fragmentation Resistance - Los Angeles Coefficient	LA_{30}
Abrasion Resistance - Micro-Deval Coefficient	$M_{DE}15$
Water Absorption	≤1 %

The aggregate mixture must also meet the following particle size distribution range:

Table 3.2.1.2 – Specified Particle Size Distribution of the Aggregates

Sieve Opening	Particle Size Distribution Range
16 mm	100
14 mm	90 – 100
12.5 mm	80 – 90
10 mm	67 – 83
8 mm	---
6.3 mm	---
4 mm	42 – 60
2 mm	30 – 42
1 mm	---
0.5 mm	14 – 22
0.125 mm	7 – 13
0.063 mm	5 – 9

- **Bituminous mixture's characteristics**

The mixture shall present the following "Marshall" characteristics:

Table 3.2.1.3 – Specified Bituminous Mixture's Characteristics

Characteristic	Specified Value
Breaking Force, KN	8 – 21
Deformation (mm)	2.5 – 4
Qmin (KN/mm)	Qmin2.5
Conserved Resistance Index, I.R.C (%)	≥ 80
Voids in Mineral Aggregate, V.M.A (%)	≥ 14
Porosity, Vm (%)	3 – 5
Filler/Bitumen Ratio (%)	1.2 – 1.5

3.2.1.2 Characterization of mixture's components

- **Bitumen characteristics**

The bituminous binder to be used in the mixture's formulation, is a bitumen of a nominal penetration range of 35/50, supplied by Repsol.

- **Aggregate characteristics**

A range of different size aggregates are selected, and are presented below together with their geological nature and source of supply:

- Fine aggregate 0/6 mm: has a granitic nature, and it's supplied by the quarry "Jaime Ribeiro e Filhos, S.A. - Vilar do Paraíso, Vila Nova de Gaia" situated in a convenient location in terms of its distance to site.
- Coarse aggregate 6/10 mm: of a granitic nature, supplied by the same above quarry.
- Coarse aggregate 10/16 mm: of a granitic nature, supplied by the same above quarry.
- Filler: of a calcareous nature, supplied by "V.A.C - Vitaliano Adrião Casinhas, Lda".

Next are presented the aggregate lab tests results, in order to compare with the required characteristics.

Table 3.2.1.4 – Aggregate Tests Results

Test	Fraction		
	0/6 mm	6/10 mm	10/14 mm
Methylene Blue Value of Fraction 0/0.125 mm (g_{dye}/kg)	3.3	---	---
Methylene Blue Value of Fraction 0/2 mm (g_{dye}/kg)	0.7		
Gross Aggregate Shape - Flattening Index (%)	---	2	3
Stretching Index (%)	---	18	19
Sand Equivalent of Fraction 0/2 mm (%)	66	---	---
Fragmentation Resistance - Los Angeles Coefficient of Fraction (%)	---	---	29
Abrasion Resistance - Micro-Deval Coefficient (%)	---	---	10
Water Absorption (%)	0.5 (Fraction 0.063/4) / 0.7 (Fraction 4/31.5)	0.7	0.7

Comparing tables 3.2.1.3 and 3.2.1.4, we can ensure the aggregates' compatibility with the required characteristics.

3.2.1.3 Characteristics of the bituminous mixture

- **Characteristics of the aggregate mixture**

Depending on the required particle size distribution, it was possible adopting certain granular material proportions, in order to obtain an adequate aggregate mixture which falls into the specified distribution range.

Table 3.2.1.5 – Aggregate Proportions

Aggregate Designation	Percentage (%)
Fine 0/6	52.5
Coarse 6/10	15
Coarse 10/14	29
Filler	3.5
Total	100

Table 3.2.1.6 presents the particle size distribution of the selected aggregate mixture.

Table 3.2.1.6 – Mixture's Particle Size Distribution

Sieve Opening	Mixture's Particle Size Distribution	Particle Size Distribution Range
16 mm	100	100
14 mm	94	90 – 100
12.5 mm	85	80 – 90
10 mm	71	67 – 83
8 mm	62	---
6.3 mm	56	---
4 mm	44	42 – 60
2 mm	33	30 – 42
1 mm	24	---
0.5 mm	18	14 – 22
0.125 mm	9	7 – 13
0.063 mm	6.5	5 – 9

- **"Marshall" characteristics of the bituminous mixture**

The objective of this stage is to find out the mixture's Marshall Characteristics, by preparing samples with five different bitumen percentages of 4%, 4.5%, 5%, 5.5%, 6%.

To prepare these samples, they should be molded according to the Marshall method, and automatically compacted by applying 75 blows on each sample end.

After that, a set of experiments is carried out for the purpose of determining the following "Marshall" characteristics: density, breaking force, deformation, porosity, voids in mineral aggregate VMA, and the conserved resistance.

- **Optimum binder percentage**

Based on the studied Marshall characteristics, it was verified that the optimum bitumen percentage is 5.0%, the following table presents the mixture's characteristics for the optimum bitumen percentage.

Table 3.2.1.7 – Characteristics of Bituminous Mixture

Characteristic	Obtained Value	Specified Value
Breaking Force, KN	17	8 – 21
Deformation (mm)	3	2.5 – 4
Qmin (KN/mm)	5.8	Qmin2.5
Conserved Resistance Index, I.R.C (%)	94	≥ 80
Voids in Mineral Aggregate, V.M.A (%)	15	≥ 14
Porosity, Vm (%)	3	3 – 5
Filler/Bitumen Ratio (%)	1.3	1.2 – 1.5
Bulk Specific Gravity (Kg/m3)	2392	---
Maximum Theoretical Specific Gravity (Kg/m3)	2466	---
Water Sensibility, ITSR (%)	98	---

3.2.1.4 Final Mix Summary

Based on the results obtained, the following formula is adopted for the mix ***AC 14 reg 35/50 (BBsb):***

Material Designation	Percentage (%)
Fine 0/6	49.9
Coarse 6/10	14.2
Coarse 10/14	27.6
Filler	3.3
Bitumen 35/50	5.0

Similarly, the rest of the main track mixtures' formula is obtained:

3.2.2 High Modulus Bituminous Mixture of the Base Layer - AC 20 base 10/20 (MBAM)

Material Designation	Percentage (%)
Fine 0/6	32
Coarse 6/10	22
Coarse 10/14	24.2
Coarse 14/20	10
Filler	6.6
Bitumen 10/20	5.2

3.2.3 Bituminous Macadam of the Base Layer - AC 20 base 35/50 (MB)

Material Designation	Percentage (%)
Fine 0/6	35.3
Coarse 6/10	15.4
Coarse 10/14	23.6
Coarse 14/20	16
Filler	5.3
Bitumen 35/50	4.4

3.2.4 Permeable Asphalt Concrete of the Surface Layer- PA 12.5 surf 50/70 (BBd)

Material Designation	Percentage (%)
Fine 0/6	10.8
Coarse 6/10	36.5
Coarse 10/14	47.4
Filler	0.9
Bitumen 50/70	4.4

3.3 Aggregates quality control

This process is frequently done prior to mixture fabrication, by conducting a list of laboratory tests for each category of aggregates, in order to ensure their compliance with the required specifications.

- **Tests on fine aggregate 0/6 mm include:**
  1. Density and Water absorption.
  2. Sand equivalent.
  3. Methylene blue.

Next will be provided the description of each of the above-mentioned tests conducted on a fine aggregates sample alongside the results obtained:

Density and Water absorption

Specific gravity is a measure of a material's density (mass per unit volume) compared to the density of water at 23°C.

Absorption, which is also determined by the same test procedure, is a measure of the amount of water that an aggregate can absorb into its pore structure. Pores that absorb water are also called "water permeable voids".

This test is used to calculate the specific gravity of a fine aggregate sample by determining the ratio of the weight of a given volume of aggregate to the weight of an equal volume of water.

The fine aggregate specific gravity test measures fine aggregate weight under three different sample conditions:

- Oven-dry (no water in sample).
- Saturated surface dry (water fills the aggregate pores).
- Submerged in water (underwater).

Using these three weights and their relationships, a sample's apparent specific gravity, bulk specific gravity and bulk SSD specific gravity as well as absorption can be calculated.

Aggregate specific gravity is needed to determine weight-to-volume relationships and to calculate voids in mineral aggregate (VMA), and voids filled by asphalt (VFA). Absorption indicates the aggregate durability as well as the volume of bitumen it is likely to absorb.

Figure 3.3.1- Fine aggregate specific gravity test pycnometer

Fraction 0.063/4 mm							
Mass of pycnometer+ aggregate	Mass of pycnometer full of water	Mass of saturated aggregate with dry surface	Mass of oven dried sample	Density of impermeable particles	Density of oven dried particles	Density of saturated particles	Absorption after 24 h immersion
M2	M3	M1	M4	$\rho_a = \rho_w \frac{M_4}{M_4 - (M_2 - M_3)}$	$\rho_{rd} = \rho_w \frac{M_4}{M_1 - (M_2 - M_3)}$	$\rho_{ssd} = 1 + \rho_{rd} - \frac{\rho_{rd}}{\rho_a}$	$WA_{24} = \frac{100 \times (M_1 - M_4)}{M_4}$
(g)	(g)	(g)	(g)	(Mg/m^3)	(Mg/m^3)	(Mg/m^3)	%
2258	1542	1147	1141	2,68	2,64	2,66	0.5 ≤ 1 **OK**

The absorption is calculated using the formula mentioned in the previous table, giving a value of 0.5% ensuring its compliance with the maximum specification limit of 1%.

Sand equivalent

Excessive dust or plastic fines in HMA aggregate lead to a lack of stability or moisture damage and stripping.

The sand equivalent test is a field test conducted to show the relative proportions of fine dust or clay materials in fine aggregate or granular soils, to determine whether or not it has enough dust or plastic fines to make a HMA mixture unstable or susceptible to stripping, which makes it valuable in preventing the manufacture of poor performing mixtures.

In the sand equivalent test, a sample of aggregate passing the No. 4 (4.75 mm) sieve and a small amount of flocculating solution are poured into a graduated cylinder in order to separate the clay from the sand particles. The sample is then irrigated with additional flocculation solution forcing the clay material into suspension above the sand. After a defined sedimentation period, the height of flocculated clay and height of sand are determined and the sand equivalent is expressed as a ratio of the height of sand over the height of clay.

Higher sand equivalent values indicate cleaner aggregates with less dust or clay material.

Figure 3.3.2- Sand equivalent cylinder

Mass of tray	M2	g	11.41
Mass of tray + wet sample	A	g	82.95
Mass of wet sample	M1 = A-M2	g	71.54
Mass of tray + dry sample	B	g	82.29
Mass of dry sample	M3 = B-M2	g	70.88
Moisture content of sample	W= (M1-M3)/M3 × 100	%	0.9
Test temperature	t	°C	19.0

Sample No.			1	2
Clay + Sand height	h1	mm	134	133
Sand height	h2	mm	87	85
Sand Equivalent of sample	EA = (h2/h1) × 100	%	64.9	63.9
Sand Equivalent			64 ≥ 55 OK	

The specification limit in this case doesn't permit a Sand Equivalent value lower than 55%, as one of the basic requirements to attain a proper mixture stability. Therefore, with the achieved value of 64% as shown in the above table, the tested specimen complies with the required test limit.

Methylene blue

This test is based on adding quantities of a standard aqueous solution of methylene blue (MB) to a sample of dry fine aggregate passing the No. 200 (0.075 mm) sieve, until adsorption of the dye stops.

After each addition of MB solution and stirring for one minute, a small drop of the aggregate suspension is removed with a glass rod and placed on a filter paper.

First, a clear circle of MB-stained dust is formed and is surrounded with an outer ring of clear water. Successive additions of MB solution are repeated until the end point is reached when the ring of clear water turns light blue.

The MB value of a specific fine aggregate fraction is reported as milligrams of MB per gram of fine aggregate. The MB value expresses the quantity of MB required to cover the total surface of the clay fraction of the sample with a single-molecule layer of MB, therefore, the MB value is proportional to the product of the clay content times the specific surface of the clay.

Thus, higher MB values indicate more clay.

Figure 3.3.3- Methylene blue test equipment

Water content				
Fraction tested			**0/2 mm**	**0/0.125 mm**
Capsule No.			48	56
Mass of capsule	P	g	11.41	11.3
Mass of capsule containing wet soil	P1	g	82.95	30.25
Mass of capsule containing dry soil	P2	g	82.29	30.13
Mass of wet soil	M	g	71.54	18.95
Mass of dry soil	M´	g	70.88	18.83
Water content of sample	W=100*(M-M´)/M´	%	0.93	0.64

Test of Fraction 0/2 mm			
Wet mass of test sample	g	200 × (1+W/100)	201.86
Wet mass of test sample of fraction 0/2 mm	g	M_0	202
Dry mass of test sample of fraction 0/2 mm	g	M_1	200.01
Total quantity V_1 of added dye solution	ml	V_1	15
MB value of fraction 0/2 mm	(g_{dye}/kg)	MB	**0.7 ≤ 2 OK**

Test of Fraction 0/0.125 mm			
Wet mass of test sample	g	30 × (1+W/100)	30.19
Wet mass of test sample of fraction 0/0.125 mm	g	M_0	30
Dry mass of test sample of fraction 0/0.125 mm	g	M_1	30
Total quantity V_1 of added dye solution	ml	V_1	10
MB_F value of fraction 0/0.125 mm	(g_{dye}/kg)	MB_F	**3.3 ≤ 10 OK**

An MB value of 0.7 g_{dye}/kg results from testing a fraction of 0/2 mm, whereas the value of the same is higher when testing a fraction of 0/0.125 mm as shown in previous tables, with both values meeting the respective specification limits.

- **Tests on coarse aggregate 6/10 mm include:**

<u>Density and Water absorption</u>

The coarse aggregate specific gravity test is used to calculate the specific gravity of a coarse aggregate sample by determining the ratio of the weight of a given volume of aggregate to the weight of an equal volume of water. The procedure is similar in nature to that of the fine aggregate specific gravity test.

Figure 3.3.4- Coarse Aggregate Specific Gravity, pavementinteractive.org

Fraction 4/31.5 mm							
Mass of pycnometer+ aggregate	Mass of pycnometer full of water	Mass of saturated aggregate with dry surface	Mass of oven dried sample	Density of impermeable particles	Density of oven dried particles	Density of saturated particles	Absorption after 24 h immersion
M2	M3	M1	M4	$\rho_a = \rho_w \frac{M_4}{M_4 - (M_2 - M_3)}$	$\rho_{rd} = \rho_w \frac{M_4}{M_1 - (M_2 - M_3)}$	$\rho_{ssd} = 1 + \rho_{rd} - \frac{\rho_{rd}}{\rho_a}$	$WA_{24} = \frac{100 \times (M_1 - M_4)}{M_4}$
(g)	(g)	(g)	(g)	(Mg/m^3)	(Mg/m^3)	(Mg/m^3)	%
4094	3055	1661	1651	2,69	2,65	2,67	$0.6 \leq 1$ **OK**

The conducted test gives an absorption value of 0.6%, which is acceptable given a superior limit of 1%.

- **Tests on coarse aggregate 10/14 mm include:**
    1. Density and Water absorption.
    2. Los Angeles abrasion test.

Density and Water absorption

Fraction 4/31.5 mm							
Mass of pycnometer+ aggregate	**Mass of pycnometer full of water**	**Mass of saturated aggregate with dry surface**	**Mass of oven dried sample**	**Density of impermeable particles**	**Density of oven dried particles**	**Density of saturated particles**	**Absorption after 24 h immersion**
M2	M3	M1	M4	$\rho_a = \rho_w \frac{M_4}{M_4 - (M_2 - M_3)}$	$\rho_{rd} = \rho_w \frac{M_4}{M_1 - (M_2 - M_3)}$	$\rho_{ssd} = 1 + \rho_{rd} - \frac{\rho_{rd}}{\rho_a}$	$WA_{24} = \frac{100 \times (M_1 - M_4)}{M_4}$
(g)	(g)	(g)	(g)	(Mg/m^3)	(Mg/m^3)	(Mg/m^3)	%
4364	3055	2094	2083	2,69	2,65	2,66	0.5 ≤ 1 **OK**

Similarly, by applying the previous test procedure on 10/14 mm aggregate, we get a complying absorption value of 0.5%.

Los Angeles abrasion test

An aggregate sample retained on the No. 12 (1.70 mm) sieve is placed inside a rotating steel drum containing a specified number of steel spheres. As the drum rotates, a shelf inside the drum picks up the aggregate and steel spheres.

The shelf carries the steel spheres around until they drop on the opposite side of the drum, subjecting the aggregate to impact and crushing. Therefore, the aggregate is subjected to abrasion and grinding as the drum continues to rotate until the shelf picks up the contents, and the process is repeated. The drum is rotated for a specified number of revolutions.

The next step is removing the aggregate from the drum and sieving it on a No. 12 (1.70 mm) sieve. The aggregate retained on the sieve is weighed and the difference between this weight and the original weight is expressed as a percentage which is defined as the L.A. abrasion loss value. Therefore, lower L.A. abrasion loss values refer to a tougher and more abrasion resistant aggregate.

The major equipment used in the L.A. abrasion test are shown in the following figures.

Figure 3.3.5.1- Los Angeles abrasion testing equipment

Figure 3.3.5.2- Steel spheres

	Gross aggregate		
	Fractions (mm)	**No. of balls**	**Ball load mass (g)**
X	10 / 14	11	4690 to 4860
	11.2 / 16	12	5120 to 5300
	8 / 11.2	10	4260 to 4420
	6.3 / 10	9	3840 to 3980
	4 / 8	8	3410 to 3540
	4 / 6.3	7	2930 to 3100

Sample mass before test (g)	**5002**	
Mass of aggregate retained on 1.6 mm sieve (g)	**3572**	
Los Angeles coefficient, LA (%)	**29 ≤ 30**	**OK**

The specification limit for this test doesn't allow an L.A. loss value higher than 30%, which makes the result adequate as shown in the previous table.

- **Tests on coarse aggregate 14/20 mm include:**

Density and Water absorption

The resulted absorption value of 0.5% falls under the maximum specified limit of 1%.

Fraction 4/31.5 mm							
Mass of pycnometer+ aggregate	**Mass of pycnometer full of water**	**Mass of saturated aggregate with dry surface**	**Mass of oven dried sample**	**Density of impermeable particles**	**Density of oven dried particles**	**Density of saturated particles**	**Absorption after 24 h immersion**
M2	M3	M1	M4	$\rho_a = \rho_w \frac{M_4}{M_4 - (M_2 - M_3)}$	$\rho_{rd} = \rho_w \frac{M_4}{M_1 - (M_2 - M_3)}$	$\rho_{ssd} = 1 + \rho_{rd} - \frac{\rho_{rd}}{\rho_a}$	$WA_{24} = \frac{100 \times (M_1 - M_4)}{M_4}$
(g)	(g)	(g)	(g)	(Mg/m^3)	(Mg/m^3)	(Mg/m^3)	%
5039	3055	3173	3157	2,69	2,65	2,67	0.5 ≤ 1 **OK**

The above-mentioned tests are conducted on a regular basis to ensure the aggregates compatibility with the specification limits, in order to proceed afterwards to the mixture fabrication, transportation, and construction processes.

4 HOT MIXTURES FABRICATION AND APPLICATION

Bituminous paving mixes are prepared at a central mixing plant.

Aggregates are blended, heated, dried, and mixed with bitumen to produce a hot asphalt paving mixture.

The basic steps in the construction of bituminous wearing courses, base courses or road bases may be summarized as follows:

1. Mixture preparation
2. Underlying or levelling course preparation
3. Mixture transportation and placement
4. Joints construction
5. Compaction and finishing

Storing, Proportioning and Mixing materials

Storage

Aggregates are stored so that separately sized aggregates will not be mixed, and asphalt binder is stored so that different grades of asphalt will not be mixed.

Any aggregate which has been mixed with another size of aggregate has to be removed and replaced with aggregate of specified grading.

Cold storage is the storing of aggregates prior to their processing in a drier, and hot storage, which is the method used, is the storing of aggregates after their processing in a drier.

Asphalt Binder Storage

The asphalt bitumen to be used as a binder for asphalt concrete is stored in tanks accurately calibrated in uniform intervals of 375 to 400 L and maintained to this accuracy. These tanks must be accessible for measuring the volume of asphalt at any time.

A suitable sampling device is provided in asphalt feed lines connecting plant storage tanks to the asphalt weighing system or spray bar. The sampling device consists of a valve with a nominal diameter between 10 and 20 mm constructed in a manner that a one-liter sample may be withdrawn slowly at any time during plant operations. The valve shall be maintained in good condition, and if it fails to function properly, it shall be replaced.
The sampling device must be readily accessible and in an area, free of dangerous obstructions and should be located between 600 and 750 mm above the platform.

The discharge end of the asphalt binder circulating pipe is maintained below the surface of the asphalt binder in the storage tank to prevent discharging hot asphalt binder into open air.

A temperature-sensing device is installed in the asphalt feed line. The device measures the temperature of the asphalt and shall be accurate to 5°C. The indicator is located and maintained at the point where the proportioning operations are controlled.

Drying

Aggregates are fed directly to a drier-drum mixer or to a drier at a uniform rate. Drying shall continue for a sufficient time and at a sufficiently high temperature that, at the time of spreading, the moisture content of the completed mixture does not exceed one percent.

The drier or drier-drum mixer is provided with a device which senses the temperature of the material leaving the drier. The temperature-sensing device has to be accurate to the nearest 5°C, and shall be installed in such a manner that changes of 5°C in temperature of the material will be shown within one minute.

The indicator is located and maintained at the point where the proportioning operations are controlled.

Proportioning

At least two weeks prior to their intended use, a set of aggregates should be presented, in the quantity requested, from the source proposed to use for the project.

In batch-mixing plants, these samples are obtained from the normal sampling area, just before the weigh hopper.

Should the contractor change the source of supply, new samples and proposed proportions should be presented, at least two weeks before their intended use.

A change which affects any portion of the total aggregate in the mix will be considered a change in source and will require a new mix design.

Proportioning for batch mixing

In this case of using a batch mixing equipment, each aggregate storage bin is equipped with a suitable, safe sampling device which will provide a sample, representative of actual production, of the aggregate discharged into the weigh hopper or volumetric proportioning bin.

The fine material collected in all dust control systems shall be proportioned. When supplemental fine aggregate is used, it should be proportioned by mass.

A suitable, safe sampling device is installed in each feed line or surge tank preceding the weigh hopper.

Moreover, the delivery point of samples should be convenient and safe.

4.1 Mixture preparation at a central mixing plant

A central mixing plant is the factory at which the bituminous paving mixture is produced, in a process involving the assembly, weighing, blending, and mixing of the aggregates and bitumen, and ending with the discharge of the mixture into hauling units for transport to the job site.

The central mixing plant used is a semi-portable type plant in which the separate units are difficult to dismantle, but can be taken down, transported on trailers, trucks, or railway cars to a new location, and then reassembled, in a process that may require a few hours or several days, depending on the scale of plant involved. The capacity of this plant ranges up to about 400 t/h of material, and most hot mixes are prepared at temperatures ranging from 110 to 185°C.

Two general types of central mixing plants are in common use: drum mix plants and batch plants.

The main components of the batch hot-mix plant, which is used for this site mixtures fabrication, are shown in Fig. 4.1.

The dryer in a batch facility is of a ‘counter-flow’ design whereby the aggregates flow in the drum in opposition to the flow of the exhaust gases.

The drier, which is mounted at an angle to the horizontal, is essentially a large rotating cylinder that is equipped with a heating unit at the lower end.

The heating unit is usually a low-pressure air-atomization system using fuel oil, and the hot gases from the burner pass from the lower end up the cylinder and out at the upper end.

The cold aggregate is fed into the upper end of the drier, picked up by steel angles or blades set on the inside face of the cylinder, and dropped through the burner flame and hot gases as it moves down the cylinder.

The hot aggregate is then discharged from the lower end of the drier onto an open conveyor or an enclosed hot elevator that transports it to storage bins that are mounted at the top of the power plant.

In the preparation of the hot mixtures, the temperature of the aggregates may be raised to 160°C or more, so that practically all the moisture is removed.

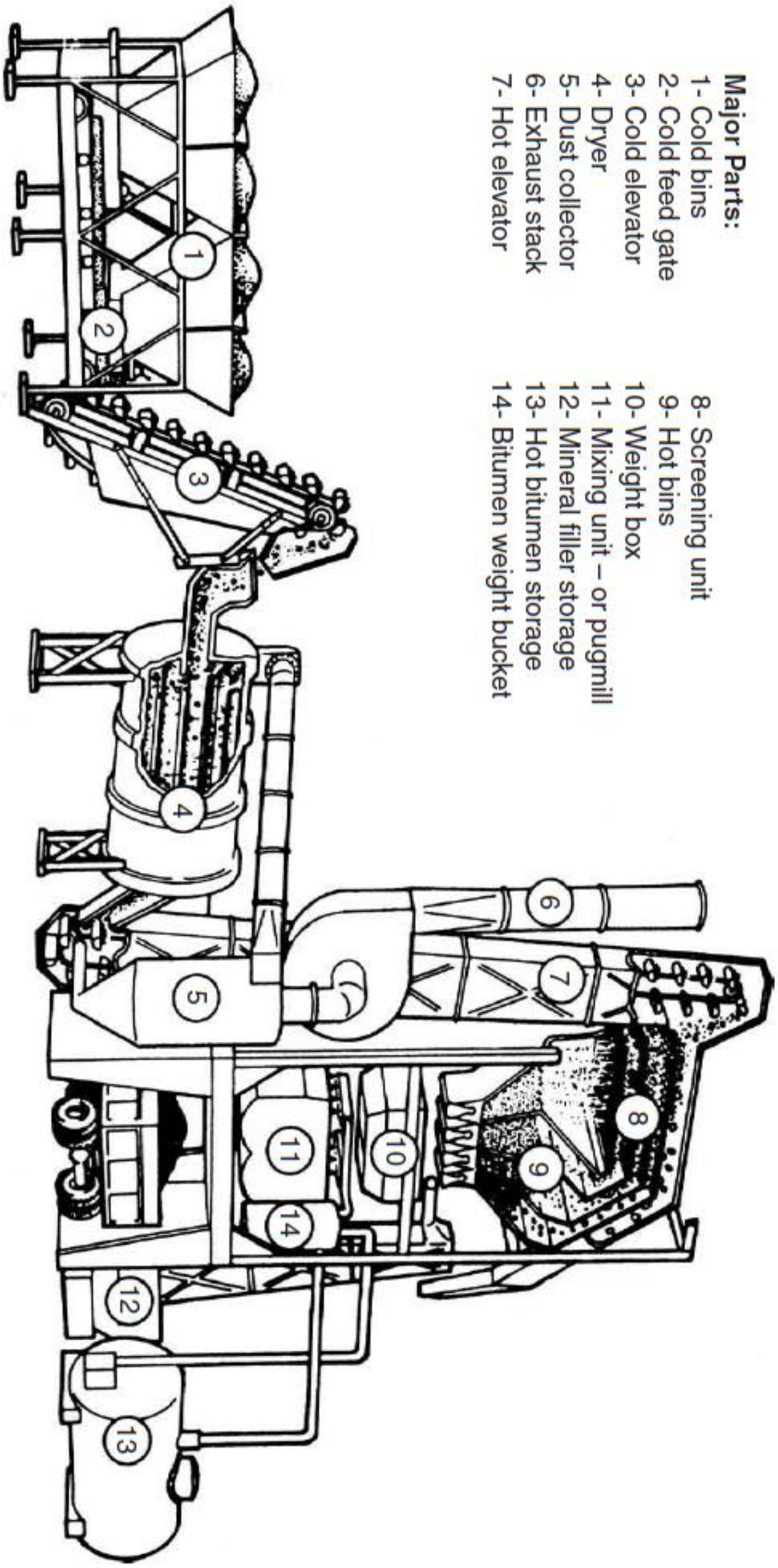


Figure 4.1 – An Asphalt Batch Plant Scheme

Figure 4.2 – Mixing Plant Used

Figure 4.3 – Cold Aggregate Supply System

Figure 4.4 – Bitumen Supply System

The hot exhaust gases from the dryer are passed through a dust collection system to remove dust particles so that emission standards are met. The collected dust is returned to the hot material elevator or filler storage silo for subsequent reintroduction into the mixture as required. Mineral filler that is added to the mixture is not normally passed through the aggregate drier, it is fed instead by a separate device directly into the mixing unit or into the aggregate batching unit.

After the aggregates exit the hot elevator at the top of the tower, they are discharged and separated into several sizes which are then stored in hot material bins. The stored aggregates are later proportioned, by the control system, from the bins into a weigh box that is mounted on a set of scales.

These dry aggregates are then discharged into the mixer with the hot bitumen, which has been weighed, stored in a weigh bucket, and sprayed into the mixer after a few seconds of dry mixing. The mixer is typically a twin-shaft, counter rotating mixer designed to coat the aggregate quickly (in about 45 s) with bitumen.

After mixing, the bituminous mixture is ready to be discharged into a truck for transport to the site.

Batch plants can be manual, semi-automatic or automatic, depending on the degree of automation.

In manual batch plants, air cylinders or hydraulic cylinders that are electrically-actuated by the operator, control the bin gates, fines feeders, bitumen supply and spray valves, the weigh box discharge gate, and the mixer's discharge gates.

In semi-automatic batch plants, the various operations constituting each mixing cycle are under automatic control, like the quantities of bitumen and aggregate introduced into the mixes, the mixing times, the sequencing of the mixing functions, and the operation of the mixer's discharge gate.

Whilst in the fully automatic batch plant used, the weighing and mixing cycle is repeated until the operator stops it, or until it stops itself because of material shortage or some other extraordinary event. Automatic plants also provide records of the amounts of the component materials in each batch.

4.2 Control of mixture uniformity

Control of the uniformity of hot mixes is very important, as any appreciable variation in aggregate gradation or bitumen content will be reflected in a change in some other characteristic of the mix. Sampling and testing are therefore among the most important functions in plant control.

Samples are typically obtained at various points in the plant to establish if the processing is in order up to those points. A final extraction test of the mixture is normally carried out to confirm its uniformity, gradation, and bitumen content.

The extraction test measures the bitumen content and provides the aggregate for gradation testing. The extraction and gradation results should fall within the job mix tolerance specified; if they do not, corrective measures must be taken to bring the mix within the uniformity tolerance.

4.3 Mixture transportation

Hot-mix material is transported from the plant to the job site by trucks with smooth metal beds that have previously been cleaned of all foreign material. The vehicle bed may be sprayed with a light coat of lime water, soap solution, or some similar substance to prevent adherence of the mixture; fuel oils should not be used as they have a detrimental effect on the mixture. The vehicle is insulated against excessive heat loss in the mixture during hauling, and it should be covered with a canvas in order to protect the material when harmful weather conditions are foreseen.

The mixture temperature, when discharged from the transporting truck to the hopper of the spreader or paver, should fall between the range of 130°C and 150°C.

In addition to the plant control measures, a mixture site verification is conducted before and after the discharge in the paver, to observe the mixture’s appearance, aggregate-binder homogeneity, contaminations, as well as its temperature.

The mixture will be rejected in any of the following conditions:

- Excessive temperatures
- Low temperatures
- Excessive amount of bitumen
- Low quality bitumen
- Lack of homogeneity
- Excessive amount of coarse aggregate
- Excessive amount of fine aggregate
- Excessive humidity
- Segregation
- Contamination

4.4 Mixture spreading

Spreading equipment

Asphalt pavers are self-propelled mechanical spreading and finishing equipment, provided with a screed assembly capable of distributing the material to not less than the full width of a traffic lane.

Screed action includes any cutting, crowding or other practical action which is effective on the mixture without tearing or shoving, and which produces a surface texture of uniform appearance. The screed is adjustable to the required section and thickness.

The paver is provided with a suitable full width compacting device. Pavers that leave ridges, indentations or other marks in the surface shouldn't be used unless the ridges, indentations or other marks are eliminated by rolling or prevented by an operation adjustment.

Figure 4.5 – Asphalt Paver Front/Rear

The asphalt paver operates independently of the vehicle being unloaded and shall can propel the vehicle being unloaded in a satisfactory manner. The load of the haul vehicle is limited to that which will ensure satisfactory spreading.

While unloading, the haul vehicle has to be in contact with the machine at all times, and the brakes of the haul vehicle shall not be depended upon to maintain contact between the vehicle and the machine.

Spreading

Surface courses of bituminous materials are placed on new or existing bases that require a thorough sweeping and cleaning to remove loose dirt and other foreign materials.

Placement of a bituminous mixture is permitted only when the underlying layer is dry and weather conditions are favorable. The placement of hot-mix materials is usually suspended when the ambient air temperature is less than 4°C.

Bituminous road base, levelling and surface courses are placed and compacted in separate operations. In some cases, thick layers composed of the same mixture may be placed in two or more layers.

Hot mixture asphalt (HMA) is placed by an asphalt paver that spreads the mixture in a uniform layer of the desired thickness, and finishes it to the desired elevation and cross-section, ready for compaction.

Pavers are widely used with hot mixes, which must be placed and finished rapidly so that they can be compacted while hot. The wheelbases of these machines are sufficiently long to eliminate the need for forms, and to minimize the occurrence of irregularities in the underlying layer. The machines can process thicknesses up to 250 mm over a width of up to 4.3 m, while working speeds generally range from 3 to 21 m/min.

As indicated in Figures 4.6 and 4.7, the mixture to be placed by the paver is tipped into a receiving hopper from a transport unit. It is then fed from the hopper towards the finishing section of the machine, spread and agitated by screws that ensure the uniformity of the spread material over the full processing width.

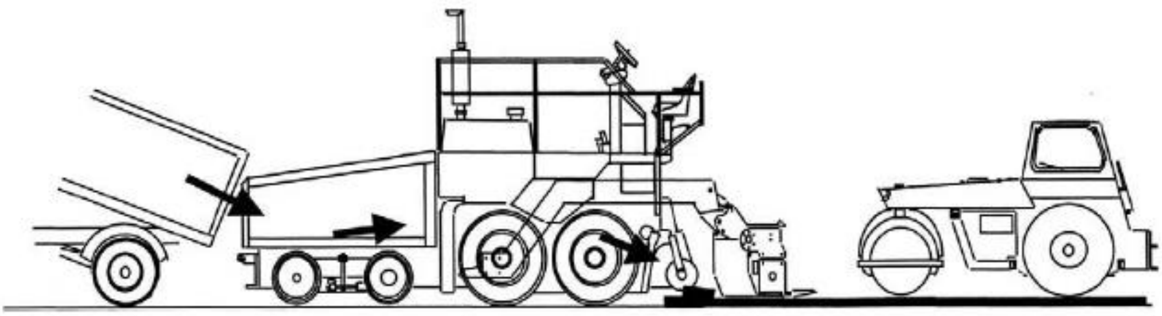


Figure 4.6 – Mode of Operation of an Asphalt Paver

Figure 4.7 – Paving Process in Action

These pavers are fully adjustable to ensure a uniform flow of material through the machine and to produce a smooth, even layer of the desired thickness and cross-section.

Bituminous pavers are provided with electronic screed control systems. These sensors operate on a reference profile, sense changes in the position of the floating screed element of the paver or of the reference profile, and then automatically apply corrections to the angle of the screed so that the surface being laid is continually parallel to the reference profile.

Figure 4.8 – Paver´s Electronic Control System

Usually the reference profile controls the longitudinal profile of the surface at one side of the machine whilst a slope sensor controls the cross-section.

A typical fixed reference profile is a string wire that is stretched between pins set at close spacing (about 7m or less).

When placing the bituminous mixture, special attention must be given to the construction of joints between old and new surfaces or between successive days' work.

It is essential that a proper bond be secured at longitudinal and transverse joints between a newly placed mixture and an existing bituminous mat. The best longitudinal joint can be achieved when the material in the edge being laid against is still warm enough for effective compaction.

4.5 Compaction of the bituminous layer

When the spreading and finishing operations have been completed, and while the mixture is still hot, rolling is begun. Rolling may be carried out by steel wheel or pneumatic tired rollers or by a combination of the two.

Steel wheel rollers used are of two-axle tandem type of 8 to 12 t.

Figure 4.9 - Steel Wheel Roller

Pneumatic tired rollers provide a closely-knit surface by kneading aggregate particles together, the tire contact pressures generally range from 276 to 620 kPa.

Figure 4.10 - Pneumatic Tired Roller

Vibratory steel-wheeled rollers, which provide a centrifugal force of up to 210 kN and up to 3000 vibrations/min, are also used to compact bituminous materials.
The bulk of the rolling is done in a longitudinal direction, beginning at the edges and gradually progressing toward the center – except on super elevated curves where rolling begins on the low side and progresses toward the high side.
Rolling procedures vary with the properties of the mixture, thickness of layer, and other factors.

Rolling is divided into three phases, which follow closely behind one another, namely initial rolling, intermediate rolling, and finish rolling. The initial and intermediate phases primarily provide the compacted density, and the final rolling gives the final smoothness. Steel tandem rollers are used for initial rolling, pneumatic tired rollers for intermediate rolling, and tandem rollers for finish rolling.

Specifications for the finished surface stipulate that it should be smooth, even, and compatible with the design grade and cross-section. While this seems to be a very high standard, these surfaces are readily attainable with most modern construction equipment. Deviations of more than 6 mm from the specified thickness of a wearing course are not allowed.

The densities to be obtained in the compacted layers are stipulated as a percentage of the theoretical maximum density or of the density of the laboratory compacted mixture.

The density of the compacted mixture is determined on specimens taken from the completed mat.

Rolling completes the construction of bituminous pavements, and traffic is normally permitted on the surface as soon as the compacted mixture has adequately cooled.

5 QUALITY CONTROL

Before construction starts, the contractor has to deliver the Quality Control Plan document to the site supervision department, which includes the various work units, the available human resources and equipment for the quality control, test types and frequencies to realize according to what's stipulated in the specifications, as well as result reports.

The contractor is not able to start working without the quality control plan being approved by the supervision department.

The control plan includes two phases:

- Pre compaction tests.
- Post compaction tests.

At least one mix specimen is collected daily in order to determine and check its particle size distribution. And at least once per week will be verified the correct functioning of the mix components including the bituminous binder.

Specimens will be taken upon mixer discharge, where will be carried out the following tests.

- Upon mixture discharge, and for each truck:
    - Mixture aspect control and temperature measure;
      All segregated, carbonized, overheated mixtures will be rejected, in addition to those which don't present homogeneity.
      Moreover, mixtures showing humidity bigger than 1% of the total mix weight will be rejected.
- At least twice a day (morning and afternoon):
    - Binder percentage calculation
    - Aggregate particle size distribution after bitumen extraction
- At least once a day:
    - 3 Marshall stability tests with 24h immersion in water of 60°C

5.1 Testing reports

The contractor must daily deliver photocopies of all the realized quality control tests to the site supervision department, as well as all dates referring to the externally received material that has been used in site, with a maximum period of 3 days.

Apart from conducting the previous tests, the contractor has to always have a quality control map in site, to be approved by the supervision department, which consists of the quality control test results, reported over the entire work done.

5.1.1 High Modulus Bituminous Mixture of the Base Layer - AC 20 base 10/20 (MBAM)

5.1.1.1 Pre-Compaction Tests

- **Particle size distribution analysis**

Consists of a typical sieve analysis performed on a sample of aggregate involving a nested column of sieves.

A representative weighed sample is poured into the top sieve which has the largest screen openings. Each lower sieve in the column has smaller openings than the one above. At the base is a rounded pan known as the receiver.

The column can be either placed in a mechanical shaker or shaken manually. After the shaking is complete, the material on each sieve is weighed. The weight of the sample of each sieve is then divided by the total weight to give the retained percentage on each sieve. The results of this test are used to verify the aggregate compliance with the particle size distribution limits specified.

m1	**Initial mass**	g	2780.0
m2	**Dry mass after wash**	g	2601.7
m1 - m2	**Wash losses**	g	178.3

Sieves	**Retained Material**		**Accumulated percentage of passing material**
mm	**g**	**%**	**%**
40.00			
31.50			**100**
20.00	64.2	2.3	**98**
16.00	231.4	8.3	**89**
14.00	125.1	4.5	**85**
12.50	144.5	5.2	**80**
10.00	251.6	9.1	**71**
8.00	281.1	10.1	**61**
6.30	233.2	8.4	**52**
4.00	292.1	10.5	**42**
2.00	241.9	8.7	**33**
1.00	201.1	7.2	**26**
0.50	175.7	6.3	**19**
0.125	249.5	9.0	**10**
0.063	92.7	3.3	**7.0**
Wash Losses	178.3	6.4	
Retained at the bottom	17.6	0.6	
Total	2780.0	100.0	

Figure 5.1- Set of Sieves shaken manually

- **Binder extraction**

A loose HMA (Hot Mix Asphalt) sample is spread out in a mesh basket and placed in a forced air furnace. The furnace heats the HMA and burns off the asphalt binder component in a process referred to as the **ignition**. Comparing the HMA sample weight before ignition and the aggregate weight after ignition gives the weight of asphalt binder burned off throughout the ignition process.

Figure 5.2- Ignition Oven

Binder Extraction			
Sample weight before ignition	M	g	2934.5
Sample weight after ignition	M_{1a}	g	2780.0

Determination of Binder Content			
Sample weight before ignition	M	g	2934.5
Sample weight after ignition	M_1	g	2780.0
Binder Content	**S**	**%**	**5.3**

By comparing both weights of the sample, before and after ignition, a binder content of 5.3% was calculated.

- **Theoretical Maximum Specific Gravity**

Is defined as the mixture's specific gravity excluding air voids. Thus, theoretically, if all the air voids were eliminated from the sample, the combined specific gravity of the remaining aggregate and asphalt binder would be the Theoretical Maximum Specific Gravity.

Significance:

The theoretical maximum specific gravities and densities of bituminous paving mixtures are properties whose values are influenced by the composition of the mixtures in terms of types and amounts of aggregates and bituminous materials.

1. They are used to calculate values for percent air voids in compacted mixtures.

2. They provide target values for the compaction of mixtures.

3. They are essential when calculating the amount of bitumen absorbed by the internal porosity of the individual aggregate particles in a bituminous paving mixture.

Test method:

A weighed sample of oven dried paving mixture in the loose condition is placed in a vacuum pycnometer. Sufficient water at a temperature of 25 ± 4°C is added to completely submerge the sample.

Vacuum is applied for 15 ± 2 minutes to gradually reduce the residual pressure in the vacuum pycnometer to 3.7 ± 0.3 kPa.

At the end of the vacuum period, the vacuum is gradually released. The volume of the sample of paving mixture is obtained by filling the vacuum container with water and weighing in air.

At the time of weighing, the temperature is measured as well as the mass.

From the mass and volume measurements, the specific gravity or density at 25°C is calculated. If the temperature employed is different from 25°C, an appropriate correction is applied.

Figure 5.3- Vacuum assembly loaded with a metal bowl

Volumetric Process			
Bitumen percentage, Pb (0.1%)	Pb	%	5.3
Mass of pycnometer + cap	m1	g	3247
Mass of pycnometer + cap + specimen	m2	g	5671
Mass of pycnometer + cap + specimen + water	m3	g	8936
Volume of vessel	Vp	m3	0.0042415
Washing temperature	-	ºC	18.0
Density of water at washing temp	ρw	kg/m3	998.7
Max theoretical specific gravity	**ρmv**	**kg/m3**	**2493**

<u>Calculation formula:</u>

$$\rho_{mv} = \frac{m2 - m1}{1000 * V_p - \frac{m3 - m2}{\rho_w}}$$

By using the previous formula, a max theoretical specific gravity value of **2493 kg/m3** was calculated.

- **VMA and VFB calculation**

The term of voids in mineral aggregate, VMA, is defined as the intergranular void space between the aggregate particles in a compacted paving mixture that includes the air voids and the effective bitumen content, expressed as a percentage of the total volume. The VMA is calculated on the basis of the bulk specific gravity of the aggregate **ρb** and is expressed as a percentage of the bulk volume of the compacted paving mixture.

<u>Calculation formula:</u>

$$VMA = V_m + \frac{B \times \rho_m}{\rho_B}$$

Where:

B – Bitumen percentage

ρ_m – Theoretical Maximum Specific Gravity

ρ_B – Bitumen Density

V_m – Porosity

$$V_m = \frac{\rho_m - \rho_b}{\rho_m}$$

Where:

ρ_b – Bulk Specific Gravity

The voids filled with bitumen, VFB, is the percentage of the intergranular void space between the aggregate particles that are filled with bitumen. The VFB, which does not include the absorbed bitumen, is determined using:

$$VFB = \frac{B \times \rho_m}{\rho_B} \times \frac{1}{VMA}$$

Samples							
Number	ρm	ρb	Vm	B	ρB	VMA	VFB
	kg/m3	kg/m3	%	%	kg/m3	%	%
1	2493	2416	3.1	5.3	1058	15.4	80.3
2	2493	2414	3.2				
3	2493	2415	3.1				
4	2493	2424	2.8				
5	2493	2412	3.3				
6	2493	2424	2.8				
7	2493	2415	3.1				
8	2493	2419	3.0				
Average	2493	2417	3.0	-	-	-	-

- **Bulk SSD Specific Gravity**

The bulk specific gravity test is used to determine the specific gravity of a compacted HMA sample by determining the ratio of its weight to the weight of an equal volume of water.

Water displacement methods of testing

Based on Archimedes Principle, these methods calculate specimen volume by weighing the specimen in a water bath and out of the water bath. The weight difference is then used to calculate the displaced water weight, which can be converted to a volume using the specific gravity of water.

Saturated Surface Dry (SSD)

According to this method, which is the most common, we proceed with calculating the specimen volume by subtracting the mass of the specimen in water from the mass of an SSD specimen. An SSD is the specimen condition when the internal air voids are filled with water and the surface is dry. It allows for considering the internal air voids as part of the specimen volume and is achieved by putting the specimen in a water bath for 4 minutes then removing it and quickly drying it with a towel.

The major equipment for this test is shown in the following figures.

Figure 5.4.1- SSD Method

Figure 5.4.2- SSD Method

Calculation formula:

$$\rho_{bSSD} = \frac{m_1}{m_3 - m_2} \times \rho_w$$

Where:

m_1 – Mass of sample in air

m_2 – Mass of sample in water

m_3 – Mass of SSD sample in air

ρ_w – Specific weight of water

	Samples							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
m_1 (g)	1199.5	1200.3	1199.7	1198.9	1200.6	1201	1201.7	1201.9
T (ºC)	18	18	18	18	18	18	18	18
ρw (kg/m3)	998.7	998.7	998.7	998.7	998.7	998.7	998.7	998.7
m_2 (g)	705	705	704.9	706.2	704.7	707.4	705.8	706.7
m_3 (g)	1200.8	1201.6	1201	1200.1	1201.9	1202.3	1202.8	1202.9
ρ_{bSSD} (kg/m3)	**2416**	**2414**	**2415**	**2424**	**2412**	**2424**	**2415**	**2419**

The test was conducted on 8 compacted samples as a part of the specifications imposed, and the bulk SSD specific gravity was calculated for each as shown in the above table.

- **The Marshall Stability and Flow Test**

The Marshall Stability and flow test measures the maximum load supported by the compacted test specimen at a loading rate of 50.8 mm/minute.

The applied load is increased until it reaches a maximum, then when the load just begins to decrease, the loading is stopped and the maximum load is registered.

During the load application, an attached device measures the specimen's plastic flow because of the loading. The flow value, measured in mm, is recorded at the same time the maximum load is recorded.

The following figure shows the Marshall Stability testing device in operation.

Figure 5.5.1- Marshall Stability Testing Device

Figure 5.5.2- Lab compacted sample

Samples									
Number	**Specific Gravity**	**Height**	**Diameter**	**Volume**	**Max Force**	**c**	**S**	**F**	**S/F**
	kg/m3	**mm**	**mm**	**ml (cm3)**	**kN**	**-**	**kN**	**mm**	**kN/mm**
1	2416	62.1	102	507	18.3	1.06	19.4	3.3	5.9
2	2414	65.5	102	535	17	0.97	16.5	3.1	5.3
3	2415	63.3	102	517	16.5	1.02	16.8	3.4	5.0
4	2424	62.1	102	507	17.4	1.06	18.4	3.3	5.6
Average	2417	63.3	102	-	-	-	17.8	3.3	5.4

Where:

S – Stability, given by:

$$S = Max\ Force \times C$$

C – Correction factor for Marshall Stability Test, whose values are given according to the below table:

Volume of specimen (cm^3)	Thickness of specimen (mm)	Correction Factor
457 - 470	57.1	1.19
471 - 482	68.7	1.14
483 - 495	60.3	1.09
496 - 508	61.9	1.04
509 - 522	63.5	1.00
523 - 535	65.1	0.96
536 - 546	66.7	0.93
547 - 559	68.3	0.89
560 - 573	69.9	0.86

F – Flow

S/F – Marshall Coefficient

- **Conserved Resistance Index (IRC)**

The IRC index is obtained by dividing the average Stability Value S2 of 4 compacted samples, submerged in water at 60°C (shown in the following figures) for 24 hours, by the average value S1 of the same number of compacted samples submerged in water at an equal temperature for 40 minutes.

Samples Set 1 (Submerged in water at 60°C for 40 minutes)								
Number	**Specific Gravity**	**Height**	**Diameter**	**Volume**	**Max Force**	**c**	**S1**	**F**
	kg/m3	**mm**	**mm**	**ml (cm3)**	**kN**	**-**	**kN**	**mm**
1	2416	62.1	102	507	18.3	1.06	19.4	3.3
2	2414	65.5	102	535	17	0.97	16.5	3.1
3	2415	63.3	102	517	16.5	1.02	16.8	3.4
4	2424	62.1	102	507	17.4	1.06	18.4	3.3
Average	2417	63.3	102	-	-	-	17.8	3.3

Samples Set 2 (Submerged in water at 60°C for 24 hours)								
Number	**Specific Gravity**	**Height**	**Diameter**	**Volume**	**Max Force**	**c**	**S2**	**F**
	kg/m3	**mm**	**mm**	**ml (cm3)**	**kN**	**-**	**kN**	**mm**
5	2412	63	102	515	15.7	1.03	16.2	3.8
6	2424	63.3	102	517	16.0	1.02	16.3	3.7
7	2415	62.6	102	511	15.6	1.04	16.2	3.6
8	2419	62.2	102	508	18.3	1.05	19.2	3.8
Average	2418	62.8	102	-	-	-	17.0	3.7

Conserved Resistance Index	**IRC=S2/S1**	95%

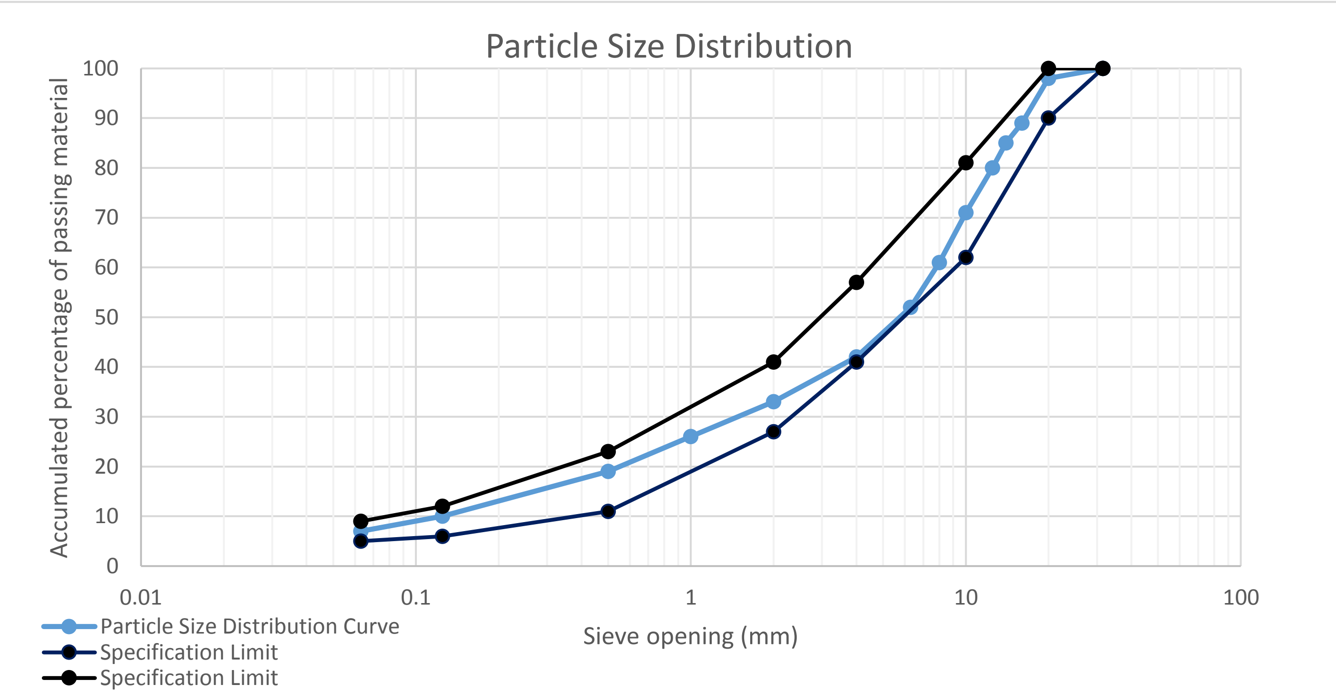
Figure 5.6.1- Banho Maria at 60°C

Figure 5.6.2- Banho Maria at 60°C

- **Summary of test results**

In this section, there will be shown the final results of each of the previously described tests, with the goal of conducting a comparison with the specification limits imposed for each case, in order to ensure the mixture's overall compatibility.

Particle size analysis			
mm	**%**	**Specification Range**	
40			
31.5	100	100	100
20	98	90	100
16	89		
14	85		
12.5	80		
10	71	62	81
8	61		
6.3	52		
4	42	41	57
2	33	27	41
1	26		
0.5	19	11	23
0.125	10	6	12
0.063	7	5	9



As shown in the previous graph, it can be noticed that the particle size distribution curve falls between the superior and the inferior specification limits, which makes the distribution curve acceptable even though it slightly touches the inferior limit curve.

			Specification Limit	Check
Bitumen percentage	**%**	5.3	`≥5.2	Acceptable
Max theoretical specific gravity	**Kg/m3**	2493	---	
Marshall samples				
Density	**Kg/m3**	2417	---	
Porosity	**%**	3.0	2-6	Acceptable
Bitumen saturation degree	**%**	80.3	---	
VMA	**%**	15.4	≥14	Acceptable
Load resistance	**KN**	17.8	≥16	Acceptable
Deformation	**mm**	3.3	2-4	Acceptable
Marshall coefficient	**KN/mm**	5.4	≥4.0	Acceptable
IRC	**%**	95	≥80	Acceptable
Filler/Bitumen	**%**	1.3	1.3-1.5	Acceptable

The table below presents the calculated parameters throughout the lab testing process, as well as the specification limit to be met for the HMA sample to be approved.

5.1.1.2 Post Compaction Tests

Several specimens are taken after the pavement execution, where the same tests are carried out to compare the output results with the specification limits as well as with those of lab compacted samples as described in the previous section 5.1.1.1.

Bitumen percentage	**%**	5.3
Specific Gravity (Marshall)	**Kg/m3**	2417
Max theoretical specific gravity	**Kg/m3**	2493

Post compaction tests - Boreholes					**Specification Limit**	**Check**
Borehole nº	1	2	3	4		
Thickness (mm)	100	99	90	89		
Specific Gravity (kg/m3)	2427	2416	2432	2366		
Vm (%)	2.7	3.1	2.5	5.1		
Vm, avg (%)	3				2-6	OK
VMA (%)	14.8	15.2	14.6	16.9		
VMA avg (%)	15				≥14	OK
Gc (%)	100	100	101	98		
Gc avg (%)	100				≥95	OK

Where:

Vm – Porosity

Gc – Degree of Compaction

The quality control tests conducted on the rest of the following mixtures can be found in Annex 1:

5.1.2 Bituminous Macadam of the Base Layer - AC 20 base 35/50 (MB)

5.1.3 Asphalt Concrete of the Sub-Surface Layer - AC 14 reg 35/50 (BBsb)

5.1.4 *Permeable Asphalt Concrete of the Surface Layer- PA 12.5 surf 50/70 (BBd)*

Since the surface layer will only be applied in the final construction phase, there weren't produced to date any mixture of such type, therefore, no quality control lab tests have been conducted.

5.2 Layer acceptance criteria

Beyond the specification limits, the layer thickness obtained shouldn't be less than 90% of that specified in the design, except in the case of surface layer where the thickness should be exactly equal to the designed thickness. The total thickness of the bituminous layers shouldn't be less than the minimum specified by the designer. Otherwise, the supervision department requires applying an additional layer.

6 FINAL COMMENTS

The project discussed the different stages of hot bituminous mixtures implementation in the pavement construction process, starting from the design based on the mechanical behavior, which uses the calculation of stress and strain induced in the pavement structure and its foundation, considering the axes of heavy vehicles.

The design is followed by mixtures formulation, with a set of steps taken, starting by defining the required specifications for the mixture and for each of its compositions, adopting specific sources for aggregates and bitumen supply, conducting lab tests over the aggregates of various sizes to check their compatibility with the specifications, choosing the aggregate percentages in compliance with the specified particle size distribution, finding out the optimum bitumen content, conducting lab tests over the mixture to verify its compatibility, and listing final percentage of each composition, as well as its source.

Hot mixtures are then fabricated at a central mixing plant, where the aggregates are blended, heated, dried, and mixed with bitumen to produce a hot asphalt paving mixture.

The basic steps in the construction of bituminous wearing courses, base courses or road bases were summarized in the following order: preparing the mixture, preparing the underlying or levelling course, transporting and placing the course mixture, joint construction, compacting and finishing.

Finally, proceeding to discuss the quality control process where the contractor is obligated to deliver the Quality Control Plan document to the site supervision department. The plan includes the various work units, the available human resources and equipment for the quality control, the test types and frequencies to realize according to what's stipulated in the specifications, as well as result reports.

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Annex 1 – Quality Control Test Results

5.1.2 Bituminous Macadam of the Base Layer - AC 20 base 35/50 (MB)

5.1.2.1 Pre-Compaction Tests

- **Particle size distribution analysis**

m1	**Initial mass**	g	2844.4
m2	**Dry mass after wash**	g	2697.7
m1 - m2	**Wash losses**	g	146.7

Sieves	Retained Material		Accumulated percentage of passing material
mm	**g**	**%**	**%**
40.00			
31.50			**100**
20.00	91.3	3.2	**97**
16.00	371.2	13.1	**84**
14.00	120.5	4.2	**80**
12.50	98.7	3.5	**76**
10.00	172	6.0	**70**
8.00	177.7	6.2	**64**
6.30	235.9	8.3	**55**
4.00	318.1	11.2	**44**
2.00	342.5	12.0	**32**
1.00	227.6	8.0	**24**
0.50	173.4	6.1	**18**
0.125	258.4	9.1	**9**
0.063	94.6	3.3	**5.7**
Wash Losses	146.7	5.2	
Retained at the bottom	15.8	0.6	
Total	2844.4	100.0	

- **Binder extraction**

Binder Extraction			
Sample weight before ignition	M	g	2979.4
Sample weight after ignition	M_{1a}	g	2844.4

Determination of Binder Content			
Sample weight before ignition	M	g	2979.4
Sample weight after ignition	M_1	g	2844.4
Binder Content	**S**	**%**	**4.5**

- **Theoretical Maximum Specific Gravity**

Volumetric Process			
Bitumen percentage, Pb (0.1%)	Pb	%	4.5
Mass of pycnometer + cap	m1	g	3247
Mass of pycnometer + cap + specimen	m2	g	6614
Mass of pycnometer + cap + specimen + water	m3	g	9495
Volume of pycnometer	Vp	m3	0.0042495
Washing temperature	-	ºC	26.0
Density of water at washing temp	ρw	kg/m3	996.8
Max theoretical specific gravity	**ρmv**	**kg/m3**	**2477**

- **VMA and VFB calculation**

Samples							
Number	**ρ_m**	**ρ_b**	**V_m**	**B**	**ρ_B**	**VMA**	**VFB**
	kg/m3	**kg/m3**	**%**	**%**	**kg/m3**	**%**	**%**
1	2477	2397	3.2	4.5	1030	13.9	78.1
2	2477	2400	3.1				
3	2477	2404	3.0				
4	2477	2406	2.9				
5	2477	2397	3.2				
6	2477	2402	3.0				
7	2477	2406	2.9				
8	2477	2401	3.1				
Average	2477	2402	3.0	-	-	-	-

- **Bulk SSD Specific Gravity**

	Samples							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
m_1 (g)	1208.3	1205.2	1206.6	1201.2	1203.2	1205.5	1205.2	1206.7
T (ºC)	24	24	24	24	24	24	24	24
ρ_w (kg/m3)	997.4	997.4	997.4	997.4	997.4	997.4	997.4	997.4
m_2 (g)	707.2	706.1	707.2	705	704.3	706.3	707	706.8
m_3 (g)	1209.9	1206.9	1207.9	1202.9	1204.9	1206.9	1206.7	1208.1
ρ_{bSSD} (kg/m3)	**2397**	**2400**	**2404**	**2406**	**2397**	**2402**	**2406**	**2401**

- **The Marshall Stability and Flow Test**

Samples									
Number	**Specific Gravity**	**Height**	**Diameter**	**Volume**	**Max Force**	**c**	**S**	**F**	**S/F**
	kg/m3	**mm**	**mm**	**ml (cm3)**	**kN**	**-**	**kN**	**mm**	**kN/mm**
1	2397	63	102	515	17.7	1.03	18.2	3.7	4.9
2	2400	63.1	102	515	16.6	1.03	17.1	3.6	4.7
3	2404	62.2	102	508	14.3	1.05	15.0	3.6	4.2
4	2406	62.8	102	513	15.1	1.04	15.7	3.6	4.4
Average	2402	62.8	102	-	-	-	16.5	3.6	4.6

- **Conserved Resistance Index (IRC)**

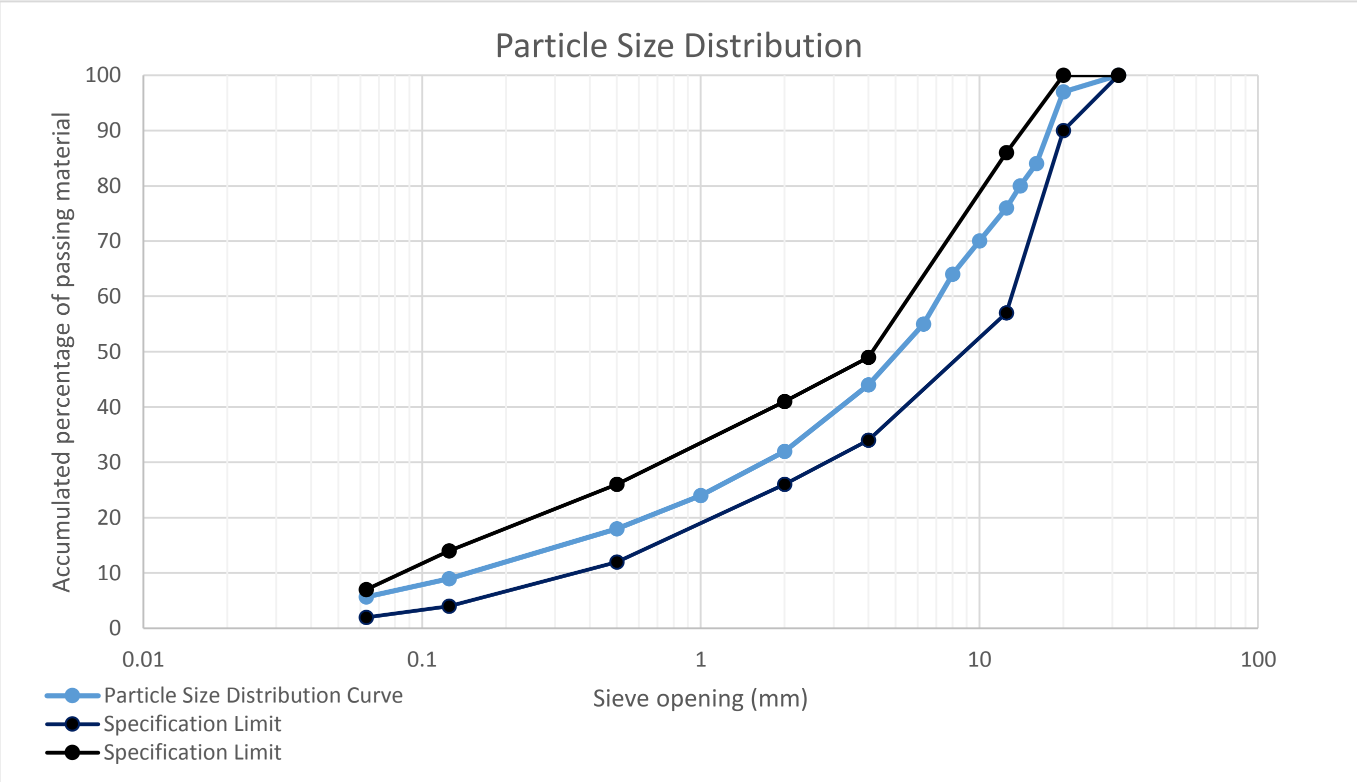
Samples Set 1 (Submerged in water at 60°C for 40 minutes)								
Number	**Specific Gravity**	**Height**	**Diameter**	**Volume**	**Max Force**	**c**	**S1**	**F**
	kg/m3	**mm**	**mm**	**ml (cm3)**	**kN**	**-**	**kN**	**mm**
1	2397	63	102	515	17.7	1.03	18.2	3.7
2	2400	63.1	102	515	16.6	1.03	17.1	3.6
3	2404	62.2	102	508	14.3	1.05	15.0	3.6
4	2406	62.8	102	513	15.1	1.04	15.7	3.6
Average	2402	62.8	102	-	-	-	16.5	3.6

Samples Set 2 (Submerged in water at 60°C for 24 hours)								
Number	**Specific Gravity**	**Height**	**Diameter**	**Volume**	**Max Force**	**c**	**S2**	**F**
	kg/m3	**mm**	**mm**	**ml (cm3)**	**kN**	**-**	**kN**	**mm**
5	2397	62.9	102	514	15.5	1.03	16.0	3.5
6	2402	63.6	102	519	16.0	1.02	16.3	3.8
7	2406	63.3	102	517	15.7	1.02	16.0	3.6
8	2401	63.9	102	522	14.3	1.01	14.4	3.8
Average	2402	63.4	102	-	-	-	15.7	3.7

Conserved Resistance Index	**IRC=S2/S1**	95%

- **Summary of test results**

Particle size analysis			
mm	**%**	**Specification Range**	
40			
31.5	100	100	100
20	97	90	100
16	84		
14	80		
12.5	76	57	86
10	70		
8	64		
6.3	55		
4	44	34	49
2	32	26	41
1	24		
0.5	18	12	26
0.125	9	4	14
0.063	5.7	2	7



			Specification Limit	Check
Bitumen percentage	**%**	4.5	`≥4.3	Acceptable
Max theoretical specific gravity	**Kg/m3**	2477	---	
Marshall samples				
Density	**Kg/m3**	2402	---	
Porosity	**%**	3.0	3-6	Acceptable
Bitumen saturation degree	**%**	78.1	---	
VMA	**%**	13.9	≥14	Acceptable
Load resistance	**KN**	16.5	9.6-15	Acceptable
Deformation	**mm**	3.6	2.5-4.0	Acceptable
Marshall coefficient	**KN/mm**	4.6	≥2.0	Acceptable
IRC	**%**	95	≥75	Acceptable
Filler/Bitumen	**%**	1.3	1.1-1.5	Acceptable

5.1.2.2 Post Compaction Tests

Bitumen percentage	**%**	4.5
Density (Marshall)	**Kg/m3**	2402
Max theoretical specific gravity	**Kg/m3**	2477

Post compaction tests - Boreholes							Specification Limit	Check
Borehole nº	1	2	3	4	5	6		
Thickness (mm)	73	73	73	75	70	70		
Specific Gravity (kg/m3)	2373	2375	2366	2328	2362	2384		
Vm (%)	4.2	4.1	4.5	6.0	4.6	3.8		
Vm, avg (%)	4.5						3-6	OK
VMA (%)	14.6	14.5	14.8	16.2	14.9	14.2		
VMA avg (%)	14.9						≥14	OK
Gc (%)	99	99	99	97	98	99		
Gc avg (%)	98						≥95	OK

5.1.3 *Asphalt Concrete of the Sub-Surface Layer - AC 14 reg 35/50 (BBsb)*

5.1.3.1 Pre-Compaction Tests

- **Particle size distribution analysis**

m1	**Initial mass**	g	3298.0
m2	**Dry mass after wash**	g	3138.7
m1 - m2	**Wash losses**	g	159.3

Sieves	**Retained Material**		**Accumulated percentage of passing material**
mm	**g**	**%**	**%**
40.00			
31.50			
20.00			
16.00			**100**
14.00	103.7	3.1	**97**
12.50	281.5	8.5	**88**
10.00	525.9	15.9	**70**
8.00	406.5	12.3	**62**
6.30	352.9	10.7	**54**
4.00	341.5	10.4	**44**
2.00	274.5	8.3	**31**
1.00	230.6	7.0	**24**
0.50	194.1	5.9	**18**
0.125	317.1	9.6	**8**
0.063	100.6	3.1	**5.1**
Wash Losses	159.3	4.8	
Retained at the bottom	9.8	0.3	
Total	3298.0	100.0	

- **Binder extraction**

Binder Extraction			
Sample weight before ignition	M	g	3468
Sample weight after ignition	M_{1a}	g	3298

Determination of Binder Content			
Sample weight before ignition	M	g	3468
Sample weight after ignition	M_1	g	3298
Binder Content	**S**	**%**	**4.9**

- **Theoretical Maximum Specific Gravity**

Volumetric Process			
Bitumen percentage, Pb (0.1%)	Pb	%	4.9
Mass of pycnometer + cap	m1	g	3247
Mass of pycnometer + cap + specimen	m2	g	5860
Mass of pycnometer + cap + specimen + water	m3	g	9042
Volume of pycnometer	Vp	m3	0.0042415
Washing temperature	-	ºC	18
Density of water at washing temp	ρw	kg/m3	998.7
Max theoretical specific gravity	**ρmv**	**kg/m3**	**2476**

- **VMA and VFB calculation**

Samples							
Number	ρ_m	ρ_b	V_m	B	ρ_B	VMA	VFB
	kg/m3	kg/m3	%	%	kg/m3	%	%
1	2476	2397	3.2	4.9	1030	14.8	79.8
2	2476	2399	3.1				
3	2476	2408	2.7				
4	2476	2403	2.9				
5	2476	2403	2.9				
6	2476	2402	3.0				
7	2476	2404	2.9				
8	2476	2400	3.1				
Average	2476	2402	3.0	-	-	-	-

- **Bulk SSD Specific Gravity**

	Samples							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
m1 (g)	1205.7	1205.9	1198.6	1204.2	1203.5	1204.9	1199.7	1208.2
T (ºC)	18	18	18	18	18	18	18	18
ρw (kg/m3)	998.7	998.7	998.7	998.7	998.7	998.7	998.7	998.7
m2 (g)	704.6	705.2	702.2	704.9	704.6	705.1	702.5	706.8
m3 (g)	1206.9	1207.3	1199.4	1205.3	1204.8	1206	1200.9	1209.6
ρb_{SSD} (kg/m3)	**2397**	**2399**	**2408**	**2403**	**2403**	**2402**	**2404**	**2400**

- **The Marshall Stability and Flow Test**

Samples									
Number	**Specific Gravity**	**Height**	**Diameter**	**Volume**	**Max Force**	**c**	**S**	**F**	**S/F**
	kg/m3	**mm**	**mm**	**ml (cm3)**	**kN**	**-**	**kN**	**mm**	**kN/mm**
1	2397	63.6	102	519	15.4	1.02	15.7	2.7	5.8
2	2399	63.8	102	521	16.6	1.01	16.8	3.3	5.1
3	2408	63	102	515	14.2	1.03	14.6	3.1	4.7
4	2403	63.5	102	519	15.3	1.02	15.6	3.5	4.5
Average	2402	63.5	102	-	-	-	15.7	3.2	5.0

- **Conserved Resistance Index (IRC)**

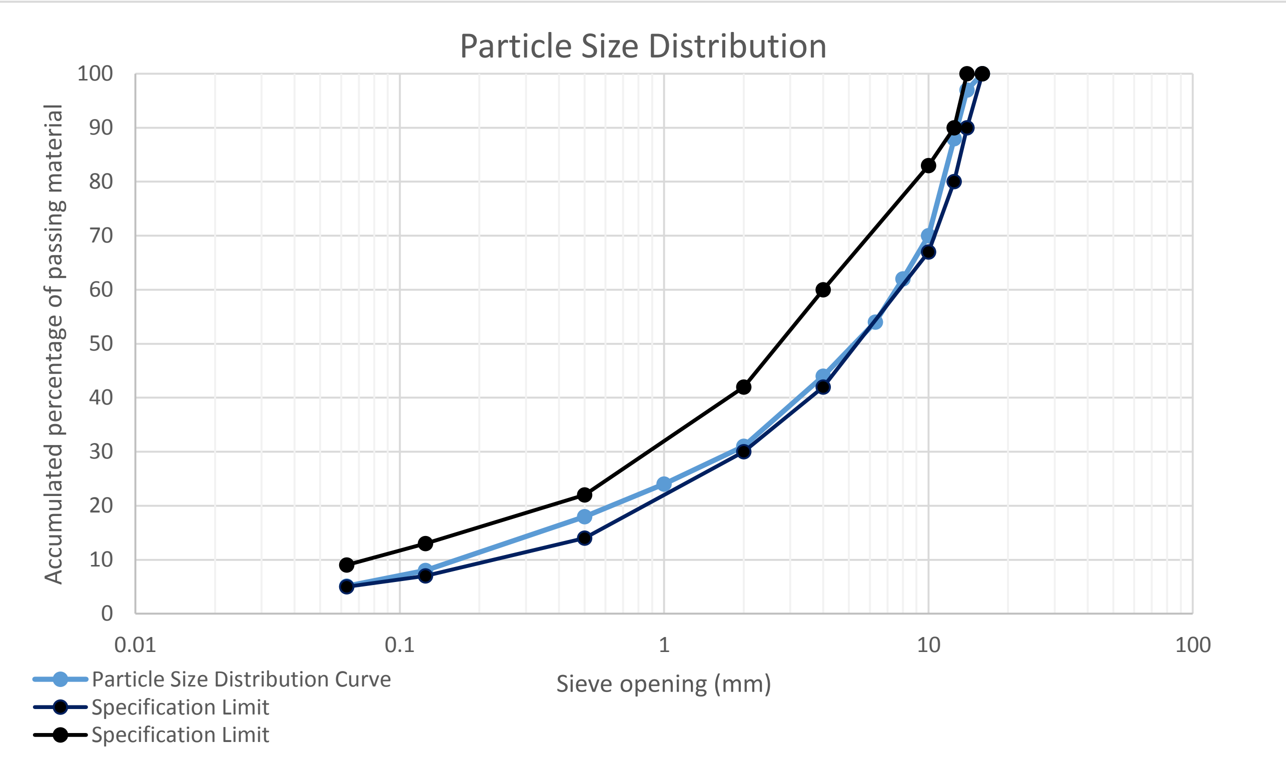
Samples Set 1 (Submerged in water at 60°C for 40 minutes)								
Number	Specific Gravity	Height	Diameter	Volume	Max Force	c	S1	F
	kg/m3	mm	mm	ml (cm3)	kN	-	kN	mm
1	2397	63.6	102	519	15.4	1.02	15.7	2.7
2	2399	63.8	102	521	16.6	1.01	16.8	3.3
3	2408	63	102	515	14.2	1.03	14.6	3.1
4	2403	63.5	102	519	15.3	1.02	15.6	3.5
Average	2402	63.5	102	-	-	-	15.7	3.2

Samples Set 2 (Submerged in water at 60°C for 24 hours)								
Number	Specific Gravity	Height	Diameter	Volume	Max Force	c	S2	F
	kg/m3	mm	mm	ml (cm3)	kN	-	kN	mm
5	2403	63.2	102	516	14.5	1.03	14.9	3.2
6	2402	63.9	102	522	15.1	1.01	15.3	3.8
7	2404	62.8	102	513	14.3	1.04	14.9	3.1
8	2400	64	102	523	14.5	1.0	14.5	2.9
Average	2402	63	102	-	-	-	14.9	3.3

Conserved Resistance Index	**IRC=S2/S1**	95%

- **Summary of test results**

Particle size analysis			
mm	**%**	**Specification Range**	
40			
31.5			
20			
16	100	100	100
14	97	90	100
12.5	88	80	90
10	70	67	83
8	62		
6.3	54		
4	44	42	60
2	31	30	42
1	24		
0.5	18	14	22
0.125	8	7	13
0.063	5.1	5	9



			Specification Limit	Check
Bitumen percentage	%	4.9	`≥5.0	Acceptable
Max theoretical specific gravity	Kg/m3	2476	---	
Marshall samples				
Density	Kg/m3	2402	---	
Porosity	%	3.0	3-5	Acceptable
Bitumen saturation degree	%	79.8	---	
VMA	%	14.8	≥14	Acceptable
Load resistance	KN	15.7	8-21	Acceptable
Deformation	mm	3.2	2.5-4.0	Acceptable
Marshall coefficient	KN/mm	5.0	≥2.5	Acceptable
IRC	%	95	≥80	Acceptable
Filler/Bitumen	%	1.0	1.2-1.5	Acceptable

5.1.3.2 Post Compaction Tests

Bitumen percentage	%	4.9
Specific Gravity (Marshall)	Kg/m3	2402
Max theoretical specific gravity	Kg/m3	2476

Post compaction tests - Boreholes					Specification Limit	Check
Pk	1	2	3	4		
Thickness (mm)	85	50	55	45		
Specific Gravity (kg/m3)	2359	2354	2355	2317		
V_m (%)	4.7	4.9	4.9	6.4		
$V_{m,\,avg}$ (%)	5.2				3-5	OK
VMA (%)	15.9	16.1	16.1	17.4		
VMA_{avg} (%)	16.4				≥14	OK
Gc (%)	98	98	98	96		
Gc_{avg} (%)	98				≥95	OK