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Amélioration de la résistance mécanique des chaussées Souples par ajout de fibres de bois

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Abstract

Undoubtedly, the road pavement industry poses significant environmental and climate challenges for both governments and researchers in this field. In our pursuit of a solution, we investigated the potential of sawdust as a renewable alternative to partially replace aggregate in asphalt-mixes. To achieve this, a comprehensive Design of Experiment (DOE) was conducted, assessing the impact of different sawdust content levels (5%, 10%, and 15% of total aggregate volume) on key parameters like Marshall Stability, flow values, density, and Marshall Quotient. Additionally, we explored various factors such as binder content (ranging from 5.77% to 6.45%), manufacturing temperature (from 140°C to 180°C), and mixing time (2 minutes to 4 minutes) to comprehensively understand their influence on the asphalt mix. To bolster durability, the sawdust underwent treatment with a proven emulsion coating. The results unequivocally demonstrate that sawdust can be effectively harnessed as a partial replacement for (3/8) aggregate in asphalt mixes. Implementing this renewable material leads to improved Marshall Stability and Marshall Quotient while reducing density and flow values, all falling within acceptable parameters and yielding positive environmental outcomes. Moreover, viewing sawdust as a waste material makes it a cost-effective solution for the road pavement industry. Hence, our study holds promise as an economically and technically efficient resolution to the challenges faced by the road pavement sector. Embracing sawdust as an aggregate replacement offers a pathway to more sustainable and eco-friendly road construction practices.

Keywords: Sawdust content, Marshall Design, full-factorial Design, binder content, mixing time, manufacturing temperature.

الملخص

لا شك أن صناعة رصف الطرق تشكل تحديات بيئية ومناخية كبيرة لكل من الحكومات والباحثين في هذا المجال. في سعينا للتوصل إلى حل ، قمنا بدراسة إمكانة ادخال نشارة الخشب كبديل متجدد لتحل محل جزاء من الركام في خلطات الإسفلت. لتحقيق ذلك ، تم إجراء تصميم شامل للتجربة (DOE) ، لتقييم تأثير مستويات محتوى نشارة الخشب المختلفة (5٪ ، 10٪ ، 15٪ من إجمالي الحجم الكلي) على معلمات رئيسية مثل استقرار مارشال ، قيم التدفق ، الكثافة ، وحاصل مارشال. بالإضافة إلى ذلك ، استكشفنا عوامل مختلفة مثل محتوى الرابط" المادة البيتومينية " (يتراوح من 5.77٪ إلى 6.45٪) ، ودرجة حرارة التصنيع (من 140 درجة مئوية إلى 180 درجة مئوية) ، ووقت الخلط (دقيقتان إلى 4 دقائق) لفهم تأثيرها بشكل شامل على مزيج الأسفلت. لتعزيز المتانة ، خضعت نشارة الخشب للمعالجة بطبقة مستحلب مثبتة. تظهر النتائج بشكل لا لبس فيه أنه يمكن تسخير نشارة الخشب بشكل فعال كبديل جزئي للركام (8/3) في خلطات الإسفلت. يؤدي تطبيق هذه المادة المتجددة إلى تحسين استقرار مارشال وحاصل مارشال مع تقليل الكثافة وقيم التدفق ، وكلها تقع ضمن المعايير المقبولة وتؤدي إلى نتائج بيئية إيجابية. علاوة على ذلك ، فإن النظر إلى نشارة الخشب على أنها مادة نفايات يجعلها حلاً فعالاً من حيث التكلفة لصناعة رصف الطرق. ومن ثم ، فإن دراستنا تبشر بالخير كحل فعال اقتصاديًا وتقنيًا للتحديات التي يواجهها قطاع رصف الطرق. يوفر تبني نشارة الخشب كبديل كلي مسارًا لممارسات بناء طرق أكثر استدامة وصديقة للبيئة.

الكلمات مفتاحية: نشارة الخشب ، تصميم مارشال ، تصميم كامل للتجربة ، محتوى الموثق ، وقت الخلط ، حرارة التصنيع.

Résumé

L'industrie du revêtement routier est en face d'importants défis environnementaux et climatiques pour les gouvernements ou les chercheurs dans ce domaine des enrobés routiers. Dans notre cas d'étude, nous avons traité le potentiel des déchets de bois en tant qu'un matériau renouvelable pour remplacer partiellement les granulats dans les enrobés. Pour cette raison, nous avons réalisé une étude complète en utilisant la méthode des plans d'expériences pour évaluer l'impact des différents niveaux de pourcentage de déchets de bois (5%, 10% et 15% du volume total de l'agrégat) sur des paramètres clés tels que la stabilité de Marshall, les valeurs de fluage, la densité et le quotient de Marshall. De plus, nous avons exploré divers facteurs tels que le taux de liant (variant de 5,77% à 6,45%), la température de fabrication (de 140°C à 180°C) et le temps de malaxage (de 2 minutes à 4 minutes) pour comprendre leur influence sur les enrobés. Pour renforcer la durabilité, les déchets de bois ont été traités avec un revêtement d'émulsion éprouvé. Les résultats ont montré que les déchets de bois peuvent être utilisés comme un remplacement partiel pour les granulats (3/8) dans les enrobés. La mise en œuvre de ce matériau renouvelable entraîne une amélioration de la stabilité de Marshall et du quotient de Marshall, tout en réduisant la densité et les valeurs de fluage, le tout se situant dans des paramètres acceptables et produisant des résultats positifs sur l'environnement. De plus, on considère que les déchets de bois comme un matériau peuvent être une solution rentable pour l'industrie du revêtement routier. Ainsi, notre étude offre une promesse en tant que résolution économique et techniquement efficace aux défis auxquels est confronté le secteur du revêtement routier. Adopter les déchets de bois comme un remplacement des granulats ouvre la voie à des pratiques de construction routière plus durables et respectueuses de l'environnement.

Mots-clés : sciure de bois, Conception de Marshall, factoriels complets, Teneur en liant, Temps de mélange, Température de fabrication.

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General Introduction

How can we effectively incorporate sustainable development principles into environmental conservation? This question holds great significance for both decision-makers and researchers. The solution lies in devising approaches and methodologies that safeguard the environment through waste recovery and recycling. In the realm of road construction, strides have already been made by reducing the reliance on non-renewable natural resources and optimizing energy consumption during their production and the manufacturing of building materials.

This thesis was initiated in March 2019. The tests carried out in this work were carried out in the Laboratory of public works for the south of Algeria - Ghardaia - with the use of local materials aggregates originating from the Alco-Gaz quarry in Metlili Ghardaia, located in the southern part of Algeria. The binder was sourced from the renowned National Hydrocarbon Company, SONATRACH.

Imagine a world where roads not only provide a smooth and durable surface for transportation but also contribute to environmental sustainability. This Ph.D. thesis delves into an innovative approach that may revolutionize road construction by exploring the possibility of replacing traditional aggregate materials with sawdust in asphalt mixes. Yes, sawdust - a by-product of wood processing - could potentially pave the way for greener and more eco-friendly roads. But how is this even possible? Let's embark on this fascinating journey to uncover the hidden potential of sawdust particles as they intertwine with asphalt, forming a road that balances performance and sustainability.

Traditional road construction has relied heavily on natural resources such as gravel and crushed stone as the main components in asphalt mixes. While natural fibers have been traditionally used as additives to enhance asphalt mix performance, this study introduces a significant research gap by focusing on utilizing sawdust as a partial replacement for traditional aggregates. By exploring this unconventional avenue, the potential to discover a novel, sustainable, and efficient road construction approach emerges. If successful, this research could significantly reduce the demand for traditional aggregates, which would positively impact natural resource preservation and the overall environmental footprint of road construction.

Previous studies have demonstrated that incorporating natural fibers into asphalt mixes can improve overall performance in various aspects such as strength, durability, and resistance to cracking. However, issues regarding the flow of asphalt mixes have been a limiting factor in fully utilizing the benefits of these additives. The addition of natural fibers often leads to an increase in viscosity, making the mixes harder to work with during construction. This research aims to address these concerns by using sawdust as a renewable material that not only improves performance but also contributes to the environment.

The literature review reveals a wealth of research using natural fibers such as sisal, coconut, and banana fibers as additives for asphalt mixes. These studies have shown positive effects on asphalt properties, including enhanced stability and increased resistance to rutting and fatigue. However, the application of sawdust as a partial replacement for aggregates in this context remains a relatively unexplored area, offering immense potential for sustainable road construction. By investigating this unique approach, this research aims to expand the knowledge base and foster innovation in the field of road construction materials.

The central hypothesis of this research posits that incorporating sawdust particles in asphalt mixes will lead to improved performance, demonstrating its potential as a replacement for traditional aggregate materials. The use of sawdust, with its fibrous structure and potential binding properties, could improve the overall cohesion of the asphalt mix while maintaining suitable workability during construction.

With promising indications from existing literature, the utilization of sawdust in asphalt mixes could represent a breakthrough in environmentally-friendly road construction. By potentially reducing the reliance on traditional aggregates and natural fibers, this study aspires to pave the way for eco-conscious road construction practices that align with sustainable development goals. Additionally, this research can contribute to the establishment of best practices for incorporating renewable materials in road construction, benefiting not only the infrastructure sector but also the environment at large.

This investigation seeks to answer critical questions, including the feasibility of using sawdust as an aggregate replacement, the optimal percentage of sawdust in the mix to achieve desirable properties, suitable treatments for sawdust particles to enhance compatibility with asphalt, ranges for manufacturing factors in asphalt mixes, and comprehensive assessments of the environmental and economic impacts of this novel approach. The findings will offer valuable insights for researchers, engineers, and policymakers in the road construction industry.

The primary objective of this research is to promote environmental protection by adopting a renewable and sustainable material - sawdust - in asphalt mixes. By reducing the consumption of traditional aggregates, which often require extensive mining and extraction processes, this study aims to contribute to sustainable road construction practices. The potential reduction in greenhouse gas emissions associated with traditional aggregate production and transportation could also make a significant contribution to combating climate change.

The thesis work consists of four chapters:

Chapter 1 provides a comprehensive literature review covering the background history of road construction, road pavement development, degradation of layers in asphalt concrete pavement, and the use of additives and modifiers for asphalt binders, along with an exploration of alternative aggregates for asphalt mixes.

In Chapter 2, the experimental design method is explained, discussing the principles, purposes, models, elements, and stages of experimental designs, with a focus on factorial design and software usage.

Chapter 3 presents the experimental study, including the use of semi-dense bituminous concrete (SDBC), materials for the control concrete, sawdust characteristics, and asphalt mix formulations with varying sawdust percentages.

The design of asphalt mixes with sawdust replacements is investigated using the full factorial design in Chapter 4, analyzing compactness, Marshall Stability, flow, and Marshall Quotient, comparing results to control samples and specifications.

The research will employ the Marshall mix design method, a widely-used procedure for asphalt mix design, to design asphalt mixes with sawdust as an aggregate replacement. Additionally, a design of experiments (DOE) approach will be utilized to optimize the mix formulation and evaluate the performance of the asphalt mixes under varying conditions. The experimental study will include laboratory tests on the mechanical properties of the asphalt mixes, including stability, and flow.

With the potential to reshape the road construction industry, this Ph.D. thesis embarks on an exciting exploration of partially replacing traditional aggregates with sawdust in asphalt mixes. By introducing this novel approach, we aim to contribute to a more sustainable and environmentally-conscious future for infrastructure development. Through rigorous experimentation and comprehensive analyses, this research seeks to shed light on the viability, efficiency, and environmental benefits of using sawdust in asphalt mixes. By promoting the adoption of renewable materials and sustainable practices, we envision a greener and more resilient road network that addresses the challenges of the 21st century.

Chapter 1 LITERATURE REVIEW

1.1 Background history of road construction:

The road has been present for as long as living beings have roamed the earth. When early humans sought sustenance, they created paths which successive civilizations followed, sometimes struggling but always advancing. Today, we stand in their place and contemplate the trails they left behind. Even animals, like boa constrictors, have established routes through dense jungles. These paths, though modest, paved the way for modern highways. In fact, many modern roads may still trace their roots to the paths established by early humans and animals who chose the most efficient routes, including the easiest gradients and the most likely mountain passes.

Since the dawn of history, kingdoms, and empires have constructed roads and paths for the purposes of trade, conquest, and connecting different parts of the state. The civilization that stands out for its establishment of roads is the one described below.

1.1.1 Road in ancient EGYPTIAN Civilization:

Roads in Egypt are as ancient as her known history fixing clans in "nomes," or districts, was one of the crucial moments in Egypt's ancient history. Each nome had a capital city and a region. The settlement, or "nut," was constructed at a crossroads, as its name suggests, and was encircled by a circular wall for protection, where both locals and visitors sought shelter at night. Each large settlement had two roads that intersected in the middle at a straight angle and ran through it from side to side [01].

A paved road connecting Widan al-Faras and Qasr al-Sagha in the northern Fayum (figure1.01) appears to have been built in the early third millennium BCE and was described as the world's oldest paved road [02;03]. Relatively few paved roads have been discovered from Pharaonic Egypt, but they are not unknown. Sandstone pavers and petrified wood logs were used to pave the 2.4-meter-wide road [03].

Figure 1.01. The road from Widan el-Faras to Qasr el-Sagha in the Fayum[03].

The Egyptians during the construction of the pyramids used, for the transport of heavy stones, stone rollers covered with a material that reduced the friction between the stone and the ground, as well as reducing the intensity of the load. Then they created a hard surface on which their rollers walk (1km consuming 10 years to build) [04], as shown in the figure (figure1.02).

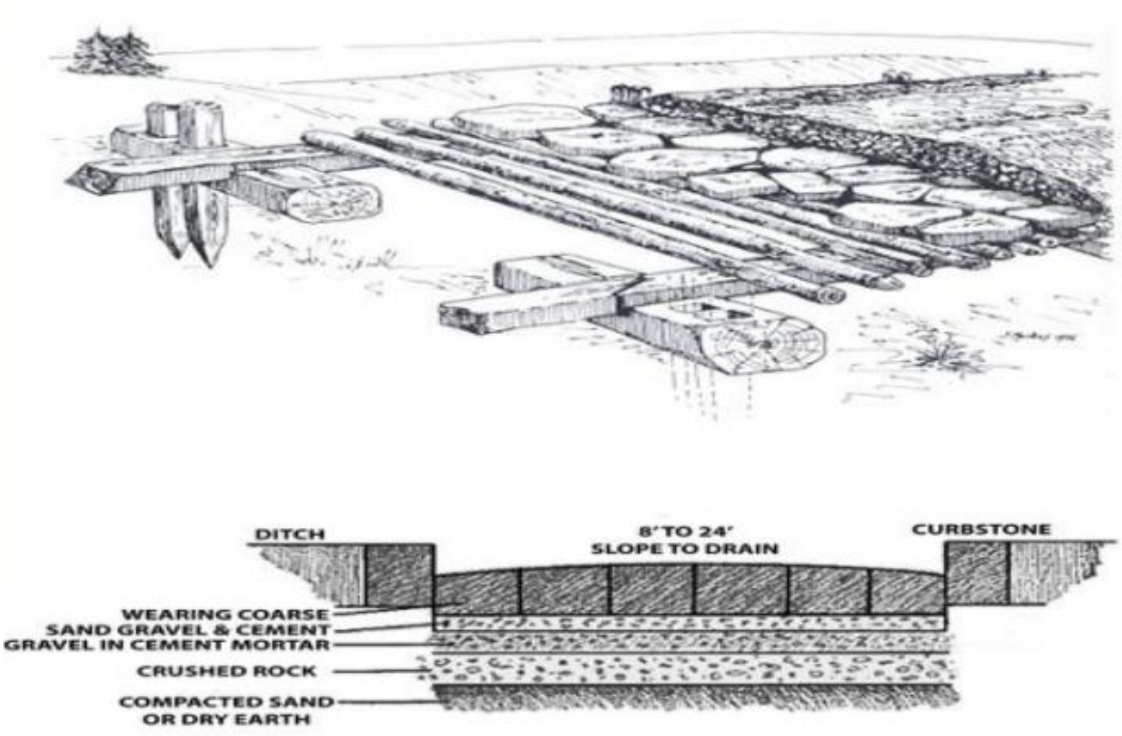


Figure 1.02. Egyptian Road design [04]

1.1.2 Road in ancient Land Between The Rivers

For nearly many years, The Land between the Rivers—Babylon in the south and Assyria in the north—would only exist in myth. Until the great and persistent research of archeologists revealed a civilization whose magnificence rivaled that described by historians, it was believed that the stories about its wondrous cities were nothing more than the rambling ramblings of wandering scribblers [01].

The goddess Ishtar was represented with lions, bulls, dragons, and flowers on enameled yellow and black glazed bricks that lined the walls of the Ishtar gate, which was part of the procession route. Each side of the Processional Way was covered with friezes that featured sixty fierce Babylonian lions that represented Ishtar and were painted with different shades of fur and manes. The Processional Way was up to 66 feet wide at some locations and was made of huge stone chunks laid in a layer of bitumen.

The bricks were put together after the glaze firing, leaving tiny, horizontal gaps that ranged in width from one to six millimeters. Then, like modern asphalt, a naturally occurring, thick black liquid known as bitumen was used to fill the seams as shown in Figure1.03. [05]

Figure 1.03. The Processional Way [05].

In the fifth century BC, Darius the Great (Darius I), monarch of the first (Achaemenid) Persian Empire, reorganized and rebuilt the Royal Road, an antiquated road. To enable quick communication on the western border of his vast empire, from Susa to Sardis, Darius constructed the road. The distance between Susa and Sardis, 2,699 km (1,677 mi), was scheduled to be covered by mounted Angarium messengers in nine days; walking the distance took 90 days [06].

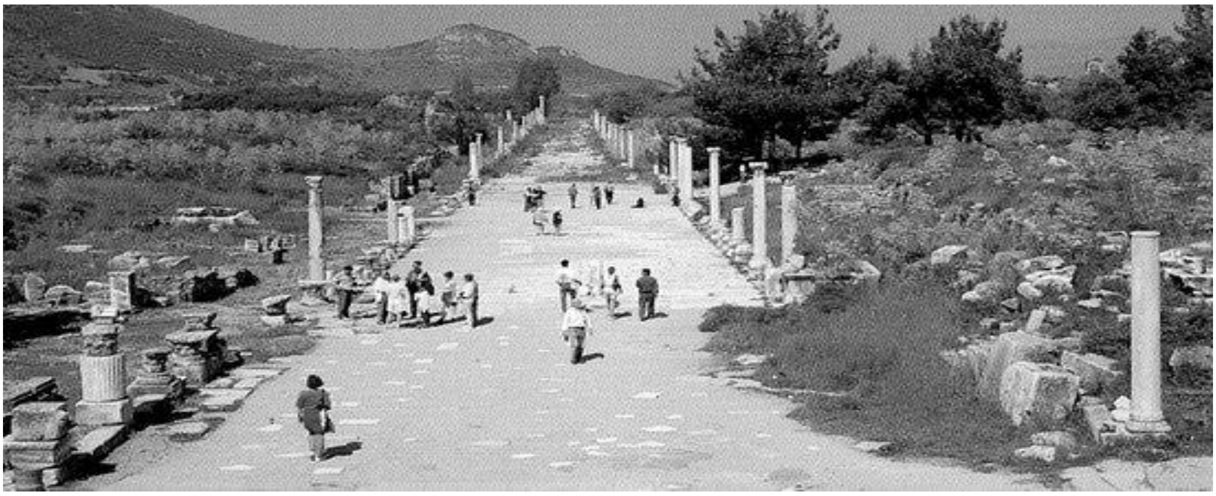


Figure1.04. Part of the Royal Road [06]

1.1.3 Road in ancient Rome

The Romans built nearly 53000 miles of roads linking the capital to their far far-flung empire to put this fantastic feat in context, consider that the United States, to date, has built 42000 miles of interstate highways [07].

It is important to note that not all roads, or even a single road's entire length, had the same structure. Not all roads, such as the Via Appia, were paved or polished with wide lava stones. Some roadways, mostly the rudus, nucleus, and summacrusta, had fewer layers depending on the soil, topography, and material accessibility. In order to provide an example, an excavation on Via Appia (4.5 km north of Itri) discovered a first layer of sand that was covered by a layer of crushed limestone into which lava stones measuring 25 to 40 cm high were embedded [08].

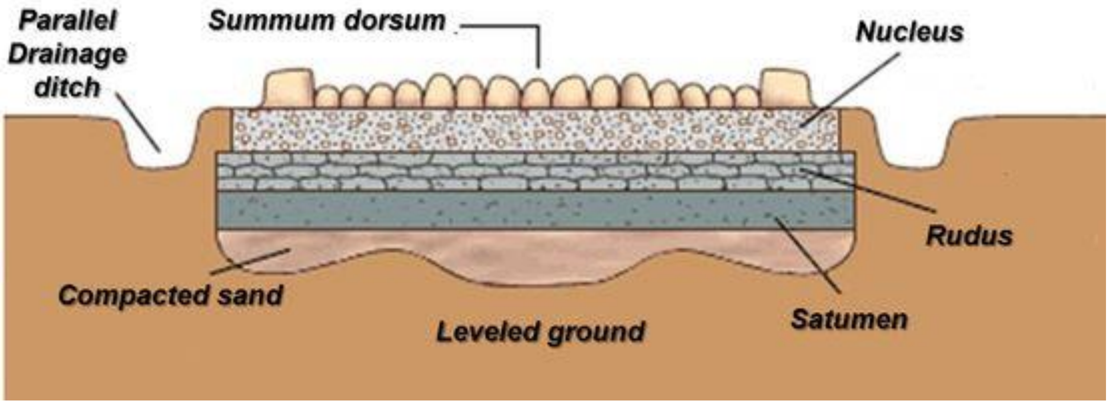


Figure 1.05**.** A cross-section of a Roman road. Source: The Encyclopedia Britannica (2000).

1.1.4 Turnpike trust Road

The main roads in Britain were maintained by turnpike trusts, which were established by specific acts of Parliament starting in the 17th century but more so in the 18th and 19th. Over 1,000 trusts existed at their peak in the 1830s [09].

A less expensive method of building good roads was developed by Scottish engineer John Macadam, who later stated: "I have typically made roads three inches higher in the center than I have at the sides... if the road be smooth and well made, the water will run easily on such a slope. I always make my surveyors carry a pair of scales and a six-ounce weight in their pocket and when they come to a heap of stones, they weigh one or two of the largest."[10]

Figure 1.06**.** Construction of the first Macadamized Road in the United States (1823).

1.2 Road Pavement Development

High-quality materials and appropriate technologies that consider sustainability issues such as environmental protection, mitigation, and compensation for effects of road construction on soil, air, wildlife, landscape, vibration, and noise are required for the construction of modern and long-lasting asphalt and cement pavements. Pavement design is a major component in road construction. A pavement is a strong structure consisting of layers of processed materials. The ultimate goal is to make sure that transmitted stresses resulting from wheel load are sufficiently decreased to prevent them from going above bearing capacity [11]. In its most general sense, a road is an open, generally public way for the passage of vehicles, people, and animals. These roads were made more resilient and able to survive traffic and the environment by being covered with a hard, smooth surface (pavement) [11].

A perfect pavement should meet the following requirements:

- Enough thickness to distribute the wheel load pressures on the subgrade soil to a safe level.
- Structurally strong to withstand all types of stresses imposed upon it.
- Smooth surface to provide comfort to road users even at high speed.
- The dustproof surface so that traffic safety is not impaired by reducing visibility.
- Adequate coefficient of friction to stop vehicles from sliding.
- Make the fewest noises when driving.
- Impenetrable surface, so that sub-grade soil is well protected from water damage.
- Long design life with low maintenance cost.

1.2.1 The Different Categories of Pavement Structures

The pavement system's goal is to create a smooth surface over which vehicles can pass safely in all climatic situations for the designated pavement performance period. In order to perform this goal, a variety of pavement systems have been developed, the components of which are basically the same. The pavement structure is a combination of subbase, base course, and surface course placed on a subgrade to support the traffic load and distribute it to the roadbed. Figure1.07 presents a cross section of a basic modern pavement system, showing the primary components [12].

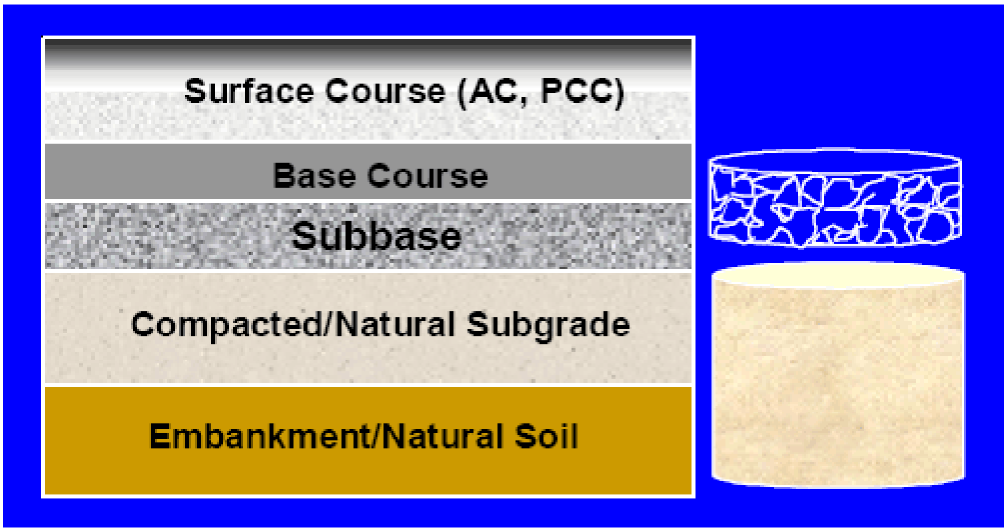


Figure 1.07. Basic components of a typical pavement system.

- The top layer of a roadbed is known as the subgrade, and it is this layer that the pavement structure and shoulders are built on. The purpose of the subgrade is to provide a platform for the construction of the pavement and to support the pavement without undue deflection that would impact the pavement's performance. For pavements constructed on grade or in cuts, the subgrade is the natural in-situ soil at the site. The upper layer of this natural soil may be compacted or stabilized to increase its strength, stiffness, and/or stability [12].

- The subbase is a layer or layers of specified or selected materials of designed thickness placed on a subgrade to support a base course.

- The base is a layer or layers of specified or select material of designed thickness placed on a subbase or subgrade (if a subbase is not used) to provide a uniform and stable support for binder and surface courses.

- Finally, the surface course is one or more layers of a pavement structure designed to accommodate the traffic load, the top layer of which resists skidding, traffic abrasion, and the disintegrating effects of climate. The surface layer may consist of asphalt (also called bituminous) concrete, resulting in "flexible" pavement, or Portland cement concrete (PCC), resulting in "rigid" pavement.

a- Flexible Pavements

As was described in Figure 1.07, flexible pavements in general consist of an asphalt-bound surface course or layer on top of unbound base and subbase granular layers over the subgrade soil. In some cases, the subbase and/or base layers may be absent (e.g., full-depth asphalt pavements), while in others the base and/or subbase layers may be stabilized using cementitious or bituminous admixtures. Drainage layers may also be provided to remove water quickly from the pavement structure. Some common variations of flexible pavement systems are shown in Figure 1.08.

Figure 1.08. Some common variations of flexible pavement sections (NCHRP 1-37A, 2002).

b- Rigid Pavements

Rigid pavements in general consist of Portland cement pavement slabs constructed on a granular base layer over the subgrade soil. The base layer serves to increase the effective stiffness of the slab foundation. The base layer serves the extra purposes mentioned above in addition to having to stop fine-grained soils from being pumped into slab joints, fissures, and edges. The base and/or subbase's gradation properties are crucial in this situation. The base might be stabilized with cement or asphalt to increase its capacity to carry out this task. A subbase layer is occasionally included between the base layer and the subgrade. The weighted average of the subbase and subgrade stiffnesses will be the effective foundation stiffness. The base and subbase layer may be skipped in cases where the coarse subgrade is of high quality (e.g., has the same stiffness as the base) or if there is little traffic (less than 1 million 80-kN (18-kip) ESALs) [12].

Rigid pavement slabs often have no reinforcement or very little reinforcement. When applied, reinforcing serves to reduce or increase the distance between joints that fail and allow water infiltration. The need for subgrade support is unaffected by concrete reinforcement. The subbase layer may be omitted if there is low truck traffic volume or good subgrade conditions.

For high traffic volumes and/or poor subgrade conditions, the subbase may be stabilized using cementitious or bituminous admixtures. Drainage layers can and should be included to remove water quickly from the pavement structure, similar to flexible pavements. A geotextile layer may be used to control migration of fines into the open graded base layer. Some common variations of rigid pavement systems are shown in Figure 1.09[12].

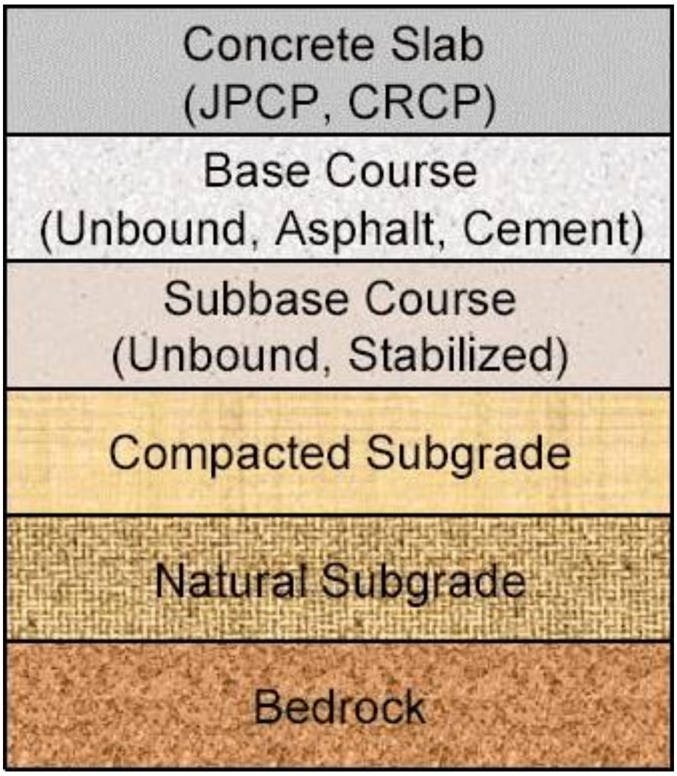


Figure 1.09. Variations for rigid pavement section (NCHRP 1-37A, 2002).

- Jointed Plain Concrete Pavements (JPCP)
- Jointed Reinforced Concrete Pavements (JRCP)
- Continuously Reinforced Concrete Pavements (CRCP)
- Prestressed Concrete Pavements (PCP)

c- Composite Pavements

Composite pavements consist of asphaltic concrete surface course over PCC or treated bases as shown in Figure 1.10.

Additionally, PCC-over-asphalt composite pavements are in use. The treated bases may be either asphalt-treated base (ATB) or cement-treated base (CTB). The base layers are treated to improve stiffness and, in the case of permeable base, stability for construction. The composite pavement type shown in Figure 1.10 of an AC overlay on top of a PCC rigid pavement system is a very common rehabilitation scenario [12].

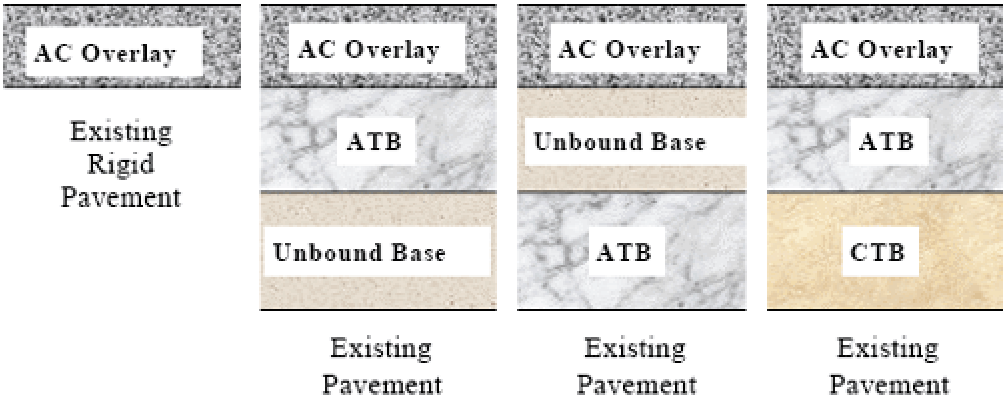


Figure 1.10. Typical composite pavement sections.

1.2.2 The Binder « bitumen »

A comprehensive definition of refined bitumen is used in the industry document The Bitumen Industry – A Global Perspective (Eurobitume and the Asphalt Institute, 2011) and is reproduced here verbatim: Bitumen is an engineering material and is produced to meet a variety of specifications based upon physical properties. Bitumen is the residual product from the distillation of crude oil in petroleum refining. The basic product is sometimes referred to as 'straight run' bitumen and is characterized by CAS# 8052-42-4 or 64741-56-6 which also includes residues obtained by further separation in a deasphalting process. Bitumen can be further processed by blowing air through it at elevated temperatures to alter its physical properties for commercial applications. The general characteristics of oxidized bitumen are described by CAS# 64742-93-4. The vast majority of petroleum bitumen's produced conform to the characteristics of these two materials as described in their corresponding CAS definitions. Bitumen is produced to grade specification either directly by refining or by blending [13].

Bitumen is largely composed of hydrocarbon molecules, with some heterocyclic species and functional groups containing sulfur, nitrogen, and oxygen atoms. Bitumen also contains trace amounts of metals such as nickel, vanadium, iron, calcium and magnesium, which occur in the form of metallic salts, oxides or in porphyrin structures. Porphyrins are complex organic compounds that occur naturally: for example, haemoglobin, found in blood, and chlorophyll, found in green plants, are examples of porphyrins associated with metal atoms. Porphyrins contain four nitrogen atoms, each of which can bond with a metal atom to result in a metalloporphyrin. Elemental analysis of bitumen manufactured from a variety of crude oils shows that most bitumen contains [13].

Carbon	82–88%
Hydrogen	08–11%
Oxygen	0–1.5%
Sulfur	0–6%
Nitrogen	0–1%

Bitumen can be obtained from various sources. Although it exists naturally, as was previously indicated, petroleum is the primary source of bitumen for the majority of applications.

Crude petroleum oil's bitumen percentage can range from 15% to 80%, but 25% to 40% is considered to be more typical [14]. The three broad classifications for crude oils are:

- Bitumen based
- Paraffin based
- Bitumen and paraffin based.

a- Types of Bitumen

There are six major classifications of petroleum bitumen produced by the refining and manufacturing process:

- **Paving grade bitumen** (or asphalt cement in the USA) is the most popular type of bitumen, and it is refined and blended to fulfill industrial and road engineering criteria that take into consideration various climatic factors. The parent bitumen from which the other kinds are formed can also be thought of as paving-grade bitumen [14].
- **Cutback bitumen** consist of bitumen that has been diluted in solvent (cutter or flux) to make it more fluid for application [14].
- **Bitumen emulsions** are dispersions of bitumen in water. Hot bitumen, water and emulsifier are processed in a high-speed colloid mill that disperses the bitumen in the water in the form of small droplets [14].
- **Modified bitumen** is formulated with additives to improve their service performance by changing such properties as their durability, resistance to ageing, elasticity and/or plasticity. The most important modifiers are polymers [14].
- **Polymer modified binders (PMB)** are a major advancement in bituminous binder technology as these materials better satisfy the demands of increasing traffic volumes and loads on our road networks. As well as natural rubbers, polymers such as styrene butadiene styrene (SBS), polybutadiene (PBD) and ethylene vinyl acetate (EVA) are commonly used to modify bitumen [14].
- **Multigrade bitumen** is a chemically modified bitumen that has the properties of a hard paving grade bitumen at high service temperatures coupled with the properties of a soft paving grade bitumen at low temperatures (i.e. it has properties that span multiple grades). Multigrade bitumen provide improved resistance to deformation and reduce the detrimental effects of high service temperatures, whilst providing reduced stiffness at low service temperatures than exhibited by a similar normal paving grade bitumen [14].

b- Main characteristics of road bitumen

The characteristics of bituminous materials can be evaluated using a variety of tests. The following tests are typically carried out to assess various bituminous material qualities.

- Penetration Test

It measures the hardness or softness of bitumen by measuring the depth in tenths of a millimeter to which a standard loaded needle will penetrate vertically in 5 seconds. BIS had standardized the equipment and test procedure.

The penetrometer consists of a needle assembly with a total weight of 100g and a device for releasing and locking in any position. The bitumen is softened to a pouring consistency, stirred thoroughly and poured into containers at a depth at least 15 mm in excess of the expected penetration. The test should be conducted at a specified temperature of 25°C.

It may be noted that penetration value is largely influenced by any inaccuracy with regards to pouring temperature, size of the needle, weight placed on the needle and the test temperature. In hot climates, a lower penetration grade is preferred. The Figure 1.11 shows a schematic Penetration Test setup [15].

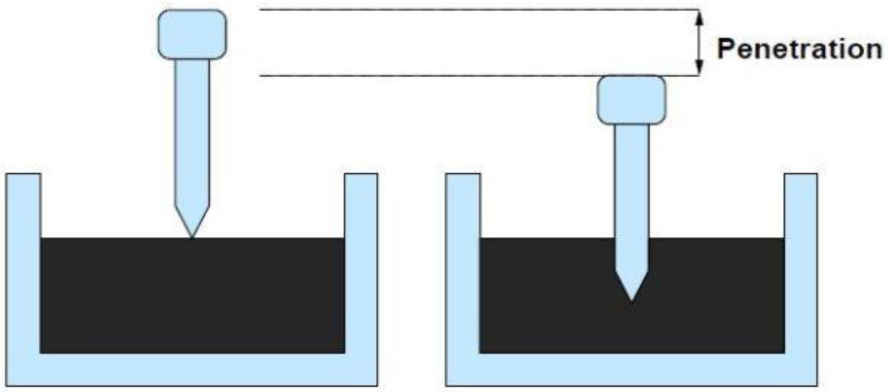


Figure 1.11. Penetration Test Setup

- Softening Point Test

Softening point denotes the temperature at which the bitumen attains a particular degree of softening under the specified condition of test. The test is conducted by using Ring and Ball apparatus. A brass ring containing test sample of bitumen is suspended in liquid like water or glycerin at a given temperature. A steel ball is placed upon the bitumen sample and the liquid medium is heated at a rate of 50C per minute. Temperature is noted when the softened bitumen touches the metal plate which is at a specified distance below. Generally, higher softening point indicates lower temperature susceptibility and is preferred in hot climates. Figure 1.12 shows Softening Point test setup [15].

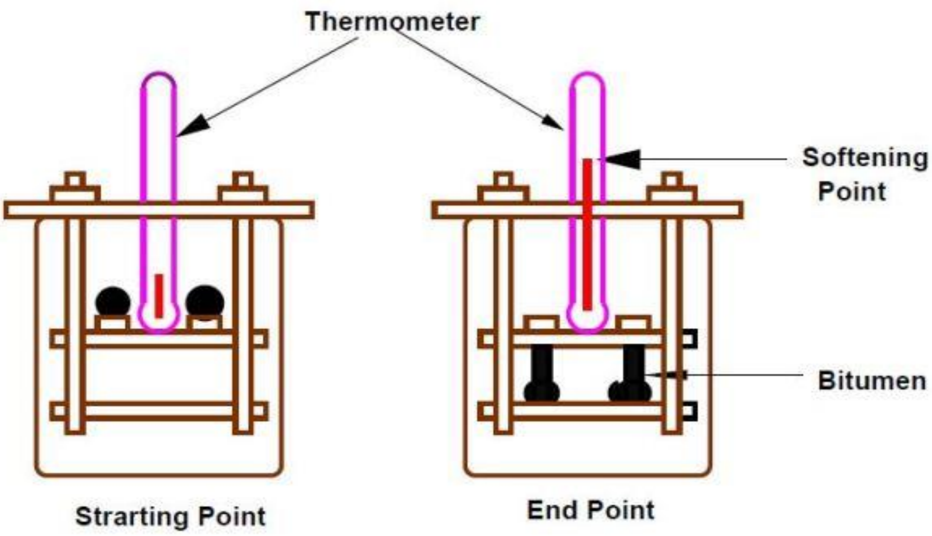


Figure1.12. Softening Point Test Setup

- Ductility Test

Ductility is the property of bitumen that permits it to undergo great deformation or elongation. Ductility is defined as the distance in cm, to which a standard sample or briquette of the material will be elongated without breaking. Dimension of the briquette thus formed is exactly 1 cm square. The bitumen sample is heated and poured in the mold assembly placed on a plate. These samples with moulds are cooled in the air and then in water bath at 270C temperature. The excess bitumen is cut and the surface is leveled using a hot knife. Then the mould with assembly containing sample is kept in water bath of the ductility machine for about 90 minutes. The sides of the moulds are removed, the clips are hooked on the machine and the machine is operated. The distance up to the point of breaking of thread is the ductility value which is reported in cm. The ductility value gets affected by factors such as pouring temperature, test temperature, rate of pulling etc. A minimum ductility value of 75 cm has been specified by the BIS. Figure 1.13 shows ductility Test Process [15].

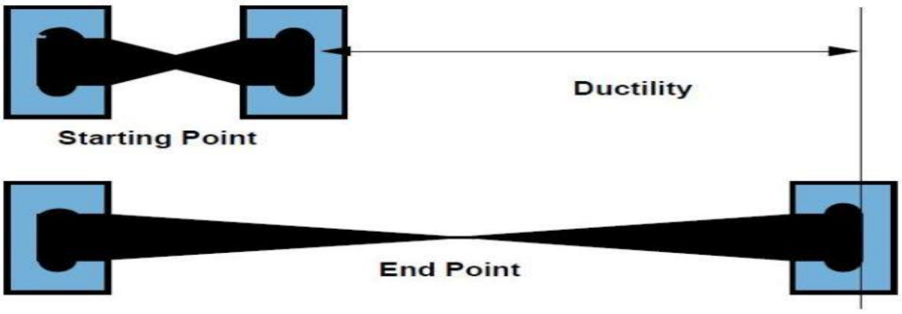


Figure 1.13. Ductility Test

Table 1.01: Classification of Bitumen According to Penetration Test and Softening Point Test.

	unit	Classes								
		20/30	30/45	35/50	40/60	50/70	70/100	100/150	160/220	250/330
Penetration	0.1mm	20/30	30/45	35/50	40/60	50/70	70/100	100/150	160/220	250/330
Softening Point Test	°C	22-63	52-60	50-58	46-56	46-54	43-51	39-47	35-43	30-38

- Specific Gravity Test

The specific gravity of bitumen is defined as the ratio of mass of given volume of bitumen of known content to the mass of equal volume of water at 27°C. The specific gravity can be measured using either pycnometer or preparing a cube specimen of bitumen in semi solid or solid state.In paving jobs, to classify a binder, density property is of great use. In most cases bitumen is weighed, but when used with aggregates, the bitumen is converted to volume using density values.The density of bitumen is greatly influenced by its chemical composition. Increase in aromatic type mineral impurities cause an increase in specific gravity.

The specific gravity of bitumen varies from 0.97 to 1.02 [15].

c- Classification of road bitumens

The rolling thin-film oven test (RTFOT) is one of the most commonly used standardized tests to simulate the STA of binders. This test is used to measure the combined effects of heat and air on a thin film of bitumen or bituminous binder in permanent renewal. It aims to simulate the hardening that a bituminous binder undergoes during the mixing, transporting, and compacting processes, referred to as STA. A moving film of bituminous binder is heated in an oven to a specified temperature, for a given period of time, with a constant supply of air. The effects of heat and air are determined on the basis of the change in mass (expressed as a percentage) or the change in the bituminous binder's characteristics before and after the period in the oven.

The RTFOT is used as the conditioning regime in many binder specifications to provide a sample of binder representing the "as laid" properties. The standardized test conditions differ in different standards, but are typically 163 °C (325 °F) for 75 min (EN 12607-1) or 85 min (ASTM D2872, AASHTO T240) [16]. The Softening Point Test temperature and the penetration of the bitumen are then measured. A significant change in these two quantities after RTFOT reflects an excessive sensitivity to aging, the test is illustrated in the figure 1.14.

160-220 bitumens are mainly used for the manufacture of emulsions and the production fine asphalt applied in thin layers.

The 70-100, 400-70 and 35-50 bitumens, if they are also used for the manufacture of emulsions, are mainly intended for the preparation of dense mixes, bituminous concretes and gravel bitumens.20-30 bitumens are mainly used for making sand-bitumen base layers [17].

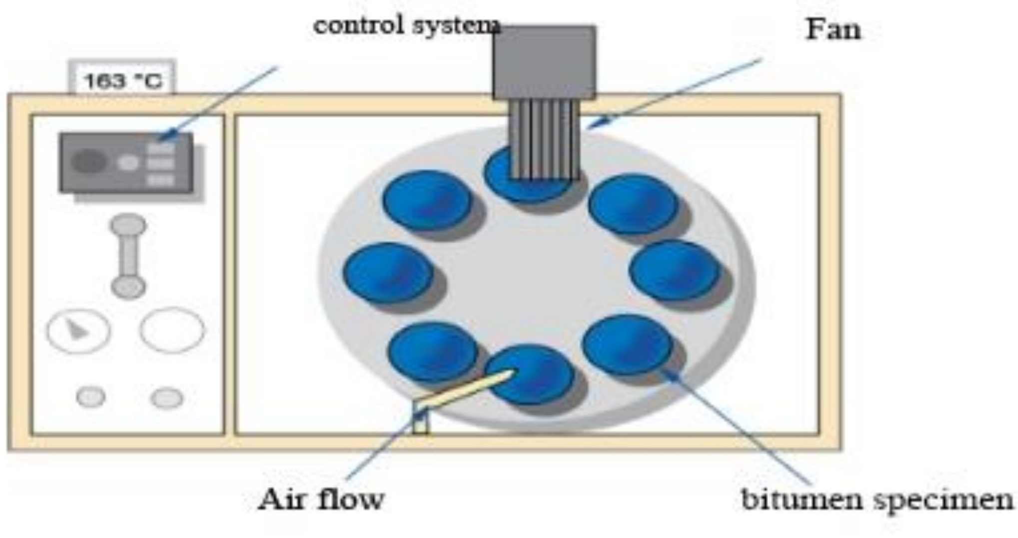


Figure 1.14. The rolling thin-film oven test (RTFOT)

The 70-100, 400-70 and 35-50 bitumens, if they are also used for the manufacture of emulsions, are mainly intended for the preparation of dense mixes, bituminous concretes and gravel bitumens.20-30 bitumens are mainly used for making sand-bitumen base layers [17].

In the case of crushed sands, bitumen 40-50 can also be used.

In warmer climates, higher hardness bitumens can be used [17].

1.2.3 The Aggregates of Asphalt

Hot mix asphalt (HMA) combinations contain 94–95 percent by weight of aggregates. Therefore, the performance of the pavement system in which the HMA is utilized depends greatly on the characteristics of coarse and fine aggregate. Often pavement distress, such as rutting, stripping, surface pop-outs, and lack of adequate surface frictional resistance is traced directly to improper aggregate selection and use. Clearly, aggregate selection based on the results of proper aggregate tests is necessary for attaining desired performance [18].

Hot Mix Asphalt aggregate testing have been divided into the following categories:

- Particle Shape and Exterior Texture (Coarse Aggregate)
- Particle Shape and Exterior Texture (Fine Aggregate)
- Absorption and Porosity
- The absence of harmful materials and Cleanliness
- Strength and Resistance to Abrasion
- Durability and Soundness
- Expansive Qualities
- Frictional and Polishing Qualities

Aggregates used in Hot Mix Asphalt are classified according to their source in three classes:

- Igneous rocks its origin Natural aggregates and used for Coarse-grained and Medium-grained and Fine-grained it's generally composed of Acidic > 66% of silica, Intermediate 55 to 66% silica, Basic < 55% silica.
- Sedimentary rocks there are a lot of types of it such as Chalk, Limestone Siliceous, Sandstone, Flint, chert, Argillaceous, Clay, shell, etc.
- Metamorphic rock a by-product of industrial processes, such as blast furnace slag, is artificial aggregate.

a- Characteristics of Aggregates

According to the definition of an aggregate used for roads, it is "an assemblage of soil and/or rock particles (natural or processed) that, when massed in layers within the pavement, possess stability and load spreading ability. “However, the term "aggregate" is frequently used to refer to both loose material (as stored in the quarry) and material that has been compacted into a layer. Crushed rock, naturally occurring river gravels, blast furnace slag, or other synthetic materials can all be used to make aggregates. They may contain very small particles, like sand, or very massive particles, like "run of pit gravel" [19].

Aggregates are first categorized in road construction according to their degree of granularity; there are six basic granular classes, each of which is distinguished by the extreme dimensions d and D of the aggregates encountered. (Norm XP P 18-540, 1997):

- Clay – less than 0.002mm. } Filler
- Silt – 0.002mm to 0.63mm. }
- Sand – 0.063mm to 2mm.
- Gravel –2mm to 63mm.
- Cobbles - 63mm to 200mm.
- Boulders – greater than 200mm.

The fines content of an aggregate is defined by the passer at 0.063 mm. [17]

b- Main tests specific to aggregates

RYAN The term "aggregate" refers to a group of mineral components, such as sand, gravel, and crushed stone, that are combined with a binder (such as water, bitumen, Portland cement, lime, etc.) to create composite materials. Examples of these materials include bituminous concrete and concrete made of Portland cement.

Bituminous concrete and Portland cement concrete both contain between 92 and 96 percent by volume of aggregate, respectively. Additionally, base and sub-base courses for both flexible and rigid pavements are made of aggregate. Aggregates can be created artificially or naturally. Larger rock formations are typically mined for natural aggregates using an open excavation called a quarry. Usually, mechanical crushing is used to reduce extracted rock to sizes that may be used. Aggregate that has been manufactured is frequently a byproduct of other industrial sectors. This chapter also covers the requirements for aggregates in pavement [20].

✓ **Particle size distribution of aggregate**

The Particle Size Distribution Test (NF P 18-560) can be used to determine the particle size distribution curves of various aggregates. The test entails sorting the various grains that make up the sample using a succession of sieves that are nested on top of one another and have decreasing opening sizes from top to bottom. The material being researched is put in the upper portion of the sieves, and the sieve column is vibrated to classify the grains.

The percentage of sieves beneath sieves whose meshes D are marked on the abscissa according to a logarithmic gradation comprise the ordinate of the graph on which the granulometric curve is plotted.

✓ **Sand Equivalent Test**

Fines and dust have always been an issue in concrete and asphalt aggregates. Unwanted or unidentified fines can affect the performance and cost of composite materials, whether they are produced naturally or as a result of degradation during handling and transit.

The behaviors of the materials are badly impacted by excessive fines and dust, despite the fact that controlled amounts might improve some aspects of asphalt or concrete mixtures. Concrete with too much fines has more solid surfaces overall, which makes it harder to work with and uses more water. High particles in asphalt cause the asphalt binder and aggregate to lose adhesion, necessitating the use of extra binder.

Using the (NF P 18-598) norm the Sand Equivalent Test is the ratio multiplied by 100 of the height of the sediment sandy part (clean), to the total height of the flocculate and the sediment sandy part. The test consists of flocculating the fine elements of a sand suspended in a washing solution then, after a given resting time, measuring the height of the sediment elements. It is carried out on the fraction of the sand passing through a 5 mm square mesh sieve.

✓ **Methylene blue test**

This test, commonly used to characterize the activity of clays contained in the soil, is also used to assess the influence of fines of clay origin contained in soils.

Sand and gravel of natural or artificial origin. The test is carried out on a sample containing at least 200g of particle size fraction 0/2 mm.

✓ **Aggregate Abrasion Testing: The Micro-Deval Test Method**

Testing for abrasion and impact determines the relative strength and quality of mineral aggregates. The Micro-Deval Test and the Los Angeles (L.A.) Abrasion Test are two common tests that are still in use today. The results of either of these processes will provide you precise details regarding the longevity of a sample aggregate.

The Micro-Deval Test has grown in acceptability and popularity as a practical and reliable method for assessing aggregate abrasion in recent years. As mineral aggregates are ground with steel balls in the presence of water, the methodology's foundation was created in France in the 1960s and offers a measurement of the toughness, abrasion resistance, and durability of the aggregates.

Abrasion loss is determined by measuring the quantity of degraded material passing a 1.18mm (No. 16) or 75µm (No. 200) sieve after the test. Materials that produced a low loss in the test are less likely to degrade significantly when handled, mixed, or placed, which will improve the long-term performance of pavements. For materials with fine or coarse aggregate, different test procedures exist [21].

✓ **Aggregate Abrasion Testing: The Los Angeles Abrasion Test**

The relative quality of aggregates is frequently determined using the Los Angeles (L.A.) Abrasion Test. When normal aggregate gradings are subjected to impact and abrasion in a spinning steel drum with an abrasive charge of steel balls, it quantifies the amount of degradation that occurs.

With each revolution, the charge and sample are raised and lowered by an internal shelf in the drum, creating impact pressures. Contents are removed and the percent loss is calculated when the machine has completed the required rpm [22].

It consists of placing the aggregates to be tested and steel balls in a cylinder with a horizontal axis 70 cm in diameter and 50 cm in length. 500 revolutions are performed at 30 rpm.

The weight and granularity of the test sample are determined according to the maximum diameter of the aggregate. After testing, the materials are screened with a 1.6 mm mesh sieve and the weight of the passing fraction is related to the weight of the test portion. The ratio, multiplied by 100, is called the Los Angeles (LA) coefficient [23].

✓ **Specific gravity**

The specific gravity of aggregates is usually determined for two reasons:

- To allow the calculation of voids in asphalt concrete in the compacted state.
- To adjust the amounts of constituent fractions of the aggregate in asphalt concrete, when the relative density of these constituent fractions varies significantly.

1.2.4 Asphalt Pavement

Asphalt pavement is also known as asphaltic concrete, plant mix, bituminous mix, bituminous concrete, hot-mix asphalt, warm-mix asphalt, and a variety of other names. It combines aggregates and asphalt binder as its two main components. By weight, the aggregates make up around 95% of the entire mixture. To create asphalt pavement, they are combined with an asphalt binder that makes up around 5% of the mixture [24]. Aggregates: (about 90% by weight) composed of several fractions in variable percentages:

- Fines < 80 µm
- Sands (0/3)
- Gravel (3/8, 8/15)

- Bitumen: (5 to 7% by weight)
- Voids: (from 2 to 20% depending on the materials)

A manufacturing facility that may produce the following materials combines the aggregates and asphalt. Plant machinery includes: cold bins for storage and controlled proportioning of graded aggregate; a dryer for drying and heating aggregates to the required mixing temperature; a pug mill or drum for combining the graded, tanks for storing the heated

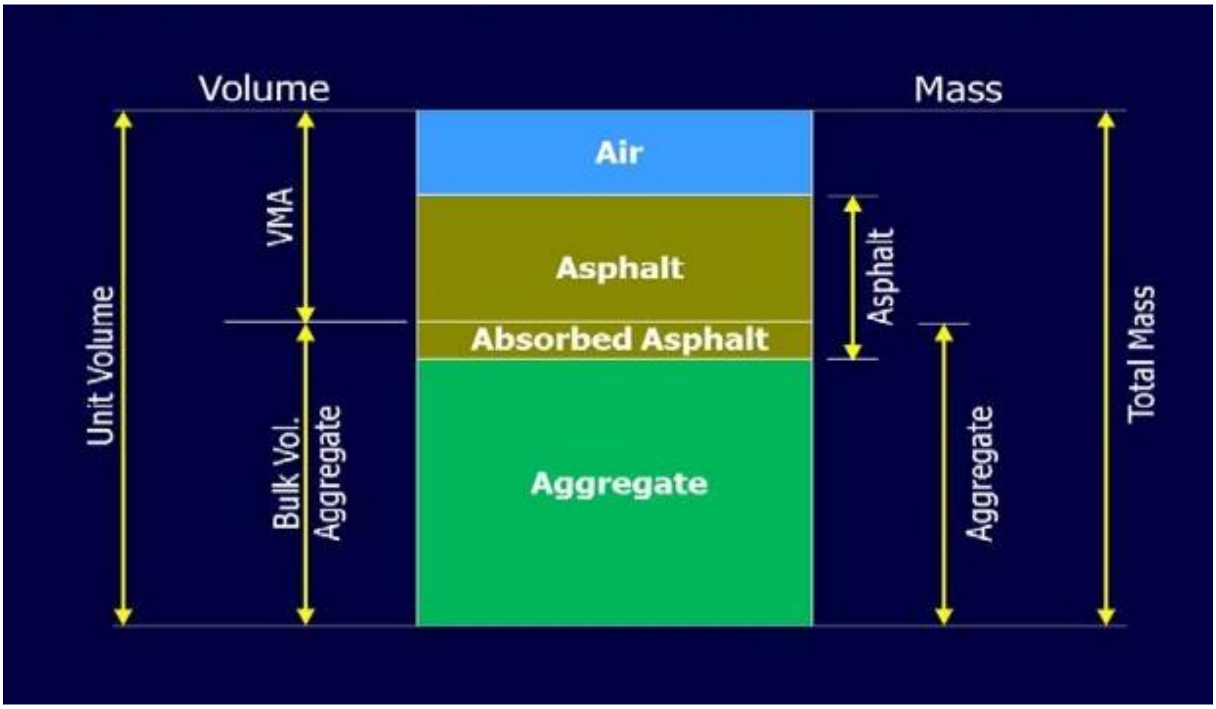


Figure 1.15. Component Diagram of Asphalt Pavement.

liquid asphalt, heated aggregate, and heated liquid asphalt cement in accordance with the prescribed mix formulas [24].

a- category of asphalt by usage

The asphalt can be categorized the usage role here we talk about the usage different layers there are three categories:

✓ Asphalt for Base Course

Bitumen gravel (B.G): Developed in the early 1970s, today they represent the first technique for constructing pavement bases on the motorway network. The design of these asphalt mixes results from observations made between 1950 and 1970. Is obtained by the use of relatively hard bitumen (35/50) at a relatively low dosage and with the use of completely crushed aggregates. From 12 to 18cm. Conventional gravel bitumen is a hot mix with a 0/20 (or 0/14) grain size containing approximately 4% 35/50 bitumen.

In view of the excellent results obtained with this mix, particularly in terms of resistance to rutting, it was possible to increase the bitumen content to improve its resistance to fatigue. The road technician now has "grave improved bitumen" or B.G which contains 4.5 to 4.8% 35/50 bitumen. In addition to the gains obtained in terms of service life, the increase in the percentage of bitumen makes compaction easier and allows thicknesses to be reduced. The B.G have a field of use of 10 to 15cm [25].

Bitumen sands (B.S): It is a mixture of natural sand (often rounded), crushed sand and very hard bitumen, the latter compensating for the lack of stability of natural sand. This 0/4 or 0/6 grain mix contains 4 to 4.2% 20/30 bitumen, it is spread in a layer 10 to 15 cm thick [25].

✓ Asphalt for Binder Course (B.B.C)

The binding layer being a transition layer between the base layer and the wearing course, its formulation is intermediate between the formulations of these two layers.

It is generally a 0/14 mix containing approximately 5/ of hard bitumen 35/50. This bonding bituminous concrete (B.B.C) is implemented in a layer 5 to 8cm thick [25].

✓ Asphalt for Surface Course (B.C)

Called Bituminous Concrete (B.C), they correspond to semi-grained asphalt. Commonly used on all road networks, they represent the major part of asphalt for the wearing course.

SPECIAL CASE of studded asphalt: In this region there are no materials with the correct intrinsic characteristics to be able to be used in wearing courses.

This problem often arises with calcareous materials whose accelerated polishing coefficient (APC) is insufficient. Studded asphalt was developed based on processes used in Northern European countries in England with “Hot Rolled Asphalt”.

The studded asphalt consists of a hot mix made from often polishable aggregates on which hard, unpolished-sanded gravel is spread, after the finisher, before compacting the layer. There are 3 types of studded asphalt:

Bituminous concrete studded 0/10 in 5 or 6 cm thickness studded with gravel of caliber 10/14.

The 0/6 studded bituminous micro-concretes in 3 cm thickness studded with 10/14 gravel.

Asphaltic sand studded 0/4 in 2 cm thick doubtful with 16/20 gravel.

These coatings have given excellent results, particularly in terms of adhesion, but are now being replaced by new, less expensive and more efficient processes such as BBTM (Very Thin Bituminous Concrete). In fact, all these asphalt mixes for surface courses based on pure bitumen as well as the bonding Bituminous Concrete (B.C) are today at the limit of their field of use for all cases of heavy, slow and channeled traffic [25].

b- category of asphalt by manufacturing temperature

Due to the various requirements that, for example, a road must meet (heavy traffic, harsh weather conditions, etc.), the corresponding mix must have enough stiffness and resistance to deformation to deal with the applied pressure from vehicle wheels on the one hand, and sufficient flexural strength to resist cracking caused by the various pressures exerted on them on the other. Moreover, great workability during application, it's crucial to make sure they can be completely compacted for maximum durability [26].

✓ **Hot Mix Asphalt (HMA)**

This mix is common type used in road of Algeria, the temperature of manufacturing of hot mix asphalt HMA is between 150 and 190 °C [26]. There are several subtypes of hot mix asphalt depending on the usage:

- Porous Asphalt
- Stone Mastic Asphalt (SMA)
- Asphalt Concrete
- Asphalt Concrete for very thin layers
- Double layered Porous Asphalt

✓ **Warm Mix Asphalt (WMA)**

A typical WMA is created at a temperature that is typically 20 to 40 degrees Celsius cooler than a comparable hot mix asphalt. Roadway opening is accelerated and crew working conditions are enhanced because to the use of less energy and a lower mix temperature during paving operations [26]. This proven method can:

- Reduce paving costs
- Extend the paving season
- Improve asphalt design
- Longer distance hauling of asphalt mix

- Reducing exposure to gasoline emissions, fumes, and odors will improve working conditions.
- Reduce emissions of greenhouse gases

✓ **Cold Mix**

Cold mixes are manufactured with no heating of the aggregate. This is just possible, due to the use of a particular bitumen emulsion that separates either during mixing or compaction. The emulsion coats the aggregate after it has broken, gradually boosting its strength. For roads with little traffic, cold mixes are especially advised [26].
The cold mix's primary benefits are:

- Cost-effectiveness
- Environment friendly
- Lower emissions
- Easy availability

c- Algerian bituminous mixtures formulation

The formulation in Algeria is based on the verification of the characteristics of the components as well as on the Duriez and Marshall tests according to the granular materials. A formula is chosen which gives a mixture having the best ability to compaction and which could give better stability to the bituminous mixture. We must first check that the granulometric curve of the mixture is perfectly in line with the specific reference zone for bituminous concrete 0/14 of SETRA-LCPC intended for a wearing course.

The granular fractions of the 0/14 bituminous concrete are chosen from the following aggregates: 0/3, 3/8, 8/15, the spindle of the aggregates is represented as follows:

Table 1.02: Bituminous Concrete (B.C) 0/14 Particle Size Range

SIEVE (mm)	PASSING B.C 0/14
20	/
14	94-100
10	72-84
6.3	50-66
2	28-40
0.08	07-10

✓ **Fines content:**

The fines content of the mixes must be defined based on the laboratory study. It will be within the ranges indicated in Table 1.02, above. When the fines content from the materials is insufficient, filler fines are used.

✓ **Determination of binder content (bc):**

The bitumen content (bc) is the mass of binder on the mass of dry aggregates expressed as a percentage. Duriez established the formula (Eq.1.1) to determine the bitumen content of asphalt mixes according to the specific surface of the mixture:

$$bc = k \propto \sqrt[5]{\Sigma} \qquad \text{(Eq.1.1)}$$

Such as:

k: richness modulus

It represents a quantity of binder depending on the specific surface area of the dry mix. It therefore characterizes the thickness of the binder film around the aggregates. The richness module makes it possible to classify bituminous mixtures:

- Bitumen gravel (2 < k Bitumen gravel < 3.2)
- Bituminous concretes (3 < k bituminous concrete <3.9)

Table.1.03: Usual values of the richness modulus for asphalt concrete

asphalt concrete	Richness Modulus			
0/14	3.45	3.60	3.75	3.90

∝: Correction coefficient

This coefficient makes it possible to take into account the real density of the aggregates, if this differs from 2.65 t/m3, the following formula is used (Eq.1.2):

$$\propto = \frac{2.65}{M_v} \qquad \text{Eq.1.2}$$

Mv: aggregate specific gravity

The method used is the classic pycnometer method. A weight of the aggregate dried at 105° C. is measured, then its volume is determined by liquid displacement in a pycnometer as follows:

A known mass MG of dried aggregates (by passing through an oven at 105° C. until constant mass) is introduced into a container containing distilled water. Released air bubbles are sucked out by an air gap (water pump). After ensuring that no air bubbles are trapped between the aggregates, the volume of water displaced by the particles is determined very carefully.

The volume of VG aggregates, equal to the volume of water displaced.

M_1: mass of the pycnometer containing distilled water with its stopper

M_2: mass of the pycnometer containing the aggregates, the distilled water and the stopper.

$$M_2 = M_1 + M_G - M_{VE}.V_G \qquad \text{Eq.1.3}$$

The volume of the aggregates is expressed by the formula (Eq.1.4):

$$V_G = \frac{M_1+M_1}{M_{VG}} - M_2 \qquad \text{Eq.1.4}$$

With:

M_G: Mass of aggregates;

M_{VE}: Density of distilled water;

V_G: Aggregate volume;

M_{VG}: Density of the aggregates.

Σ: conventional specific surface

The specific surface of an aggregate represents the total surface area of the particles in relation to its volume. It is expressed in m2/m3 of aggregate. This way of expressing the specific surface makes it possible to make the comparison between the different aggregates. It is then expressed in m2/kg, which is essentially comparable between materials with the same density [27].

$$\Sigma: 0.25G + 2.3S + 12s + 135f \quad \text{in} \quad m^2/kg \quad \text{(Eq.1.5)}$$

G: weight proportion of elements greater than 6.3 mm.
S: proportion by weight of the elements between 0.315 mm and 6.3 mm.
s: proportion by weight of the elements between 0.08 mm and 0.315 mm.
f: weight proportion of elements less than 0.08 mm

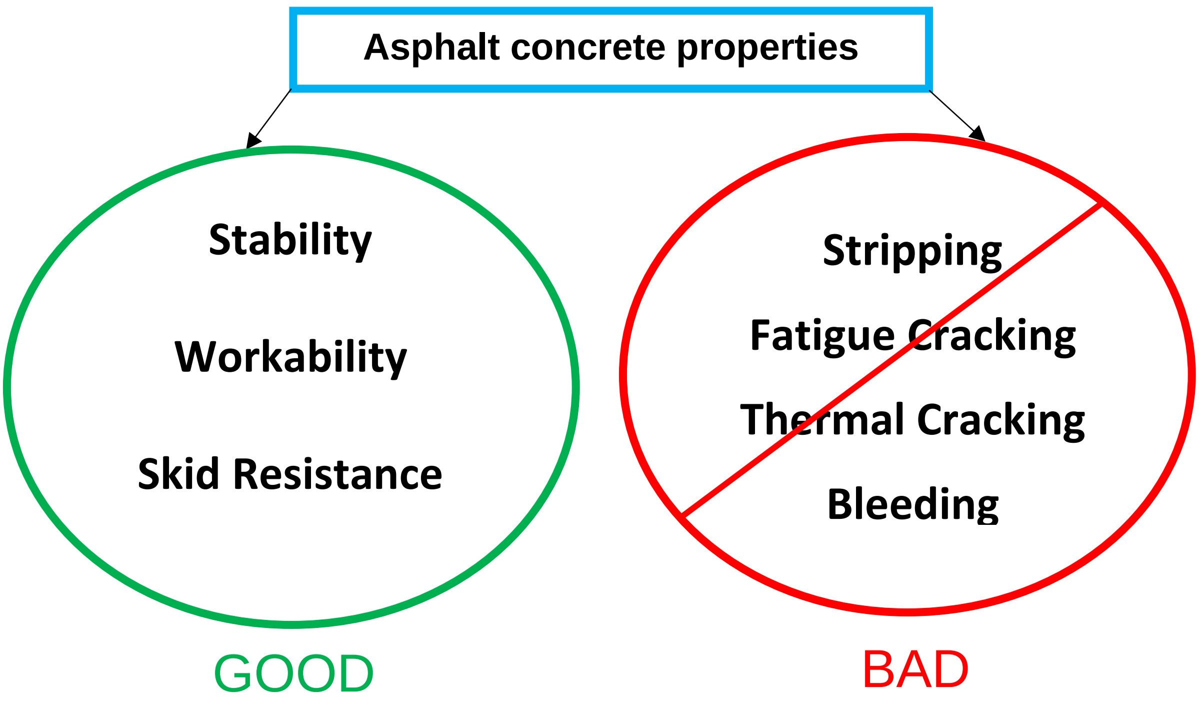
In some cases, the following simplified formula is used:

$$\Sigma: 2.5\,G + 1.3\,f \quad [m^2/kg] \quad \text{(Eq.1.6)}$$

The specific surface is influenced by:
Maximum aggregate size: the specific surface is inversely proportional to the maximum aggregate size.
Particle size of the aggregates: for an aggregate of the same maximum size, the specific surface will be proportional to the passing percentages or to the fineness of the aggregate.
Shape of aggregates: the specific surface of a cubic particle is twice as large as that of a spherical particle [27]. The flat, elongated particles have the largest specific surface area [28]. However, specifies that the specific surface area method, which uses predetermined factors for each sieve, is not always realistic, because it uses the same factors regardless of the shape of the aggregate. This is a source of inaccuracy [23].

d- Asphalt concrete mix tests

The formulations of Asphalt concrete are determined by means of tests in the laboratory making it possible to evaluate the behavior of the materials under compaction (Giratory shear press PCG), to assess their mechanical characteristics (fatigue tests, MARSHALL tests, LCPC tests - DURIEZ) and to estimate their risks of permanent deformation (rutting tests). [28] The tests are aimed to define asphalt properties, the down below diagram shows the desirable and undesirable characteristics of asphalt concrete properties:



✓ **Marshall Test**

The Marshall test is frequently used in testing procedures for paving operations. A compacted specimen's maximum load at a standard test temperature of 600 °C is used to determine the stability of the mixture. When performing a stability test, the flow is calculated as the deformation in units of 0.25 mm between zero load and the maximum load carried by the specimen (the flow value may also be calculated as the deformation in units of 0.1 mm). The goal of this test is to determine the optimum binder content given the kind of aggregate mix and traffic volume. This test aids in the calculation of Marshall Stability vs. percent bitumen.[29] The Marshall test is applicable to all hot mixes that do not contain aggregates larger than 20 mm.The preparation of the mixture and the making of the test specimens is done in a metal container that can contain approximately 2000 cm3, the quantity of bitumen and 1200 g of mix reconstituted from 3 granular classes whose percentages vary according to the desired mix are poured. For a given composition of the aggregate, the study focused on 3 different bitumen contents. For each given content, 5 specimens were made (3 for stability and creep; 2 for the apparent density of the mixture by hydrostatic weighing).

Figure 1.16. Automatic Marshall Stability Test Machine

The mixture is brought to 140° C. before being poured into the mold and then compacted at the rate of 50 strokes of the hammer on each of the two faces of the specimen; a disc of filter paper is placed on the surface of the asphalt before compaction. The compaction time (tamping and handling) must not exceed 3 minutes.

To avoid any risk of cooling. The mold is then placed for 15 minutes under a jet of cold water, held in such a way that the mix is not wet. After 5 hours at room temperature, the specimen is removed from the mold by exerting slight pressure on the extractor piston placed in contact with the asphalt before being immersed in a hydrostatic bath set at 60°C for 30 minutes. Finally, the test specimen is placed in the Marshall device consisting of two jaws resting on two opposite generatrices of a press capable of developing a force of 2 tons during diametric crushing at a speed of 0.846 mm/s. For each composition we determine:

- Bulk density;
- Stability at 60°C;
- Flow;
- Compactness;
- Percentage of voids filled with bitumen.

✓ **Duriez compression test**

Specifically for the water sensitivity of bituminous specimens, the test sets are utilized to ascertain the physical and mechanical properties of bituminous mixes. According to the maximum aggregate upper sieve size, one set is used to prepare 80 mm specimens, while the second set is used to prepare 120 mm specimens.
Steel that has been treated against corrosion is used for all parts.

The compression test has to be performed with an electromechanical universal test machine such as UTM8300.SMDL2 or UTM-8300.SMPR model machine (300 KN Electromechanical Universal Test Machine.UTM-8300 can also be used for compaction transaction acc. to EN 12697-12 (Method B) for preparation of test specimens.

Grooved or Non-Grooved piston set includes upper and lower pistons. Grooved piston set for cold mixes and Non-Grooved piston set for hot mixes should be ordered separately [30]. Duriez compression test sets are supplied complete with the following:

- Mould
- Container
- Extraction Piston
- pcs Half Spacers

Finally, the crushing of the specimens is done using a press at a speed of 1 mm/s and, at the moment when the rupture occurs, the direction of advancement is reversed. A dead index, driven by a needle of the pressure gauge of the press, makes it possible to identify the maximum value of the applied load, that is to say the sought value of the resistance to compression. By dividing this value by 50, we obtain the compressive strength called Duriez stability.
For each composition, we determine:

- The bulk density. of the coated material;
- Compressive strength at 18°C
- The percentage of subsidence: it is 100 times the relative decrease in the height of the specimen caused by the crushing load;

These results show that the optimal formulation retained has good stability. The stability values found are all significantly higher than the specific value.

✓ **Gyratory Compaction test**

Gyratory laboratory compaction is regarded as one of the best techniques for both producing test samples and determining whether a substance is compatible. A bulk of asphaltic material

is placed into a 100- or 150-mm diameter mold using platens to apply vertical stress, approximately 600 kPa. The longitudinal axis of the mold rotates at a set angle to the vertical axis while the platens are kept parallel and horizontal.
The mixture density and void content are determined throughout the test, and the height of the specimen is automatically measured [31].
The key uses of this test are:

- Compaction of asphaltic paving material to a target mixture density or void content
- Assessment of mixture compactibility
- SHRP Super-pave asphalt mixture design
- Preparation of cylindrical test specimens

✓ **Rutting test**

one of the mean tests of asphaltic concrete is the rutting test which is simply a determination of the resistance to deformation of bituminous mixes compacted by the passage of a loaded test wheel.

Execution of the test are:

- Manufacture of 2 test plates (50 x 18 x 10 cm) ‘with a special compacting device’
- Condition the test plates at a temperature of 60°C
- Perform a traffic simulation with 30,000 passages

As result of this test Rut depth after 10,000 cycles for grades type S resp. 30,000 cycles for type H takes effect measurement for resistance to deformation.

✓ **Fatigue test**

An important reference for designing asphalt mixtures and pavement structures is provided by fatigue performance evaluation on asphalt mixtures. Due to its low cost, high efficiency, and robust operability, laboratory fatigue testing has been frequently utilized by engineers and researchers to evaluate the fatigue performance of asphalt mixtures.

The trapezoidal specimens are subjected to a displacement imposed by bending in 2 points for a given frequency of sinusoidal displacement. The test is repeated for 3 deformations in a ventilated atmosphere at a controlled temperature. The result is the slope of the fatigue line calculated from the three deformations and the allowable deformation ε6 to obtain a life of 10^6 cycles.
Complex modulus test:
The specimens are subjected at the head to stresses constant sine waves for frequencies and temperatures defined.
The result is the average of the moduli of the 4 test specimens tested. The modulus value retained in the product standards is the modulates at 15°C and 10 Hz.

Figure 1.17. Fatigue machine

1.3 Degradation of Layers in Asphalt Concrete Pavement

Asphalt paving is renowned for its durability and resilience. Due to its advantages, it is a widely utilized material for numerous pavement applications and the material of choice for the majority of state road projects.

The laws of nature, however, make it subject to deterioration just like other paved surfaces do. Despite the lengthy lifespan of well-installed asphalt pavement, it is nevertheless possible for it to be short-lived due to subpar surface preparation, bad building method, or even just prolonged exposure to the weather. Let's examine more closely what leads to asphalt deterioration.

1.3.1 Types of causes of asphalt road deterioration

a. Traffic cause

Every pavement layer experience crushing and bending as a result of traffic. The repeated tractions at the base of the layers, under the effect of the passage of vehicles, create micro-degradations which accumulate and can lead to the ruin of the material. This is the phenomenon of fatigue that is observed for many materials. A crack can also appear and propagate in the roadway. The repeated compressions under the passage of the load can create permanent deformations sometimes inducing a rutting on the surface of the roadway. This rutting may be due to the settling of the asphalt concrete layers or to the deformations of untreated lower layers [32].

b. Thermal cause

Throughout its life, a pavement is exposed to different and varied climatic conditions, most often without any protection. It is the temperature, in the behavior of the pavement, that plays the preponderant role, and this particularly for flexible pavements, which can manifest itself in three ways that we will detail.

- ✓ Effect on the stiffness of asphalt: Bitumen and aggregates are the ingredients of the bituminous mix. Even though bitumen only makes up 4 to 7% of the total mix by mass, the behavior of the mix at various levels is controlled by the bitumen. The latter gives the mixture a thermo-susceptible quality because of its viscoelastic behavior. Asphalt stiffness decreases with increasing temperature. The modulus of stiffness is also impacted by the strain rate and decreases when the strain rate decreases. The modulus of the asphalt therefore varies from a few hundred mega pascales at high temperature and low speed, to more than thirty giga pascales at very low temperature [33].

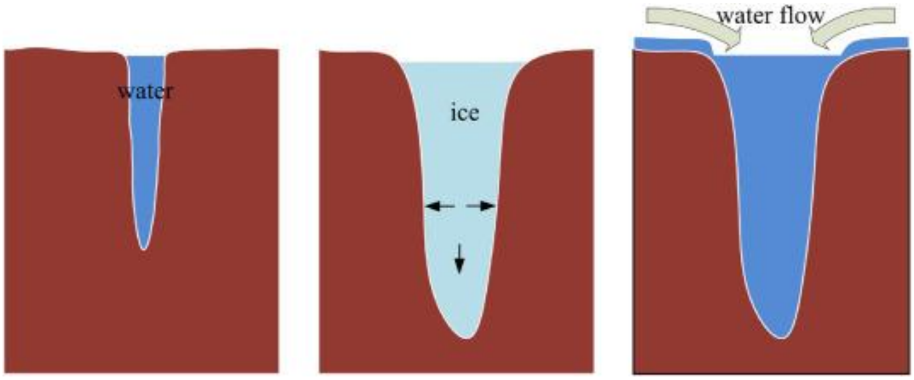


Figure 1.18. Potholes forms by the freeze-thaw cycle

- ✓ The freeze-thaw cycle: When the temperature varies above and below freezing, a natural occurrence called the freeze-thaw cycle takes place. This cycle can severely harm roads and other pavement surfaces in regions with a temperate environment. Water penetrates into pavement pores and cracks as a result of the freeze-thaw cycle. The water freezes and expands when the temperature dips below freezing, causing the pavement to degrade and crack. Ice melts when the temperature climbs above freezing, weakening the pavement and making it more vulnerable to future harm.

1.3.2 Types of Pavement Deterioration

The following are examples of typical pavement distresses: cracking; distortion; disintegration; skidding hazards; and surface treatment distresses. The following are some typical reasons why pavement deteriorates: traffic loading; environment or climate influences; drainage deficiencies; materials quality problems; construction deficiencies; and external contributors, such as utility cuts [34].

a- Cracking

Asphalt pavements can experience a variety of crack kinds. Some cracks are caused by loads, while others are because of the environment or the temperature [34].

Fatigue Cracking:

Due to the interconnecting fractures' resemblance to an alligator's skin, fatigue cracking is also known as alligator cracking. Load-related deterioration brought on by a deficient base course or subgrade, insufficient pavement thickness, overloading, or a combination of these factors is what leads to fatigue cracking.

Block Cracking:

Block cracking is a pattern of wide, rectangular fractures on the surface of an asphalt pavement, usually measuring one foot or more. This kind of cracking frequently affects wide areas and can appear in places with little to no traffic. Block cracking is typically brought on by the asphalt pavement shrinking as a result of temperature fluctuations.

Edge Cracking:

Longitudinal fractures called edge cracks appear one to two feet from a pavement's outer edge. These fractures develop as a result of inadequate support at the pavement edge.

Longitudinal Cracking:

Longitudinal cracks develop parallel to the pavement's centerline. They may result from a poorly constructed joint; shrinkage of the asphalt layer; cracks reflecting up from an underlying layer; and longitudinal segregation due to improper paver operation. These cracks are not load-related.

Transverse Cracking:

Transverse cracks develop nearly parallel to the pavement's centerline. They can be caused by shrinkage of the asphalt layer or reflection from an existing crack. They are not load-related.

Reflection Cracking:

Reflection cracks form over joints or cracks in concrete pavement or in an overlay of deteriorated asphalt pavement. The cracks form because of the movement of the old pavement.

Slippage Cracking.

Slippage cracks are crescent-shaped cracks which form because of low-strength asphalt mix or a poor bond between pavement layers. The forces generated by a vehicle's turning or braking motion cause the cracks to form.

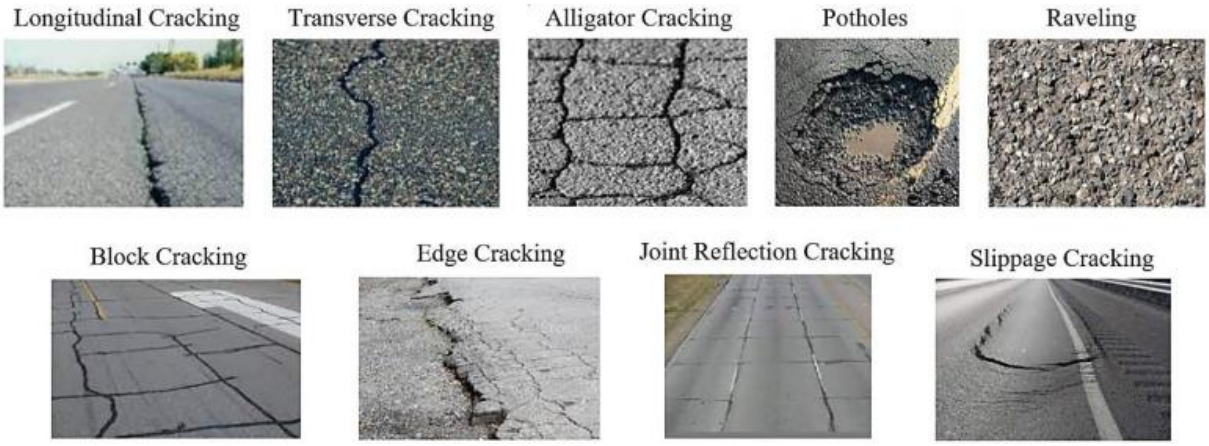


Figure 1.19. Types of cracks in asphalt pavement

b- Distortion

The instability of an asphalt mix or the fragility of the foundation or subgrade layers are what produce distortions in asphalt pavement. This distress may include rutting, shoving, depressions, swelling, and patch failures [34].

Rutting: Rutting is a linear, surface depression in the wheel path. Rutting is brought on by the deformation or consolidation of any subgrade or pavement layer. It can be brought on by thin pavements, poor asphalt blends, and inadequate compaction.

Shoving: Shoving is the formation of ripples across a pavement. Because of its distinctive shape, this kind of distress is occasionally referred to as "wash-boarding". Shoving occurs at locations having severe horizontal stresses, such as intersections. A poor granular basis, too much fine aggregate, too much asphalt, too much asphalt that is too soft, or too much asphalt that is in excess are the usual culprits.

Depressions: Bird baths are small, isolated depressions in the pavement's surface. These flaws can be caused by settlement or other failures in the lower pavement layers or by poor construction techniques.

Upheaval: Upheaval is a specific upward movement of the pavement caused by subgrade swelling. Frost heave is an example of this type of distress.

Patch Failures: When pavements are patched, some distress may begin to occur. Compaction, material choice, and the caliber of the adjacent or subsurface pavement all have an impact on how quickly a patch degrades.

Rutting

Shoving

Depressions

Upheaval

Patch Failures

Figure 1.20. Types of distortion in asphalt pavement

c- Disintegration

A pavement will disintegrate if it breaks up into small fragments that are lost over time and amid heavy traffic. The two most typical forms of disintegration are raveling and potholes [34].

Raveling:

Raveling is the wearing away of the aggregate particles from the asphalt cement. This state suggests that the asphalt has hardened or that a poor mix was employed. When there is traffic, raveling happens.

Potholes:

The localized degradation of the pavement surface results in bowl-shaped holes on the pavement called potholes. Potholes generally develop as another sort of suffering worsens over time. The beginning of a pothole may be caused by segregation, cracks, or unsuccessful fixes. Poor mixtures and weak spots in the base or subgrade accelerate pothole failures.

Raveling

Potholes

Figure 1.21. Types of disintegration in asphalt pavement

d- Skidding Hazards

Water on the pavement's surface, polished aggregates, too much asphalt, or other lubricants on the pavement's surface are all potential skidding dangers. The maintenance of a pavement that enables water to drain off the pavement is an essential factor [34].

Polished Aggregate:

Some aggregates are prone to deteriorating under traffic to a smooth finish or texture. Wearing courses shouldn't use these aggregates. If the aggregate polishes, the surface roughness must be restored.

Bleeding:

An asphalt flush can cause a pavement surface to lose its ability to resist skidding. Too much asphalt in the mix, too much tack or bond coat, or a seal coat that is poorly made can all result in bleeding. A combination that is unstable may be too compacted by traffic, pushing asphalt to the surface.


Polished Aggregate Bleeding pavement

Figure 1.22. Types of skidding hazards in asphalt pavement

Even after the treatment of the above pavement deterioration the still under the risk of surface treatment distress.

e- Surface Treatment Distress

Surface treatments can experience their own distress. These include loss of coverage aggregate and streaking [34].

Loss of Cover Aggregate:

Surface treatments can lose the aggregate cover prematurely. Spreading the chips too late in the construction process, utilizing soiled aggregate, allowing traffic to use the surface before the aggregate is seated and bonded, or using insufficient asphalt to embed the aggregate are typical causes of this.

Streaking:

The occurrence of alternating stripes of aggregate or asphalt is known as streaking. Before the aggregate chips are applied, the asphalt is applied unevenly on the pavement surface, which is the main cause of streaking.


Loss of Cover Aggregate Streaking of Aggregate

Figure 1.23. Types of surface treatment distress in asphalt pavement

1.3.3 Modern technology impact on road paving

The past years have been difficult for anyone working in the construction industry. Even while this could appear frustrating, the surroundings have given room for creativity and ingenuity. Here is a summary of six paving technologies that are sure to have an impact on the sector through the year 2022 and beyond.

a. 3D Paving Control:

Even while providing a level and smooth surface is the aim of every paving job, this isn't always possible when the existing surface is rocky and uneven. By using variable depth paving, 3D paving control systems allow the operator the ability to quickly match the planned design without having to first lay down an initial leveling course and then review the surface to determine where problems are developing. In addition to these real-time controls, there is the option to download additional apps or install other third-party programs to give the 3D paving controls more flexibility and usability. Through the use of these control algorithms, enterprises may use less asphalt during the first layer, which reduces waste and enables them to complete projects more quickly and effectively than ever before **[35]**.

b. Project Management Software:

Traditionally, spreadsheets were used to plan out the majority of paving jobs. Even though this serves the purpose, it isn't always effective, especially for bigger projects. The productivity of a project can be greatly improved by using project management software rather than attempting to complete everything manually. The building sector has already adopted project management software, but it is also starting to have an impact in the paving sector.

Multiple planning tools are combined into one simple spot by project management software. These applications also make it simpler to keep track of all the intricate details that go along with these projects, making it simple to repair issues or make changes immediately [35].

c. Smart Pavement and Nanotechnology

Numerous applications of nanotechnology, such as the adhesive damping technique covered in the 2018 article from Newtonian Technologies, are starting to impact the paving sector. By giving the pavement "weigh in motion" capabilities, smart pavement is now being investigated as a method to continuously evaluate infrastructure health. The piezoelectric sensors can gather information about the automobiles and trucks traveling a stretch of highway as well as the condition of the pavement by incorporating this technology into the pavement when it is laid down.

Also at the prototyping stage is smart pavement that can remotely charge electric automobiles. These wireless chargers, which resemble those used to power phones, may be able to recharge EV batteries as the car passes over them [35].

d. Paver-Mounted Thermal Profiling

Even though a road may appear to be flawlessly paved from the outside, hidden issues may exist that will become apparent as traffic begins to use the road. The temperature of the asphalt mix being poured can be checked using thermal cameras, infrared sensors, or a combination of the two by quality control specialists. A handheld IR thermometer can be used to detect surface temperatures; however, it cannot measure more than one point simultaneously with the industry's preferred accuracy.

Paver-mounted thermal profiling (PMTP) setups can scan the entire section being paved, often beyond the width of the paver. Typically, these scanners will divide the entire project into 30 x 30 cm grids while automatically measuring the temperature. These techniques make it simple to highlight problems if they are found so that they can be fixed either right away or after the paving is finished [35].

e. Intelligent Compaction

Let's first clarify that intelligent compaction (IC) applies to both soil compaction and asphalt pavement compaction in order to create a smooth and optimally dense surface for paving. For many years, compaction instruments like drum rollers have been a mainstay in the market.

Compaction was formerly primarily achieved by operator skill and manual monitoring. The IC technology has established itself in the American paving sector after finding success in European paving markets.

IC aims to enhance the compaction procedure. To assess the densification of the material, IC is generally understood to be hardware, software, and analysis algorithms installed on rollers and other compacting technologies. With these upgrades, rollers are now able to actively monitor the soil or asphalt layer they are compacting and even alter their rolling technique or compressive pressures in real time [35].

f. Autonomous Pavers

Autonomous or self-driving cars are the talk of the town right now, but these devices are useful for more than just getting people to work in the morning. A variety of businesses, like paving, are starting to see the value and viability of autonomous cars. Seven autonomous rollers and pavers operated remotely from a mobile base station and control room were recently unveiled by SANY in the Chinese city of Xiong'an New Area.

These autonomous pavers may alter how paving businesses handle these jobs when combined with automatic levels, other automatic tools, and sensors that can keep track of the area being built in real-time [35].

1.4 Additive and Modifier for the Binder of Asphalt Concrete

The use of asphalt binders is crucial for the performance of asphalt pavement. The behavior of asphalt mixture is complex and not easily comprehended. To gain a better understanding of this material, different techniques are employed to analyze its performance, especially when additives or modifiers are introduced in small quantities. These additional substances are incorporated to create asphalt mixtures that are more long-lasting and robust. These improved mixtures enhance the structural strength of the pavements and offer superior resistance against harsh weather conditions and the growing demands of traffic loads.

1.4.1 Reasons to modify an asphalt binder

Based on the asphalt source and prevailing climatic conditions, the primary motivations for employing asphalt modification can be summarized as follows (Roberts et al., 1996):

a- Minimizing rutting: Modifying the binder to increase stiffness at high temperatures helps reduce rutting, which refers to the permanent deformation of the pavement caused by repeated traffic loads.

b- Minimizing thermal cracking: By making the binder softer and enhancing the elasticity of the mixture at low temperatures, the risk of thermal cracking in the pavement can be reduced.

c- Improving resistance to fatigue: Modifying the binder can enhance the resistance of the asphalt mixture to fatigue, which the progressive structural damage is caused by repeated loading.

d- Reducing moisture sensitivity: Modifying the binder improves the bonding between the binder and aggregates, reducing the susceptibility of the mixture to moisture-related issues such as stripping.

e- Enhancing resistance to abrasion: Modifying the binder can help reduce raveling, which is the loss of aggregate particles from the pavement surface due to abrasion caused by traffic.

f- Addressing bleeding issues: Modifying the binder can help reduce bleeding, which is the upward movement of excess binder to the pavement surface.

g- Improving aging or oxidation resistance: Modifying the binder can enhance its resistance to aging or oxidation, increasing the longevity of the pavement.

h- Enhancing pavement durability: By achieving the above improvements, the overall durability of the asphalt pavement is enhanced, resulting in reduced life cycle costs.

i- Reducing pavement thickness: Modified binders can allow for the reduction of pavement layer thickness while maintaining the required performance, resulting in cost savings and efficient use of materials.

j- Enhancing the overall performance of Hot Mix Asphalt (HMA) pavements: Asphalt modification contributes to the overall improvement in the performance and longevity of HMA pavements.

1.4.2 Polymer Additives

a- Elastomers

Elastomers refer to a class of materials that exhibit high elasticity and can undergo significant deformation under stress, returning to their original shape once the stress is removed. In the context of asphalt modification, elastomers are commonly used as additives to enhance the performance of asphalt binders and pavement mixtures.

The commonly used polymer additives in asphalt modification include styrene-butadiene-styrene copolymer, SBR, and EVA. Polymers are large molecules composed of smaller units that link together to form long chains. The arrangement and chemical structure of these building blocks determines the physical characteristics of the resulting polymer. "Table 1.04" presents key findings from a study conducted on these polymers, detailing their effects and performance when added to asphalt [36].

Table 1.04 findings from a study conducted on these polymers [36]

Author	Study objectives	Additives used (Trade name of additives, company name, chemical compositions, dose rate, key information related to material properties)	Test method used	Major findings
Yildirim, 2007	Investigating The Temperature susceptibility of polymer modified asphalt binders.	- Styrene–butadiene–styrene (SBS) - Styrene–butadiene rubber (SBR) - Elvaloy - Rubber - Ethylene-vinyl acetate (EVA) - Polyethylene	- Elastic recovery test	• SBS modified binders have been found to perform better at low temperatures. • Elvaloy increases pavement moisture resistance. • Polymer modified binders have had proven success in the field and the laboratory.
Mcdaniel, Shah, Transportation, Lafayette, & Report, 2003	Incorporating the asphalt additives to control rutting and cracking.	- PAC - Novophalt - Multigrade asphalt cement - Polyester fiber - Neoprene - SBR - Asphalt rubber - Two controls sections using AC-20	- Field test - Laboratory test	• The Novophalt binder increased the brittleness of the binder and mixture, leading to extensive cracking. • The SBR, PAC and Asphalt Rubber sections exhibited the least cracking and good rutting performance.
Gorkem & Sengoz, 2009	Predicting stripping and moisture induced damage of asphalt concrete prepared with polymer modified	- Hydrated lime - Plastomeric and elastomeric type polymers (3%)	- The Nicholson stripping test (ASTM D 1664) - Modified Lottman test (AASHTO T283)	• Mixtures prepared with SBS and EVA PMB display reduced moisture susceptibility. • The mixtures prepared with basalt–limestone aggregate exhibit more moisture susceptibility

	bitumen and hydrated lime.			than the mixture prepared with limestone aggregate.
Guan, Li, Zhang, & Li, 2012	Investigating the use of ZQ-1 additive to make new high rutting asphalt mixture for heavy traffic	- ZQ-1 additive is used to design high rutting resistance asphalt mixtures. - Composition of ZQ-1, Polymer, cellulose, Ethylene vinyl acetate copolymer, Styrene butadiene rubber, Functional agent and Antioxidant agent.	- Lab: High temperature performance,water sensitivity, low temperature performance, sensitivity analysis. - Field: Compaction, rutting resistance and skidding resistance test.	• High asphalt content resulting in high workability, water resistance, and durability. • High additive content and hard asphalt resulting in high rutting resistance. • Hard aggregate resulting in high skidding resistance.
Fernandes, Peralta, Oliveira, Williams, & Silva, 2017	Replacing of bitumen with waste motor oil and elastomer modifiers for improving asphalt mixture Performance.	• Bitumen (35/50) with 10% waste motor oil and 5% (SBS) as an elastomer modifier. • (B35/50) supplied by Cepsa Portugal (located in Matosinhos, Portugal); • SBS elastomer, supplied by Indústrias Invicta S.A. (located in Porto, Portugal) (MotorOil) from heavy vehicles supplied by Correia & Correia (located in Sertã, Portugal)	• Fourier infrared spectra and dynamic shear rheology • Water sensitivity • Fatigue cracking resistance • Dynamic modulus • Rut resistance performance was evaluated.	• B35/50 & Motor Oil & SBS PG64-22 & cryo MBO both are active in rutting resistance. • New mixture with waste motor oil and SBS performs better than the conventional mixture B35/50.
Ahmedzade, 2013	Investigating and comparing the effects of SBS and SBS with new reactive	• Styrene butadiene styrene (SBS) and SBS with new reactive terpolymer (Entira _Bond 8) (1%). • The SBS polymer used was Kraton D-	• Penetration, • Softening point, • Fraas breaking point as well as rotational viscometer (RV)	• SBS and Entira_Bond 8 polymers improve elastic properties and rutting resistance of bitumen. • SBS and Entira_Bond 8 polymers reduce tempera-

	terpolymer on the rheological properties of bitumen	1101 supplied by the Shell Chemicals Company.	• Dynamic shear rheometer (DSR) • Bending beam rheometer (BBR) test methods.	ture susceptibility of bitumen which allows increasing the stiffness of the binder at high temperature to reduce rutting.

b- Plastomers

Plastomers are a class of polymers that exhibit properties of both plastics and elastomers. They are a type of thermoplastic elastomer (TPE), which means they can be melted and reshaped multiple times without undergoing significant degradation. Plastomers are known for their exceptional elasticity, flexibility, and toughness.

The specific properties of plastomers can be adjusted by modifying the polymer composition, molecular weight, or cross-linking density. This allows manufacturers to tailor plastomers to meet specific application requirements, such as enhancing adhesion, improving melt flow, or increasing softness.

Overall, plastomers offer a unique balance of plastic and elastomeric characteristics, making them valuable for numerous industrial applications where flexibility, toughness, and processability are essential.

Plastomers are sometimes known as "polyethylene" in common usage. The most popular plastics are low-density polyethylene (LDPE), high-density polyethylene (HDPE), and linear low-density polyethylene (LLDPE). Polypropylene, ethylene-propylene copolymer, and EVA copolymer are some of the other polyolefins used. Table 1.05 lists a few of the most current studies on the use of plastomers [36].

Table 1.05 some of the current studies on the use of plastomers [36].

Author	Study objectives	Additives used (Trade name of additives, company name, chemical compositions, dose rate, key information related to material properties)	Test method used	Major findings
Ahmedzade & Yilmaz, 2008	Investigating the effect of polyester resin additive on the properties of asphalt binders and mixtures.	-10, AC-5 and AC-10 with 0.75% Polyester Resin (PR).	•Marshall stability and flow • Indirect tensile stiffness modulus (ITSM) • Indirect tensile strength (ITS) • Creep stiffness test	• AC-10 with 0.75% PR binder has better physical properties than AC-5 control asphalt binder. • PR has an effect on improving a mixture’s resistance to moisture damage and strength properties.

Baghaee Moghaddam, Soltani, & Karim, 2014	Investigating the rutting performance of polyethylene terephthalate modified asphalt mixtures under static and dynamic loads.	• Polyethylene terephthalate, PET (0%, 0.1%, 0.2%, 0.3%, 0.4%, 0.5%, 0.6%, 0.7%, 0.8%, 0.9% and 1% by weight of mixed aggregates)	•In the first step, bulk specific gravity test, Marshall test, indirect tensile stiffness modulus test and indirect tensile strength test. • In the second step, permanent deformation of PET modified asphalt mixtures were assessed under static and dynamic loads.	•PET modified asphalt mixture had different rutting behavior under static and dynamic loadings. • Using PET might superior modification for the pavements facing dynamic loadings than under static loading. • Marshall, stiffness and strength tests which previously were used cannot be appropriate criteria to evaluate the rutting resistance of PET modified asphalt mixture.
Attaelmanan, Feng, & Ai, 2011	Evaluating of HMA with high density polyethylene as a modifier	• High density polyethylene (HDPE) blended with 80/100 paving grade asphalt.	•Marshall Stability • Marshall Quotient (MQ) • Tensile strength ratio • Flexural strength and resilient modulus.	•HDPE content of 5% by weight of asphalt is recommended as it reduces the moisture susceptibility and temperature susceptibility.
Gawande, Zamare, Renge, Tayde, & Bharsakale, 2012	Improving desired mechanical characteristics for particular road mix by partial replacement of waste plastic	•Plastic waste (dry process < 2%) (wet process 6-8%)	•Aggregated impact value • Los Angel's abrasion test • Marshall stability • Softening point test • Penetration index test • Ductility index test • Softening point test • Flash and fire point test.	•The use of modified bitumen with 5-10% waste plastic by weight of bitumen helps in improving the Marshall stability, strength, fatigue life and other desirable properties of bituminous concrete mix.
Md. Yusoff, Ibrahim, Memon, & Othman, 2017	Investigating the moisture damage on asphalt mixtures modified with	• Nano clay • 2 and 4% by weight of bitumen polymer modified bitumen (PG76) • Hydrated lime • Cement.	•Indirect tensile test.	•The addition of polymer appears to result in the greatest potential benefit amongst the modified binders and least susceptible to moisture damage.

	additives and polymer.			

c- Crumb Rubber (GTR)

Crumb rubber, also known as ground tire rubber (GTR), is a granulated material derived from recycled tires. It is produced by mechanically grinding or shredding discarded tires into small particles. Crumb rubber has gained significant attention as an environmentally-friendly alternative to traditional materials due to its recycling potential and various beneficial properties.

The use of crumb rubber contributes to waste tire management, reduces landfill waste, and promotes sustainability by repurposing discarded tires. However, it is important to ensure that the crumb rubber used in various applications meets relevant safety and quality standards to mitigate any potential health and environmental concerns.

Tire rubber can be broken down into tiny, crumb-like pieces and used in HMA pavements as one solution to the disposal issue. It is possible to combine this crumb rubber substance, sometimes referred to as a crumb rubber modifier (CRM), with HMA formulations using either a wet method or a dry process [37]. Table 1.06 provides a summary of several recent initiatives to employ crumb rubber.

Table 1.06 summary of several studies about employee crumb rubber in the pavement

Author	Study objectives	Additives used (Trade name of additives, company name, chemical compositions, dose rate, key information related to material properties)	Test method used	Major findings
Moreno Navarro, Sol Sánchez, Rubio Gámez, & Segarra Martínez, 2014	Improving the mechanical behavior of high modulus asphalt mixes by using acrylic fibers and crumb	•Acrylic fibers, AF-0.3%, and crumb rubber. • CR-1.5% were used to modify the mechanical properties of an HMAM manufactured with a conventional high modulus bitumen B20/30.	•Marshall tests, water sensitivity tests (including freeze/thaw cycles), • Wheel tracking tests, • Creep triaxial tests (at different temperatures), • Stiffness tests (at different temperatures) • Fatigue four-point bending tests.	• The presence of acrylic fiber and crumb rubber increase the resistance to plastic deformations and also reduces their temperature susceptibility.
Kim, Mazumder, Lee, & Lee, 2019	Evaluating the performance of polymer	• SBS modified binder was used as a base binder (PG 76- 22),	•Dynamic shear rheometer (DSR), • Bending beam rheometer (BBR)	•Rubberized PMA binders showed better rutting resistance with the increase of GTR.

	modified asphalt (PMA) binders containing ground tire rubber(GTR)	• Crumb rubber (5% and 10% by weight of the base binder) • Normal tire rubber & treated tired rubber	• Multiple stress creep recovery (MSCR) test.	• PMA binder containing 10% treated rubber exhibited the best low temperature cracking resistance.

1.4.3 Other Non-bituminous Modifiers

a- Gilsonite

Gilsonite, also known as uintaite, is a naturally occurring solid hydrocarbon resin that is found in various parts of the world. It is a unique form of asphalted, characterized by its glossy appearance, black color, and high carbon content.

In tropical countries, roads built with asphalt layers must be made with bituminous mixtures containing asphalt that is reasonably stiff, to increase resistance against rutting. Gilsonite modified HMAs were prepared using either wet or dry processes. Gilsonite increases stiffness and improves the performance grade of a virgin binder at high temperatures of service [38]. Table 1.07 shows some of the recent studies done on the Gilsonite.

Table 1.07 some of the recent studies done on the Gilsonite [36]

Author	Study objectives	Additives used (Trade name of additives, company name, chemical compositions, dose rate, key information related to material properties)	Test method used	Major findings
Ameri, Mansourian, Ashani, & Yadollahi, 2011	Evaluating the temperature susceptibility of the Iranian Gilsonite as an additive for modification of asphalt binders used in pavement construction.	• 4%, 8% and 12% Gilsonite on two types of asphalt binders PG58-22 and PG64-22.	• Rotational viscosity (RV) test • Dynamic shear rheometer (DSR) test • Bending beam rheometer (BBR) test	• The addition of gilsonite to base bitumen can cause improvement in high performance temperature; it has no positive impact on low performance temperature.
Yilmaz & Yalcin, 2016	Investigating the effects of styrene butadiene–styrene (SBS), American	•4.0% SBS, 11.0% AG and 10.0% IG were used with respect	•Marshall stability and flow • Indirect tensile stiffness modulus • Wheel-tracking test	• 4.0%SBS shows the maximum resistance to moisture induced damage. • 11.0%AG

	gilsonite (AG) and Iranian gil-sonite (IG) us-age in bitumen modification, and hydrated lime usage in mixture modification on the performance of hot mix as-phalts (HMAs)	to bitumen weight. • Hydrated lime was used as filler in proportion of 2% with respect to aggregate weight.		provide maximum resistance on the base of wheel-tracking test.
Babagoli, Hasaninia, & Mohammad Namazi, 2015	Investigating the benefits of modifying as-phalt and stone matrix asphalt (SMA) mixtures in flex-ible pavement.	•Gilsonite	•Conventional test for Marshall stability • Indirect tensile strength • Moisture susceptibil-ity • Resilient modulus • Rutting resistance test	• Gilsonite improves the performance of SMA mixture

b- ZycoTherm

ZycoTherm's nanotechnology enhances the coating of asphalt binder on aggregates, provides constant and greater compaction, and prevents stripping, all of which contribute to the creation of asphalt pavements that are durable for the duration of the pavement. Zyco-soil, a new anti-stripping chemical, is simple to use, mixes with asphalt, and reacts with inorganic gravels. Additionally, it makes the asphalt harder [39]. Table 1.08 shows the use of ZycoTherm as an asphalt binder modification.

Table 1.08 the use of ZycoTherm as an asphalt binder modification [36]

Author	Study objectives	Additives used (Trade name of addi-tives, company name, chemical compositions, dose rate, key information related to material properties)	Test method used	Major findings
Ameri, Vamegh, Chavoshian Naeni, & Molayem, 2018	Evaluating the moisture susceptibility of asphalt mix-tures containing Evonik,	•Asphalt binder 60-70penetration grade • Evonik and Zycotherm (0.3% and 0.1%)	•Marshall stability Texas boiling test • Indirect tensile strength (ITS) • Modified Lottman tests • Resilient modulus	• The mixtures with Zycotherm and hy-drated lime had the highest resistance against moisture dam-age and rutting respec-tively.

	Zycotherm and hydrated lime.	• Hydrate lime (1 and 2%)	test • Dynamic creep test	• Evonik showed inferior performance comparing to mixtures modified with Zycotherm though it was satisfactory.
Khodaii et al., 2014	Evaluating the effect of zycosoil on moisture damage of hot mix asphalt using the surface energy method.	• Zycosoil (1.5% and 1.2% by weight for limestone and granite aggregate) • The optimum asphalt content with limestone and granite aggregates were found to be 5.6% and 5.1%, respectively.	•Surface free energy (SFE) method • Laboratory dynamic modulus test	•Zycosoil decreases the difference between the free energy of the adhesion of aggregate asphalt binder in dry and wet conditions. • Coating of the aggregate surface with Zycosoil decreases this difference and subsequently causes the mixture to be more resistant to moisture damage.
Arabani, Tahami, & Hamedi, 2018	Improving the usage of CR using the dry process by modification of binder with nanomaterial namely Zycosoil.	•Zycosoil at three contents of 1%, 2.5% and 4% by weight of the binder. • CR at three contents of 1%, 3% and 5% by weight of aggregate obtained from Yazd Tire Company located at Yazd in Iran. •60/70penetration grade obtained from Isfahan Mineral Oil Refinery was used.	• Ductility • Softening point • Penetration • Rotational viscosity • DSR tests • Moisture susceptibility • Indirect tensile strength • Stiffness modulus • Rutting resistance • Fatigue behavior	• Zycosoil could improve the moisture susceptibility than CR. 2. 4%Zy + 1%CR, 2.5%Zy + 1%CR and 4%Zy + 3%CR were higher than control mixture. • 3. 4%Zy + 3%CR, 2.5% Zy + 3%CR, 1%Zy + 3%CR, 4%Zy + 1%CR, 3%CR, 2.5%Zy + 1%CR, 1%Zy + 1%CR, 1%CR had better rutting performance.

c- Steel and Copper Slag

Steel slag and copper slag are both by-products of industrial processes and have various applications. Steel slag is a by-product generated during the steelmaking process. It is formed when molten blast furnace slag, a by-product of iron and steel production, is rapidly cooled. Steel slag is typically granulated or air-cooled and has a glassy appearance. Copper slag is a by-product generated during the smelting and refining of copper ore. It is the residue left after the copper metal is extracted, and it typically has a black glassy appearance.

Steel slag is noted for its excellent adhesion, durability, and resistance to rutting [40]. A byproduct of copper production, copper slag is primarily made up of heavy metals. This substance has accumulated in vast quantities throughout the planet, posing a severe environmental risk. Increased durability and resistance might be possible by using it in place of mineral aggregate in asphalt mixtures [41]. Some of the key conclusions from the latest study are summarized in Table 1.09

Table 1.09 some of the latest study of Steel slag and copper slag [36]

Author	Study objectives	Additives used (Trade name of additives, company name, chemical compositions, dose rate, key information related to material properties)	Test method used	Major findings
Shafabakhsh & Ani, 2015	Investigating the effect of Nano TiO2/SiO2 modified bitumen on the rutting and fatigue performance of asphalt mixtures containing steel slag aggregates.	• Steel slag asphalt mixture (SSAM) containing TiO2 and Nano SiO2 particles.	• Penetration grade • Softening point, • Ductility • Rotational viscosity (RV) • Dynamic shear rheometer (DSR) • Marshal test • Repeated load axial (RLA) test and fatigue test	• Nano TiO2 and Nano SiO2 improve Toughness and viscosity by an average of 30% and 109%, respectively. • The asphalt's rutting resistance and fatigue life were improved.
Abdelfattah et al., 2018	Evaluating the rutting resistance of asphalt mixes containing Copper Slag (CS) as a fine aggregate with up to 40%, by total aggregate weight.	• Limestone aggregate • 60/70 binder • Copper slag • CS was used as a replacement of the 0–3mm size aggregate with a percentage of 5, 10, 15, 20, 30 and 40%, by total aggregate weight.	• The dynamic modulus from MEPDG performant deformation model. • Flow Number (FN) test according to AASHTO TP79	• The use of CS reduced the dynamic modulus |E*| values. • The results of the rutting analysis predicted by the MEPDG permanent deformation model agreed with the relative values of resilient axial strain.

1.5 The Aggregates of Asphalt Replacement and Modification

When it comes to the replacement and modification of aggregates for asphaltic concrete, there are several factors to consider to ensure the desired performance and characteristics of the pavement. Here are some considerations for the replacement and modification of aggregates in asphaltic concrete:

-Gradation
-Size and Shape
-Aggregate Hardness
-Aggregate Durability
-Gradation Bandwidth
-Compatibility with Binder
-Performance Testing

It is essential to fully understand the physical and mechanical and chemical impact of the new material, and follow established industry guidelines and specifications when considering the replacement or modification of aggregates in asphaltic concrete to ensure successful and long-lasting pavement performance.

1.5.1 Aggregate and some of the common replacement of aggregate

Aggregates are the primary component of asphalt mixtures and are responsible for providing strength, stability, and durability to the pavement. Here are some common aggregates used in asphalt replacement and modification:

- **Crushed Stone:** Crushed stone is a widely used aggregate in asphalt mixtures. It is produced by mechanically crushing larger rocks into smaller fragments. Crushed stone provides excellent load-bearing capacity and contributes to the overall strength of the asphalt pavement.
- **Gravel:** Gravel is another commonly used aggregate in asphalt mixtures. It consists of small, rounded stones and is available in various sizes. Gravel aggregates enhance the workability of asphalt mixes and provide good drainage properties.
- **Sand:** Sand is a fine aggregate that is often used in asphalt mixtures. It helps fill the voids between larger aggregates, improving the overall compactness and stability of the asphalt pavement. Sand also contributes to the smoothness of the road surface.
- **Recycled Asphalt Pavement (RAP):** RAP is a sustainable alternative to traditional aggregates in asphalt mixtures. It consists of reclaimed asphalt pavement that has been milled and crushed. Incorporating RAP into new asphalt mixtures reduces the demand for virgin aggregates and conserves natural resources.
- **Reclaimed Aggregates:** Reclaimed aggregates are obtained from the demolition of old asphalt pavements and concrete structures. These aggregates are processed and reused in new asphalt mixtures. Reclaimed aggregates offer similar performance to virgin aggregates while promoting sustainability.
- **Polymer-Modified Aggregates:** Polymer-modified aggregates are created by adding polymers to the asphalt mixtures. The polymers improve the properties of the asphalt, such as elasticity, resistance to cracking, and durability. This modification enhances the overall performance of the pavement.

- **Fibers:** Fiber reinforcement is sometimes added to asphalt mixtures to improve its strength and resistance to cracking. Fibers, such as polyester or fiberglass, are mixed into the asphalt to provide additional structural integrity.

It's important to note that the specific aggregate types and proportions used in asphalt mixtures can vary based on factors like climate, traffic loads, and desired performance characteristics. Asphalt engineers and pavement designers consider these factors to determine the appropriate aggregate blend for each project.

1.5.2 Waste materials and their possible uses:

Waste materials can be used in pavement construction and maintenance in various ways, providing both economic and environmental benefits. It's worth noting that the use of waste materials in pavement construction requires proper testing and evaluation to ensure they meet the necessary performance standards and do not compromise the quality and safety of the pavement.Table 1.10 present some of the use for waste materials as replacement of aggregate or modification

Table 1.10 some of waste materials in pavement

Author & Year	Materials by Percentage	Material Used	Test	Findings and Summary
Mashaan et al. 2013[42]	6, 12, 16, and 20%	Crumb rubber	•Marshall test • Wheel tracking • Indirect tensile	•Better stability • Better adhesion • The best enhancement was 12% in the wet process.
Pasandín et al., 2017 [43]	0, 35 and 42%	Crushed concrete & Waste tire rubber	•Indirect tensile fatigue test (ITFT)	•Improvement in fatigue performance •HMA containing RCA are suitable for medium and light traffic because of its low resistance to the fragmentation of RCA.
Ahmadinia et al., 2012 [44]	0, 2, 4, 6, 8 and 10%	Waste plastic	•Resilient modulus test •Drain down test • Wheel tracking test •Tensile strength test	1-Optimum PET is 4 and 6% by weight of optimum bitumen content 2- PET has better rutting resistance than the ordinary mixture.
White 2019 [45]	6%	1- Plastic bags 2-Waste plastic bottle	• Indirect tensile fatigue test (ITFT)	•Enhanced deformation resistance

			• Wheel tracking test	
Maharaj et al., 2017 [46]	0 to 20%	Steel slag	• Marshall stability test	•The Marshall specification for the design of HMA is 15% of steel slag aggregate addition has similar features as the 0% formulation.
Gowtham et al., 2018 [47]	0 to 10%	Steel slag	•Marshall test	• Optimum stone substitution of 10% in the mixtures. •Increasing in the percentage of air voids and decrease in voids filled with bitumen because of the porous nature of the steel slag.
Li, et al., 2018 [48]	5%	Powder steel slag	•Extended bending beam Rheometer test •Double-edge notched tension test	•The addition of particles that are 5% larger can diminish the severity of reversible aging. • In regions with cold climate, steel slag has a better low-temperature performance than conventional limestone powder system.

In study under the title “A study on the suitability of solid waste materials in pavement construction: A review” there’s a table summarized some the use of waste materials in pavement aggregate replacement and additive

Table 1.11 waste materials in pavement aggregate replacement and additive [49]

Waste materials	Source	Application	Advantages
Concrete waste	Construction industry	• Base/ Subbase material • stabilization of subgrade • filler in asphalt mixture	•Dynamic modulus can be increased, dynamic creep can be reduced. •Conservation of natural resources.
Retrieved asphalt road/ Reclaimed asphalt pavement	Road industry	• Base/ Subbase material	•Enhance mechanical performance and efficiency of pavement. •Conservation of natural resources.
Glass waste	Glass industry	• Glass fiber reinforcement • filler in asphalt mixture	• Enhance fatigue performance

Ceramic waste	Ceramic industry	●Base/ Subbase material ● filler in asphalt mixture	● Enhance thermal conductivity and rutting resistance of pavement
Bottom ash and Fly ash	Thermal power station	●Aggregate in asphalt mixture ● filler in asphalt mixture ●as subgrade stabilizer	●Enhance mechanical performance of pavement. ●Enhance stiffness ● Enhance stripping and rutting resistance of pavement.
Steel slag waste	Steel industry	● Base/ Subbase material ● as subgrade stabilizer	● Enhance skid resistance ●Improves modulus of resilience and reduce permanent deformation
Textile waste	Textile industry	● Textile fiber reinforcement	●Enhance mechanical performance of pavement ● Enhance moisture susceptibility, rutting resistance, freeze and throw resistance ● Improves dynamic modulus, creep compliance etc.
Wood waste	Wood/ furniture industry	●Aggregate in asphalt mixture ● Bio-oil bitumen modifier	● Enhance fatigue and rutting resistance ●Improves dynamic modulus and skid resistance

1.5.3 Natural and Raw Materials and their Possible Uses in Pavement

Natural and raw materials can be used in pavement construction for various purposes. Here are some natural and raw materials in the form of fibers and replacements that can be used in pavement construction:

a- **Synthetic Fiber Reinforcement:** Synthetic fibers like polypropylene or polyester can be added to asphalt mixtures to improve their strength and durability. These fibers help control cracking, reduce rutting, and enhance the overall performance of the pavement.

b- **Natural Fiber Reinforcement:** Natural fibers such as coir, jute, or hemp can also be used as reinforcements in pavement construction. They offer similar benefits as synthetic fibers, providing increased tensile strength and crack resistance to the pavement.

c- **Natural Pozzolans:** Natural pozzolans, such as volcanic ash or calcined clay, can be used as partial replacements for cement in concrete pavement. They contribute to the development of cementitious compounds, improving strength, and durability.

d- **Wood Fiber:** Wood fibers, obtained from wood byproducts or waste materials, can be added to asphalt mixtures or used in soil stabilization techniques. They enhance the tensile strength, reduce cracking, and improve the overall performance of the pavement.

e- **Organic Additives:** Organic additives derived from natural sources, such as vegetable oils or bio-based polymers, can be used as modifiers in asphalt binders or additives in concrete mixtures. They help improve the workability, durability, and environmental sustainability of the pavement.

It's important to note that the suitability and performance of these materials may vary depending on specific project requirements, local regulations, and the compatibility of the materials with the existing pavement systems. Proper testing and evaluation are essential to ensure their effectiveness and adherence to standards. The table 1.12 summarized some of the studies about the natural and raw materials can be used in aggregate pavement or modifier in the mix

Table 1.12 Natural and Raw materials in pavement

Author & Year	Materials	Test	Findings and Summary
R.S. McDaniel, 2015 [50]	Polyester fibers	-Marshall test -Rutting test -Tensile strength	-Resists cracking, rutting, and potholes -Increases mix strength and stability -Higher melting point than polypropylene -High tensile strength
J. Bijwe ,1997 [51]	Carbon fibers	-Rutting test -Tensile strength -Modulus test	-High strength and modulus -High thermal stability
H. Wang, J. Yang, H. Liao, X. 2016 [52]	Steel fibers	-Marshall test -Rutting test -Indirect Tensile test	- Increases Marshall stability, rutting resistance, indirect tensile strength, and low-temperature cracking resistance - Self-healing properties
R.S. McDaniel, 2015 [50]	Aramid fibers	-Marshall test -Rutting test -Tensile strength	High tensile strength Increases mix strength and stability
O.S. Abiola, W.K. Kupolati, E.R. Sadiku, J.M. Ndambuki, 2014 [53]	Coconut (Coir)	- drain down test - fatigue test	Prevents drain-down during production 100% natural and ecological recycling
R.S. McDaniel, 2015 [50]	Cellulose	-SMA stability test -drain down test -Marshall test	-Stabilizes binder in open- and gap-graded stone matrix asphalt (SMA) mixtures -Absorbs binder, allowing high binder content for more durable mixture -Relatively inexpensive -May be made from a variety of plant materials -May be from recycled materials such as newsprint
L.M.G. Klinsky, K.E. Kaloush, V.C. Faria, V.S.S. Bardini. 2018	Polypropylene fibers Aramid fibers	Resilient modulus Dynamic modulus Flow number Fatigue cracking Reflective cracking	-The fibers enhanced the mechanical qualities of the control hot mix asphalt, according to the results. By incorporating polypropylene and aramid fibers into HMA,

			-Asphalt pavements may be better able to withstand common problems such rutting, raveling, fatigue, and reflective cracking.
Hasan Taherkhani, 2017 [55]	Nanoclay Fiber Nylon Fiber	-Marshall test -Fatigue test	The findings also demonstrate that the mixture with the best robust modulus, Marshall stability, -Fatigue life is one reinforced with 0.4% nylon fibers and 7% nanoclay. -However, the mixture with the strongest resistance to permanent deformation only contains 7% nanoclay.
Hassan Ziari, M.R.M. Aliha, Ali Moniri , Yasha Saghafi . 2019 [56]	glass fiber	Cracking test SCB fracture test	it was discovered that 100% RAP mixtures can be used without significantly reducing fracture resistance, and that the detrimental effects of RAP material on the crack resistance of asphalt mixtures can be partially reversed using 0.12% glass fiber.
Saswat Biswapriya Dash Mahabir Panda. 2016 [57]	-Fly ash -Bottom ash - Sisal fiber	-Marshall test -Indirect tensile strength	- better Marshall stability -great Tensile strength - decrease binder uses
Laiana F. C; Lêda C F ; Adriano E; Ablenya G B. 2019 [58]	Banana Fibers	- Resilient modulus - Rutting test	Enhancement of: -Indirect tensile strength, - resilient modulus, -dynamic modulus, -flow number, - fatigue life tests.
Osuya, D. O. and Mohammed, H.2017 [59]	SAWDUST ASH	-bulk density -Marshall test	-The result showed that, the inclusion of sawdust ash in asphaltic concrete improved its stability and density.

The traditional pavement is frequently supplemented with natural and raw materials to enhance its functionality, long-term sustainability, and aesthetic appeal. Natural and raw materials may be used for a variety of reasons, including the following:

Improved Performance: Natural materials, can enhance the durability and strength of the pavement. These materials may possess specific qualities that enhance resistance to wear and tear, weathering, and other damaging factors. Additionally, the inclusion of raw materials like certain polymers or additives can improve the pavement's performance in terms of flexibility, crack resistance, and water permeability.

Cost-Effectiveness: Using natural and raw materials in the construction of pavement might occasionally be more affordable than using only virgin materials, depending on their availability and local sourcing. For pavement construction projects, using recycled or locally accessible materials can assist lower transportation costs and offer a more cost-effective alternative.

Aesthetics and Visual Appeal: Natural materials, such as colored aggregates or decorative stones, can be used to create visually appealing pavements. By incorporating different colors, textures, or patterns, the pavement can blend better with its surroundings or contribute to the overall design aesthetics of a project. This is particularly important in urban or architectural settings where visual appeal is desired.

It's worth noting that the specific choice and combination of natural and raw materials for pavement construction depend on factors such as project requirements, climate conditions, local availability, and engineering considerations.

1.6 Conclusion

The history, evolution, deterioration, additives, and aggregates in asphalt concrete pavement have all been discussed in Chapter 1 of the literature review on the pavement. Each section offers insightful information on various facets of paving design and upkeep. The first section, "Background history of road construction," takes us on a journey through time, highlighting the evolution of road construction techniques from ancient civilizations to modern times. This historical context helps us understand the challenges faced by early road builders and the advancements that have shaped today's pavement engineering practices.

Moving on to "Road Pavement Development," the chapter explores the various types of pavements, including flexible, rigid, and composite pavements. It discusses their characteristics, applications, and performance attributes, providing a comprehensive overview of the different pavement options available for various scenarios.

The section on "Degradation of Layers in Asphalt Concrete Pavement" focuses on the factors that contribute to the deterioration of asphalt concrete pavements. It examines the mechanisms behind distresses such as cracking, rutting, and fatigue, shedding light on the importance of proper design, construction, and maintenance practices to mitigate these issues.

"Additive and Modifier for the Binder of Asphalt Concrete" delves into the use of additives and modifiers to enhance the performance of asphalt binders. It discusses various types of additives, such as polymers, fibers, and rejuvenators, and their effects on the properties of asphalt, including improved durability, elasticity, and resistance to aging.

Lastly, "The Aggregates of Asphalt Replacement and Modification" focuses on the use of different aggregates in asphalt mixtures. It explores the utilization of recycled aggregates, reclaimed asphalt pavement, and other modified aggregates such as "natural or raw materials" as replacements or additives of aggregates to improve sustainability, reduce environmental impact, and enhance pavement properties.

Collectively, these sections provide a comprehensive review of the literature on pavement, covering historical context, pavement development, degradation mechanisms, binder additives, and aggregate options. This knowledge serves as a foundation for further chapters, allowing for deeper exploration of specific topics related to pavement engineering and construction. By understanding the challenges and advancements discussed in this chapter, with this, we can understand the following chapters and the importance of this work.

Chapter 02: Explanation of the Experimental Design Method

2.1 An overview

In the realm of scientific inquiry, the process of experimentation plays a pivotal role in expanding our understanding of the world around us. At its core, experimentation aims to generate reliable evidence that can modify and refine our current state of knowledge in a particular scientific field. However, designing experiments that effectively achieve this goal is a complex task, requiring careful consideration of various factors. The experimental design method serves as a guiding framework that empowers researchers to navigate the intricacies of designing robust experiments. It encompasses a delicate balance between multiple features, such as power, generalizability, validity, practicality, and cost. Each of these features influences the overall quality and utility of the experimental findings.

In this chapter, we delve into a comprehensive exploration of the experimental design method. We highlight the importance of striking a thoughtful balance between the aforementioned features to maximize the chances of obtaining useful and meaningful evidence. Furthermore, we shed light on the inherent trade-offs associated with the design process, where improving one feature may inadvertently compromise others. Moreover, we recognize the unfortunate reality that many experiments suffer from avoidable flaws, undermining the reliability and validity of their findings. However, we emphasize that statistical analysis alone can only rescue researchers in rare circumstances. Thus, we embrace the age-old adage that prevention is far superior to cure when it comes to experimental design, stressing the significance of meticulous planning and foresight. Throughout this chapter, we will navigate the conceptual landscape of the experimental design method, exploring its fundamental principles and discussing practical considerations. By gaining a deeper understanding of this method, researchers will be equipped with the necessary tools to enhance the integrity and impact of their scientific investigations. The methodology of experimental design aims to plan an experimental research called "Experimental Designs." Experimentation cannot be arbitrary; it must provide the desired information. This experimental approach helps the experimenter structure their research differently, validate their own hypotheses, gain a better understanding of the studied phenomena, and solve problems. The success of this methodology lies in changing the way experiments are conducted [60]. In addition, it is essential to incorporate techniques that aid in formulating a problem, highlighting the eminent importance of the reflective step that should precede any experimentation. This technique consists of three main parts [61], as outlined in Figure 2-1.

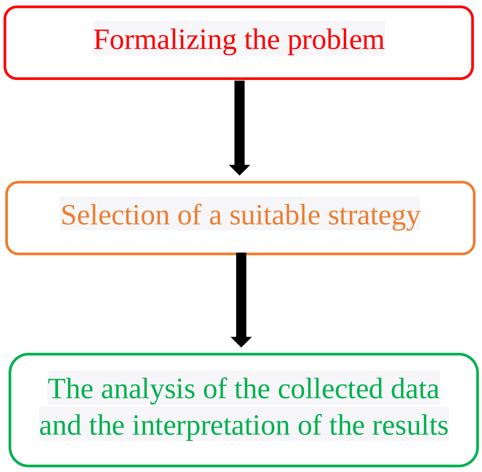


Figure. 2.01: The Steps of an Experimental Design Plan

The figure illustrates the various steps involved in an experimental design plan. These steps guide researchers through the process of conducting a systematic and well-structured experiment. While I cannot provide a visual representation of the figure, I can describe the steps typically involved in an experimental design plan:

Formalization of the problem: This initial step involves clearly defining and articulating the research question or objective, along with identifying the variables and factors that will be investigated.

Selection of a strategy: Researchers choose an appropriate strategy or approach to address the research question. This decision considers factors such as available resources, level of control and precision required, and the nature of the problem.

Experimental design: This step involves designing the experiment, including decisions about the experimental groups, sample size, randomization, and control conditions. The goal is to maximize the validity and reliability of the experiment.

Data collection: Researchers collect relevant data based on the designed experiment. This may involve implementing measurements, surveys, observations, or other data collection methods.

Analysis and interpretation of results: Once the data is collected, researchers apply statistical techniques and analytical methods to analyze the data and draw meaningful conclusions. The results are then interpreted in the context of the research question or objective.

Conclusion and reporting: In this final step, researchers summarize the findings, draw conclusions based on the results, and communicate their findings through scientific reports, publications, or presentations.

By following these steps, researchers can systematically plan and execute experiments, ensuring the generation of reliable and meaningful evidence to advance knowledge in their respective fields.

2.2 Basic Principles of Experimental Design

In this section, we delve into the fundamental principles that form the basis of experimental design. Understanding these principles is crucial for designing effective and reliable experiments. The section covers the following topics:

2.2.1 Randomization

Randomization forms the fundamental basis for incorporating statistical methods into experimental designs. It involves the random assignment of treatments to the experimental units. Randomization ensures that each possible treatment assignment has an equal probability of occurring. For instance, if there are three treatments (A, B, and C) and four replications (r = 4), the total number of experimental elements would be 3 * 4 = 12 (n). With replication set at four, each treatment would be repeated four times. Let the design is:

A	C	B	C
C	B	A	B
A	C	B	A

The design elements have been allocated to different treatments as follows: Elements 1, 7, 9, and 12 are designated for Treatment A, elements 3, 6, 8, and 11 are assigned to Treatment

B, and elements 2, 4, 5, and 10 are assigned to Treatment C. Each treatment has an equal probability of being selected, with P(A) = 4/12, P(B) = 4/12, and P(C) = 4/12. This means that Treatment A, B, and C have an equal chance of being chosen in the experiment [62].

2.2.2 Replication

Replication refers to the act of repeating the fundamental experiments. To illustrate, when comparing the grain yield of two wheat varieties, each variety is tested on multiple experimental units. The number of times these varieties are applied to the experimental units is known as the replication count. Replication possesses two significant characteristics:

- It allows the experimenter to obtain an estimate of the experimental error.
- More replication would provide increased precision by reducing the standard error (SE) of the mean as $s_{\bar{y}} = \frac{s}{\sqrt{r}},$ where s is sample standard deviation and r is a number of replications. Note that an increase in r value $s_{\bar{y}}$ (standard error of $\bar{y}$) [62].

2.2.3 Local Control

Despite the implementation of randomization and replication, it has been noted that certain extraneous sources of variation remain uncontrollable. Consequently, there is a need for further refinement in the experimental technique. In other words, it is necessary to select a design that effectively controls all extraneous sources of variation. To achieve this, the concept of local control is employed, which encompasses the practices of (i) balancing, (ii) blocking, and (iii) grouping of experimental units. These techniques aim to bring the extraneous sources of variation under control and improve the overall precision and validity of the experimental results.

Balancing: Balancing means that the treatment should be assigned to the experimental units in such a way that the result is a balanced arrangement of treatment.

Blocking: Blocking means that the like experimental units should be collected together to far relatively homogeneous groups. A block is also called a replicate.

Grouping of experimental units: refers to the practice of organizing or categorizing the units based on certain characteristics or factors that may influence the outcome of the experiment. This grouping helps in controlling the variation within each group and allows for a more accurate analysis of the treatment effects.

The main objective/ purpose of local control is to increase the efficiency of experimental design by decreasing experimental error [62].

2.3 The purpose of experimental designs

The progress of science and technology is linked to the answers that humans have been able to provide to the questions posed by nature. These answers often result from the analysis of experimental observations obtained through a rigorous methodological approach [63].

The purpose of experimental designs is to systematically investigate and analyze the relationship between variables in a controlled setting. Experimental designs aim to uncover causal relationships, test hypotheses, and generate reliable and valid conclusions. They provide a structured approach for planning, executing, and interpreting experiments, allowing researchers to manipulate independent variables and measure their effects on dependent variables. By carefully controlling extraneous factors, experimental designs help researchers isolate the specific factors that contribute to observed outcomes. The ultimate goal of experimental designs is to enhance understanding, contribute to scientific knowledge, and inform decision-making in various fields of study. Therefore, we can say that without physical or numerical experimentation, there is no solution. Experimentation is, therefore, one of the privileged means to acquire or improve knowledge. However, it must be optimized because the objective is to obtain the most reliable information possible with a minimum number of trials.

2.3.1 Traditional Method of Trials

The traditional method of trials refers to a conventional approach used in experimental research to investigate and evaluate different treatments or interventions. This method typically involves conducting a series of trials or experiments where each treatment is applied to separate groups or units. The purpose is to compare the outcomes or results of the treatments and assess their effectiveness or impact.

The traditional method of trials often follows a sequential or systematic process, where treatments are assigned randomly or systematically to experimental units or subjects. The data collected from the trials are then analyzed to determine any significant differences or effects among the treatments.

As a result, the decision to stop or continue the tests, is essentially based on results obtained step by step. The experimenter tries a first trial, draws conclusions that will lead to a second trial, and so on, often varying only one factor at a time between two consecutive trials. The interpretation of the results of this traditional method, called trial and error, is done step by step, by comparing the result of the test carried out with a previous result, in order to deduce the effect on the response of the parameter whose level has just been modified [64].

While the traditional method of trials has been widely used in scientific research, it is important to note that other more advanced or specialized experimental design methods have emerged, offering improved control, efficiency, and reliability. Nonetheless, the traditional method of trials still holds value and is often utilized in various fields to address research questions and explore treatment effects.

2.3.2 Methodology of Experimental Designs

The methodology of experimental designs is considered a combination of both new and old approaches. In the context of engineering, which traditionally relies on precise sciences, experimental designs offer a fresh perspective by acknowledging and enhancing technical knowledge. Originally developed by Sir Ronald Fisher, a British mathematician, in the 1930s, experimental designs were introduced to quantify the influence of controlled factors in situations characterized by various sources of heterogeneity. Following the year 1945, there was a surge in publications and research on experimental designs. Prominent statisticians such as Yates, Cochran, Plackett, and Burmann contributed to the methodology's enrichment and exposition. They introduced specific techniques for constructing fractional factorial designs at two levels and focused on studying quantitative factors. Additionally, they incorporated response surface models into designs, such as composite-centered designs [65-67].

The methodology of experimental designs refers to the systematic approach and techniques used to plan, conduct, and analyze experiments. It encompasses a set of principles, procedures, and best practices that guide researchers in designing experiments to effectively investigate and understand the relationships between variables.

The methodology of experimental designs involves several key components, included in the section 2.1 an overview

The methodology of experimental designs aims to maximize the validity, reliability, and generalizability of the experimental results. It provides a systematic framework for researchers to gather empirical evidence, test hypotheses, and contribute to scientific knowledge in their respective fields.

Taguchi and Masuyama developed tables that enable the construction of experimental designs tailored to the majority of industrial problems. These tables, known as Taguchi designs or orthogonal arrays, provide a systematic approach to efficiently explore and analyze multiple factors and their interactions in industrial processes. By using these tables, researchers and engineers can plan and conduct experiments in a structured manner, optimizing the resources and efforts required.

Taguchi and Masuyama's work in developing these tables has greatly contributed to the field of experimental design in industrial settings. The use of Taguchi designs allows for cost-effective experimentation, efficient optimization of processes, and improved product quality. These designs have become widely adopted and have proven to be valuable tools for engineers and researchers in various industries [68].

The applications of experimental designs are currently expanding, leading to the emergence of new designs. Their widespread adoption in businesses, their incorporation into university curricula, and their practical implementation are still in their early stages. The ongoing efforts initiated by Taguchi continue, and user-friendly software tools for constructing and analyzing experimental designs are being developed and refined.

2.4 The Different Models of Experimental Designs

In the field of scientific research and experimentation, the selection of an appropriate experimental design is crucial for obtaining reliable and meaningful results. Different models of experimental designs have been developed to suit various research objectives, constraints, and variables under investigation. These models provide structured frameworks for systematically varying and controlling factors to understand their effects on the response variable.

In this section, we will explore and discuss the different models of experimental designs commonly used in research. Each model represents a unique approach to designing experiments and offers specific advantages and applications. By understanding these models, researchers can make informed decisions about which design best suits their research goals and optimizes the use of resources.

By delving into the features and applications of each model, researchers can gain insights into the design choices that can yield valid and reliable results. Furthermore, understanding the strengths and limitations of different experimental design models empowers researchers to make informed decisions when planning and conducting their experiments.

2.4.1 The Full Factorial Design

It is commonly acknowledged that full and fractional factorial designs are extensively employed in manufacturing companies. These designs are typically conducted at 2-levels or 3-

levels. By employing factorial designs, researchers can examine the combined impact of various factors or process/design parameters on a response variable. Factorial designs can take the form of either full designs, which encompass all possible combinations, or fractional designs, which include a subset of the combinations.

A full factorial-designed experiment encompasses all possible combinations of factor levels for all factors under investigation. For a 2-level full factorial design with k factors, the total number of experiments required is 2^k. This type of design is particularly valuable in the initial stages of experimental work, especially when the number of factors, such as process parameters or design parameters, is four or fewer.

When using factors at 2-levels, an underlying assumption is that the response variable demonstrates approximate linearity across the chosen range of factor settings. The first design in the 2k series focuses on two factors, denoted as A and B, with each factor examined at 2-levels. This specific design is referred to as a 2^2 full factorial design [69].

2.4.2 Taguchi Design

Genichi Taguchi, a renowned Japanese engineer, introduced several approaches to experimental designs aimed at improving product and process quality. One of Taguchi's notable contributions is the Taguchi design, also known as an orthogonal array design.

A Taguchi design is a carefully planned experiment that focuses on achieving consistent functionality of a product or process in its operational environment. Taguchi designs acknowledge that not all factors contributing to variability can be controlled. These uncontrollable factors are referred to as noise factors. The objective of Taguchi designs is to identify control factors that can be manipulated to minimize the impact of noise factors.

During the experimentation phase, the experimenter intentionally manipulates the noise factors to induce variability. By doing so, optimal settings for the control factors are determined, aiming to make the process or product robust or resistant to variation caused by the noise factors. The ultimate goal is to create a process that yields more consistent output or a product that delivers consistent performance regardless of the environmental conditions in which it is used. Implementing Taguchi designs enables engineers and researchers to develop products and processes that are less sensitive to external influences and exhibit improved reliability. By optimizing control factors based on the noise factor-induced variability, the overall quality and consistency of the end result can be enhanced. Taguchi designs have been widely utilized across various industries to achieve higher levels of product performance and customer satisfaction.

2.4.3 The Latin Square Design

Latin Square Designs are highly efficient experimental designs that may not be utilized to their full potential. These designs offer a valuable solution for controlling or eliminating two sources of nuisance variability simultaneously. Typically, Latin square designs are employed when there are two blocking factors that need to be considered.

For example, in the context of a plot of land, the fertility of the soil might exhibit variations in both the North-South and East-West directions due to factors like soil or moisture gradients. In such cases, both the rows and columns can serve as blocking factors in a Latin square design. However, Latin square designs can be applied in various other settings as well. Whenever there are multiple blocking factors, a Latin square design allows researchers to remove the variation caused by these factors from the overall error variation.

To illustrate, in the case of a plot of land, the design could involve blocking the experiment based on rows and columns. Each row represents a level of the row factor, and each column represents a level of the column factor. By considering both rows and columns as factors in the design, the variation in the measured response caused by both directions can be minimized.

The Latin Square Design derives its name from its representation as a square, with treatments labeled using Latin letters. The treatment factor levels are assigned Latin letters within the Latin square design. The number of rows and columns in the square corresponds to the number of treatment levels. For instance, if there are four treatments, the Latin square design would require four rows and four columns to be constructed. This results in a design where each treatment appears once in each row and each column. Latin Square Designs offers a powerful experimental framework for efficiently controlling multiple sources of variation. By incorporating blocking factors and utilizing the square structure, these designs allow researchers to reduce unwanted variability and enhance the precision of their experiments.as it is illustrated in figure 2.02.

Columns

Rows				
	A	B	C	D
	B	C	D	A
	C	D	A	B
	D	A	B	C

Each treatment occurs in every column and row

Figure 2.02. Explanation of Latin Square Designs.

This particular 4x4 Latin square is just one example among many possible configurations. In fact, Latin squares can be created in any size and for any number of treatments, as long as they possess a specific property. This property requires that each treatment appears exactly once in each row and once in each column of the square.

2.4.4 Response Surface Design

Response Surface Design is a statistical experimental design approach used to model and optimize the relationship between multiple input variables, known as factors, and a response variable. This design methodology helps researchers understand the complex interactions between factors and identify optimal factor settings for achieving desired responses.

The key objective of Response Surface Design is to construct a mathematical model, typically a polynomial regression model, which represents the relationship between the factors and the response variable. By systematically varying the levels of the factors and measuring the corresponding response, researchers can estimate the coefficients of the mathematical model.

Response Surface Design involves three main stages: design, experimentation, and analysis. In the design stage, an appropriate experimental design is chosen based on the number of factors and the desired level of precision. Common designs include central composite designs, Box-Behnken designs, and others.

Response Surface Design allows researchers to explore the optimal factor settings for achieving desired response levels, as well as to investigate interactions and curvature effects. This design approach is widely used in various fields, such as engineering, manufacturing, and process optimization, where it is essential to identify the optimal combination of factors that maximize performance or minimize variability.

2.4.5 Box-Behnken designs

Another class of response surface designs, known as Box-Behnken designs, offers valuable benefits in a similar context to central composite designs. These designs excel in resolving the challenge of determining the appropriate boundaries for experimentation, especially in avoiding treatment combinations that are excessively extreme.

When we refer to extreme points, we are primarily concerned with the corner points and the star points. These points represent the boundaries of the experimental region in which we conduct our experiments. However, Box-Behnken designs are specifically structured to exclude these corner points and star points from the design.

By omitting the extreme points, Box-Behnken designs offer a more balanced and efficient approach to exploring the factor space. This helps to ensure that the experimental conditions are within a reasonable and manageable range, avoiding the need to venture into the extreme regions of the design space. This can simplify the experimentation process and provide more reliable and interpretable results.

To better understand the distinction between central composite designs and Box-Behnken designs, we can use an analogy. Imagine the central composite design as a ball, where all the corner points of the design are located on the surface of the ball. In contrast, the Box-Behnken design can be visualized as a box with a wire frame structure formed by its edges.

Now, envision blowing up a balloon inside this wireframe box until it barely extends beyond the sides of the box. As the balloon expands, observe where it first touches the wireframe structure. These contact points between the balloon and the wireframe represent the selected points used to create the Box-Behnken design.

The key distinction is that while the central composite design extends beyond the box boundaries, incorporating the extreme corner points on its surface, the Box-Behnken design remains within the box defined by the wireframe structure. This ensures that the design focuses on points within a more constrained and manageable region of the factor space.

By confining the design within the box, Box-Behnken designs avoid exploring the more extreme regions of the experimental space. This can be advantageous when the extreme points are not of particular interest or pose practical challenges in experimentation.

2.4.6 Mixed designs

Mixed designs, also known as mixed-model or mixed-factorial designs, combine elements of within-subjects and between-subjects designs. They involve manipulating at least one factor as a within-subjects factor, while another factor is manipulated as a between-subjects factor. Key features of mixed designs include:

Within-Subject Factor: A factor manipulated within each participant or experimental unit, where all levels or conditions of the factor are experienced by each participant. This allows for the assessment of individual differences and increases statistical power by reducing variability associated with individual characteristics.

Between-Subject Factor: A factor manipulated between different groups or participants, with each group assigned to only one level or condition of the factor. The purpose is to examine the effects of individual differences or group-level variables on the response variable.

Advantages: Mixed designs combine the advantages of both within-subjects and between-subjects designs. They provide information on overall effects of between-subjects factors and within-subjects effects, while also increasing statistical power and efficiency by requiring fewer participants compared to fully between-subjects designs.

Flexibility: Mixed designs offer flexibility by allowing researchers to investigate within-subject and between-subject effects simultaneously. This is particularly beneficial when studying complex phenomena or when factors of interest have practical or ethical considerations regarding their manipulation.

Analytical Methods: Analyzing mixed designs typically involves using mixed-effects models or analysis of variance (ANOVA) models that account for both within-subject and between-subject sources of variability. These models estimate fixed effects (main effects and interactions) and random effects (subject-level variability).

Mixed designs are commonly used in psychology, medicine, and social sciences to study within-individual changes and between-individual differences. They provide a valuable approach for examining multiple sources of variability and their effects on the response variable [70].

2.4.7 Hybrid Experimental Designs

Hybrid experimental designs are novel designs that emerge from the combination of features found in established designs. These designs offer a range of possibilities by integrating elements from traditional design frameworks. In this discussion, I will introduce two specific hybrid designs that serve as excellent examples of how a design can be tailored to mitigate potential challenges to internal validity [71].

The Solomon Four-Group Design: is a specific type of hybrid experimental design that incorporates elements from the pretest-posttest control group design and the posttest-only control group design. It was developed to address potential confounding factors and enhance the internal validity of an experiment. In the Solomon Four-Group Design, participants are randomly assigned to one of four groups. Two groups receive a pretest followed by the experimental treatment, while the other two groups only receive the experimental treatment without a pretest. This design allows researchers to examine the effects of the treatment while also assessing the potential impact of the pretest itself.

The Switching Replications Design: is another example of a hybrid experimental design that combines elements of different designs to address specific research challenges. This design is commonly used in situations where there are limited resources or practical constraints that make it difficult to conduct a traditional randomized controlled trial with a large sample size. In the Switching Replications Design, the experiment is divided into multiple replications or phases. Each replication consists of different groups or conditions, and participants are assigned to these groups in a non-randomized manner. However, the key feature of this design is that participants are "switched" between groups or conditions across the replications.

2.5 Elements of an Experimental Design

An experimental design comprises several essential elements that collectively contribute to the success and reliability of the experiment. These elements include the experimental objectives, factors, levels of factors, sampling plan, replication, experimental sequence, randomization, data collection, data analysis, and interpretation of results.

The experimental objectives outline the specific goals and research questions that the experiment aims to address. These objectives guide the overall design and implementation of the study. Factors, which are the independent variables, are manipulated to examine their effects on the dependent variables. Each factor is defined with its various levels or conditions that participants or experimental units will be exposed to.

A well-designed sampling plan determines the number of participants, units, or observations needed to achieve statistical power while considering practical constraints. Replication involves repeating the experiment to ensure the reliability and generalizability of the results. It helps account for the variability of measurements and strengthens the validity of the findings.

The elements of an experimental design include the following:

Experimental objectives: This involves clearly defining the research objectives or questions that the experiment aims to address. It guides the design and implementation of the experimental plan.

Experimental factors: These are the independent variables or factors that are to be manipulated in the experiment. They can be qualitative or quantitative and should be selected based on their relevance to the research objectives.

Levels of factors: Each experimental factor needs to be defined with its different levels or modalities. The levels can be fixed (pre-determined) or variable (chosen according to a specific method).

Sampling plan: This involves deciding on the number of participants, experimental units, or observations required to conduct the experiment. The sampling plan should be determined based on the desired statistical power and practical constraints.

Replication: Repetition of the experiment is important to obtain reliable and generalizable results. The number of replications depends on the variability of the measurements and the research objectives.

Experimental sequence: In some cases, it may be necessary to define a specific sequence or order in which the different experimental conditions are presented to the participants. This can help control for learning or adaptation effects.

Randomization: Randomization involves assigning participants or experimental units to different conditions randomly. This helps reduce potential biases and ensures fair distribution of individual characteristics or uncontrolled variables.

Data collection: It is important to determine the measures to be collected for each dependent variable to address the research objectives. Data collection methods should be clearly defined and standardized.

Data analysis: It is necessary to choose appropriate statistical analysis methods to evaluate the effects of experimental factors and address the research questions. This may include hypothesis testing, analysis of variance (ANOVA), regression, or other statistical techniques.

Interpretation of results: Once the data is analyzed, it is important to draw appropriate conclusions and interpret them in relation to the research objectives. The results can contribute to understanding the relationships between variables and formulating new hypotheses or recommendations.

These elements form the foundation of a robust and rigorous experimental design, and their proper design and implementation are crucial for obtaining reliable and meaningful results. This step allows researchers to draw accurate conclusions, make inferences, and generate new hypotheses or recommendations based on the observed patterns and relationships in the data. Overall, the careful consideration and incorporation of these elements are crucial in designing an effective and robust experimental study, ensuring the generation of reliable and meaningful findings.

The terms commonly used in the methodology of Design of Experiments (DOE) include controllable and uncontrollable input factors, responses, hypothesis testing, blocking, replication, and interaction. Controllable input factors, also known as x factors, are the parameters that can be intentionally modified during an experiment or process. Taking the example of cooking rice, these factors would include the quantity and quality of the rice, as well as the amount of water used for boiling. On the other hand, uncontrollable input factors are the parameters that cannot be directly changed or controlled. In the rice-cooking scenario, an uncontrollable input factor could be the temperature in the kitchen. It is important to acknowledge these factors to understand their potential impact on the response. Responses, or output measures, refer to the specific elements of the process outcome that are used to evaluate the desired effect. In the context of cooking rice, the taste and texture of the rice would serve as the responses that indicate the quality of the cooked rice [72].

To improve the outcome, the controllable input factors can be changed. Figure 2.03. Depicts the link between the variables and the outcomes [72].

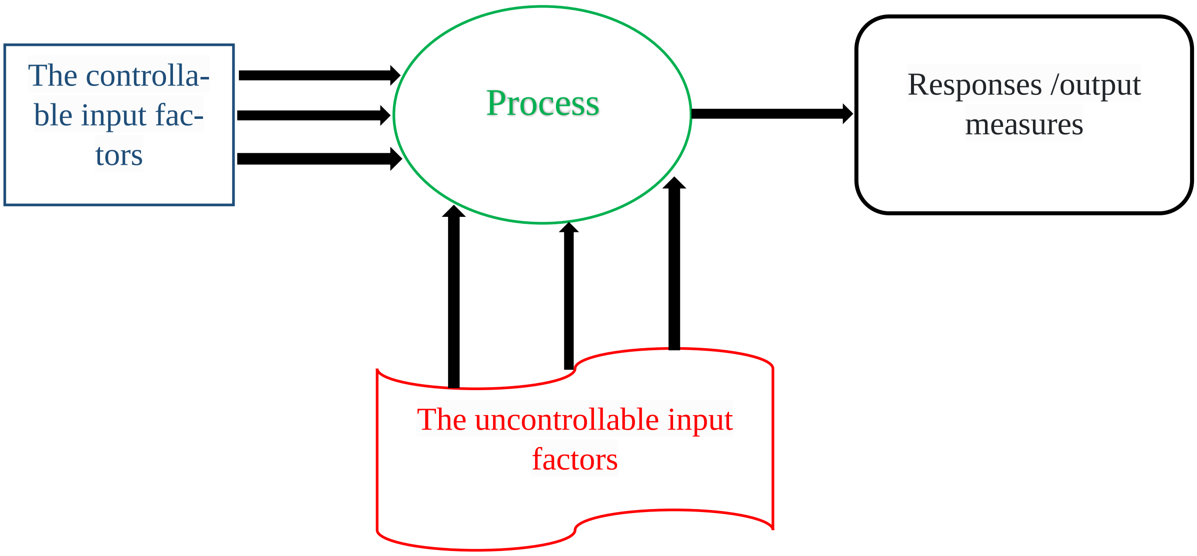


Figure 2.03. Process Factors and Responses.

2.6 The stages of an experimental design

Typically refer to the systematic process followed in designing and conducting scientific experiments. While specific methodologies may vary depending on the field of study, here is a general overview of the steps involved in an experimental design:

2.6.1 The First Stage

The first step in an experimental design is to identify the research question or objective. This involves clearly defining the purpose of the experiment and specifying the specific question or hypothesis that you want to investigate. The research question should be focused and precise, guiding the entire experimental process. It helps to determine the direction of the study and provides a clear goal to work towards. Additionally, the research question should be based on existing knowledge and gaps in understanding to contribute to the scientific knowledge in the field.

a- Determination of the response and study factors

The study should have a clear objective, aim to minimize manufacturing costs, and examine factors that impact the response. It is crucial to collect comprehensive data that can provide essential information for the following inquiries:

- Choosing the most appropriate response.
- Employing suitable measurement methods.
- Identifying potentially influential factors.
- Defining the range of study for these factors.
- Investigating potential interactions.
- Controlling unexplored factors.

The researcher's prior knowledge on the subject can be highly beneficial at this stage. The final outcome can have disastrous consequences for the researcher if a neglected factor turns out to be influential. One significant challenge is determining the study's scope. The range of variation for the factors should encompass the actual usage range.... but not exceed it.

b- Model selection

In factorial experimental designs, a common mathematical model is used to establish the relationship between the response variable Y and the factors x_1, x_2... x_i, x_n. This model is predetermined and assumes a polynomial form. The coefficients of the polynomial, denoted as a_0, a1... represent the respective terms in the model.

The product terms such as $a_{ij} \cdot x_i \cdot x_j$ correspond to interactions. In a factorial design with 3 factors, x_1, x_2, and x_3, we obtain the equation (Eq. 2.1).

$$Y = a_0 + a_1 .x_1 + a_2 .x_2 + a_3 .x_3 + a_{12} .x_1.x_2 + a_{13} .x_1.x_3 + a_{23} .x_2.x_3 + a_{123} .x_1.x_2.x_3 \qquad \text{(Eq.2.1)}$$

c- Selection of experiments to be conducted

The method of experimental design can be summarized as a comparison to the traditional "one-factor-at-a-time" approach. When studying the influence of two factors on a response, there are two experimental strategies that can be employed for trial design.

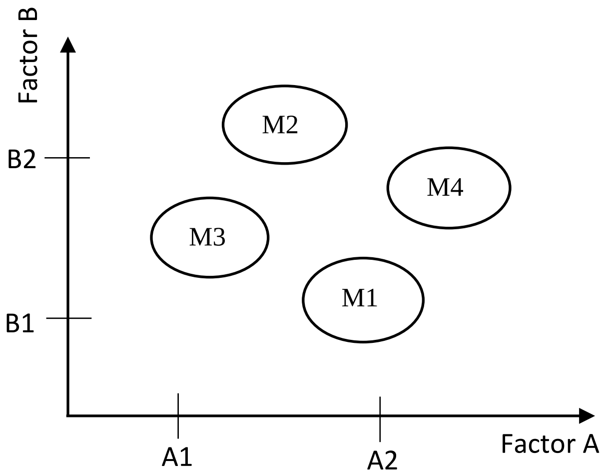


Figure. 2.04. The traditional method

Under the traditional method, the factor A is held constant at the center of its range, while the factor B is varied at both ends of its range, resulting in measurements M1 and M2. The same process is repeated with factor A to obtain measurements M3 and M4. In this approach, the effect of factor B is determined based on measurements M1 and M2, and the effect of factor A is determined based on measurements M3 and M4. Consequently, only half of the measurements are utilized to evaluate the impact of each factor.

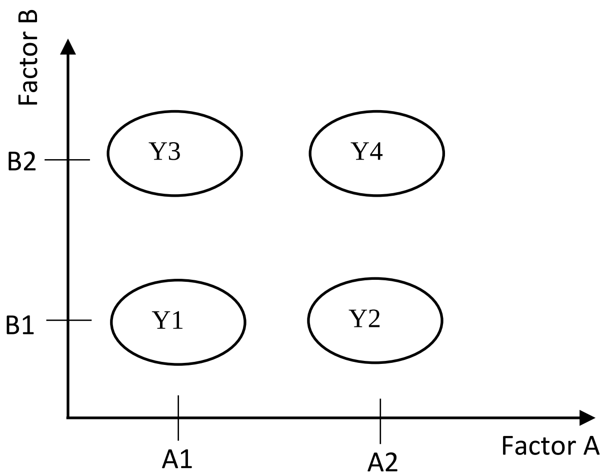


Figure. 2.05. The design of experiments method

On the other hand, the experimental design method involves conducting four experiments at the extreme points of the experimental range. The effect of factor A is calculated as the difference between the averages of measurements (Y2+Y4)/2 and (Y1+Y3)/2, while the same approach applies to the effect of factor B. In this second strategy, all measurements are utilized to calculate the effects of the factors. It is evident that the experimental design method provides higher precision in estimation. Additionally, one advantage of the experimental design method is that it requires significantly fewer experiments compared to the traditional method, particularly when the number of factors increases. However, it is crucial to understand the general methodology for determining the appropriate experiments, which depends on the chosen mathematical model.

d. Conducting the experiments

Conducting experiments requires careful attention to detail. When experiments are not conducted personally, it becomes crucial to ensure that the controllable factors are precisely and accurately set to specific values. This verification process is vital to maintain the integrity and reliability of the experimental results. Furthermore, if one of the factors being investigated is a chemical compound, it is highly advisable to minimize or eliminate the need to change the batch of raw materials throughout the entire duration of the experimentation process. By maintaining consistency in the raw materials used, any potential variations or confounding factors related to different batches can be minimized, leading to more robust and accurate conclusions from the experiments.

2.6.2 The Second Stage

In the second stage of the experimental design process, several important steps are carried out to ensure a comprehensive analysis of the results. This stage involves coding the variables, interpreting the test results, applying a simple method to calculate coefficients, conducting a statistical analysis of the results including the estimation of confidence intervals for the coefficients, and performing a graphical analysis. Each of these steps plays a crucial role in understanding the relationship between the variables and the response, providing valuable insights for further decision-making. By systematically implementing these procedures, researchers can gain a deeper understanding of the experimental data and make informed conclusions about the factors influencing the response variable.

a. Variable coding

The utilization of centered and scaled variables offers the advantage of extending the applicability of experimental design theory to various factors and study domains. By converting the natural variables into coded variables, all factors are placed within the same range of variation (-1 to +1). This standardization enables a fair comparison of the effects of different factors, facilitating a comprehensive analysis of their impact on the response variable. The use of coded variables allows for a more robust and versatile interpretation of experimental results, enhancing the overall understanding of the underlying relationships between factors and the response.

The low level is coded as -1, while the high level is coded as +1. The following application illustrates the transformation from natural variables to coded variables. First, the study domain for a particular factor is selected. For example, let's consider temperature varying from 10°C to 40°C. The temperature levels of 10°C and 40°C correspond to the low and high levels of the factor, respectively. By applying the coding scheme, the natural temperature values are transformed into coded values that allow for standardized comparisons and analysis across different factors and their respective ranges. We assign the value of -1 to 10°C and the value of

+1 to 40°C. Here, we denote the coded variable as "t" and the natural variable as "T." These two variables can be related through the following equation, where T_0 represents the midpoint of the interval in the study domain, and ΔT represents half of the width of the study domain. Both T_0 and ΔT are expressed in terms of the natural variable. In this case, T_0 is equal to 25°C, and ΔT is equal to 15°C. This relationship allows for the conversion between the coded variable and the natural variable, enabling standardized comparisons and analysis across different temperature levels within the chosen study domain.

$$t = \frac{T - T_0}{\Delta T} \qquad \text{(Eq2.02)}$$

The centered and scaled variables are dimensionless. A temperature of 20°C corresponds to a centered and scaled variable of -0.33. This means that when the natural variable, such as temperature, is converted to a centered and scaled variable using the coding scheme, a value of 20°C is standardized to a dimensionless value of -0.33. This normalization allows for comparisons and analysis across different variables without being influenced by their original units or scales.

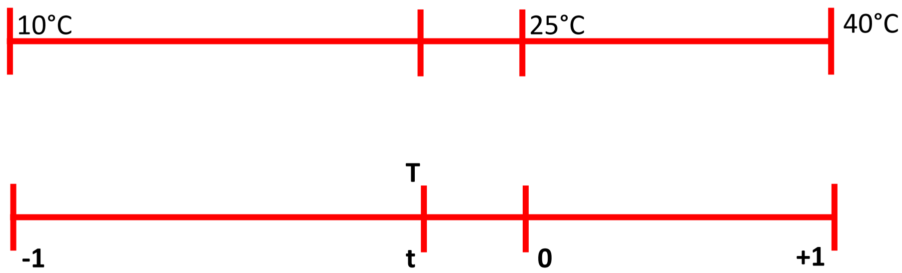


Figure. 2.06. The method of coding a design of experience

b. Interpretation of test results

As a first approach, the experimental design serves as a method to identify which factors or interactions have a statistically significant influence on the studied response. Analyzing experimental results is often a swift process, especially with software assistance. The analysis principle is straightforward: calculating the coefficients of the polynomial model. The higher the absolute value of a coefficient, the greater the impact of the corresponding term (either a single factor or an interaction) on the studied response. The challenge lies in distinguishing genuine influence from the uncertainties inherent in any measurement. In concluding the study, a list of influential factors is provided, typically expressed in the model by considering only the coefficients that are statistically significant.

It is important to note that the obtained model can only be used within the study domain. Therefore, conducting a thorough preliminary study is crucial. Extrapolating the results beyond this domain is highly risky, as it may lead to significantly different outcomes than what is expected. It cannot be stressed enough that the provided model lacks physical significance and should not be considered equivalent to a physical law.

Before utilizing the model in production, it is essential to undergo one final obligatory step: testing the predicted value against the experimental value through an experiment conducted at the center of the experimental domain. The factorial experimental design models under study do not account for potential "curvature" within the domain; they solely assume linear behavior. If the verification yields inconclusive results, it becomes crucial to consider more sophisticated models that incorporate second-degree terms.

c. Statistical Analysis of Results

All the assumptions we discussed regarding experimental designs must be verified to validate the conclusions. At this stage, we use statistical tools to assess the descriptive and predictive quality of the obtained models. The user of statistical tests is closely connected to understanding the experimental standard deviation R^2. R^2, also known as the coefficient of determination, is used to evaluate the model's quality. A higher R^2 value indicates a better model, with calculated responses strongly correlated to experimental responses, as confirmed by repeatability tests.

The experimental values used in the model are affected by errors, including both systematic and random errors, which propagate to the model's coefficients b_j and, subsequently, to the calculated values. Statistical tests enable us to evaluate the model's quality in terms of descriptive and predictive performance, validate it through Analysis of Variance, and determine the significance of the coefficients using Student's t-test.

d. Confidence interval of coefficients

The purpose of studying the variance of a coefficient is to determine its confidence interval. In a full or fractional factorial design with N trials, the responses Yi and the coefficients a_i are values of random variables. We have seen that each coefficient a_i of the model is calculated using a formula of the following type:

$$a_i = (\Sigma Y_i\ X_i) / \Sigma(X_i)^\wedge 2$$

Where Y_i represents the response variable for the i-th trial, X_i represents the value of a specific factor or interaction, and the summation is performed over all N trials.

By analyzing the variance of the coefficient a_i, we can estimate the uncertainty associated with its value. This uncertainty is reflected in the confidence interval, which provides a range of values within which the true value of the coefficient is likely to lie with a certain level of confidence.

Calculating the confidence interval typically involves considering the standard error of the coefficient estimate, which is derived from the variance and sample size. With this information, statistical techniques such as t-distribution or bootstrap resampling can be used to determine the confidence interval.

Understanding the confidence interval of a coefficient is important for assessing its significance and reliability in the statistical model. It allows us to make inferences about the population parameter and provides a measure of the precision of the coefficient estimate.

e. Graphical Analysis of Results

Graphical analysis of results is one of the key benefits of experimental designs, as demonstrated by Figures 2.07 and 2.08. Graphs serve as a powerful tool for interpreting results and offer a more communicative approach during meetings. They enable researchers to quickly draw conclusions and make informed decisions about the next steps in a study.

By visually representing data and relationships between variables, graphs provide valuable insights into patterns, trends, and interactions. They enhance the understanding of complex data sets and allow for a comprehensive exploration of the experimental outcomes.

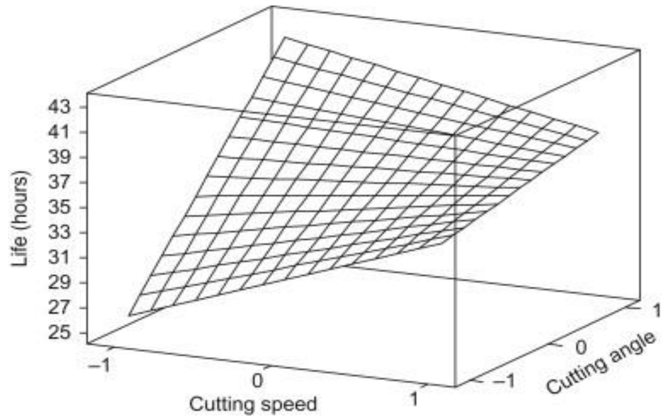


Figure 2.07. Representation of experimental design results in response surface [74]

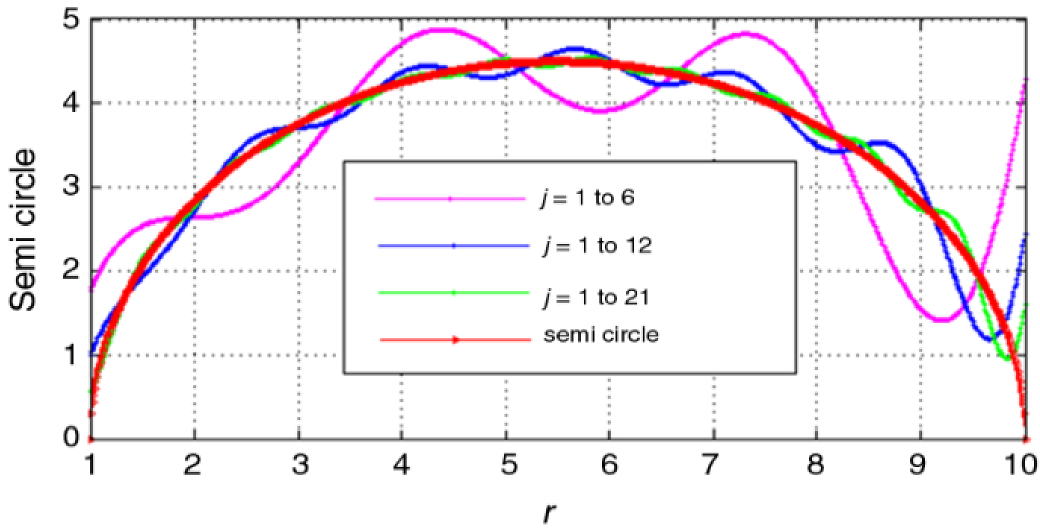


Figure 2.08. Representation of experimental design results in iso-response [75]

Furthermore, graphs facilitate effective communication among researchers, stakeholders, and decision-makers. They simplify the presentation of findings, making it easier for others to grasp the main insights and implications of the study. This expedites the decision-making process and helps steer the direction of future investigations.

In summary, the graphical analysis of results in experimental designs offers multiple advantages, including improved interpretation, efficient communication, and informed decision-making, ultimately driving the progress and success of a study.

2.7 Factorial Design and the Software usage

Factorial design refers to an experimental design where multiple factors are simultaneously investigated, allowing for the examination of main effects and interactions between factors. It is a powerful approach for studying the effects of multiple variables on a response variable.

When conducting a factorial design, software tools can be incredibly useful for designing the experiment, analyzing the data, and interpreting the results. There are various software programs available that are specifically designed for factorial design, such as Minitab, JMP, R, and Python libraries like SciPy and Stats models.

These software tools provide features for efficiently generating experimental designs, conducting statistical analyses, and visualizing the results. They often offer functions for estimating main effects, interactions, and conducting analysis of variance (ANOVA) to assess the significance of the factors and their interactions.

Furthermore, the software can generate graphical representations, such as main effects plots and interaction plots, to aid in the interpretation of the results. These visualizations allow researchers to easily understand the relationships between the factors and the response variable.

Overall, utilizing software for factorial design can greatly enhance the efficiency, accuracy, and interpretability of the experimental process, making it an essential tool for researchers in this field.

2.7.1 A brief about factorial design

Factorial design is a powerful experimental design methodology that allows researchers to study the effects of multiple factors simultaneously. It involves manipulating two or more independent variables, known as factors, and examining their influence on a dependent variable, also known as the response variable.

Probably the easiest way to begin understanding factorial designs is by looking at an example

a. Simple example:

Imagine that we have an instructional program and that we would like to examine many program versions to see which performs the best. For instance, we'd like to change how much time the kids spend in class, giving one group an hour a week of training while giving the other four. And, we want to change the environment by pulling one group out of the classroom to receive education in another room while the other group receives instruction in class (presumably in a corner of the room). We could consider breaking this up into four different groups, but which setting would we choose—pull-out or in-class—when we are modifying the duration of instruction? And how long would we spend teaching if we were researching a setting: an hour, four hours, or something else? [73].

In factorial designs, we can explore multiple combinations without compromising. By crossing the two conditions of time in instruction with the two settings, we can address both questions simultaneously. Let's clarify some terms: factors are the main independent variables, and in this example, we have two factors: time in instruction and setting. Each factor has subdivisions called levels, with two levels for time in instruction and two levels for setting. We can represent a factorial design using a numbering notation, such as a 2 x 2 (spoken as "two-by-two") factorial design. The numbers indicate the number of factors and the values indicate the number of levels. The order of numbers doesn't matter, so a 3 x 4 factorial design is equivalent to a 4 x 3 design. To determine the number of treatment groups, we multiply the numbers in the notation. In our example, we have 2 x 2 = 4 groups. In the notational example, we would need 3 x 4 = 12 groups [73].

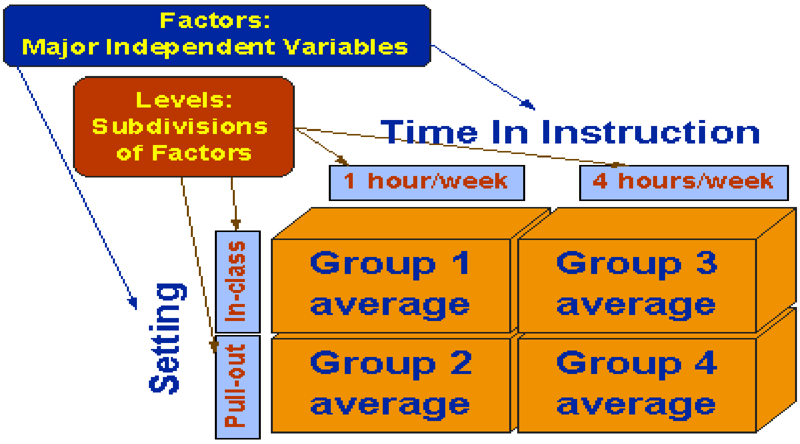


Figure 2.09 groups division by factors and levels [73].

- **The Main Effects**

A main effect in factorial designs refers to a consistent difference observed between the levels of a factor. For example, if we observe a statistically significant difference between the averages of the in-class and pull-out groups across all levels of time in instruction, we would conclude that there is a main effect for setting. The figure 2.10 (A) in the provided resource illustrates a main effect of time, where the condition of 4 hours per week resulted in better outcomes compared to the condition of 1 hour per week, regardless of the setting. It is also important to note that it is possible to have a main effect for setting without any significant main effect for time [73]. Figure 2.10 (B) shows the second main effect graph we see that in-class training was better than pull-out training for all amounts of time.

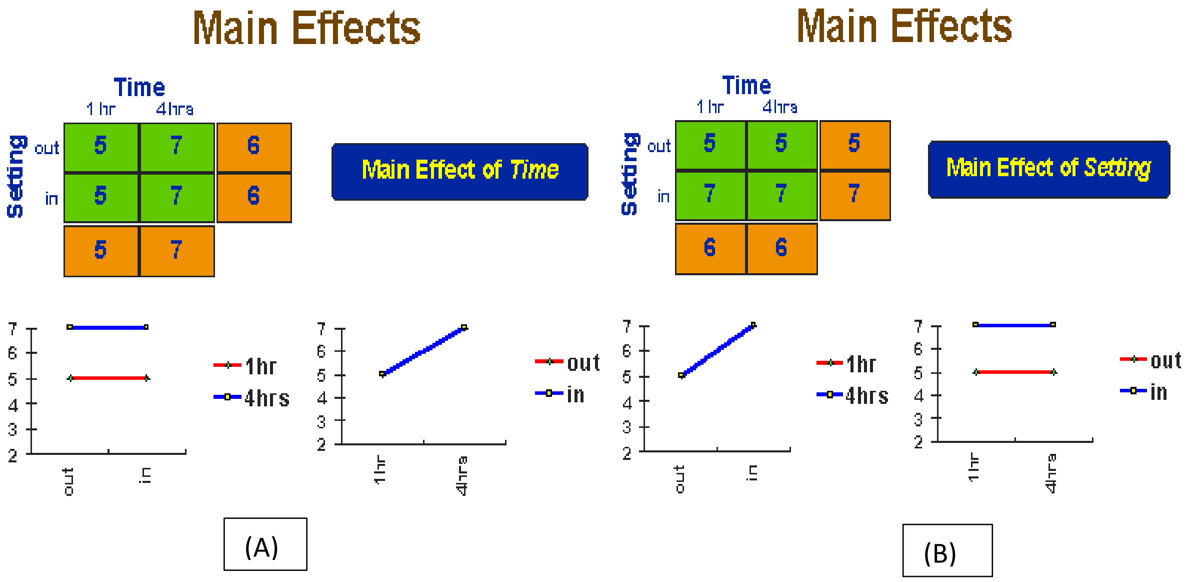


Figure 2.10. (A) Mean Effects of time and (B) Mean Effects of setting [73].

In factorial designs, it is also possible to have a simultaneous main effect on both variables, as shown in the third main effect figure. In this case, the condition of 4 hours per week consistently yields better outcomes than the condition of 1 hour per week, and the in-class setting consistently outperforms the pull-out setting. This indicates that both time in instruction and setting have independent and significant effects on the outcomes being studied.

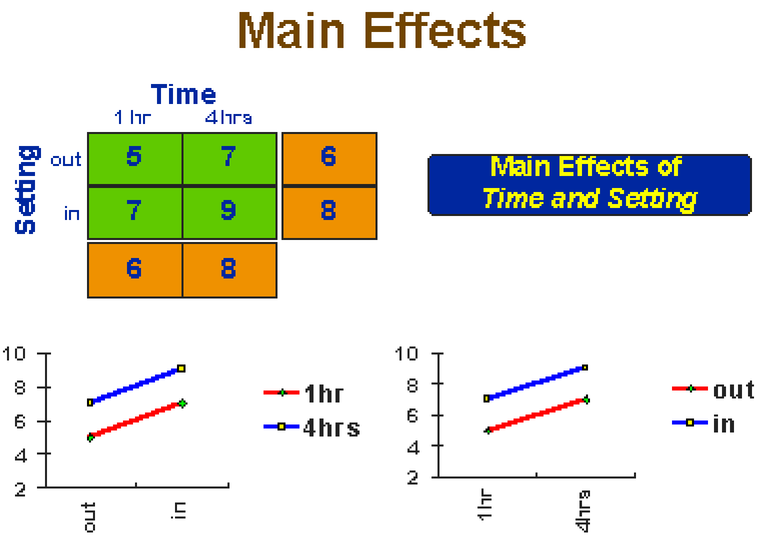


Figure 2.11. Mean Effects of both time and setting [73]

- **Interaction Effects**

If we focus solely on main effects, factorial designs would still be valuable. However, the combination of levels in factorial designs allows us to investigate interaction effects between factors. An interaction effect occurs when the differences observed on one factor depend on the level of another factor. It's crucial to understand that interactions are between factors, not levels. We wouldn't say there's an interaction between 4 hours per week and the in-class treatment specifically. Instead, we would state that there's an interaction between time and setting, and then provide further details about the specific levels involved.

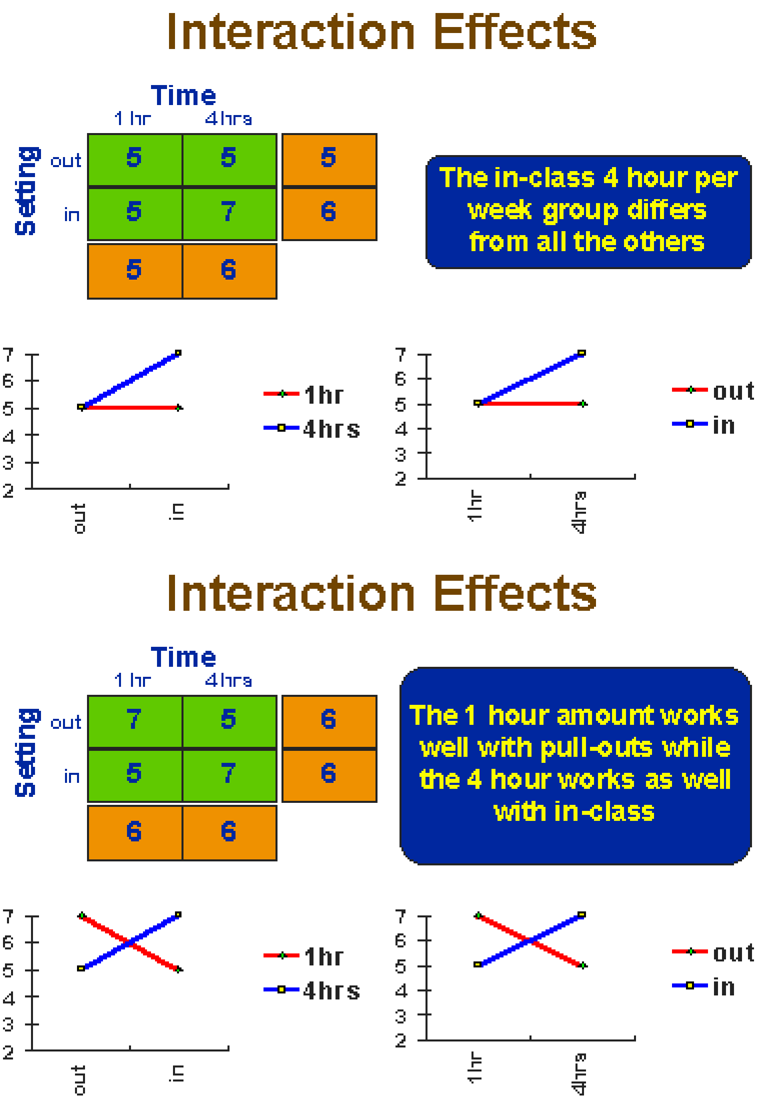


Figure 2.12 Interaction Effects between factors [73].

To determine if there is an interaction in a factorial design, there are three ways to consider. First, the statistical analysis will provide information on main effects and interactions. Second, if it is necessary to mention both factors when discussing the effects, then an interaction is present. In contrast, if one factor can be discussed independently, it indicates a main effect rather than an interaction. Lastly, interaction effects can be observed visually in graphs of group means, where non-parallel lines indicate an interaction. In the presented graphs, all lines within main effect graphs are parallel, while in the interaction graphs, the lines are not parallel. In the first interaction graph, one combination of levels performs better than the other three. In the second interaction, a more complex "cross-over" interaction is observed, where the pull-out group performs better at 1 hour/week, while the in-class group performs better at 4 hours/week. Additionally, both combinations of levels perform equally well in this interaction.

b. Importance of the factorial design

In summary, factorial designs allow us to examine both main effects and interaction effects between factors. Main effects indicate consistent differences between levels of a factor, while interaction effects demonstrate that the effects of one factor depend on the level of another factor. Main effects can be identified by looking at statistical analyses, determining if one factor can be discussed independently. On the other hand, interactions require considering both factors together to accurately describe the results. Interaction effects can also be visually observed in graphs of group means, where non-parallel lines indicate the presence of an interaction. By analyzing the results, we can gain insights into the effects of each factor and their interactions in a factorial design.

The factorial design offers efficiency by allowing the simultaneous investigation of multiple factors, optimizing resources and reducing the number of experimental runs. It helps uncover interaction effects between factors, providing insights into how factors interact with each other. The design enhances generalizability by studying the effects of multiple factors on a response variable. It enables the identification of the main effects, representing the independent influence of each factor. Factorial design aids in identifying optimal conditions for desired responses, benefiting process optimization and product development. Additionally, it provides a statistical framework for analyzing data, assessing significance, estimating model parameters, and making reliable inferences. Overall, the factorial design offers an efficient and structured approach to experimental research, facilitating deeper insights, process optimization, and evidence-based decision-making in various domains.

2.7.2 Minitab Software presentation

Minitab is a widely used statistical software package known for its comprehensive features and user-friendly interface. It is utilized for data analysis, statistical modeling, and quality improvement initiatives. With its diverse range of tools, users can manipulate data, perform statistical analyses, generate graphs, and interpret results. Minitab is popular in academia, research, industry, and quality control settings, offering robust statistical capabilities and ease of use. It is highly regarded for its ability to aid professionals and researchers in making data-driven decisions across various fields.

Minitab offers several advantages that make it a preferred choice for statistical analysis and data visualization:

User-friendly interface: Minitab provides a user-friendly interface that is easy to navigate, making it accessible to users with varying levels of statistical expertise. Its intuitive design and layout allow users to quickly access the desired tools and perform analyses efficiently.

Wide range of statistical analyses: Minitab offers a comprehensive set of statistical analyses, including descriptive statistics, hypothesis testing, regression analysis, ANOVA, design of experiments, time series analysis, reliability analysis, and more. It provides a versatile platform for analyzing data and conducting in-depth statistical investigations.

Powerful data visualization capabilities: Minitab offers a variety of graphing and visualization options to effectively represent data. Users can create various types of graphs, such as histograms, scatter plots, boxplots, control charts, and Pareto charts, to visualize patterns, trends, and relationships in the data. These visualizations aid in understanding and communicating complex data effectively.

Quality improvement tools: Minitab is widely used in quality improvement initiatives, such as Six Sigma, due to its extensive set of quality control tools. It provides features for process capability analysis, control charts, measurement system analysis (MSA), design of experiments (DOE), and other quality-related analyses. These tools help identify and address process variations and improve overall quality and efficiency.

Data import and compatibility: Minitab allows users to import data from various file formats, including Excel, CSV, and databases, simplifying the data input process. It also supports integration with other statistical software and data analysis tools, allowing for seamless collaboration and data sharing across different platforms.

Comprehensive documentation and support: Minitab provides comprehensive documentation, tutorials, and online resources to assist users in learning and utilizing its features effectively. Additionally, Minitab offers technical support and a vibrant user community that can provide assistance and guidance when needed.

Overall, the advantages of Minitab include its user-friendly interface, extensive statistical analysis capabilities, powerful data visualization tools, suitability for quality improvement initiatives, data compatibility, and available support resources. These features contribute to its popularity and make it a valuable tool for data analysis and decision-making in various fields. With all this advantage there are some limitations. Here are a few:

- Complexity for beginners
- Limited customization
- Lack of programming capabilities
- Data size limitations
- Limited support for specialized analysis techniques

It's important to note that these limitations are relative, and Minitab continues to be a popular choice for many statistical analyses. However, for certain advanced or highly specialized requirements, users may need to consider additional tools or software packages.

2.8 Conclusion

In conclusion, this Chapter provides a comprehensive understanding of the experimental design method by addressing various key aspects. It begins with an overview, which highlights the importance of experimental design in research. The chapter then explores the basic principles of experimental design, emphasizing randomization, replication, and control as essential elements for robust experimental designs.

The purpose of experimental designs is discussed, emphasizing their role in establishing cause-and-effect relationships, evaluating treatment effects, and optimizing processes. The chapter further delves into different models of experimental designs, including completely randomized design, randomized complete block design, factorial design, and Latin square design. Each model is explained in terms of its characteristics and appropriate applications.

The elements of an experimental design are thoroughly examined, covering crucial components such as experimental units, treatments, factors, levels, and responses. Their significance in experimental design is highlighted, as they contribute to the validity and reliability of the results.

The stages of an experimental design are presented, providing a step-by-step guide to the entire experimental design process. This includes problem formulation, selection of factors and levels, determination of the experimental design model, execution of the experiment, and analysis of the results. These stages ensure a systematic and well-structured approach to conducting experiments.

Lastly, the chapter discusses factorial design and the utilization of software tools. Factorial design allows for the simultaneous study of multiple factors and their interactions. The chapter emphasizes the importance of using software tools to facilitate the design, execution, and analysis of factorial experiments, enhancing efficiency and accuracy.

Overall, this Chapter serves as a comprehensive resource for understanding the experimental design method. It covers the fundamental principles, different models, key elements, stages, and advanced techniques such as factorial design and software usage. The chapter enables us to design and conduct effective experiments.

Chapter 03: EXPERIMENTAL STUDY

3.1 Introduction

The evaluation of alternative materials for use in construction is a vital area of research aimed at achieving sustainable and eco-friendly solutions. In the context of hot mix asphalt (HMA) production, the search for viable alternatives to conventional aggregate materials has led to the investigation of various waste products and by-products. One such potential substitute is treated sawdust, which has shown promise as a partial replacement for traditional aggregates.

In this chapter, the focus shifts toward the experimental study conducted to evaluate the feasibility and effectiveness of using treated sawdust as a partial replacement for aggregate in HMA. The primary objective is to investigate the categorization and characteristic properties of the materials involved, determine appropriate control samples, devise a suitable treatment method for the sawdust, and ascertain the optimum percentage of sawdust that can be utilized in the asphalt mixture.

To ensure a comprehensive understanding of the materials involved in the study, a thorough categorization and characterization process is undertaken. This involves assessing the physical, mechanical, and chemical properties of the materials, such as particle size distribution, specific gravity, density, moisture content, and composition. By obtaining a clear understanding of the materials' characteristics, a foundation is laid for subsequent experiments and analysis.

Before introducing treated sawdust as a potential replacement material, it is essential to establish control samples using conventional aggregate materials. These control samples serve as a benchmark against which the performance of the treated sawdust can be compared. The preparation of the control samples involves selecting and grading conventional aggregates, proportioning the mixture constituents, and following specific mixing processes. Testing procedures and standards are utilized to assess the properties and performance of the control samples.

The successful integration of sawdust into the HMA mixture necessitates an effective treatment method to address its inherent limitations. Sawdust possesses characteristics that can potentially hinder its compatibility and performance within the asphalt mixture. Therefore, the development of an appropriate treatment process to enhance the sawdust's properties is crucial. This process may involve drying, grinding, sieving, and chemical treatments to optimize the sawdust for inclusion in HMA.

Finding the right balance between the amounts of sawdust incorporated and the desired performance of the asphalt mixture is crucial. Various experimental tests are conducted to evaluate the mechanical and physical properties of the asphalt mixtures containing different percentages of treated sawdust. The results obtained from these experiments provide insights into the optimum percentage of sawdust that can be effectively utilized without compromising the overall performance of the HMA.

In conclusion, this chapter provides a comprehensive analysis of the experimental study conducted to assess the potential applications of treated sawdust as a partial substitute for aggregate in HMA. The focus has been on thoroughly examining the materials involved, preparing control samples, developing an appropriate treatment method for sawdust, and determining the optimal percentage of sawdust for effective utilization in the asphalt mixture. Following this chapter, the subsequent and final chapter of this thesis will delve into an analytical study of the results obtained from the experimental study, providing further insights and interpretations.

3.2 Semi-Dense Bituminous Concrete SDBC

The wearing course is the top layer of a roadway that directly comes into contact with vehicle tires. Its primary function is to provide suitable safety and comfort conditions that are compatible with the class and service level of the road. The wearing course is subjected to various external forces, such as weather conditions and tire impacts. As a result, it represents the ultimate goal of road engineering in terms of pavement construction, and it must fulfill its intended role effectively.

Semi-Dense Bituminous Concrete (SDBC) is a type of asphalt concrete mixture that falls between the dense and open-graded asphalt concrete mixtures in terms of aggregate gradation and void content. The aggregate used in SDBC typically consists of a combination of coarse, fine, and mineral filler materials. The gradation of the aggregate is carefully selected to achieve a semi-dense structure, where the voids between the aggregate particles are moderately filled with asphalt binder.

It is important to note that specific design guidelines and specifications may vary depending on regional or project-specific requirements. Therefore, it is recommended to consult local standards and specifications to ensure compliance and optimal performance of the Semi-Dense Bituminous Concrete mixture (SDBC).

In contemporary road construction, most road surfaces are covered with surface dressings or asphalt mixes, such as dense asphalt mixes and bituminous concrete. One commonly encountered asphalt mix on Algerian roads is Semi-Dense Bituminous Concrete (SDBC). SDBC is a type of bituminous concrete with a particle size distribution of 0/14. It is used as both the wearing course and binder course in road pavements and must comply with the NF P 98-130 standard. The average application thickness for SDBC 0/14 ranges from 6 to 8 cm. In the southern region of Algeria, which is the focus of this study, the recommended pure bitumen grade for SDBC is 40/50, particularly for areas with high traffic loads.

Semi-Dense Bituminous Concrete (SDBC) is specifically designed to meet the requirements of a wearing course. It provides a balance between stability, durability, and drainage properties. The aggregate gradation in SDBC is carefully selected to achieve a semi-dense structure, where the voids between the aggregate particles are moderately filled with the asphalt binder. This ensures adequate stability and resistance to rutting while also allowing for effective drainage.

The wearing course, made of SDBC, plays a crucial role in providing a smooth and safe driving surface for road users. It withstands the direct impact of weather conditions and vehicle tires, ensuring a comfortable and secure driving experience. The selection of the appropriate grade of pure bitumen and adherence to relevant standards ensure that SDBC performs effectively in the southern region of Algeria.

In summary, Semi-Dense Bituminous Concrete (SDBC) is a commonly used asphalt mixture in Algerian road construction, serving as the wearing course and binder course. It meets the requirements of safety, comfort, and durability for the road surface. The specific selection of pure bitumen grade and compliance with relevant standards ensure that SDBC performs optimally in the southern region of Algeria.

3.3 Materials Used in the Control Concrete

By conducting detailed characterizations of the materials used in our study, we can comprehensively evaluate their properties and behavior. This section focuses on the characterization and properties of the materials employed in our experimental research. In our investigation of using treated sawdust as a partial replacement for aggregate in hot mix asphalt, understanding the characteristics of these materials is essential for evaluating their feasibility and effectiveness.

3.3.1 Choice of aggregates

The selection of aggregates is a critical aspect in the formulation of asphalt mixes, considering their position on the road surface, direct contact with tires, and exposure to weather conditions. The mechanical qualities of aggregates play a significant role, which can be categorized into two types:

- Those inherent to the original rock, such as hardness, resistance to polishing, and shock resistance.
- Those resulting from the manufacturing process, including cleanliness, shape, granularity, angularity, and homogeneity.

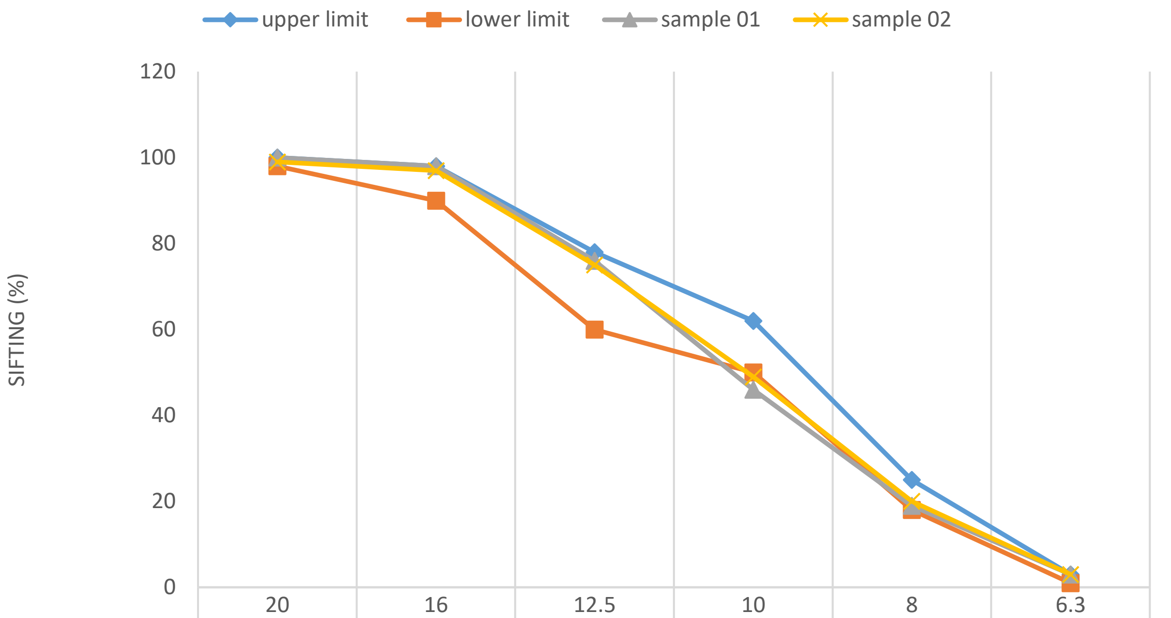
Evaluating these qualities involves tests like Los Angeles and Micro-Deval wet tests to assess hardness, and standardized accelerated polishing tests to determine resistance to polishing. Therefore, the analysis and selection of aggregates are vital steps in formulating asphalt mixes, involving sample preparation and analysis based on the NF EN 932-3 standard.

3.3.2 Sample identification

The objective of this identification process is to verify whether the provided aggregates conform to the guidelines outlined in standard NF EN 932-3, specifically in terms of their granularity, hardness, and cleanliness. The test results are compiled and presented in Table 3.1. The aggregates utilized in this study consist of the fractions 0/3, 3/8, and 8/15. These aggregates originate from the Alco-Gaz quarry in Metlili Ghardaia, located in the southern part of Algeria. The rocks in this region are renowned for their hardness, which is reflected in the test results. Size of sand (0/3) and gravel (3/8) and gravel (8/14), the outcomes of the particle size tests are illustrated in Figures 3.1.a, 3.1.b, and 3.1.c.

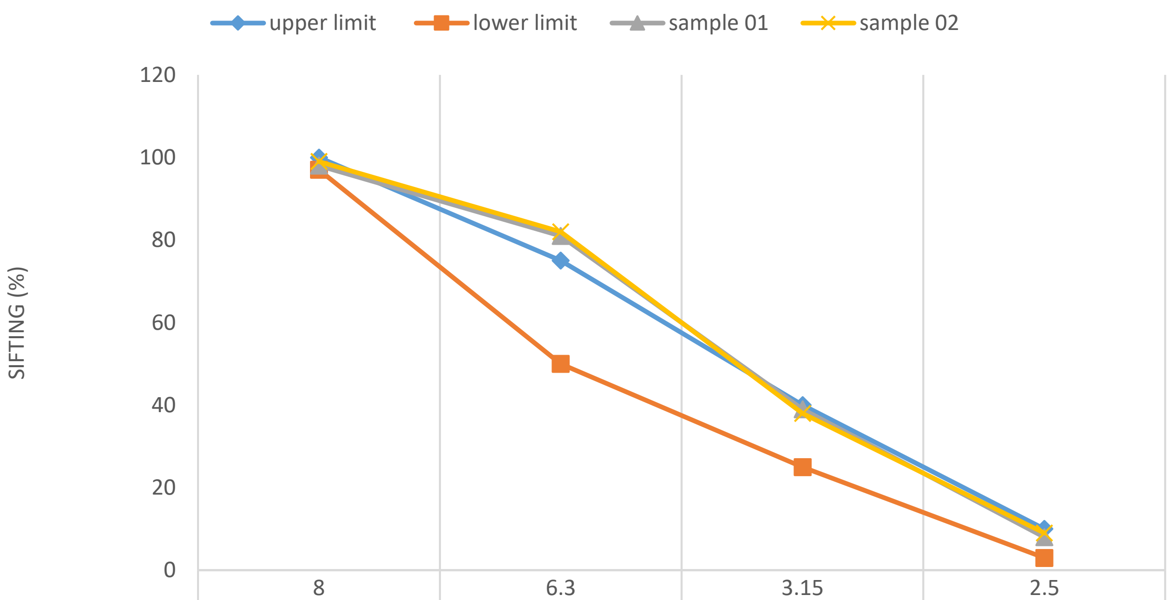
Table 3.01: physical characteristics of aggregates

Aggregates tests	Sand (0/3)	Gravel (3/8)	Gravel (8/15)	Specifications
Specific weight (g/cm^3)	2.76	2.74	2.76	---
Los Angeles	---	19.0	17.7	<25
Micro- Deval	---	19.0	15.9	≤20
Flattening coefficient (%)	---	21.6	14	≤30
Sand equivalent SE (%)	65	---	---	60≤SE≤80



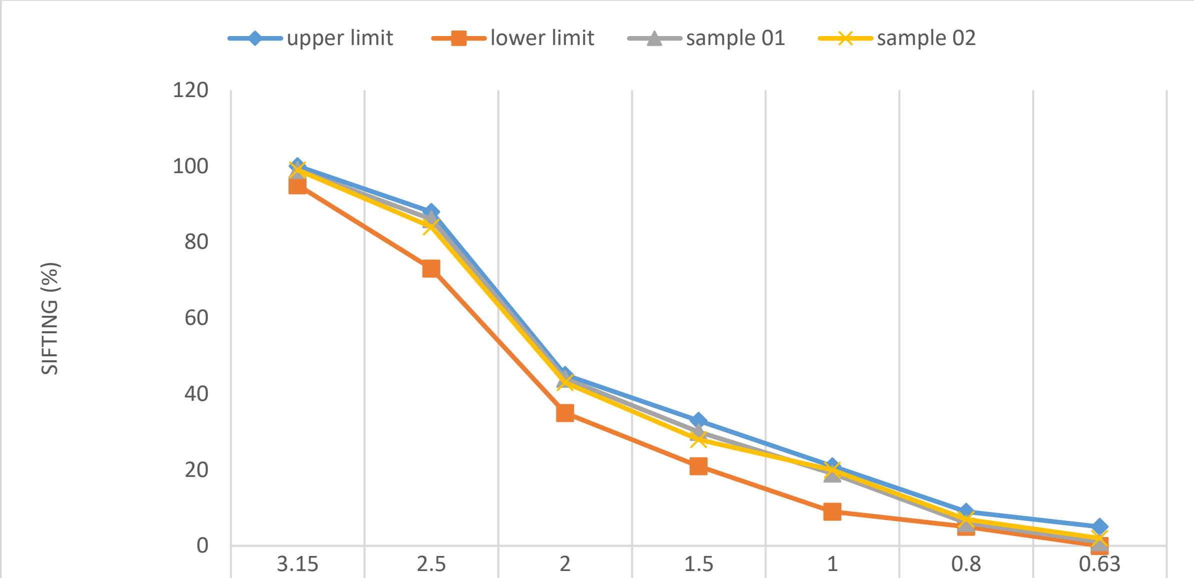
	20	16	12.5	10	8	6.3
upper limit	100	98	78	62	25	3
lower limit	98	90	60	50	18	1
sample 01	100	98	76	46	19	3
sample 02	99	97	75	49	20	3

Figure 3.01 (a). Particle size analysis of gravel 8/14.



	8	6.3	3.15	2.5
upper limit	100	75	40	10
lower limit	97	50	25	3
sample 01	98	81	39	8
sample 02	99	82	38	9

Figure 3.01 (b). Particle size analysis of gravel 3/8.



	3.15	2.5	2	1.5	1	0.8	0.63
upper limit	100	88	45	33	21	9	5
lower limit	95	73	35	21	9	5	0
sample 01	99	86	44	30	19	6	1
sample 02	99	84	43	28	20	7	2

Figure 3.01 (c). Particle size analysis of sand 0/3.

3.3.3 Aggregate cleaning

The granular sample underwent a meticulous cleaning process to ensure its suitability for subsequent tests. This involved employing a water jet within a 3 mm sieve, effectively removing fines and residues that could potentially introduce errors or inaccuracies into the analysis. Furthermore, this cleaning step played a vital role in enhancing the visual inspection of petrography, particularly when dealing with aggregates that were contaminated or covered in dust.

Following the cleaning process, the wet aggregates were carefully transferred to an oven and subjected to drying at a controlled temperature of 100°C. This step was crucial in eliminating any remaining moisture from the samples, thereby preventing moisture-induced artifacts and preserving the integrity of the subsequent analysis. To maintain clear sample identification and avoid confusion, each drying tray was diligently labeled to ensure proper tracking throughout the process.

Once the drying phase was completed, special attention was given to assessing the readiness of the aggregates for further analysis. This entailed confirming the evaporation of water from the containers and ensuring that the aggregates were superficially dry. It was important to be thorough in this assessment to prevent any residual moisture from interfering with subsequent measurements. Additionally, allowing the aggregates to reach room temperature before proceeding with the analysis was essential, as it ensured a stable and consistent starting point for the investigation.

By adhering to these meticulous steps and precautions, the integrity and reliability of the granular sample analysis were upheld. The comprehensive cleaning process and the careful drying and cooling procedures laid the foundation for accurate and consistent results, minimizing potential confounding factors and maximizing the overall validity of the subsequent tests conducted on the granular sample.

3.3.4 Chemical Characteristic of the Aggregate

The primary objective of conducting these tests is to accurately determine the presence and extent of aggressive materials that may be coating the aggregates used in the asphalt mixture. The existence of such materials can have detrimental effects on the performance and durability of the asphalt mix, potentially leading to premature deterioration and compromised structural integrity. Thus, it is crucial to assess the level of aggressiveness present, as it directly impacts the interpretation and reliability of the test results obtained.

Through rigorous testing procedures, it has been revealed that the percentage of aggressive material within the body of the aggregates, which make up the healthy asphalt mix, is found to be almost negligible. This significant finding is clearly demonstrated and supported by the data presented in Table 3.02 and Table 3.03. The low presence of aggressive materials in the aggregates affirms the sound composition and quality of the materials used, suggesting a reduced likelihood of potential degradation issues.

The results obtained from these tests play a pivotal role in providing crucial insights into the overall performance and longevity of the asphalt mixture. By confirming the minimal presence of aggressive materials, these findings contribute to a more accurate assessment of the asphalt mix's durability, structural stability, and resistance to environmental factors. This valuable information enables informed decision-making during the construction, maintenance, and design processes, ensuring the selection of appropriate materials and techniques to optimize the performance and longevity of the asphalt infrastructure.

Moreover, the comprehensive nature of these tests enhances our understanding of the interactions between the aggregates and the surrounding asphalt binder, shedding light on potential chemical reactions or compatibility issues that could compromise the integrity of the mixture. By identifying and quantifying the extent of aggressiveness in the aggregates.

Table 3.02 gravel chemical analysis results

Fraction	3/8	8/15
Insoluble content [%]	1.5	1.4
CaCo3 carbonate content [%]	89	91
Chloride Cl^- content [%]	0.012	0.013
Sulphates SO_3 rate [%]	00	00

Table 3.03 sand chemical analysis results

Fraction	0/3
Insoluble content [%]	2.5
CaCo3 carbonate content [%]	87
Chloride Cl^- content [%]	00
Sulphates SO_3 rate [%]	00

In conclusion, the meticulous testing conducted to determine the presence of aggressive materials on the aggregates reveals a favorable scenario with a negligible percentage of such materials in the healthy asphalt mixture. This crucial finding strengthens confidence in the durability and performance of the asphalt mix, affirming its suitability for various infrastructure applications. The acquired knowledge empowers stakeholders to make informed decisions, implement appropriate maintenance practices, and ensure the long-term success of asphalt-based projects.

3.3.5 Binder Characteristic

The properties of bituminous binder serve as key indicators of its behavior and performance in asphalt mixtures, particularly with regard to its consistency at room temperature (as measured by NF EN 1426 - penetration test) and its temperature susceptibility (measured by EN 1427 - ball and ring test). These essential characteristics play a pivotal role in classifying bituminous binders into specific grades, as defined by the standard specification for road bitumens (NF EN 12591). The grading system assigns a range of penetration values that encompass the measured penetration of the binder under consideration, resulting in grade designations such as 35/50, 70/100, or 160/220.

The bituminous binder serves as the crucial component that imparts the desired viscoelastic properties to the asphalt mixture. These properties, in turn, determine the stiffness and structural behavior of the pavement, especially in response to temperature variations. The consistency of the bituminous binder, as well as its proportion within the mixture, significantly influences the overall rigidity of the asphalt mix at different temperature conditions.

For our study, we utilized bitumen of class 40/50, which was sourced from the renowned National Hydrocarbon Company, SONATRACH. The detailed characteristics of this particular bitumen are outlined in Table 3.04. The presented data serves as concrete evidence that the analyzed bitumen exhibits characteristics that align precisely with the requirements and specifications outlined for the 40/50 class. This ensures that the selected bitumen satisfies the necessary criteria for its intended application and guarantees that the asphalt mixture will possess the desired viscoelastic and performance properties.

The compliance of the bitumen's characteristics with the prescribed standards further validates its suitability and reliability in paving applications. By adhering to established industry norms, we can confidently anticipate the bitumen's favorable performance in terms of durability, resilience, and resistance to temperature-related distresses. These findings instill confidence in the overall quality and long-term performance of the asphalt mixture, affirming that the selected bitumen from SONATRACH meets the stringent specifications of the 40/50 class.

Table 3.04 Binder characterization

	specimen 01	Specimen 02	Average	Specifications
Penetration at 25°C, (1/10 mm)	41	43	42	40-50
The temperature of the ball and the ring C°	51	53	52	47-60
Relative density at 21° C (at the pycnometer)	1.040	1.042	1.041	1.00 to 1.10

By carefully evaluating and considering the binder's characteristic properties, engineers and researchers can make informed decisions regarding the selection, formulation, and optimization of the asphalt mix design. This ensures that the binder used in the mixture is compatible with the anticipated traffic loads, climate conditions, and desired performance criteria, resulting in long-lasting and reliable asphalt pavements.

3.4 Sawdust Characteristic and Preparation

Sawdust is a common waste material generated by various industries, particularly those involved in woodworking and timber processing. As a byproduct of these operations, sawdust is often considered waste and requires appropriate disposal. However, it is essential to recognize the potential value and opportunities that sawdust holds. Despite being classified as waste, sawdust can be repurposed and utilized in various ways, such as for biomass fuel, animal bedding, composting material, or even as a component in manufacturing certain products. By exploring innovative and sustainable approaches to manage sawdust waste, we can reduce its environmental impact and unlock its inherent value, contributing to a more circular and resource-efficient economy.

3.4.1 gathering and clean and sizing of sawdust

The selection of redwood sawdust as a waste material for repurposing is a strategic choice driven by its availability and desirable mechanical properties. Redwood is widely accessible in carpentry shops throughout Algeria, making it a convenient and abundant source of sawdust waste. Additionally, redwood possesses commendable mechanical characteristics that make it suitable for various applications. Its strength, durability, and resistance to decay and insects make it an attractive choice for repurposing sawdust waste.

By opting for redwood sawdust, we not only capitalize on its widespread availability but also leverage its inherent mechanical properties, ensuring that the repurposed waste material retains its integrity and contributes to sustainable practices in the woodworking industry.

A combination of manual cleaning and water jet cleaning methods is commonly used to thoroughly clean and prepare sawdust waste for repurposing. Manual cleaning involves carefully inspecting the sawdust and removing larger impurities by hand. Water jet cleaning utilizes high-pressure water to dislodge and rinse away finer particles and remaining impurities. By combining these methods, the sawdust undergoes a comprehensive cleaning process, ensuring high-quality results. The cleaned sawdust can then be utilized in various applications, contributing to sustainable waste management practices.

Sizing sawdust involves selecting particles between 3 mm and 8 mm using sieves as shown in figure.3.02.Sawdust for use as a replacement for 3/8 mm aggregates in asphalt concrete. The sieving process ensures the desired particle size range is achieved, allowing the sawdust to be integrated into the asphalt mixture. This substitution offers benefits such as sustainability improvements, cost reduction, and reduced environmental impact.

The sized sawdust, after treatment mixed with bitumen and mineral aggregates, forms a modified asphalt mixture that retains the integrity and performance characteristics of traditional asphalt concrete while incorporating the unique properties of sawdust. Careful consideration, testing, and evaluation of moisture content, physical properties, and blending proportions are necessary for successful implementation. By sizing and incorporating sawdust into asphalt concrete, we can explore sustainable alternatives, optimize resource utilization, and promote recycling and waste reduction practices in construction.

Ensuring the quality of sawdust involves understanding its chemical composition. Physical parameters such as moisture content, particle size distribution, and cleanliness are assessed to ensure proper handling and suitability for the intended use. Understanding the chemical composition, including components like cellulose and lignin, helps determine its reactivity, combustion properties, and potential applications.

The step is unsure of the good quality of sawdust and after the step, we have to understand the chemical composition of the sawdust.

Figure 3.02 Sieving the sawdust and cleaning by hand

3.4.2 chemical composition of sawdust

The chemical composition of sawdust from redwood, a specific type of wood, plays a crucial role in understanding its properties and potential applications. table 3.05 presents the chemical elements composed of the redwood sawdust.

Redwood sawdust typically consists of various organic compounds, with the primary constituents being cellulose, lignin, hemicellulose, and extractives. Cellulose is a complex carbohydrate that provides structural integrity to the wood fibers. Lignin, another major component, gives wood its strength and rigidity. Hemicellulose is a polysaccharide that acts as a bonding agent between cellulose and lignin.

Table 3.05 the chemical elements composed of the redwood sawdust.

Elements	Redwood sawdust weight (%)
C	45.52
O	30.65
Ca	0.61
Cu	2.39
Zn	1.80
Au	19.04
S	00
Total	100.00

Understanding the chemical composition of redwood sawdust is important for several reasons. It helps determine its reactivity, combustion properties, and potential for chemical modifications or treatments. Additionally, knowledge of the chemical composition aids in evaluating the environmental impact, compatibility with other materials, and potential applications.

3.4.3 Sawdust Treatment

Sawdust treatment for use in asphalt concrete involves drying, size reduction, treatment, blending, and performance testing. The sawdust is dried to the appropriate moisture content, resized if needed, and treated to improve its compatibility with bitumen. It is then blended with other asphalt components and subjected to performance tests to ensure its suitability. These treatment steps optimize the sawdust for use in asphalt concrete, enhancing its performance and promoting sustainability in construction practices.

The main criterion for this treatment is to protect the sawdust from the water to evaluate the effects of treatment using the water absorption ratio after each treatment.

a- Chemical Treatment

Chemical treatments were conducted using a sodium hydroxide (NaOH) solution at three different concentrations: 5%, 10%, and 15%. Each concentration was tested with three different immersion times of 24 hours, 48 hours, and 72 hours. Figure 1 illustrates the sawdust samples during the immersion process. And the table 3.06 also shows the treatment results. Among the various treatments, the most favorable result was achieved with a concentration of 15% for 72 hours, which outperformed the control sample with 7.8% less absorption. This finding suggests that the specific chemical treatment significantly improved the properties or characteristics of the sawdust, making it more suitable for its intended application in asphalt concrete.

Figure3.03 Sawdust treated with NaOH (5%, 10%, and 15%) [74].

Table 3.06 Weight of absorbed water after chemical treatment with NaOH [74].

Concentrate	5%	10%	15%
Weight of absorbed water after-24 hours of treatment (g)	188.8	185.3	181.3
Weight of absorbed water after-48 hours of treatment (g)	182.7	183.9	181.2
Weight of absorbed water after-72 hours of treatment (g)	182.9	185.9	180.7

NB: The weight of absorbed water in 100 grams of sawdust in the control sample is 196.1 grams.

To improve the efficiency of NaOH sawdust treatment, it is important to carefully evaluate and optimize the treatment conditions, including contact time, NaOH concentration, mixing/agitation, and consider the specific characteristics of the sawdust being treated.

b- Heating Treatment

The second type of treatment involves heating the sawdust to different temperatures: 140°C, 160°C, and 180°C for a duration of 24 hours. The results of this treatment showed that the best outcome was a 7.3% improvement compared to the control sample. Figure 3.04 provides a visual representation of the sawdust after the heating treatment and table 3.07 also shows the results of heating treatment in numbers.

Heating treatments can be effective in modifying the properties of sawdust. The elevated temperatures can induce chemical reactions and physical changes within the sawdust structure. The specific temperature and duration chosen for the treatment can significantly influence the results obtained.

Based on the information provided, it appears that the heating treatment at 180°C for 24 hours resulted in the highest improvement, with a 7.3% increase compared to the control sample. This improvement suggests that the treatment at this temperature was able to enhance certain desired characteristics of the sawdust.

In summary, the heating treatment applied to the sawdust at temperatures of 180°C for 24 hours resulted in a 7.3% improvement compared to the control sample. The specific characteristics and implications of this improvement would depend on the intended application and objectives of the treatment.

Figure 3.04 Sawdust treated with heating [74].

Figure 2, which illustrates the sawdust after the heating treatment, would provide a visual reference to observe any visible changes in the structure, color, or other physical aspects of the sawdust resulting from the treatment.

Table 3.07 Weight of absorbed water after heating treatment [74].

Degree of heating	140°C	160°C	180°C
Weight of absorbed water after-24 hours of treatment (g)	185.3	184.1	181.8

NB: The weight of absorbed water in 100 grams of sawdust in the control sample is 196.1 grams.

c- Coating Treatment

The treatment of coating involves using an over-established emulsion to coat the sawdust. The concentration of the over-established emulsion used in the treatment is varied, with options of 25%, 33%, and 50%. The results of this treatment indicate that the sample treated with a concentration of 50% performed better than the control sample. Table 3.08 simplify the treatment the procedure of treatment by coating. Figure 3 provides a visual representation of the sawdust after the coating treatment.

Coating treatments can be applied to modify the surface properties of materials, in this case, sawdust. The over-established emulsion, which typically consists of a combination of substances, is used to form a protective or decorative layer on the surface.

the treatment using a 50% concentration of the over-established emulsion resulted in better performance compared to the control sample. with 40% better performance compared to the control sample.

In summary, the treatment involving the coating of the sawdust using an over-established emulsion at various concentrations revealed that the sample treated with a 50% concentration performed better than the control sample and this treatment gives better homogeny with the binder.

Figure 3.05 Sawdust treated with coating [74].

Table 3.08 Weight of absorbed water after coating treatment [74]

Concentrate of emulsion	50%	33%	25%
Weight of absorbed water after-24 hours of treatment (g)	117.7	147	166.7

NB: The weight of absorbed water in 100 grams of sawdust in the control sample is 196.1 grams.

3.5 Formulation of an ordinary pavement mix

Formulating an ordinary pavement mix involves carefully selecting and proportioning the necessary components to create a standard-compliant mixture. This process includes choosing suitable aggregates with appropriate particle size distributions, selecting the right binder grade based on performance requirements, and determining the optimal proportions of aggregates and binder. Thorough mixing ensures proper coating and distribution of the binder throughout the aggregates. Quality control testing is conducted to assess the mix's properties, including density, strength, durability, and deformation resistance. By following these steps, an ordinary pavement mix can be formulated to meet industry standards and perform reliably in typical road construction applications.

3.5.1 aggregate selecting

The pavement mixes to be formulated is a Semi-Dense Bituminous Concrete known as SDBC. It consists of granular fractions of 0/3, 3/8, and 8/15. The formulation process focuses on determining a mixture that exhibits the best compatibility and provides improved stability to the hydrocarbon mix. The aim is to find the optimal combination of the different granular fractions that will result in a high-quality pavement mix with satisfactory performance. Careful analysis of the aggregate properties and the proper dosage of the bituminous binder are crucial in achieving a consistent and durable mix, ensuring optimal durability and structural strength. By formulating this pavement mix appropriately, it will be possible to ensure effective and reliable use of the paved surfaces, contributing to a robust and sustainable road infrastructure. Using local materials characterized above.

To determine the percentage of fractions in the mixture, a particle size analysis is conducted for the following three mixtures:

- First mixture: (8/16: 40%; 3/8: 30%; 0/3: 30%);
- Second mixture: (8/16: 37%; 3/8: 27%; 0/3: 36%);
- Third mixture: (8/16: 30%; 3/8: 30%; 0/3: 40%).

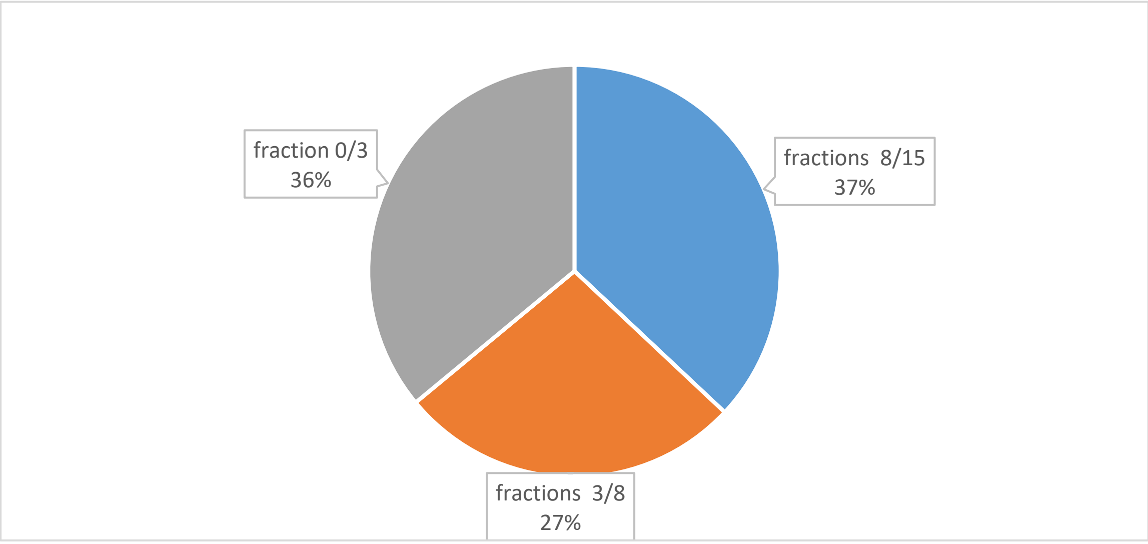


Figure 3.06 Representation of the dosages of the chosen formula.

By performing particle size analyses on these three mixtures, the particle distribution can be assessed, allowing for informed decisions about the percentage of each fraction. This ensures the creation of a well-balanced and properly graded mixture that exhibits desired properties such as compatibility and stability, meeting the requirements for an effective and durable pavement mix.

The particle size curve of the mixture retained is that of the second mixture shown in the figure 3.06. This mixture gave a granulometric continuity perfectly in the specific reference spindle for bituminous concrete 0/14 intended for wearing course.

3.5.2 Finding the Binder Content

Determining the binder content is crucial in formulating a pavement mix as it directly affects the performance and durability of the mixture. Various methods, including empirical testing and laboratory analysis, can be used to find the optimal binder content. The trial-and-error approach involves preparing mixtures with different binder contents and testing them for stability, flow, and density. Mathematical models and predictive equations can also be employed to estimate the ideal binder content based on factors like aggregate characteristics, desired performance requirements, and climatic conditions. Finding the appropriate binder content is essential for achieving proper coating and binding of aggregates, ensuring the mix has the necessary strength, flexibility, and resistance to environmental factors. Regular quality control testing during production is vital to maintain the binder content within the specified range.

- Theoretical Information

  Laws:

$$\text{Binder content} = k.\alpha.(\Sigma)\ \hat{}\ 0.2$$

With:

k: Modulus of richness: express the coating thickness

α: Density correction coefficient

Σ: Specific Surface

α = 2,65 / MVRg

MVRg: Density

In our case:

Σ= 13,893

K	3,2	3,4	3,6	3,8
MVR	2,449	2,438	2,428	2,418
Binder Content (%)	5,43	5,77	6,11	6,45

Based on the Marshall Test results, we select the binder content that best meets the desired performance criteria for the pavement mix. The Marshall test evaluates the stability and flow properties of asphalt mixes and helps determine the suitable binder content for the specific application.

3.5.3 Marshall study

The objective of this test is to assess and compare the performance characteristics, such as stability and compactness, of asphalt mixes prepared with varying proportions of aggregates and bitumen. The test aims to evaluate the influence of different mix compositions on these performance parameters. Additionally, it seeks to determine the Marshall flow, which measures the deformation behavior of the asphalt mix under applied loads. By analyzing the test results, we can identify the optimal formulation that exhibits desirable performance attributes, ensuring a stable and compact pavement mix that meets the specified requirements.

a- Preparation of the Mixture and Preparation of the Test Specimens

The experiment involved using a metal container with a capacity of around 2000 cm3 to hold a mixture consisting of 1200 g of bitumen from the selected second mix. The figure (fig. 3.06) presents the results of this mix. The study specifically examined three different bitumen contents: 5.77%, 6.11%, and 6.45%. For each of these content levels, a total of five specimens were prepared, with three specimens used for stability and creep tests, and two specimens used to determine the apparent density of the mixture.

Regarding the operating mode, it has been well explained in Chapter 1 LITERATURE REVIEW in section (1.2.4 Asphalt Pavement).

Table.3.09 Results of the Marshall test for different binder content.

Composition (%)	Fractions 8/16: 37% Fractions 3/8: 27% Fractions 0/3: 36% Binder 5.77%	Fractions 8/16: 37% Fractions 3/8: 27% Fractions 0/3: 36% Binder 6.11%	Fractions 8/16: 37% Fractions 3/8: 27% Fractions 0/3: 36% Binder 6.45%
Apparent density	2.274	2.249	2.262
Marshall Stability at 60°C (daN)	1461.4	1887.4	1392.1
Compactness (%)	94.26	97.41	96.90
Void ratio (%)	5.74	2.82	4.92
Flow (mm)	3.062	2.749	3.352

Table.3.10 Optimization with respect to CTTP

Data	Experimental	CTTP
Bitumen content (%)	6.11	5.00-7.00
Compactness (%)	97.41	≥93
Marshall Stability at 60°C (daN)	1887.4	S>1000
Flow (mm)	2.749	F<4.00

N.B: “CTTP is Contrôle technique des travaux publics” Technical Control of Public Works of south-Algeria

b- Analysis of the results of the Marshall test

Based on the findings from the method described in Chapter I, the determined binder percentage in the composition of the ordinary pavement mixture is 6.11%. This percentage aligns with the results obtained from the Marshall test, indicating that a binder content of 6.11% (specifically type 40/50) is appropriate. This binder content ensures good compactness and resistance to flow. Therefore, for a mixture containing the specified fractions as shown in Figure (fig. 3.6), a binder rate of 6.11% (type 40/50) is recommended to produce high-quality asphalt that meets the requirements of the CTTP (Technical Center for Public Works).

3.5.4 Immersion Tests - LCPC Compression – Duriez

The purpose of conducting immersion tests - Duriez compression is to characterize the mechanical strength (static) and water stripping resistance qualities of asphalt materials and provide additional indicators of resistance. The Duriez test is primarily applied to dense or semi-dense materials (asphalt mixes with bitumen) where all aggregates pass through a 20 mm sieve.

a- Preparation of the Mixture and Preparation of the Test Specimens

For the LCPC Duriez test, the aggregate weight used is 1000 g. The aggregates, along with the bitumen, are placed in a metal container and heated to a temperature of 140°C. Subsequently, specimens are prepared by compacting the mixture into cylindrical molds with an internal diameter of 80 mm and a height of 150 mm. This standardized procedure ensures uniformity in the test specimens for accurate evaluation of their mechanical properties and water stripping resistance.

In the CBR test, compaction is carried out using a CBR press. The pressure is applied in a gradual manner, with the target of reaching 120 kg/cm3 on the specimen base after one minute. This pressure is maintained for a duration of 5 minutes before being slowly released. To ensure proper demolding without any deformation, the specimen is adequately cooled prior to the demolding process.

Concerning the operating mode is clarified in the Chapter 1 LITERATURE REVIEW in section (1.2.4 Asphalt Pavement).

Table.3.11: Results of the Duriez test for a binder content of 6.11

Composition (%)	Fractions 8/16: 37% Fractions 3/8: 27% Fractions 0/3: 36% Binder 6.11%			
Density of Mixture	2.26			
7 days in air at 18°C	Stability (kg)	1882	Compression Resistance (MPa)	11.145
7 days immersion at 18°C		1524		8.353
Immersion report = (Compression Resistance of 7 days immersion at 18°C)/ (Compression Resistance of 7 days in air at 18°C)	74.95 %			
Compactness (%)	94.8 %			

b- Analysis of Duriez test results

The results presented in Table 3.11 indicate that the selected optimal formulation exhibits favorable stability characteristics. The stability values obtained are consistently higher than the specified threshold, indicating good performance in terms of resistance to deformation. Although the compactness and immersion ratio are slightly above the lower boundary, they remain in close proximity to the specified value. While they may not exceed expectations, they still meet the acceptable range, indicating satisfactory compactness and resistance to water stripping. Overall, the results suggest that the chosen formulation demonstrates desirable stability and adequate compactness for the intended application.

- Compactness: 94.8% < 92%;
- Immersion / compression ratio: 0.7495 < 0.75

Based on the information provided, the asphaltic concrete in question already exhibits good density, indicating that it does not require any additional filler. However, a small amount of filler under 3% is recommended to enhance the Immersion/compression ratio. This filler helps improve the resistance of the asphaltic concrete to water stripping and ensures its durability and longevity. By incorporating a small quantity of filler, the overall performance and resistance of the asphaltic concrete can be further enhanced, resulting in a more robust and reliable pavement.

3.6 Formulation of asphalt mix with percentages of sawdust

The experimental part of this study focuses on the formulation of asphalt mixtures with different percentages of sawdust as a partial replacement for the 3/8 fraction of the aggregate volume. Specifically, the percentages examined are 5%, 10%, and 15%. The aim of this experimental investigation is to assess the impact of incorporating sawdust as a sustainable alternative in asphalt mixtures. By replacing a portion of the 3/8 fraction with sawdust, the study aims to evaluate the potential effects on key properties such as stability, compactness, and durability. This research contributes to understanding the feasibility and potential benefits of utilizing sawdust as a partial replacement material in asphalt mixtures, providing insights into sustainable practices in road construction and maintenance. The percentages (5%, 10%, and 15%) are from the full volume of the aggregate.

3.6.1 Marshall compactness for the modified asphalt mix

The table3.12 down below present the Marshall Compactness and weight for the modified asphalt mix with different percentages of sawdust

Table 3.12 Marshall Compactness with different percentages of sawdust

Designation	5%	10%	15%
Thickness of specimen (mm)	660	670	670
Mass of the specimen (g)	1198.50	1199.40	1197.30
Average of Compactness (%)	93.50	92.30	90.61

N.B: these experiments are realized with 6.11% binder content and 3 minutes mixing time and 160°C temperature of mixing.

Based on the evaluation of the Marshall Compactness for the modified asphalt mixtures incorporating different percentages of sawdust, it has been observed that the inclusion of sawdust results in lower compactness compared to the ordinary mix. This indicates that the modified mixtures are lighter in weight. These findings suggest that the use of this new mix, particularly in low traffic regions, could be advantageous. The lighter nature of the modified mix with sawdust may offer benefits such as reduced material requirements and improved workability during construction. However, it is important to consider the specific requirements and traffic conditions of each project to ensure that the lighter mix still meets the necessary performance standards for durability and stability.

Considering both the positive environmental impact and potential economic advantages, the incorporation of sawdust in asphalt mixtures presents an opportunity for sustainable and economically viable road construction practices. However, it is crucial to conduct further comprehensive studies and field trials to assess the long-term performance, durability, and suitability of the modified mixtures for different traffic conditions and climatic regions.

3.6.2 Marshall stability for the modified asphalt mix

The Marshall Stability test is widely used in the asphalt industry as a standard method for evaluating the mechanical properties and performance characteristics of modified asphalt mixtures. It provides valuable insights for the design, quality control, and performance assessment of asphalt pavements, helping to ensure safe and durable road surfaces. Table 3.13 provide Marshall Stability and density for asphalt mix with 5 %, 10%, and 15% of sawdust.

Table 3.13. Marshall Stability for modified mix

asphalt mixes	5% of sawdust	10% of sawdust	15% of sawdust	Specification
Average of Density (g/cm^3)	2.27	2.24	2.20	2.1-2.5(g/cm^3)
Average of Marshall Stability (Kn)	12.01	11.41	11.93	>8Kn

The table shows the Marshall Stability values for modified asphalt mixes with different percentages of sawdust (5%, 10%, and 15%). The Marshall Stability test is used to evaluate the strength and stability of asphalt mixtures.

The density of the modified mixes decreases as the percentage of sawdust increases. The density values range from 2.27 to 2.20 g/cm3. These values are within the specified range, indicating that the modified mixes meet the density specification.

The Marshall Stability values also show a decreasing trend as the percentage of sawdust increases. The Marshall Stability values are from 12.01 Kn to 11.93 Kn. The specified requirement is greater than 8 Kn. Therefore, all of the modified asphalt mixes, including the 5%, 10%, and 15% sawdust mixes, meet the Marshall Stability specification.

We can consider the modified asphalt mixes with different percentages of sawdust suitable for low and medium-traffic roads. The mixes meet both the density and Marshall Stability specifications, indicating that they possess adequate strength and stability for such road applications.

However, it is worth noting that further modifications may be required to improve the stability of the mixes. While the mixes meet the current specifications, additional enhancements can be explored to ensure even better performance. These modifications will be discussed in the next chapter, providing an opportunity to address any potential limitations and optimize the mixes for higher levels of traffic or specific road conditions.

By undertaking these modifications and considering the recommendations presented in the subsequent chapter, it is possible to enhance the stability of the modified asphalt mixes even further. This iterative process of analysis, modification, and improvement allows for continuous progress in developing road materials that meet the specific requirements of various traffic conditions and road types.

3.6.3 Flow value and The Marshall Quotient for the modified asphalt mix

The Marshall Flow value is an important parameter used in the design and evaluation of asphalt mixes, as it helps assess the rutting resistance and performance of the mixture under traffic loading and high temperatures.

The Marshall Quotient (MQ) is defined as the ratio of Marshall Stability (kN) to flow value (mm) obtained from the Marshall Stability test. It serves as a measure of the stiffness and resistance to deformation of asphalt mixtures. A higher MQ value indicates a stiffer mixture with greater resistance to shear stresses and permanent deformation, contributing to improved resistance against rutting. The MQ is a useful parameter for evaluating and comparing different asphalt mixtures in terms of their durability and resistance.

Based on the examination of our modified mixes, which incorporated different percentages of sawdust (5%, 10%, and 15%), we evaluated their flow values. Additionally, we calculated the Marshall Quotient (MQ) for each mix. The results of these assessments are presented in Table 3.14 below:

Table 3.14 Flow value and The MQ for modified asphalt mix

asphalt mixes	5% of sawdust	10% of sawdust	15% of sawdust	Specification
Average of Flow value (mm)	3.05	2.772	3.176	2 to 4.5 mm for light traffic 2 to 4 mm for medium traffic 2 to 3.5 mm for Heavy traffic
Average of Marshall Quotient (MQ) (Kn/mm)	4.063	4.153	3.758	1.3 < for light traffic 2 < for medium traffic 2.86 < for Heavy traffic

The table presents the results of flow value and Marshall Quotient (MQ) for modified asphalt mixes containing different percentages of sawdust (5%, 10%, and 15%). The flow values for the mixes ranged from 2.772 mm to 3.176 mm. The MQ values ranged from 3.758 Kn/mm to 4.153 Kn/mm, with all mixes meeting the specified requirements for light, medium, and heavy traffic. The mixes with 5%,10%, and 15% sawdust appeared to meet the specified requirements for flow value and MQ across various traffic conditions, while further analysis and testing may be needed to ensure overall performance and durability.

To summarize, after considering the Marshall Quotient, it can be concluded that incorporating sawdust as a partial replacement for aggregate in asphalt mixes does not negatively affect the performance of the asphalt. In fact, it can bring about favorable environmental outcomes and cost advantages in road construction endeavors. It is essential to conduct thorough testing and evaluation, taking into account factors like stability, flow, and density, to ensure the appropriate and optimal utilization of sawdust in modified asphalt mixtures.

3.7 Conclusion

The experimental study conducted in this chapter has provided valuable insights into various aspects of asphalt mixtures and the inclusion of sawdust as a partial replacement for aggregate. The study involved the formulation of a semi-dense bituminous concrete mix, characterization of materials used in the control concrete, analysis of sawdust characteristics, formulation of an ordinary pavement mix, and formulation of asphalt mixtures with different percentages of sawdust.

In conclusion, the experimental study conducted in this chapter has provided valuable insights into the use of sawdust as a partial replacement for aggregate in hot-mix asphalt. The results demonstrate that the presence of sawdust in asphalt mixtures does not harm the performance of the asphalt. On the contrary, it offers several benefits, including positive environmental impacts and reduced costs in road projects.

Through the formulation of an ordinary pavement mix and an asphalt mix with varying percentages of sawdust, the study has shown that the inclusion of sawdust does not adversely affect the essential properties of the asphalt, such as stability, flow, and density. These findings support the viability of incorporating sawdust in asphalt mixtures, thereby utilizing a waste material and promoting sustainability.

Moreover, the environmental impact of using sawdust in road construction is favorable. Sawdust, being a byproduct of the timber industry, is often considered as waste. By repurposing it as a partial replacement for aggregate, road projects can contribute to reducing waste and embracing the principles of a circular economy. This eco-friendly approach aligns with the growing global focus on sustainability and the preservation of natural resources.

Furthermore, the utilization of sawdust in asphalt mixtures can lead to cost reductions in road projects. Sawdust is typically available at low cost or even as a byproduct with minimal value. By incorporating it into the asphalt mix, the overall cost of the mixture can be reduced, allowing for a more efficient allocation of resources and potentially facilitating more extensive road construction within a given budget.

To further enhance the findings of this chapter, the subsequent chapter will employ a full factorial design. By manipulating the mixing temperature, mixing time, and binder content, researchers aim to optimize the results achieved thus far. This approach will provide a comprehensive understanding of the factors influencing the performance of asphalt mixes with sawdust, enabling the development of guidelines and recommendations for practical implementation.

Overall, the experimental study provides a foundation for the development of sustainable and cost-effective road construction practices using sawdust as a partial replacement for aggregate.

Chapter 04: Design of Asphalt Mix with Sawdust as an Aggregate using the Full Factorial Design

4.1 Introduction

In recent years, researchers and engineers have explored alternative materials to replace or supplement conventional aggregates in asphalt mixtures. One such material is sawdust, a byproduct of wood processing industries. Sawdust has several advantageous properties, including its lightweight nature, thermal insulation capabilities, and potential for reducing the overall density of asphalt mixtures. The incorporation of sawdust as an aggregate in asphalt mixtures offers the potential to address environmental concerns, reduce material costs, and improve the sustainability of road construction. Asphalt, a commonly used material in road construction, provides a durable and flexible surface for transportation infrastructure. Traditional asphalt mixes typically consist of aggregates, such as crushed stone or sand, mixed with bitumen. However, the availability of natural aggregates has become a concern due to environmental issues and the increasing demand for road construction.

The use of sawdust in asphalt mixtures presents various challenges, such as its compatibility with bitumen, its effect on the mechanical properties of the mixture, and its potential impact on the long-term performance of the pavement. To overcome these challenges, a systematic approach is required to design asphalt mixtures incorporating sawdust as an aggregate. The primary objective of this chapter is to design and evaluate asphalt mixtures containing sawdust as an aggregate using the Full Factorial Design methodology. By employing this approach, we aim to determine the optimal combination of factors that will result in asphalt mixtures with desirable properties, such as adequate strength, durability, and performance characteristics.

This chapter is organized as follows: The design of the experiments considers four factors, namely sawdust percentage, binder content, mixing time, and temperature mixing. These factors are studied at two levels, along with a single central point, using the Full Factorial Design methodology with the assistance of Minitab19 software. The subsequent section, Results, and Analysis, presents and analyzes the experimental results obtained from the designed experiments, delving into the effects of the different factors on the properties of the asphalt mixtures. It provides insights into their influences and interactions. Following the analysis, the Discussion and Conclusion section engages in a comprehensive discussion of the findings, drawing comparisons with previous research and offering conclusions regarding the feasibility and performance of asphalt mixtures with sawdust as an aggregate. This section highlights the strengths, limitations, and potential applications of the developed asphalt mixtures.

Finally, the Recommendations for Future Research section suggests further investigations and improvements in the design and application of asphalt mixtures incorporating sawdust as an alternative aggregate, identifying areas that require additional exploration and proposing potential avenues for enhancing the understanding and implementation of these sustainable asphalt mixtures.

4.2 Concept of Formulation

This part focuses on the feasibility study of formulating an asphalt mix incorporating sawdust as an aggregate while ensuring mechanical characteristics that comply with the prevailing standards. The principles of sustainable development are applicable in this phase, where we utilized an optimization method seeking to maximize the addition of sawdust and minimize the manufacturing temperature and mixing time.

Accordingly, the time and temperature were modified for the different mixtures. In light of the limitations identified in the conclusion of Chapter 3, conventional testing methods were unable to provide reliable results regarding the desired mechanical quality in relation to the varying percentage levels in the mixture. This led us to explore the use of the experimental design methodology as a solution to determine the percentages with manageable reliability. As explained in Chapter II, this methodology aims to reduce the number of required experimental tests while maximizing the information obtained. It necessitates the preparation of the materials used, including ordinary aggregates, ordinary binders, and sawdust aggregates. In this study, the selected materials aim to formulate an asphalt mix with a granulometric curve and binder content that meet the regulatory requirements. The formulation hypothesis employed here seeks to maximize the proportion of sawdust aggregates while minimizing the mixing time and manufacturing temperature.

4.3 The design of experience approach

The design of experiments (DOE) approach was employed in this study to systematically investigate the effects of various factors and their interactions on the performance of asphalt mixtures incorporating sawdust as an aggregate. DOE allows for the efficient and effective exploration of multiple factors while minimizing the number of experimental tests required.

4.3.1 Full factorial design method

The design of experiments (DOE) allows for the optimal organization of tests in scientific and industrial studies. In our case, the number of tests was reduced from the initial plan of 4X16 = 64 to 16, plus one central point.

The experimental design used was a full factorial design, which enabled the characterization of the relationship between a response variable and four parameters. To achieve this, the experimental points needed to be characterized. These points were predetermined by the experimental design. The experimenter selected the parameters to be considered, as well as the range of values for each parameter, including a minimum and maximum value.

According to DOE theory, the midpoint of the parameter range is an important point to characterize. The three midpoints for each parameter define the center of the experimental domain. Table 4.1 presents the points used in the experimental design.

The a priori model is formulated as $YJ = f(X_i)$, where f is a polynomial function of varying degree based on the X_i parameters. The degree of the polynomial depends on the desired level of precision and is represented by Equation (Eq.4.1):

$$\begin{aligned} Y(X_1, X_2, X_3, X_4) = {} & a_0 + a_1 \bullet X_1 + a_2 \bullet X_2 + a_3 \bullet X_3 + a_4 \bullet X_4 \\ & + a_{12} \bullet X_1 \bullet X_2 + a_{13} \bullet X_1 \bullet X_3 + a_{14} \bullet X_1 \bullet X_4 \\ & + a_{23} \bullet X_2 \bullet X_3 + a_{24} \bullet X_2 \bullet X_4 \\ & + a_{34} \bullet X_3 \bullet X_4 + e \end{aligned} \quad \text{(Eq.4.1)}$$

The coefficients a_i and the residual term e in the equation are unknowns. They are determined by solving a system of (n) equations obtained from the set of experimental points conducted during the full factorial design. The expertise lies in identifying the factors Xi and the form of the model, which can include potential interactions between factors. The values that the factors take in each experiment are then chosen.

To facilitate the analysis of results, it is advisable to work with dimensionless factors by normalizing their values. For example, if the factor X_i varies in the interval $[X_i^-, X_i^+]$, it can be normalized to the interval [-1, +1] using the relation (Eq.4.2):

$$X_i = \frac{2X_i-(X_i^-+X_i^+)}{(X_i^- - X_i^+)} \qquad \text{(Eq.4.2)}$$

Thus, all the coefficients of the polynomial model are expressed in the same unit as the response variable Y_i. The magnitude of each coefficient is directly proportional to the sensitivity of the response to the corresponding factor or interaction between multiple factors. Mathematical regression allows for the estimation of the effects of different factors and interactions. Optimization is a solution to determine the preferred range of the response variable (optimization P), which can be defined as P = Min y(x), where $b_{inf} \leq x \leq b_{sup}$, and b_{inf} and b_{sup} represent the lower and upper limits of the factors, respectively.

Furthermore, the reliability of the proposed model can be evaluated by comparing the total experimental variance, V_{exp}, with the variance explained by the model, V_{mod}. The ratio of V_{exp} to V_{mod}. Provides an indication of the degree of reliability.

Table 4.01 Factors Coding

Code	Sawdust percentage (%)	Binder content (%)	Mixing time (minutes)	The manufacturing temperature (°C)
-1	5	5.77	2	140
0	10	6.11	3	160
+1	15	6.45	4	180

4.3.2 Study parameters

a- Sawdust percentage

The sawdust percentage in the asphalt mix was chosen as a replacement for the (3/8) aggregate at percentages of 5%, 10%, and 15% of the total volume of the aggregate. These percentages were selected considering the low mechanical performance of sawdust as compared to conventional aggregate materials. By starting with lower percentages, such as 5% and 10%, we can evaluate the impact of sawdust on the overall performance of the asphalt mix while minimizing potential risks.

Sawdust, being a lightweight and less mechanically strong material, may have limitations in providing the necessary strength and durability required for asphalt mixtures. Hence, starting with lower percentages allows for a gradual assessment of the effects on the mechanical properties of the mixture. By incrementally increasing the sawdust percentage to 15%, we can observe the potential changes in performance and determine the maximum acceptable level of sawdust incorporation without compromising the mechanical integrity of the asphalt mix.

This approach ensures a cautious evaluation of the sawdust's viability as an aggregate replacement, mitigating the potential risks associated with a large amount of sawdust. By systematically examining the impact at different percentages, the study can provide insights into the optimal sawdust content that balances sustainability objectives with the required mechanical performance of the asphalt mix.

b- Binder content

The binder content in this research was varied at three percentages: 5.77%, 6.11%, and 6.45%. These percentages were chosen as control samples to establish a baseline for comparison. It should be noted that the same percentages were used for the control samples to maintain consistency and evaluate the effects of sawdust incorporation on the asphalt mix.

The research did not consider new binder content percentages that would align with the increased percentages of sawdust. The decision was based on the objective of keeping the cost as low as possible or reducing it. By using the same binder content percentages as the control samples, the focus was primarily on investigating the effects of the sawdust aggregate on the performance of the asphalt mix.

Introducing new binder content percentages that correspond to higher percentages of sawdust would potentially increase the cost of the asphalt mix. The objective was to explore the feasibility of utilizing sawdust as an alternative aggregate while optimizing cost efficiency. Therefore, maintaining the same binder content percentages allowed for comparative analysis and determination of the most suitable sawdust percentage without incurring additional costs associated with modifying the binder content.

Overall, the research aimed to strike a balance between the desired mechanical performance, cost-effectiveness, and the incorporation of sawdust as an aggregate. By considering the existing binder content percentages, the study could provide valuable insights into the potential benefits and limitations of using sawdust in the asphalt mix, while minimizing the associated costs.

c- Mixing time

In accordance with the standard [NF EN 12697-35 2007] governing laboratory mixing, the maximum duration for mixing constituents in the asphalt mix is specified as 3 minutes. However, in our case, we considered two additional mixing times, namely 2 minutes and 4 minutes. This was done to understand the effect of mixing time on the asphalt mix and to explore any potential modifications that could be made. By varying the mixing time, we aimed to investigate how different durations would impact the properties and performance of the asphalt mix. The inclusion of both shorter (2 minutes) and longer (4 minutes) mixing times allowed us to assess the influence of this parameter on the mixture's characteristics.

Importantly, the decision to limit the mixing time to a maximum of 4 minutes was driven by the objective of minimizing costs. By adhering to this constraint, we aimed to keep the duration of the mixing process as efficient as possible while achieving the desired outcomes. This approach balanced the need to understand the effects of mixing time while considering the economic implications of longer mixing durations.

Overall, by examining the impact of mixing time within the range of 2 to 4 minutes, the study aimed to optimize the asphalt mix while being mindful of cost considerations and complying with the standard guidelines for laboratory mixing.

d- The manufacturing temperature

The manufacturing temperature is a crucial factor in the production of asphalt mixtures. In this study, the 40/50 type binder was utilized for the manufacturing process. The selection of specific temperature values was based on several considerations. To capture the effects of different temperature ranges, three manufacturing temperatures were chosen: 140°C, 160°C, and 180°C. The range between 140°C and 180°C encompasses both lower and higher temperature extremes, allowing for a comprehensive assessment of the impact on the asphalt mix's properties. The choice of an intermediate point at 160°C was influenced by the manufacturing temperature commonly used for standardized asphalt mixes. This temperature is in close proximity to typical industry practices, facilitating comparisons with established asphalt mixtures. Additionally, the upper limit of 180°C was set to ensure that the manufacturing temperature does not exceed a certain threshold. This decision was made to maintain the cost-effectiveness of using sawdust as an aggregate. Higher temperatures can lead to increased energy consumption and production costs. Therefore, by limiting the upper temperature to 180°C, the study aimed to strike a balance between achieving the desired asphalt mix properties and keeping the overall production costs as economical as possible.

In summary, the choice of three manufacturing temperatures, including 140°C, 160°C, and 180°C, allowed for a comprehensive evaluation of the effects of temperature on the performance of the asphalt mixtures. The consideration of an intermediate temperature and the limitation of the upper temperature aimed to align with industry practices, ensure cost-effectiveness, and provide valuable insights into optimizing the use of sawdust as an aggregate in the asphalt mix.

4.4 Input of the design experiment

In this study, the full factorial design methodology was employed, which involves considering all possible combinations at all levels of the four factors under investigation. These factors include the sawdust percentage, binder content, time of mixing, and temperature of manufacturing. For each factor, there are two levels: 5% and 15% for the sawdust percentage, 5.77% and 6.45% for the binder content, 2 minutes and 4 minutes for the mixing time, and 140°C and 180°C for the temperature. Consequently, a total of 16 experiments were conducted, along with one additional central point experiment. The central point experiment utilized 10% sawdust, 6.11% binder content, 3 minutes of mixing time, and a temperature of 160°C. Table4.01 present a summery design. This comprehensive experimental approach allowed for a thorough investigation of the effects of these factors on the performance of the asphalt mixture incorporating sawdust as an aggregate.

Table 4.02 Design Summary

Factors:	4 (sawdust percentage, binder content, mixing time, temperature mixing)	Base Design:	4; 16
Runs:	17	Replicates:	1
Blocks:	1	Center points:	1

Table 4.02 provides the details of the full factorial design utilized in this study. It outlines the four factors considered, along with their respective levels and the corresponding formulations to be tested.

Table 4.03 Full factorial design details.

	Factors			
Mixture formula	Binder percentage (%)	Sawdust percentage (%)	Mixing temperature (°C)	Mixing time (minutes)
1	5,77	5	140	4
2	6,45	5	180	4
3	5,77	15	180	2
4	6,45	5	140	4
5	6,11	10	160	3
6	5,77	5	140	2
7	5,77	5	180	4
8	6,45	15	180	2
9	5,77	15	140	2
10	6,45	15	180	4
11	6,45	5	140	2
12	5,77	5	180	2
13	6,45	5	180	2
14	6,45	15	140	2
15	5,77	15	140	4
16	5,77	15	180	4
17	6,45	15	140	4

These formulations represent the specific combinations of factors and levels that were tested in the full factorial design, allowing for a comprehensive exploration of their effects on the asphalt mixtures incorporating sawdust as an aggregate.

4.5 Compactness of mixes

These compactness results provide valuable insights into the performance of the asphalt mixtures under different conditions. The data allows for comparative analysis and evaluation of the influence of each factor on the compactness of the asphalt mix. By examining the results, trends, and patterns can be identified, aiding in the understanding of the optimal combination of factors for achieving the desired compactness of the asphalt mixtures incorporating sawdust as an aggregate.

4.5.1 the results of compactness

The results of the Marshall Compactness test for the various asphalt mix formulations are presented in Table 4.04. This table includes the combinations of factors such as binder content, sawdust percentage, mixing time, and manufacturing temperature, along with their corresponding compactness percentages. The binder content was varied between 5.77%, 6.11%, and 6.45%, while the sawdust percentage ranged from 5% to 15%. The mixing time was examined at intervals of 2 minutes, 3 minutes, and 4 minutes, and the manufacturing temperature was tested at 140°C, 160°C, and 180°C. By analyzing the compactness results, valuable insights can be gained regarding the influence of these factors on the performance of the asphalt mixtures. The data allows for a comparative evaluation, enabling the identification of trends and patterns that can aid in determining the optimal combination of factors to achieve the desired compactness of the asphalt mixtures containing sawdust as an aggregate.

Table 4.04 Results of Marshall Compactness

	Factors				Results
Runs	Binder percentage (%)	Sawdust percentage (%)	Temperature (°C)	Mixing time (minutes)	Compactness (%)
1	5,77	5	140	4	91,06
2	6,45	5	180	4	96,36
3	5,77	15	180	2	90,65
4	6,45	5	140	4	95,95
5	6,11	10	160	3	92,3
6	5,77	5	140	2	90,65
7	5,77	5	180	4	93,11
8	6,45	15	180	2	90,98
9	5,77	15	140	2	86,55
10	6,45	15	180	4	93,47
11	6,45	5	140	2	92,64
12	5,77	5	180	2	93,11
13	6,45	5	180	2	95,12
14	6,45	15	140	2	88,09
15	5,77	15	140	4	87,78
16	5,77	15	180	4	91,06
17	6,45	15	140	4	89,74

4.5.2 Regression Equation in Uncoded Units

In this section, we will discuss the regression equation in uncoded units. The regression equation is derived from the analysis of the experimental data and is used to model the relationship between the response variable and the independent variables in a form that is easier to interpret.

The regression equation in uncoded units provides a straightforward representation of the relationship between the response variable and the independent variables, enabling a clear interpretation of their effects and facilitating the analysis and optimization of the asphalt mix formulation.

Results of Marshall Compactness=220,0 - 23,19 binder percentage - 16,44 sawdust percentage- 0,7929 temperature - 66,51 mix time + 2,640 binder percentage*sawdust percentage + 0,1454 binder percentage*temperature + 11,59 binder percentage*mix time + 0,1016 sawdust percentage*temperature + 6,095 sawdust percentage*mix time + 0,3496 temperature*mix time - 0,01673 binder percentage*sawdust percentage*temperature - 1,037 binder percentage*sawdust percentage*mix time - 0,06103 binder percentage*temperature*mix time - 0,03573 sawdust percentage*temperature*mix time+ 0,006103 binder percentage*sawdust percentage*temperature*mix time + 0,6550 Ct Pt

4.5.3 Charts of Compactness and discussion

Overall, utilizing Minitab to create charts based on the data from Table 4.04 enhances the analysis and understanding of the compactness results, facilitating data-driven decision-making and providing a clear visual representation of the relationship between the factors and the compactness of the asphalt mixtures.

a- Effects Pareto for Results Marshall Compactness

The Pareto chart is a valuable tool for summarizing the significant effects of various factors on the Marshall Compactness results of asphalt mixtures. By ranking the effects from

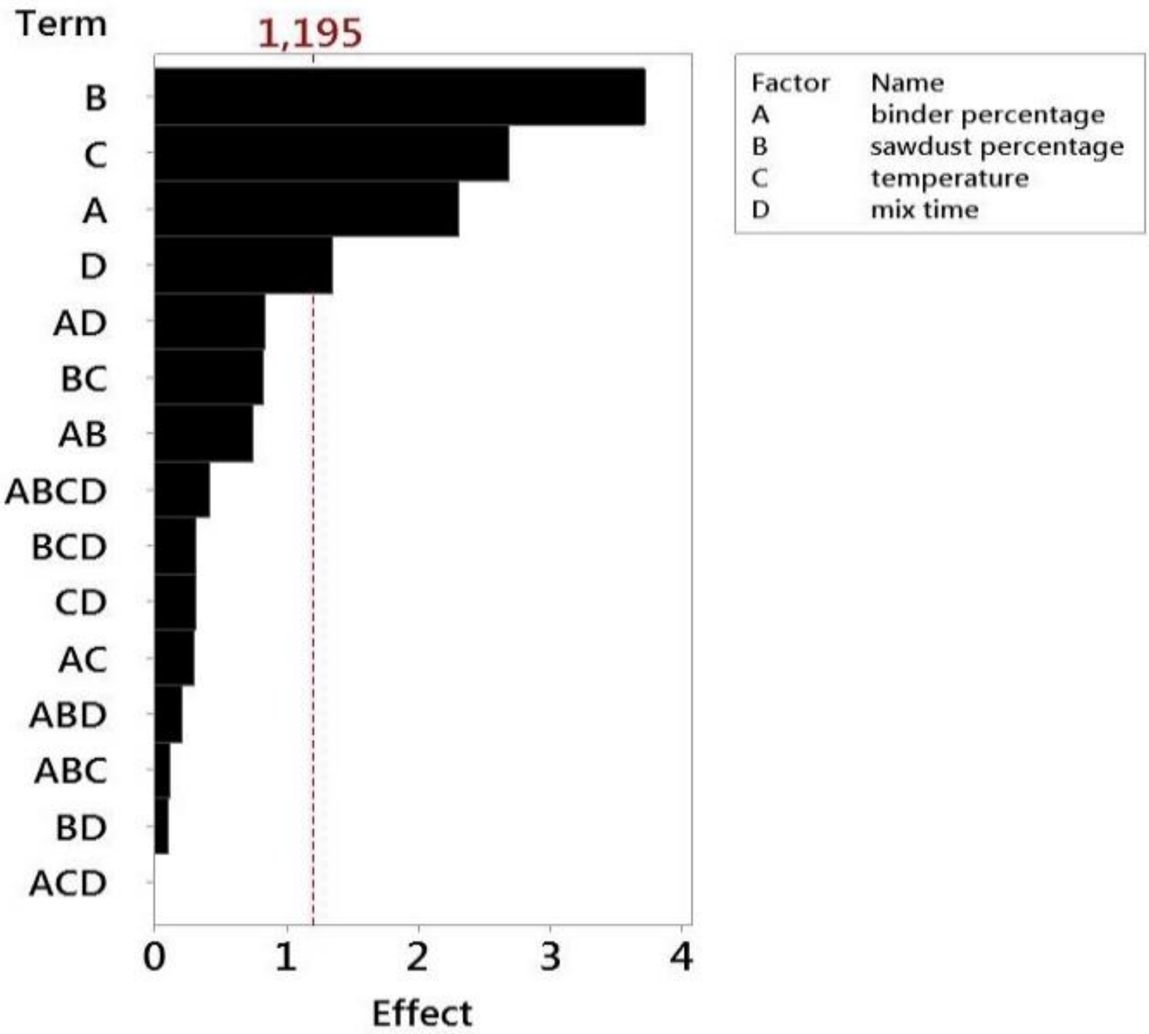


Figure 4.01 Effects Pareto for Results Marshall Compactness

Largest to smallest, the chart visually represents the magnitude and significance of each factor's impact. This helps identify the key factors that contribute significantly to the compactness of the asphalt mixtures. By focusing on these influential factors, informed decisions can be made to optimize the mix design and achieve the desired level of compactness. The Pareto chart provides a clear summary of the factors that should be prioritized for further investigation and potential adjustments in the asphalt mix formulation.

The Pareto analysis of the Marshall Compactness results highlights the main factors influencing the compactness of asphalt mixtures with sawdust as an aggregate. The primary factor is the sawdust percentage, as its low density and high binder absorption contribute to increased voids and reduced compactness. The mixing temperature is the second significant factor, with higher temperatures causing sawdust shrinkage, reducing voids, and increasing density. Binder content is the third main factor, where excessive binder fills voids and improves compactness. Lastly, mixing time plays a role, with longer mixing times leading to better integration of sawdust and reduced voids. Understanding and optimizing these factors can enhance the compactness of asphalt mixtures with sawdust as an aggregate.

b- Main Effects and Interaction plots for Results Marshall Compactness

The Main Effects plot provides a visual representation of the individual effects of each factor on the compactness of asphalt mixtures. It allows for the identification of the factors that have the most significant impact on compactness, considering their magnitude and direction. By analyzing the plot, we can prioritize the factors that have pronounced individual effects and focus on optimizing them to achieve the desired compactness. This plot, along with the Pareto analysis, provides valuable insights into the factors influencing compactness and guides decision-making for enhancing the overall quality of asphalt mixtures.

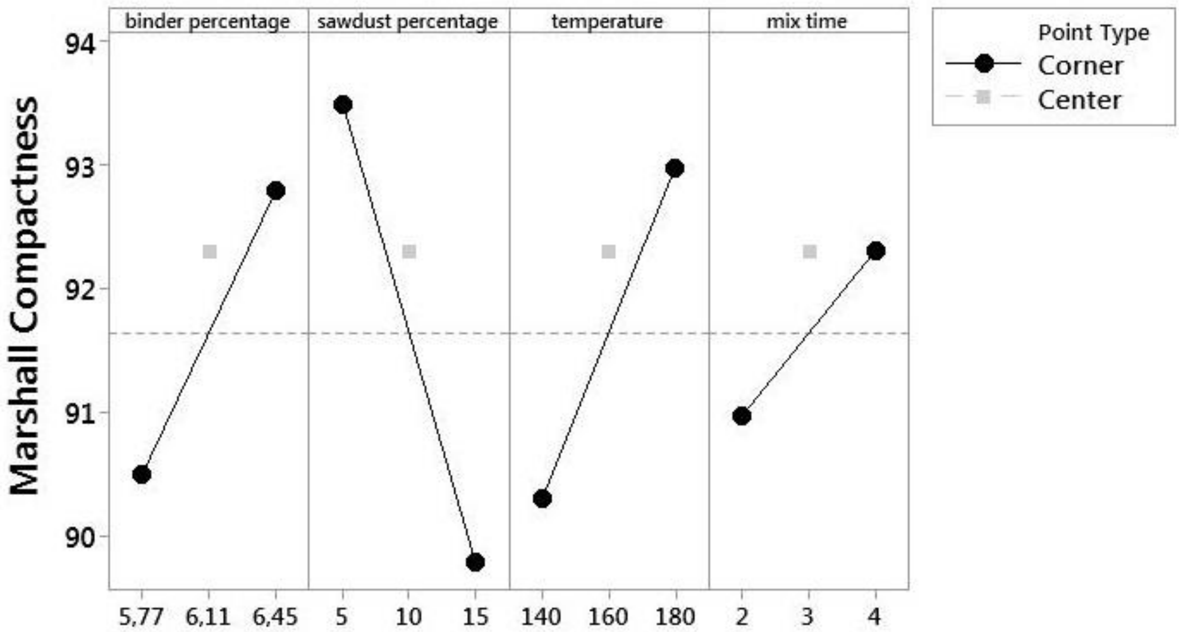


Figure 4.02 Main Effects Plot for compactness

The Main Effects plot confirms the findings from the Pareto analysis and reveals the order of factors based on their impact on compactness. According to the plot, the factors are ranked as follows: 1st sawdust percentage, 2nd manufacturing temperature, 3rd binder contact, and 4th mixing time. The Main Effects plot effectively illustrates the relationships between these factors and their individual effects on compactness. This information is crucial for making informed decisions in optimizing the factors to achieve the desired level of compactness in asphalt mixtures. Understanding the relative importance of each factor helps guide the design and adjustment of the asphalt mixtures for improved performance and quality.

The Interaction Plot for the Results of Marshall Compactness examines the interactions between various factors: binder content vs sawdust percentage, binder content vs manufacturing temperature, sawdust percentage vs manufacturing temperature, binder content vs mixing time, sawdust percentage vs mixing time, and manufacturing temperature vs mixing time. The plot in figure 4.03 helps illustrate how these interactions affect the compactness of the asphalt mixtures.

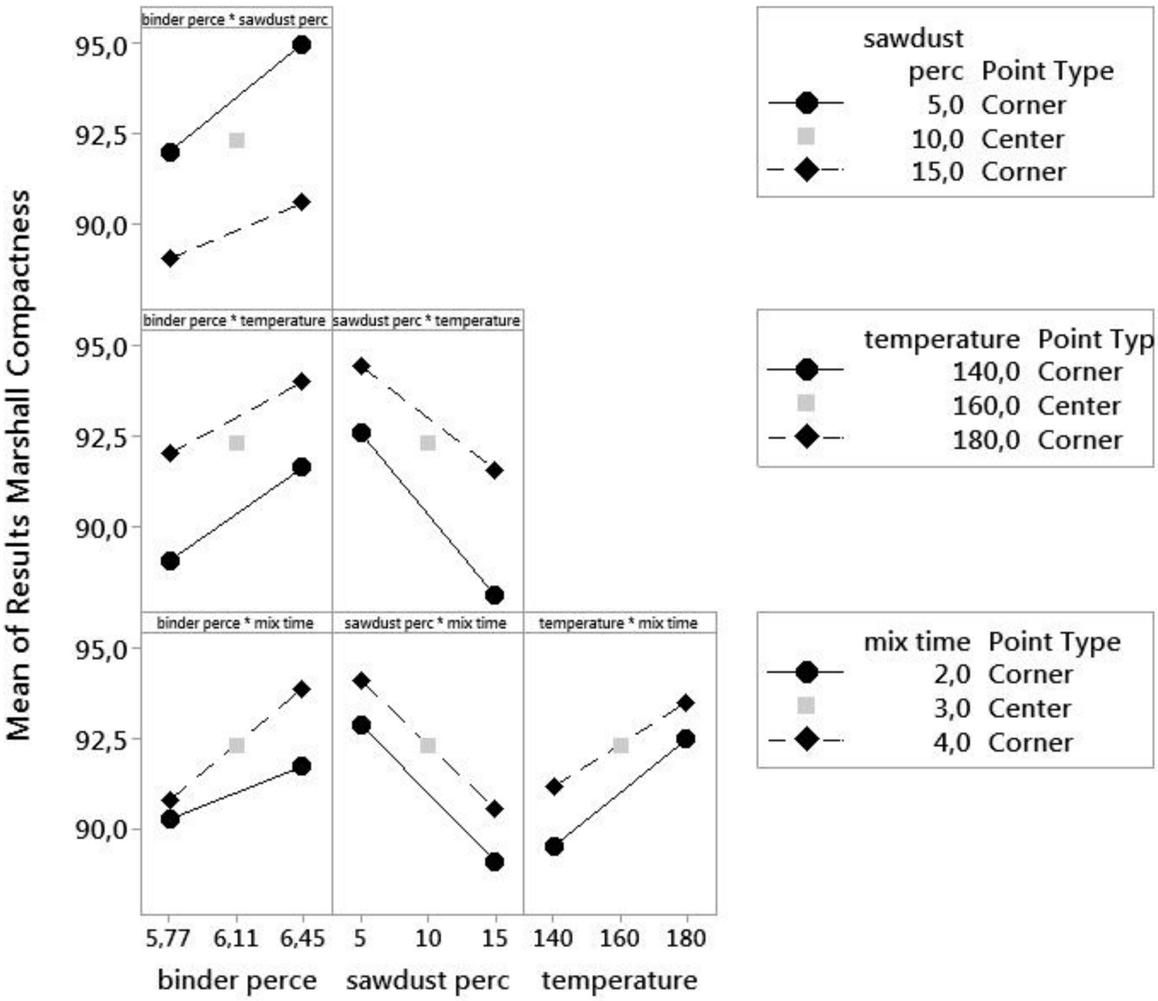


Figure 4.03 the Interaction Plot for Marshall Compactness

The plot reveals that the interaction effect between binder content and mixing time significantly influences the compactness of the asphalt mixtures. Higher binder content combined with higher mixing time leads to increased compactness, while lower binder content and lower mixing time result in decreased compactness. This highlights the importance of finding the optimal balance between binder content and mixing time for achieving the desired level of compactness. By understanding and considering these interaction effects, informed decisions can be made to optimize the mix design and improve the overall quality of the asphalt mixtures.

c- Contour Plot and Surface Plot of Compactness

As shown in figure 4.04 The Contour Plot of Results shows the relationship between compactness and two factors: sawdust percentage and binder percentage. The plot specifically focuses on fixing the manufacturing temperature at 160°C and the mixing time at 3 minutes. The contour plot provides a visual representation of these relationships, allowing for a clear understanding of how the selected factors impact compactness. By observing the contour lines, one can identify regions of higher compactness and assess the influence of the variables on the outcome.

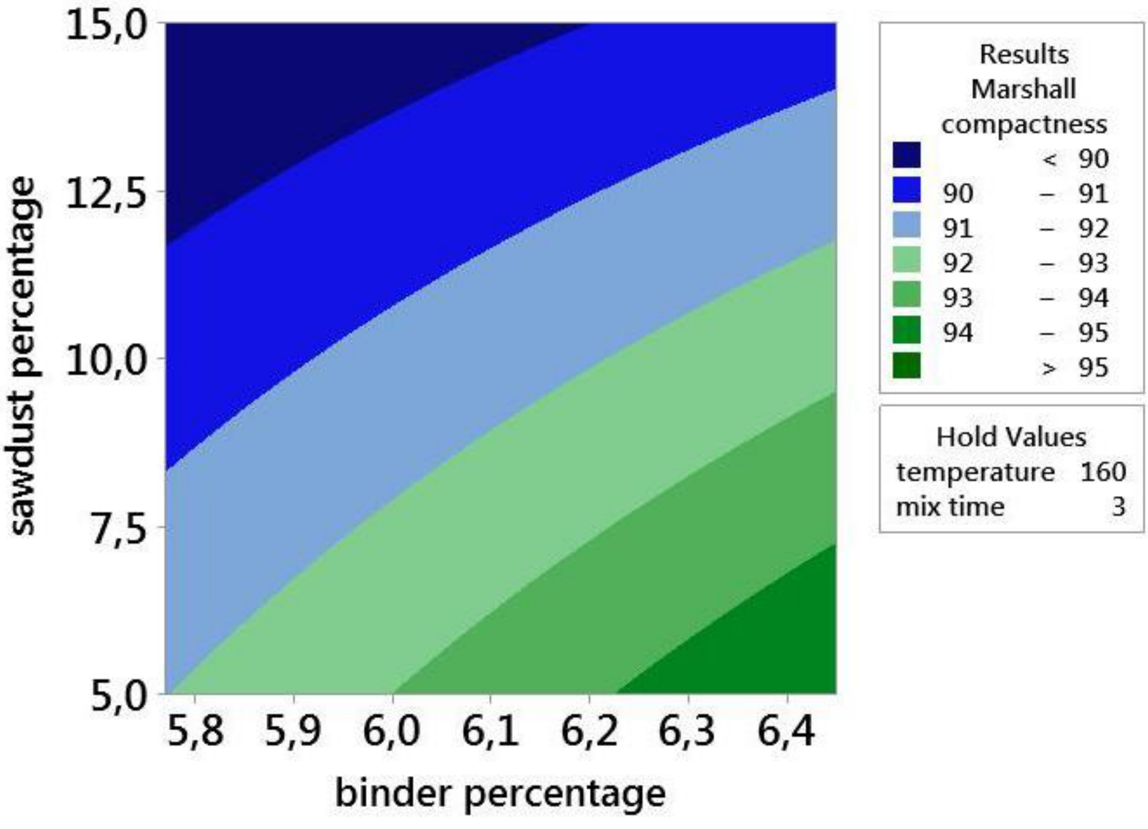


Figure 4.04 the Contour Plot of Compactness

The contour plot analysis reveals that increasing the binder content leads to improved compactness in asphalt mixtures, indicating a positive relationship between binder percentage and compactness. Additionally, the plot demonstrates that reducing the sawdust percentage results in higher levels of compactness, indicating a negative relationship between sawdust percentage and compactness.

In summary, the contour plot confirms that increasing the binder content and decreasing the sawdust percentage contribute to higher compactness in asphalt mixtures when the manufacturing temperature is fixed at 160°C and the mixing time is set to 3 minutes. This information is valuable for making informed decisions during the optimization process of mixture formulation, helping achieve the desired level of compactness.

The Surface Plot of Compactness presents the relationship between compactness and two factors: sawdust percentage and binder percentage. The plot specifically focuses on fixing the manufacturing temperature at 160°C and the mixing time at 3 minutes, as illustrated in figure 4.05.

By examining the surface plot, one can anticipate the outer limits of the factors and their impact on compactness. The plot illustrates how variations in the sawdust percentage and binder percentage influence the compactness outcome. It provides a three-dimensional visualization of the relationship, allowing for a comprehensive understanding of the factors combined effects.

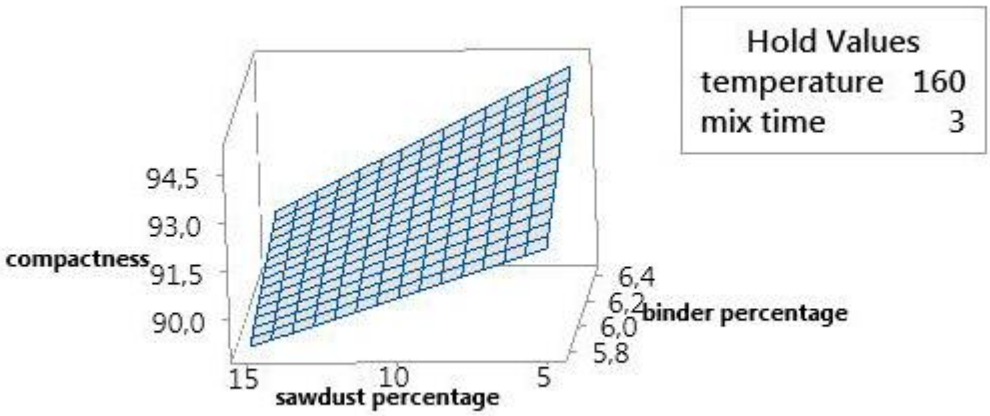


Figure 4.05 the Surface Plot of Compactness

By examining the surface plot, it becomes evident that higher binder content and lower sawdust percentage result in higher compactness. Conversely, lower binder content and higher sawdust percentage lead to lower compactness. This relationship suggests that manipulating these factors within their respective limits can significantly influence the compactness of the asphalt mixtures.

Moreover, the surface plot reveals an interesting relationship between the upper limits of sawdust and binder content. If there is a desire to exceed the upper limit of sawdust, it is necessary to exceed the upper limit of binder content as well. This implies that increasing the binder content becomes crucial when pushing the boundaries of sawdust percentage to achieve higher levels of compactness.

The surface plot serves as a valuable tool for understanding the interplay between sawdust percentage, binder percentage, and compactness. It allows engineers and researchers to anticipate the outer limits of these factors and make informed decisions during the mixture formulation process. By optimizing the levels of sawdust and binder content within their respective limits, the desired level of compactness in the asphalt mixtures can be achieved.

4.5.4 General discussion and results

In conclusion, the analysis and results of this study provide valuable insights into the factors influencing the compactness of asphalt mixtures. The Pareto chart and Main Effects plot highlight the significant effects of various factors, ranking them in order of importance. The Interaction Plot reveals the combined influence of different factors on compactness. The Contour Plot and Surface Plot offer visual representations of the relationships between compactness and the sawdust percentage, binder percentage, manufacturing temperature, and mixing time.

Based on these findings, it can be concluded that higher binder content, higher manufacturing temperature, and higher mixing time contribute to higher compactness in asphalt mixtures. On the other hand, a lower sawdust percentage is also associated with higher compactness. These conclusions provide valuable guidance for optimizing the factors to achieve the desired level of compactness in asphalt mixtures. By considering and adjusting the binder content, manufacturing temperature, mixing time, and sawdust percentage within their optimal ranges, it is possible to improve the compactness of asphalt mixtures.

In conclusion, the analysis and results of this study provide valuable insights into the factors influencing the compactness of asphalt mixtures. The findings indicate that higher mixing time leads to increased compactness by reducing voids and allowing for better binder distribution throughout the mixture. Higher manufacturing temperature also contributes to increased compactness by reducing the volume of sawdust, resulting in improved density. Additionally, higher binder content improves compactness by filling the voids in the mixture. On the other hand, a higher sawdust percentage decreases compactness due to the lower density of the treated sawdust. These findings highlight the importance of considering and optimizing factors such as mixing time, manufacturing temperature, binder content, and sawdust percentage to achieve the desired level of compactness in asphalt mixtures. By adjusting these factors within their appropriate ranges, it is possible to enhance the compactness and overall performance of asphalt mixtures.

4.6 Marshall Stability of Mixes

The Marshall Stability test was conducted on a total of 16 mixtures, and one central mixture, as part of the experimental design. The mixtures were formulated based on predetermined factors and their respective levels. The factors considered in this study included sawdust percentage, binder content, mixing time, and manufacturing temperature. The levels of these factors were chosen to represent a range of values that are relevant to asphalt mixture design.

The Marshall Stability test is a widely accepted method for evaluating the strength and performance of asphalt mixtures. It measures the maximum load-carrying capacity and resistance to deformation of the compacted mixture. The test involves subjecting cylindrical specimens of the asphalt mixture to a compressive load under specific conditions.

Overall, the Marshall Stability test provides crucial data on the strength and performance of the asphalt mixtures, allowing for informed decisions regarding the optimization of factors to achieve the desired stability levels in asphalt mixtures incorporating sawdust as an aggregate.

4.6.1 Results of Marshall Stability

The Marshall Stability test was conducted on the asphalt mixtures formulated with different combinations of factors such as binder content, sawdust percentage, mixing time, and manufacturing temperature. The test results are presented in Table 4.05, providing The Marshall Stability for each combination. The binder content varied between 5.77%, 6.11%, and 6.45%, while the sawdust percentage ranged from 5% to 15%. The mixing time was tested at intervals of 2 minutes, 3 minutes, and 4 minutes, and the manufacturing temperature was examined at 140°C, 160°C, and 180°C.

Table 4.05 Marshall Stability of mixtures

	Factors				Results
Tests	Binder Content (%)	Sawdust Percentage (%)	manufacturing temperature (°C)	Mix Time (minutes)	Marshall Stability (Kn)
1	5,77	5	140	4	17,125
2	6,45	5	180	4	23,642
3	5,77	15	180	2	19,261
4	6,45	5	140	4	24,151
5	6,11	10	160	3	18,41
6	5,77	5	140	2	13,018
7	5,77	5	180	4	18,674
8	6,45	15	180	2	13,36
9	5,77	15	140	2	13,702
10	6,45	15	180	4	15,529
11	6,45	5	140	2	17,431
12	5,77	5	180	2	20,578
13	6,45	5	180	2	21,923
14	6,45	15	140	2	17,72
15	5,77	15	140	4	19,666
16	5,77	15	180	4	24,024
17	6,45	15	140	4	13,212

The Marshall Stability test provides crucial information for evaluating the strength and structural integrity of the asphalt mixtures. It helps assess the influence of various factors on the stability of the mixtures and aids in determining the optimal formulation. By examining the Marshall Stability for different combinations of factors, researchers can identify the factors and levels that contribute to higher stability.

4.6.2 Regression Equation in Uncoded Units

The regression equation in uncoded units offers a straightforward representation of how the response variable is influenced by the independent variables. It allows for a clear interpretation of the effects of these variables and facilitates the analysis and optimization of the asphalt mix formulation. By understanding the relationship expressed in the regression equation, researchers can make informed decisions and adjustments to achieve the desired outcomes in the asphalt mixtures.

Results Marshall stability =71,25 - 21,00 binder percentage - 49,24 sawdust percentage - 0,1656 temperature - 58,52 mix time + 8,927 binder percentage*sawdust percentage + 0,1023 binder percentage*temperature + 12,97 binder percentage*mix time + 0,2740 sawdust percentage*temperature + 15,00 sawdust percentage*mix time + 0,1519 temperature*mix time - 0,05044 binder percentage*sawdust percentage*temperature - 2,730 binder percentage*sawdust percentage*mix time - 0,04456 binder percentage*temperature*mix time - 0,06683 sawdust percentage*temperature*mix time

+ 0,01262 binder percentage*sawdust percentage*temperature*mix time + 0,09650 Ct Pt

4.6.3 Charts of Marshall Stability and discussion

The use of Minitab software to generate charts based on the Marshall Stability data enhances the analysis and understanding of the relationship between the factors and the stability of the asphalt mixtures.

a- Effects Pareto for Results Marshall Stability

The Pareto chart is a valuable tool for identifying the significant factors that impact the Marshall Stability of asphalt mixtures. It ranks the effects of various factors, allowing for a clear understanding of their magnitude and importance. The Pareto chart serves as a useful

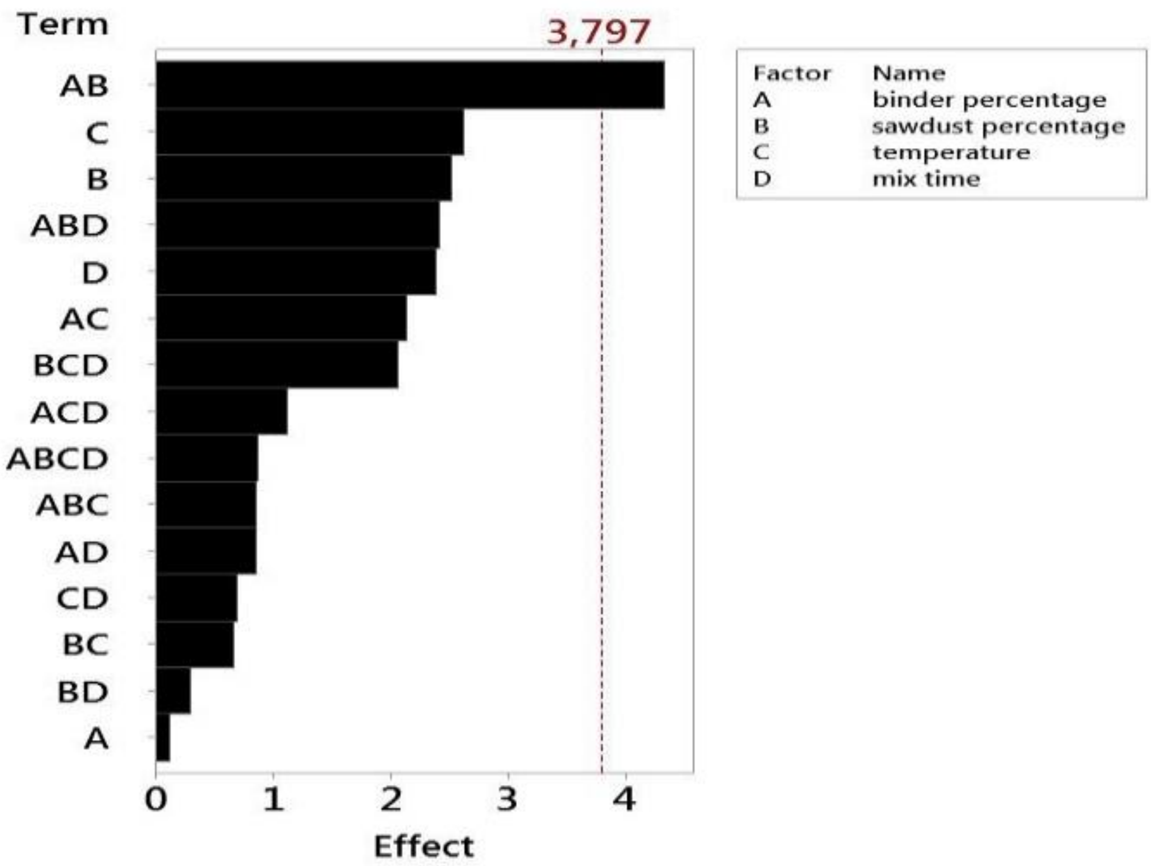


Figure 4.06 Effects Pareto for Results Marshall Stability

Summary, guiding further investigations and potential adjustments in the formulation of asphalt mixes for improved stability.

As shown in Figure 4.06, the Pareto chart highlights that the most significant factor influencing Marshall Stability is the interaction between binder content and sawdust percentage. This interaction effect plays a crucial role in determining the stability of the asphalt mixtures. By considering the combined impact of these two factors, we can make informed decisions to optimize the mix design and enhance the overall stability of the asphalt mixtures.

b- Main Effects and Interaction plots for Results Marshall Stability

The Main Effects plot visually depicts the individual effects of each factor on the Marshall Stability of asphalt mixtures. It enables the identification of factors with significant impacts, taking into account their magnitude and direction. Analyzing the plot allows us to prioritize factors that have notable individual effects and concentrate on optimizing them to achieve the desired level of stability. This plot, along with the Pareto analysis, offers valuable insights into the factors influencing Marshall Stability and assists in making informed decisions to improve the overall quality of asphalt mixtures.

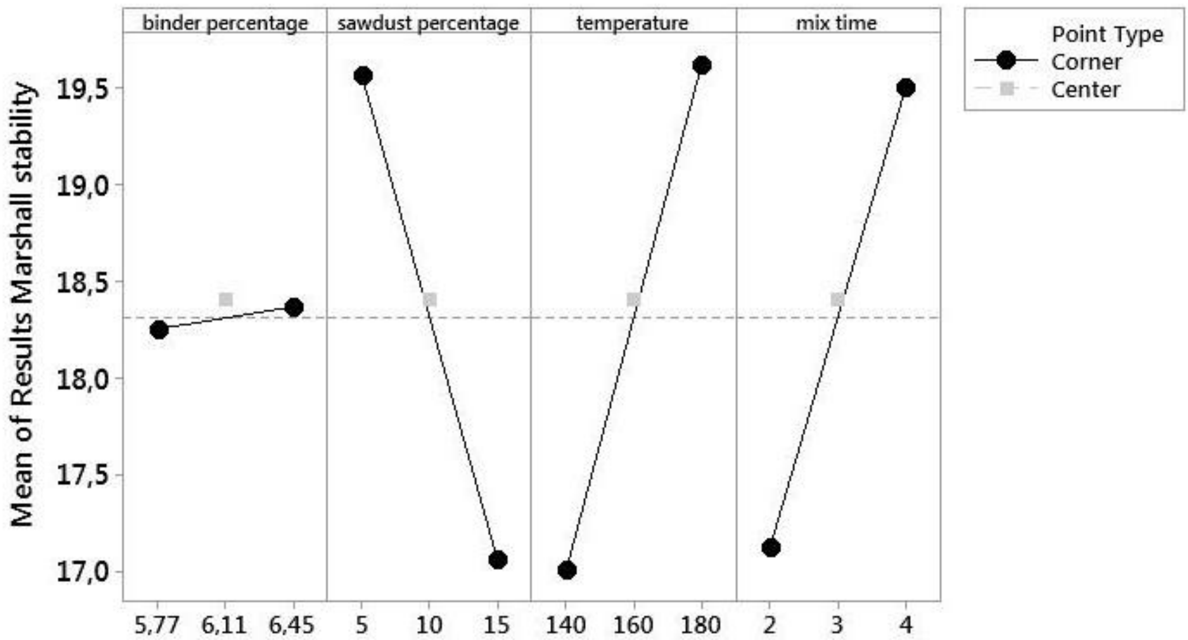


Figure 4.07 Main Effects Plot for Marshall Stability

Based on the Main Effects plot for Marshall Stability presented in Figure 4.07, the factors can be ranked based on their effects on the results. The ranking is as follows:

- 1st Manufacturing temperature
- 2nd Sawdust percentage
- 3rd Mixing time
- 4th Binder content

The plot indicates that manufacturing temperature has the most significant effect on Marshall Stability, followed by sawdust percentage and mixing time. The effect of binder content appears to be relatively negligible in this analysis. The Main Effects plot provides valuable insights into the individual effects of these factors on Marshall Stability.

However, to fully understand the impact of interactions between factors, further analysis is required. The next chart, specifically the Interaction Plot, will provide insights into the combined effects of factors and shed light on any significant interactions influencing Marshall Stability.

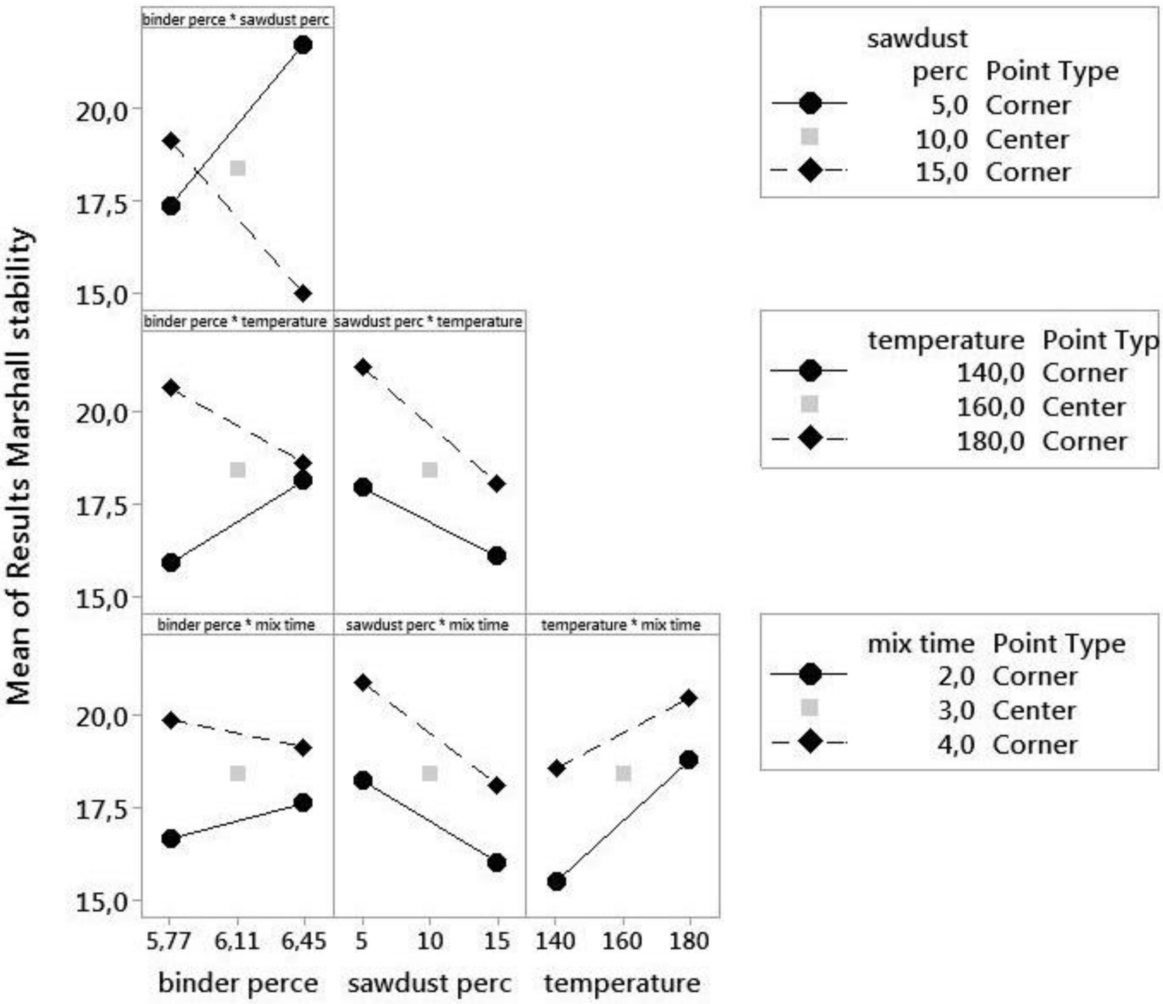


Figure 4.08 the Interaction Plot for Marshall Stability

Based on Figure 4.08, the Interaction Plot for Marshall Stability, it is evident that there are several interactions between factors that influence the results. Among the six interactions presented, the two key interactions are:

- 1st Binder content VS Sawdust percentage
- 2nd Binder content VS Manufacturing temperature

These interactions highlight the combined effects of binder content with sawdust percentage and manufacturing temperature on Marshall Stability. Analyzing these interactions will provide valuable insights into the relationship between these factors and their impact on the stability of asphalt mixtures.

In the analysis of the interaction between Binder content and Sawdust percentage, it was observed that the combination of lower sawdust percentage and lower binder content leads to lower Marshall Stability, while the combination of lower sawdust percentage with higher binder content results in higher Marshall Stability. Similarly, higher sawdust percentage with lower binder content leads to lower Marshall Stability compared to higher sawdust percentage with higher binder content. This highlights the importance of finding the optimal balance between binder content and sawdust percentage to achieve higher Marshall Stability in asphalt mixtures. Understanding and considering this interaction is crucial for optimizing the mixture formulation and achieving the desired level of stability.

By analyzing the Binder content VS Manufacturing temperature interaction, it was observed that a lower Manufacturing temperature combined with a lower Binder content results in lower Marshall Stability compared to a lower Manufacturing temperature with a higher Binder content. Conversely, a higher Manufacturing temperature combined with a lower Binder content leads to higher Marshall Stability compared to a higher Manufacturing temperature with a higher Binder content. This indicates that the combination of lower Manufacturing temperature and lower Binder content contributes to lower Marshall Stability, while the combination of higher Manufacturing temperature and lower Binder content enhances Marshall Stability in asphalt mixtures. Understanding and considering this interaction is important for optimizing the mixture formulation and achieving the desired level of stability.

c- Contour Plot and Surface Plot of Marshall Stability

After observing the significant influence of Binder content, Manufacturing temperature, and their interaction on Marshall Stability results, we will now examine the impact of mixing time and sawdust percentage using the Contour Plot of Marshall stability in Figure 4.09. In this analysis, the Binder content is fixed at 6.11%, and the Manufacturing temperature is set to 160°C.

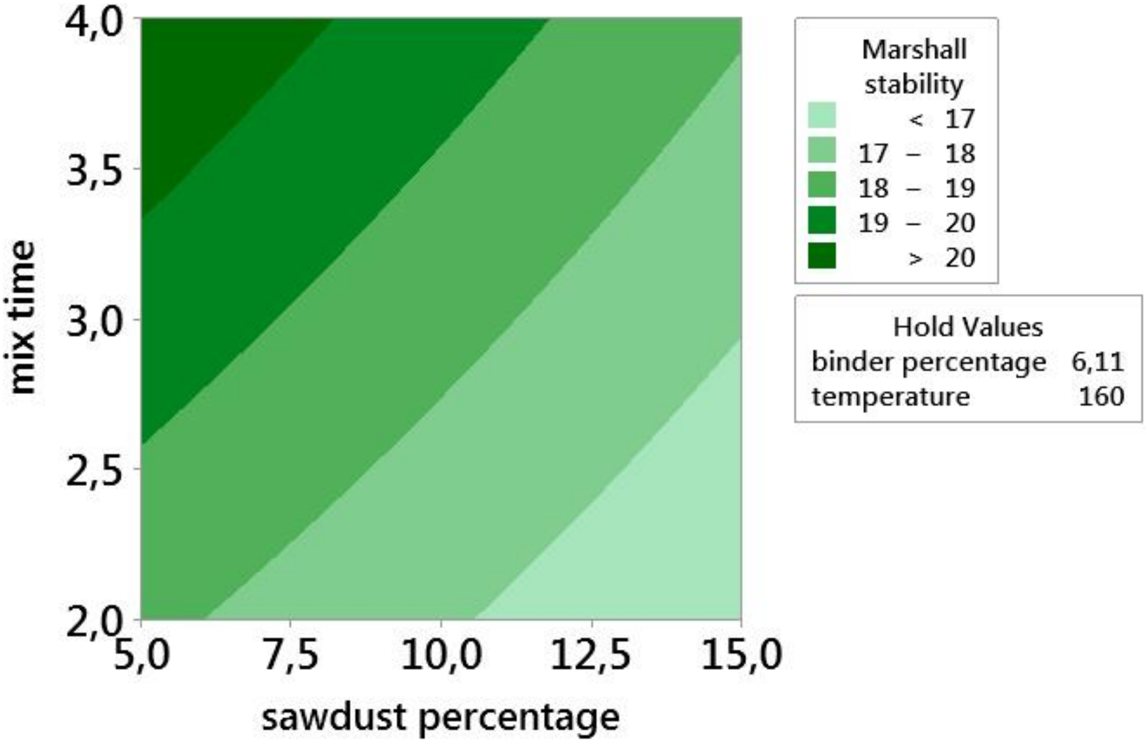


Figure 4.09 Contour Plot of Marshall Stability

The Contour Plot of Marshall Stability reveals the interplay between mixing time, sawdust percentage, and Marshall Stability. The plot demonstrates that a combination of high mixing time and a low sawdust percentage yields the highest Marshall Stability, indicating a positive correlation. On the other hand, a low mixing time and a high sawdust percentage result in a lower Marshall Stability, suggesting a negative correlation. These insights are valuable for optimizing asphalt mixtures and making informed decisions to achieve the desired level of Marshall Stability. Even the mixes with the lowest Marshall stability still exhibit satisfactory results, indicating the robustness of the asphalt mixtures.

The surface plot analysis allows us to explore the potential outer limits of the factors and their impact on Marshall Stability in asphalt mixtures. By examining the plot, we can observe how changes in the sawdust percentage and mixing time influence the Marshall Stability outcome. The surface plot provides a three-dimensional visualization of this relationship, providing a comprehensive understanding of the combined effects of the factors. In this particular analysis, we focus on fixing the Binder content at 6.11% and the Manufacturing temperature at 160°C. By studying the surface plot within these specific parameter constraints, we can gain insights into the optimal ranges of the sawdust percentage and mixing time to achieve the desired level of Marshall Stability in the asphalt mixtures.

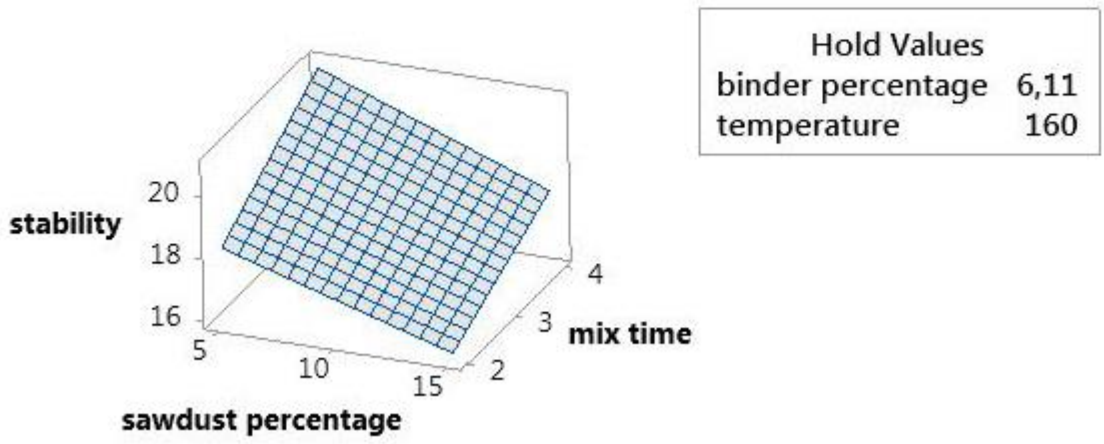


Figure 4.10 the Surface Plot of the Marshall Stability

Figure 4.10, reveals promising results within the inner limits of the factors and also highlights the outcomes in the outer limits of the factors. This plot provides valuable insights into the relationship between the factors and the Marshall Stability of the asphalt mixtures. By analyzing the plot, we can observe the variations in Marshall Stability across different combinations of factors. It enables us to understand the effects of the factors within their respective ranges and assess the potential performance at extreme values. The plot assists in identifying the optimal ranges of the factors that lead to desirable levels of Marshall Stability in the asphalt mixtures.

4.6.4 General discussion and results

The analysis and results presented in this study provide valuable insights into the factors influencing Marshall Stability in asphalt mixtures. The Pareto chart highlighted the significant role of the interaction between binder content and sawdust percentage in determining Marshall Stability. This interaction effect plays a crucial role in optimizing the mix design and enhancing the overall stability of the asphalt mixtures.

The Main Effects plot further ranked the factors based on their effects on Marshall Stability. Manufacturing temperature was identified as the most significant factor, followed by sawdust percentage and mixing time. The effect of binder content was relatively negligible in this analysis.

The Interaction Plot revealed significant interactions between factors, particularly the interactions between binder content and sawdust percentage, as well as binder content and manufacturing temperature. These interactions shed light on the combined effects of these factors on Marshall Stability. It was observed that the optimal balance between binder content and sawdust percentage, as well as manufacturing temperature and binder content, played a crucial role in achieving higher levels of Marshall Stability.

The Contour Plot demonstrated the relationship between mixing time, sawdust percentage, and Marshall Stability. It revealed that a combination of a high mixing time and a low sawdust percentage led to the highest Marshall Stability, while a low mixing time and a high sawdust percentage resulted in lower stability. These findings offer valuable insights for optimizing asphalt mixtures and making informed decisions to achieve the desired level of Marshall Stability.

Overall, the results indicate that incorporating sawdust in the asphalt mixtures positively influenced Marshall Stability. The elastic nature of sawdust contributed to delaying the rupture and increasing the overall stability of the mixtures. The study highlights the importance of considering and optimizing the various factors to enhance Marshall Stability in asphalt mixtures and improve their overall performance.

These findings provide valuable guidance for the design and formulation of asphalt mixtures with treated sawdust, allowing for informed decisions to be made in achieving the desired level of stability. By considering the interaction effects and optimizing the mix design based on the identified factors, we can enhance the performance and durability of asphalt mixtures in various applications.

4.7 Flow of Mixes

The flow of asphalt mixes is a critical factor in their performance and construction. It determines the ability of the mixture to spread evenly during placement, achieve proper compaction, and ensure a smooth pavement surface. The flow is influenced by viscosity, aggregate gradation, temperature, and additives. Higher viscosity binders result in lower flow ability, while well-graded aggregates promote better flow. Temperature affects viscosity and can impact flow characteristics. Additives can be used to enhance flow and workability. Understanding the flow of asphalt mixes and its underlying physics helps optimize mixture design and ensure successful construction and long-term performance of asphalt pavements.

4.7.1 Results of Flow of Mixes

In Table 4.06, the flow characteristics of asphalt mixes containing different sawdust percentages (5%, 10%, and 15%) are presented, along with variations in other factors. These factors may include binder content, mixing time, and manufacturing temperature. By analyzing the data in the table, valuable insights can be gained regarding the influence of sawdust percentage on the flow of the asphalt mixes. This information allows for a comparative evaluation of the flow characteristics and helps identify trends and patterns that can aid in optimizing the mix design.

Table 4.06 Flow Value of mixtures

	Factors				Results
Tests	Binder Content (%)	Sawdust Percentage (%)	Manufacturing Temperature (°C)	Mix Time (minutes)	Flow Value (mm)
1	5,77	5	140	4	3,244
2	6,45	5	180	4	3,037
3	5,77	15	180	2	3,459
4	6,45	5	140	4	3,051
5	6,11	10	160	3	3,452
6	5,77	5	140	2	3,488
7	5,77	5	180	4	3,265
8	6,45	15	180	2	3,618
9	5,77	15	140	2	3,805
10	6,45	15	180	4	3,674
11	6,45	5	140	2	3,493
12	5,77	5	180	2	2,983
13	6,45	5	180	2	3,456
14	6,45	15	140	2	3,631
15	5,77	15	140	4	3,753
16	5,77	15	180	4	3,391
17	6,45	15	140	4	3,74

4.7.2 Regression Equation in Uncoded Units

The regression equation in uncoded units provides a clear and easily interpretable representation of how the response variable, in this case, the flow value, is affected by the independent variables. This equation allows researchers to understand and analyze the effects of these variables on the flow properties of asphalt mixtures. With this understanding, informed decisions can be made to optimize the mix formulation and achieve the desired flow outcomes. The regression equation serves as a valuable tool in guiding the adjustments and improvements necessary to achieve the desired results in asphalt mixtures.

Results Flow Value=42,26 - 5,850 binder percentage - 1,561 sawdust percentage-0,3043 temperature - 10,89 mix time + 0,2302 binder percentage*sawdust percentage + 0,04675 binder percentage*temperature + 1,617 binder percentage*mix time + 0,01450 sawdust percentage*temperature + 0,6441 sawdust percentage*mix time + 0,08803 temperature*mix time - 0,002210 binder percentage*sawdust percentage*temperature - 0,09353 binder percentage*sawdust percentage*mix time - 0,01353 binder percentage*temperature*mix time

- 0,005620 sawdust percentage*temperature*mix time + 0,000857 binder percentage*sawdust percentage*temperature*mix time + 0,009000 Ct Pt

4.7.3 Charts of Flow Value and discussion

The utilization of Minitab software for generating charts based on the Flow Value data significantly improves the analysis and understanding of the relationship between the factors and the Flow Value of asphalt mixtures. These charts assist in identifying the key factors that contribute to variations in flow behavior, guiding decision-making processes, and enabling optimization of the mix design to achieve the desired flow characteristics in asphalt mixtures.

a- Effects Pareto for Results Flow Value

The Pareto chart is a valuable tool for identifying the significant factors that impact the Flow Value of asphalt mixtures. It ranks the effects of various factors, providing a clear understanding of their importance and guiding further investigations and potential adjustments in mix

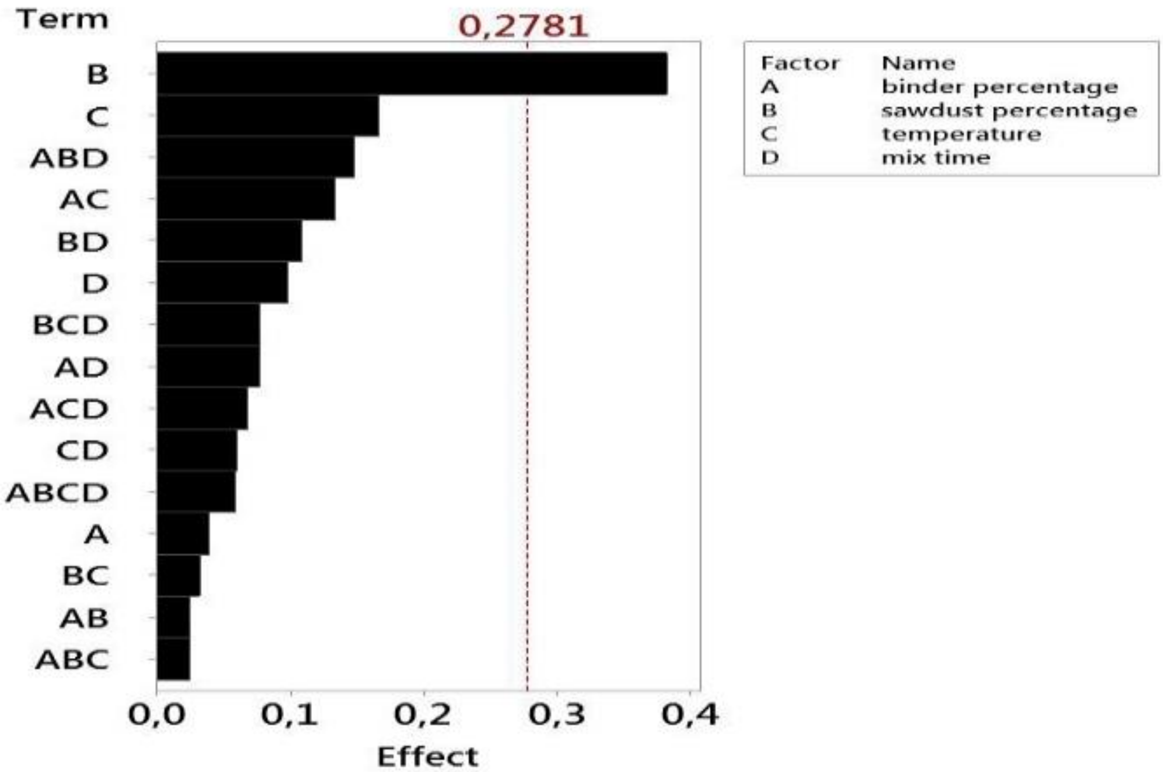


Figure 4.11 Effects Pareto for Results Flow Value

formulation. The chart helps prioritize factors for optimization, facilitating informed decision-making to improve the Flow Value of asphalt mixtures.

Based on Figure 4.11, the Effects of Pareto for Results Flow Value highlights that the most critical factor influencing the Flow Value of asphalt mixtures is the sawdust percentage. The ranking of non-critical factors is as follows: 1st manufacturing temperature, 2nd the interaction between binder content, sawdust percentage, and manufacturing temperature, 3rd the interaction between binder content and manufacturing temperature, and 4th the interaction between sawdust percentage and mixing time. The least influential factor is the binder content. This information provides valuable insights into the factors that significantly impact the Flow Value and guides further analysis and adjustments in the formulation of asphalt mixes.

b- Main Effects and Interaction plots for Results Flow Value

The Main Effects plot provides a visual representation of the individual effects of each factor on the Flow value of asphalt mixtures. It allows for the identification of factors that have significant impacts, considering their magnitude and direction. Analyzing the plot helps prioritize factors with notable individual effects, enabling optimization to achieve the desired level of flow.

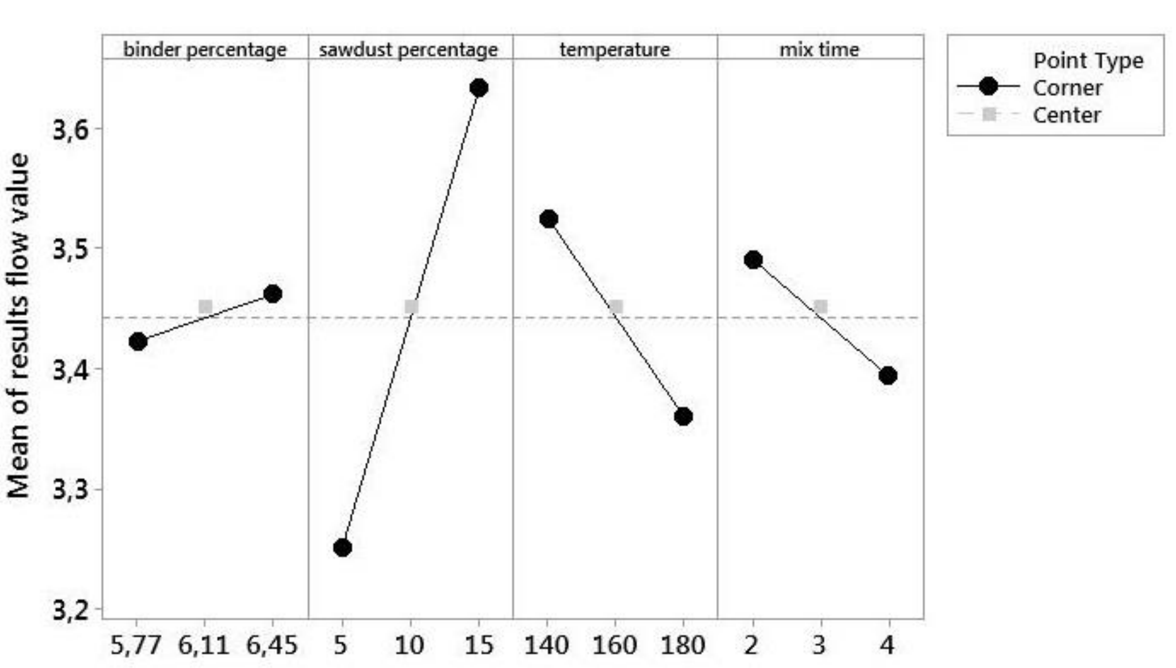


Figure 4.12 Main Effects Plot for Flow Value

Based on the analysis of Figure 4.12, the Main Effects plot for Flow Value reveals the ranking of factors based on their impact. The factors are ranked as follows: 1st sawdust percentage, 2nd manufacturing temperature, 3rd mixing time, and 4th binder content.

In terms of the impact on Flow value, higher sawdust percentage and higher binder content have a negative effect, indicating that an increase in these factors leads to an increase in Flow value. On the other hand, lower sawdust percentage and lower binder content have a positive impact, suggesting that a decrease in these factors leads to an improvement in Flow value.

Furthermore, higher manufacturing temperature and higher mixing time have a positive impact on Flow value, meaning that an increase in these factors results in a decrease in Flow value. Conversely, lower manufacturing temperature and lower mixing time have a negative impact on Flow value, indicating that a decrease in these factors leads to an increase in Flow value. These findings provide insights into the relationship between the factors and their effects on Flow value, allowing for informed decision-making and optimization of asphalt mixtures to achieve the desired Flow value.

Based on the analysis of Figure 4.11, the Interaction Plot for Flow Value, it is evident that there are significant interactions between factors that influence the Flow value of asphalt mixtures. Specifically, the interactions between binder content VS sawdust percentage VS mixing time and binder content VS manufacturing temperature, as well as the interaction between sawdust percentage VS mixing time, exhibit notable effects.

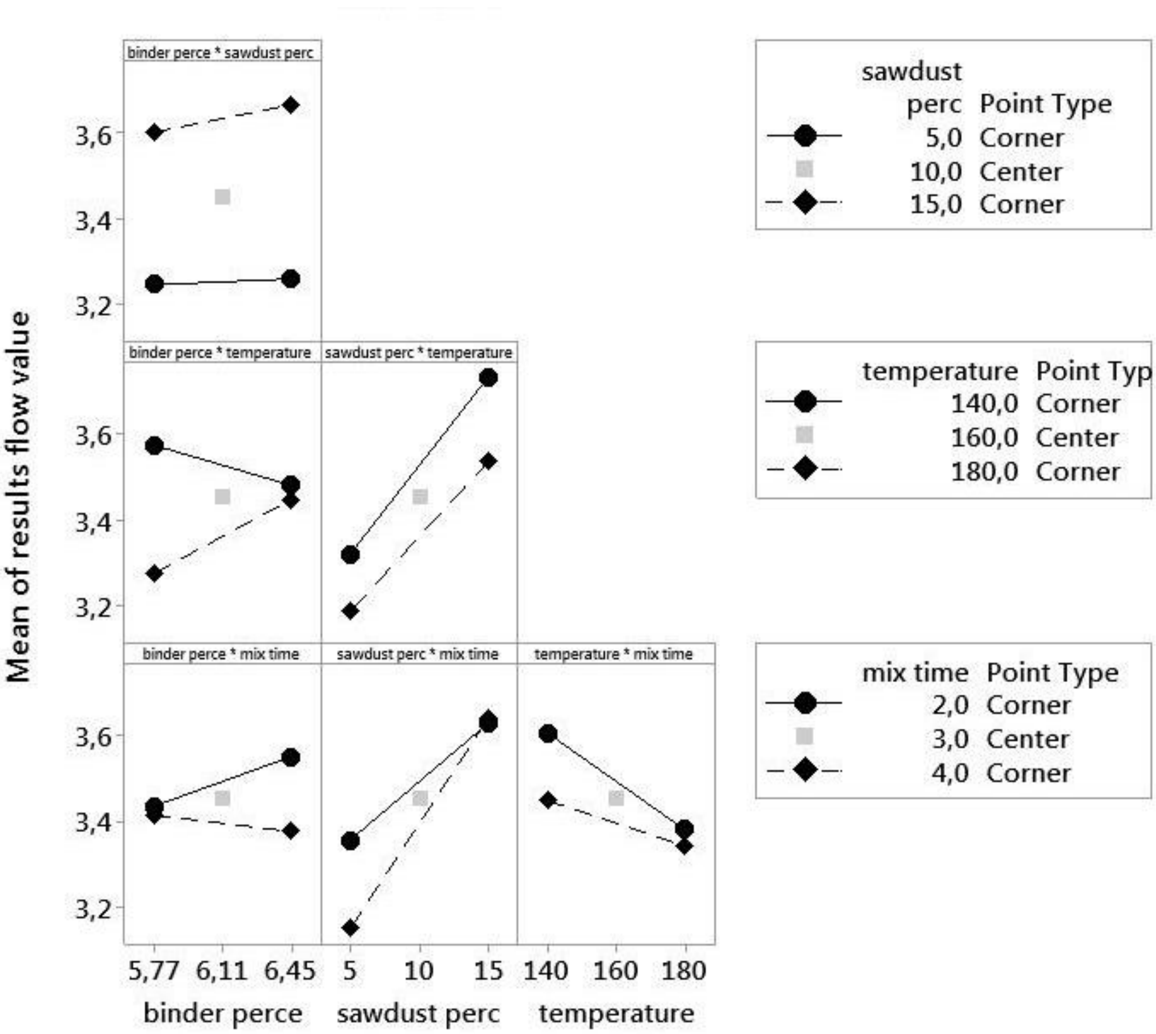


Figure 4.13 the Interaction Plot for Flow Value

The Interaction Plot for Flow Value (Figure 4.13) provides insights into the combined effects of factors on the Flow value of asphalt mixtures. The interaction between binder content and sawdust percentage shows that a lower sawdust percentage combined with lower binder content leads to a decrease in the flow value, which is considered favorable. Conversely, a higher sawdust percentage with higher binder content results in an increase in the flow value. The interaction between binder content and manufacturing temperature reveals that a lower binder content with a higher manufacturing temperature contributes to a decrease in the flow value, while a higher binder content with a lower manufacturing temperature leads to an increase in the flow value. Lastly, the interaction between sawdust percentage and manufacturing temperature demonstrates that a lower sawdust percentage combined with a higher manufacturing temperature leads to a decrease in the flow value, whereas a higher sawdust percentage with a lower manufacturing temperature increases the flow value. Understanding these interactions helps optimize the mix design and achieve the desired flow value in asphalt mixtures.

c- Contour Plot and Surface Plot of Flow Value

After analyzing the considerable effects of sawdust percentage, and manufacturing temperature on Flow Value results, we will now explore the influence of mixing time and binder content using the Contour Plot of Flow Value presented in Figure 4.14. This plot focuses on a fixed sawdust percentage of 10% and a manufacturing temperature of 160°C. By examining the contour plot, we can gain insights into the relationship between mixing time, binder content, and Flow Value. It provides a visual representation of how variations in these factors impact the Flow Value of asphalt mixtures within the specified conditions. The contour plot aids in identifying optimal ranges of mixing time and binder content that result in desirable levels of Flow Value.

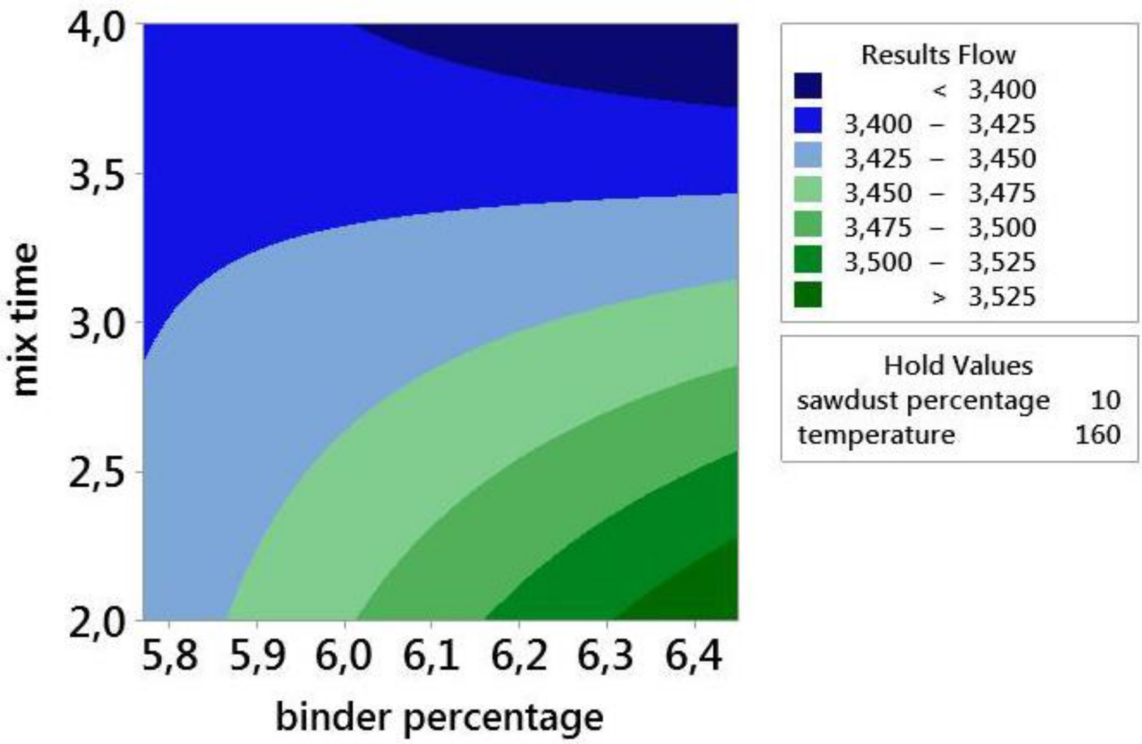


Figure 4.14 Contour Plot of Flow value

Based on the analysis of Figure 4.14, it can be concluded that higher mixing times lead to lower flow values, which is considered beneficial. This relationship holds true regardless of the binder content within the interval of 5.77% to 6.45%.

Furthermore, the effect of binder content on flow values is relatively small. Within the specified binder content interval, two sub-intervals can be identified:

In the sub-interval of 5.77% to 6.11% binder content, there is a positive effect of decreased binder content on flow value. This means that as the binder content increases within this range, the flow value tends to increase.

In the sub-interval of 6.11% to 6.45% binder content, there is a negative effect of decreased binder content on flow value. Therefore, as the binder content increases within this range, the flow value tends to decrease.

These observations indicate that higher mixing times generally improve flow values, irrespective of the binder content within the specified interval. Additionally, the effect of binder content is more pronounced in the two sub-intervals, with a negative effect in the lower sub-interval and a positive effect in the higher sub-interval.

The analysis using surface plots in Figure 4.15 enables us to investigate the upper boundaries of the factors and their influence on the Flow Value of asphalt mixtures. By studying the plot, we can observe the impact of variations in binder content and mixing time on the resulting Flow Value. The surface plot presents a three-dimensional representation of this correlation, offering a holistic view of the combined effects of these factors. In this specific analysis, our attention is directed toward keeping the Sawdust percentage fixed at 10% and the Manufacturing temperature at 160°C, allowing us to focus on the relationship between binder content and mixing time and their influence on Flow Value.

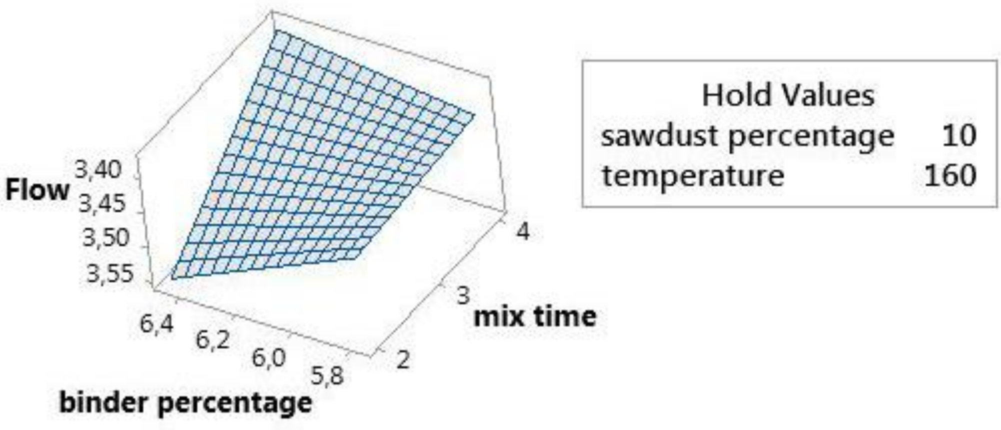


Figure 4.15 the Surface Plot of Flow value

According to the Contour Plot of the flow value, it is evident that an extended mixing time significantly contributes to decreasing the flow value. This observation suggests that a longer duration of mixing has a notable role in reducing the flow value. Additionally, lower binder content is also favorable for decreasing the flow value. It is worth noting that a decrease in the flow value is considered beneficial in this context.

4.7.4 General discussion and results

The analysis of Figures 4.11, 4.12, 4.13, and 4.14 yields important findings regarding the factors influencing Flow Value in asphalt mixtures. Firstly, the Effects of Pareto plot highlights that the sawdust percentage is the most critical factor, while the binder content has the least influence. The Main Effects plot ranks the factors in terms of impact, with sawdust percentage having the highest effect, followed by manufacturing temperature, mixing time, and binder content. The Interaction Plot uncovers the combined effects of factors, revealing that interactions involving sawdust percentage, binder content, and manufacturing temperature play significant roles. Additionally, the Contour Plot demonstrates that higher mixing times lead to lower flow values, irrespective of the binder content within the 5.77% to 6.45% interval.

Indeed, the presence of sawdust in asphalt mixtures can increase the flow value due to its low density. Sawdust, being less dense than the other components of the mixture, can be easily compacted during the mixing process, leaving behind relatively larger voids. These voids contribute to increased flow ability within the mixture, resulting in higher flow values. Therefore, the low density and ease of compaction of sawdust can lead to a higher flow value in asphalt mixes.

A longer mixing time and higher manufacturing temperature can help mitigate the effects of the sawdust's light density on the mixture. Here's how:

- Longer Mixing Time: Increasing the duration of mixing allows for better dispersion and distribution of the sawdust particles throughout the asphalt mixture. This extended mixing time promotes more uniform incorporation of the sawdust, reducing the presence of voids and improving the overall compactness of the mixture. As a result, the detrimental impact of the sawdust's light density on flowability can be minimized, leading to a decrease in the flow value.
- Higher Manufacturing Temperature: Elevating the manufacturing temperature of the asphalt mixture has several benefits. Firstly, it helps enhance the workability of the mixture by reducing its viscosity. This improved workability enables better coating and bonding of the sawdust particles with the asphalt binder and aggregates. Consequently, the sawdust is more effectively integrated into the mixture, reducing the presence of voids and improving the overall density. The higher temperature also promotes better compaction and consolidation of the mixture, further minimizing the impact of the sawdust's light density on the flow value.

A larger amount of binder in an asphalt mixture can increase the flow value due to the viscosity nature of the binder and the resulting void formation. The binder in an asphalt mixture provides cohesion and acts as a binding agent. When the binder content is increased, the viscosity of the mixture also increases. The higher viscosity creates less resistance to flow.

In conclusion, the sawdust percentage negatively affects flow value, but it remains within an acceptable range. Mitigating this negative impact can be achieved by increasing mixing time and manufacturing temperature while decreasing the binder content. This approach not only addresses the sawdust issue but also reduces project costs. These findings provide valuable insights for optimizing asphalt mixtures, achieving the desired flow value, and effectively managing the influence of sawdust in the mixture.

4.8 Marshall Quotient

The Marshall quotient is calculated by dividing the stability (measured in kN) by the flow (measured in mm). A higher Marshall quotient indicates a greater proportion of stability relative to flow, suggesting a stiffer mixture. This stiffness is associated with better resistance to rutting and deformation.

4.8.1 Results of Marshall Quotient

Table 4.07 presents the characteristics of the Marshall Quotient for various asphalt mixes, each containing different percentages of sawdust (5%, 10%, and 15%). The table also accounts for variations in other factors such as binder content, mixing time, and manufacturing temperature.

Table 4.07 Marshall Quotient of mixtures

	Factors				Results
Tests	Binder Content (%)	Sawdust Percentage (%)	Manufacturing Temperature (°C)	Mix Time (minutes)	Marshall Quotient (KN/mm)
1	5,77	5	140	4	5,279
2	6,45	5	180	4	7,785
3	5,77	15	180	2	5,568
4	6,45	5	140	4	7,916
5	6,11	10	160	3	5,333
6	5,77	5	140	2	3,732
7	5,77	5	180	4	5,719
8	6,45	15	180	2	3,693
9	5,77	15	140	2	3,601
10	6,45	15	180	4	4,227
11	6,45	5	140	2	4,990
12	5,77	5	180	2	6,898
13	6,45	5	180	2	6,343
14	6,45	15	140	2	4,880
15	5,77	15	140	4	5,240
16	5,77	15	180	4	7,085
17	6,45	15	140	4	3,533

4.8.2 Regression Equation in Uncoded Units

The regression equation, expressed in non-coded units, offers a straightforward and easily understandable depiction of how the Marshall Quotient, the response variable, is influenced by the independent variables. This equation enables researchers to comprehend and evaluate the impact of these variables on the properties of the Marshall Quotient in asphalt mixtures. This understanding empowers informed decision-making to optimize the formulation of the mix and attain the desired outcomes in terms of the Marshall Quotient.

Results Marshall quotient=-64,80 + 6,902 binder percentage - 8,666 fiber percentage + 0,6196 temperature + 5,462 mix time + 1,729 binder percentage*fiber percentage - 0,07361 binder percentage*temperature + 0,4048 binder percentage*mix time + 0,03515 fiber percentage*temperature + 2,534 fiber percentage*mix time - 0,1416 temperature*mix time - 0,007739 binder percentage*fiber percentage*temperature - 0,5173 binder percentage*fiber percentage*mix time + 0,01581 binder percentage*temperature*mix time - 0,004839 fiber percentage*temperature*mix time + 0,001402 binder percentage*fiber percentage*temperature*mix time - 0,07260 Ct Pt

4.8.3 Charts of Marshall Quotient and discussion

The utilization of Minitab software greatly enhances the analysis and comprehension of the relationship between factors and the Marshall Quotient in asphalt mixtures by generating informative charts. These charts play a crucial role in identifying the primary factors that impact the variations in the Marshall Quotient. They guide decision-making processes and facilitate the optimization of mix designs to attain the desired Marshall Quotient in asphalt mixtures. Overall, Minitab software enables a more comprehensive understanding of the factors influencing the Marshall Quotient and supports effective decision-making for mix design optimization.

a- Effects Pareto for Results Marshall Quotient

The Pareto chart is a useful tool for identifying the most significant factors affecting the Marshall Quotient in asphalt mixtures. It ranks the effects of various factors, helping prioritize further investigations and potential adjustments in mix formulation for optimization.

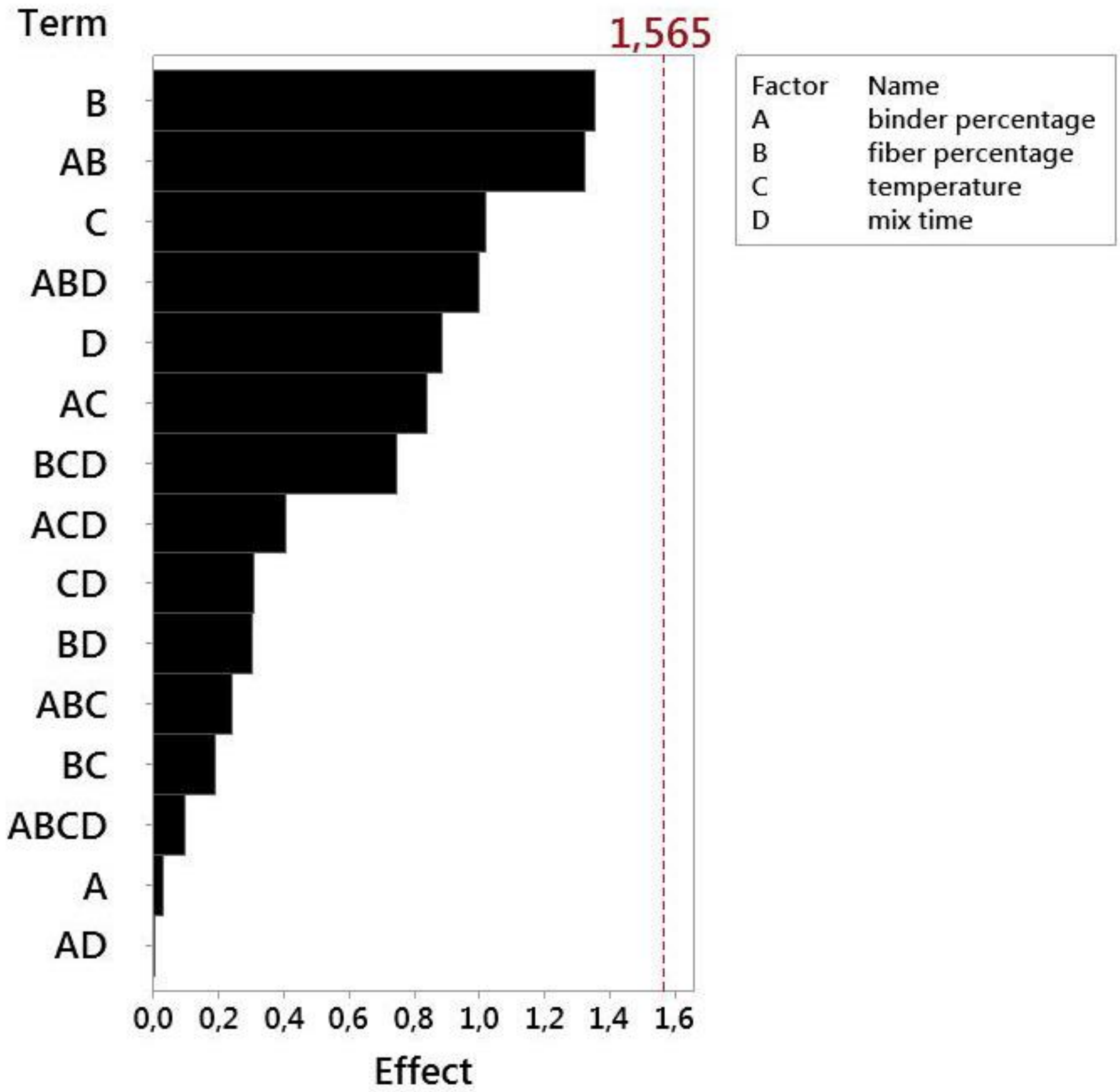


Figure 4.16 Effects Pareto for Marshall Quotient

Figure 4.16, the Effects Pareto for Marshall Quotient, indicates that no individual factor or interaction between factors has a critical effect on the Marshall Quotient. However, this chart is still beneficial in ranking the factors based on their respective impacts on the Marshall Quotient.

b- Main Effects and Interaction plots for the Marshall Quotient

The Main Effects plot visually displays the individual effects of each factor on the Marshall Quotient in asphalt mixtures. It facilitates the identification of factors that exert significant impacts, considering both the magnitude and direction of their effects. By analyzing the plot, it becomes possible to prioritize factors with substantial individual effects, guiding the optimization process to attain the desired level of Marshall Quotient.

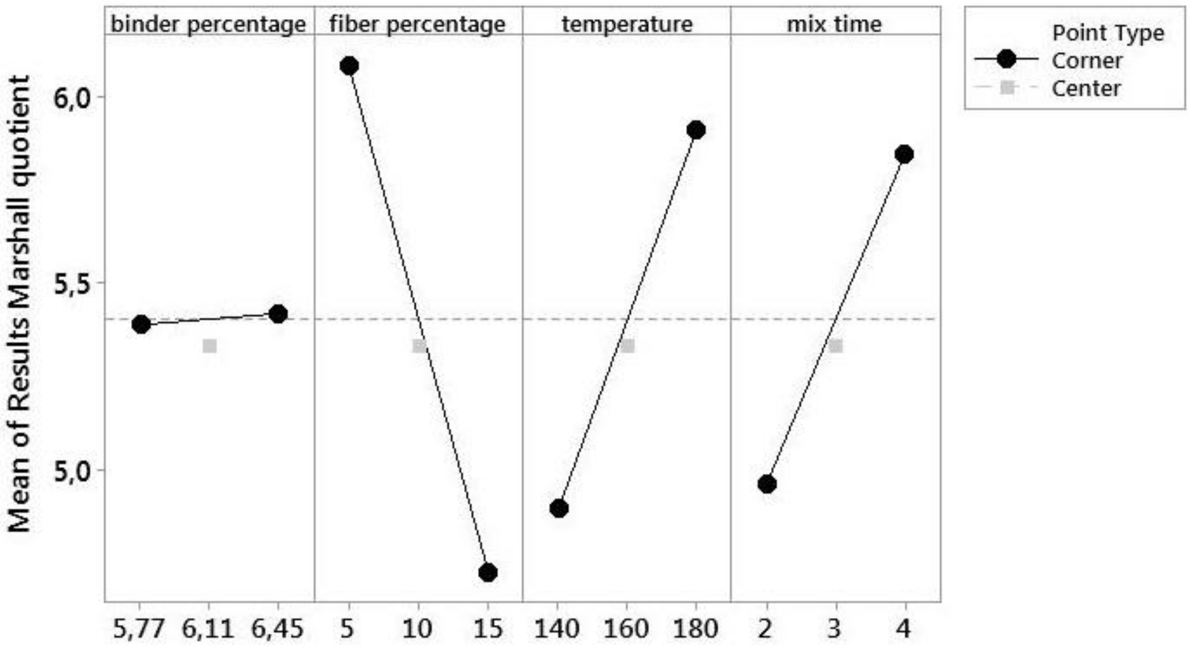


Figure 4.17 Main Effects Plot for Marshall Quotient

Base on Figure 4.17 is valuable for ranking factors based on their effect on the Marshall Quotient. According to the plot, the factors can be ranked as follows:

1st Sawdust percentage, 2nd Manufacturing temperature, 3rd Mixing time, 4th Binder content

The plot also reveals specific variations in the Marshall Quotient based on different levels of these factors. For instance, when the sawdust percentage varies from 5% to 15%, the Marshall Quotient ranges from 7.20 kN/mm to 4.00 kN/mm. Similarly, the variation of manufacturing temperature from 140°C to 180°C yields Marshall Quotient values ranging from 4.50 kN/mm to 5.90 kN/mm. Furthermore, the variation of mixing time from 2mm to 4mm results in Marshall Quotient values ranging from 4.80 kN/mm to 5.70 kN/mm. On the other hand, the effect of binder content is found to be almost negligible based on the plot's indications.

After analyzing the Main Effects Plot for Marshall Quotient, it is beneficial to examine the Interaction Plot for Marshall Quotient. The Interaction Plot provides insights into how different factors interact with each other and their combined effects on the Marshall Quotient. By

studying this plot, we can gain a better understanding of the interplay between factors and how it influences the overall Marshall Quotient in asphalt mixtures.

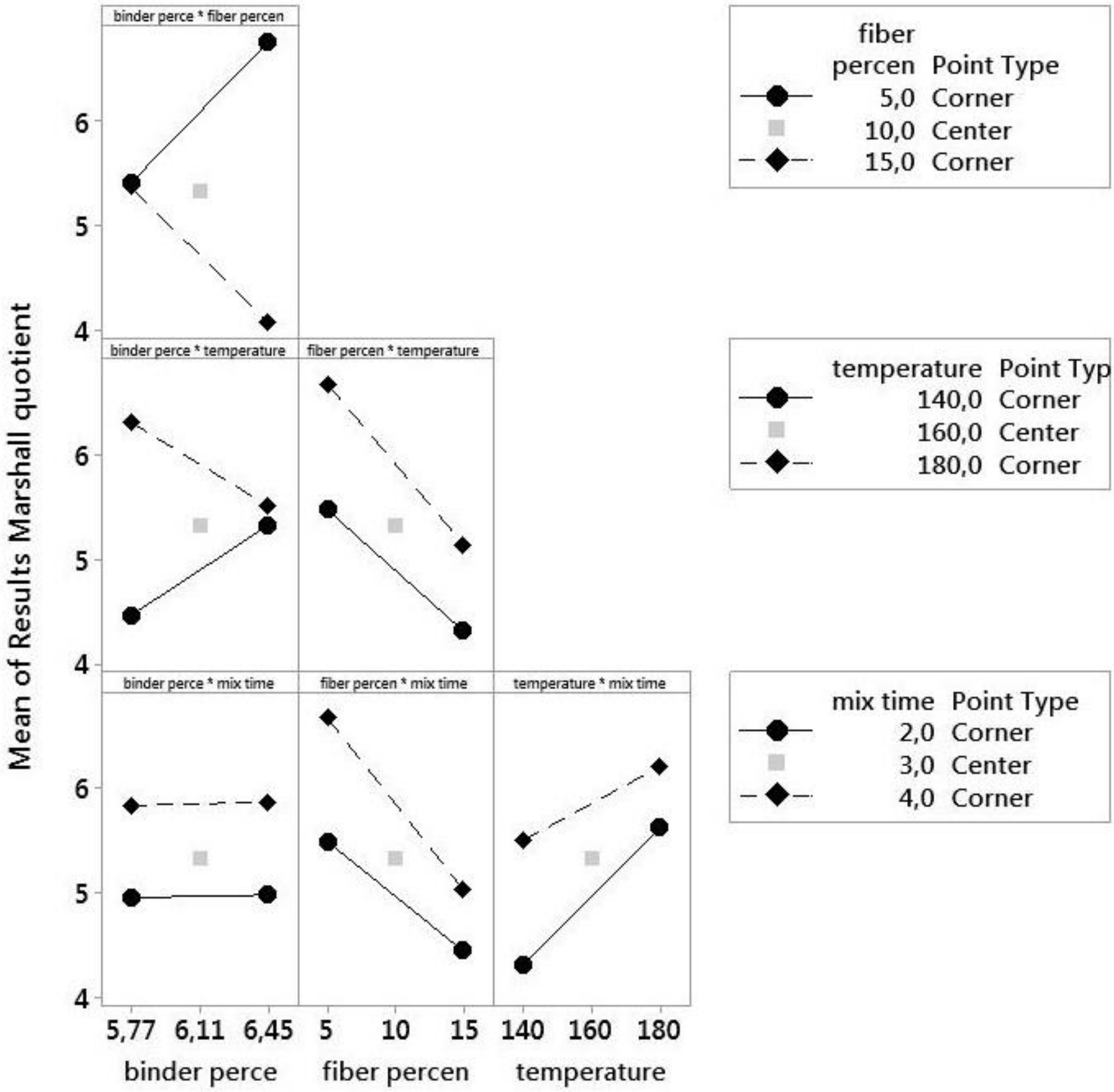


Figure 4.18 the Interaction Plot for Marshall Quotient

Figure 4.18 illustrates the relationship between binder content, sawdust percentage, manufacturing temperature, and the resulting Marshall Quotient. The plot shows how the interaction between these factors affects the Marshall Quotient. In the case of 5% sawdust, increasing the binder content leads to an increase in the Marshall Quotient. Conversely, decreasing the binder content would likely result in a decrease in the Marshall Quotient.

For 15% sawdust, increasing the binder content would lead to a decrease in the Marshall Quotient, while reducing the binder content would likely increase the Marshall Quotient. Regarding the interaction between binder content and manufacturing temperature, at 140°C manufacturing temperature, increasing the binder content increases the Marshall Quotient. Conversely, decreasing the binder content would likely result in a decrease in the Marshall Quotient. At 180°C manufacturing temperature, the trend is reversed, meaning that increasing the binder content would decrease the Marshall Quotient, while reducing the binder content would likely increase it.

Considering the interaction between sawdust percentage and manufacturing temperature, at both 140°C and 180°C, increasing the sawdust percentage leads to a decrease in the Marshall Quotient. Conversely, decreasing the sawdust percentage would likely result in an increase in the Marshall Quotient. The other three interactions (binder content vs. mixing time, manufacturing temperature vs. mixing time, and sawdust percentage vs. mixing time) do not have a significant effect on the Marshall Quotient, it suggests that these factors may have a minimal or negligible impact on the outcome.

c- Contour Plot and Surface Plot of the Marshall Quotient

After analyzing the significant impacts of sawdust percentage, manufacturing temperature, and mixing time on the Marshall Quotient, we will now investigate the influence of binder content using the Contour Plot of the Marshall Quotient depicted in Figure 4.19. This plot specifically focuses on a fixed mixing time of 3 minutes and a manufacturing temperature of 160°C. By examining the contour plot, we can gain insights into the correlation between sawdust percentage, binder content, and the Marshall Quotient. It visually illustrates how changes in these factors affect the Marshall Quotient of asphalt mixtures within the specified conditions.

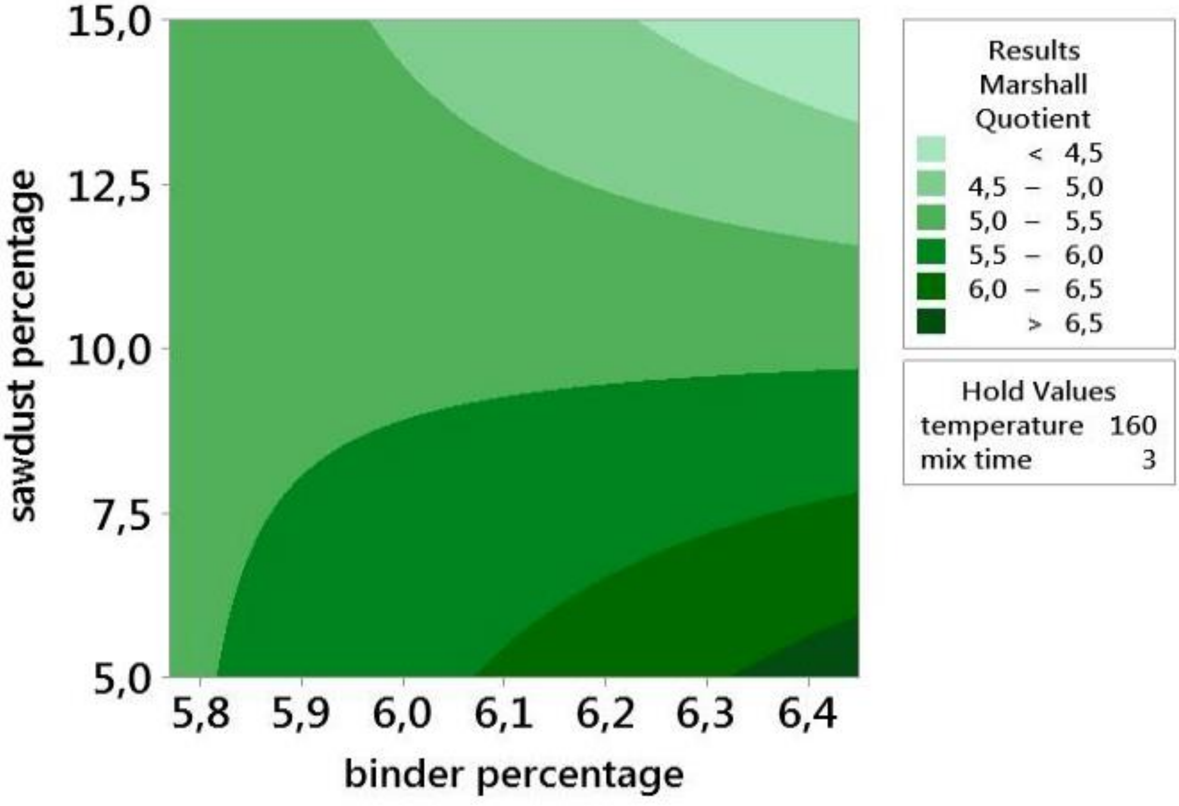


Figure 4.19 Contour Plot for Marshall Quotient

The contour plot helps identify optimal ranges of sawdust percentage and binder content that led to desirable levels of the Marshall Quotient.

In Figure 4.19, the Contour Plot for Marshall Quotient presents a division of the sawdust range into two sub-ranges: sub-range 01 [5%-10%] and sub-range 02 [10%-15%]. For sub-range 01, we observe that increasing the binder content leads to an increase in the Marshall Quotient while increasing the sawdust percentage results in a decrease in the Marshall Quotient. Conversely, in sub-range 02, the relationship is reversed compared to sub-range 01. Here, increasing the binder content leads to a decrease in the Marshall Quotient, while increasing the sawdust percentage results in an increase in the Marshall Quotient. These distinct patterns within the sub-ranges provide valuable insights into the relationship between binder content, sawdust percentage, and the resulting Marshall Quotient.

The utilization of surface plots, as depicted in Figure 4.20, allows us to examine the upper limits of the factors and their impact on the Marshall Quotient of asphalt mixtures. By analyzing the plot, we can observe how changes in binder content and sawdust percentage affect the resulting Marshall Quotient. The surface plot presents a three-dimensional representation of this relationship, providing a comprehensive understanding of the combined effects of these factors. In this particular analysis, our focus is centered on maintaining a fixed mixing time of 3 minutes and a manufacturing temperature of 160°C. This allows us to specifically investigate the correlation between binder content, sawdust percentage, and their influence on the Marshall Quotient.

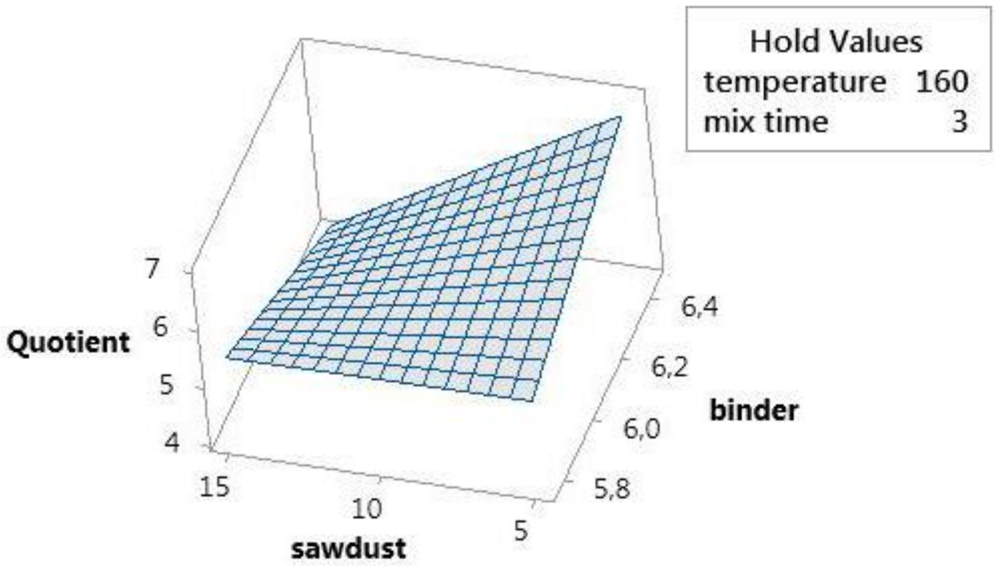


Figure 4.20 the Surface Plot of the Marshall Quotient

Based on the analysis of Figure 4.20, in accordance with the Contour Plot for Marshall Quotient, it is evident that to increase the sawdust percentage while maintaining a high Marshall Quotient, it is necessary to decrease the binder content. This relationship allows for maximizing the desired Marshall Quotient level. Moreover, it is important to exercise caution when approaching or surpassing the upper limit of the sawdust percentage, which is set at 15%. In such cases, careful consideration must be given to the binder content to ensure the Marshall Quotient remains at a desirable level.

Conversely, when dealing with a low sawdust percentage, increasing the binder content becomes essential in order to maintain a high Marshall Quotient value. This highlights the importance of balancing the factors of sawdust percentage and binder content to achieve the desired outcome for the Marshall Quotient.

4.8.4 General discussion and results

The analysis of multiple plots and charts regarding the Marshall Quotient reveals important findings. The Effects Pareto plot ranks factors without identifying a critical factor, but it helps prioritize them. Sawdust percentage is ranked as the most influential factor, followed by manufacturing temperature, mixing time, and binder content. Other plots highlight interactions between factors, such as the impact of binder content and sawdust percentage in different sub-ranges. Additionally, the three-dimensional surface plot emphasizes the need for careful adjustment of binder content when increasing the sawdust percentage to maintain a desirable Marshall Quotient level. Balancing factors like binder content and sawdust percentage is crucial for optimizing the Marshall Quotient in asphalt mixtures.

The key findings of this study indicate that high mixing time and high manufacturing temperature contribute to an increased Marshall Quotient value. Additionally, it was observed that a high binder content combined with a low sawdust percentage lead to a higher Marshall Quotient, while a low binder content with a high sawdust percentage also yields a higher Marshall Quotient. The interaction between these factors plays a crucial role in enhancing the Marshall Quotient.

The Marshall Quotient serves as a reliable indicator of mix rutting, and based on the results obtained, it can be concluded that all the Marshall Quotient values are promising in terms of rutting resistance. By carefully manipulating the levels of the factors involved, particularly when incorporating sawdust, improvements in the Marshall Quotient results can be achieved.

In summary, a combination of factors including mix time, manufacturing temperature, binder content, and sawdust percentage influences the Marshall Quotient. The study highlights the importance of optimizing these factors to enhance the Marshall Quotient, which ultimately contributes to improved resistance against rutting.

4.9 Comparison of the results to control samples and specification

The comparison involves two aspects: evaluating 17 experimental mixes with varying factors (sawdust percentage, manufacturing temperature, binder content, and mixing time) and comparing them to specifications set by the Algerian National Authority for Public Works Service. The key parameters for comparison are compactness, Marshall Stability, Flow Value, and Marshall Quotient. We will also compare the outcomes of control samples with 0% sawdust, 160°C manufacturing temperature, 6.11% binder content, and 3 minutes of mixing time to the same specifications. This analysis will determine if the experimental mixes with sawdust meet the required standards and assess the impact of incorporating sawdust and other factors on the asphalt mixtures' performance.

Table 4.08 Comparison of the results to control samples and specification

	Compactness (%)	Marshall Stability (Kn)	Flow Value (mm)	Marshall Quotient (Kn/mm)
Range of mixes results	From 86.55 to 96.36	From 13.01 to 24.02	From 2.98 to 3.75	From 3,533 to 7,785
Mean Control results	94.19	16.02	3.41	4.70
Specification range	From 92.00 to 97.00	For Light traffic >9.5 For Medium traffic >10.5 For Heavy traffic >12.5	Flow value Should be less than 4.00 mm	For Light traffic >2.375 For Medium traffic >2.63 For Heavy traffic >3.13

Based on this comparison, the experimental mixes with sawdust show a range of values within the specified requirements for Marshall Stability, flow value, and Marshall Quotient. The control samples also meet the specified ranges for these parameters. However, further assessment of these values against the traffic load requirements is needed to determine their suitability for different road types.

The chosen mixture with a 15% sawdust percentage, 5.77% binder content, 140°C manufacturing temperature, and 2 minutes of mixing time was unexpected to yield good results due to its low binder content and short mixing time. However, it surprisingly showed favorable outcomes for Marshall Stability, Flow Value, and Marshall Quotient. The compactness, although below the specified range, could be improved with adjustments to the binder content, mixing time, or manufacturing temperature. This experimental mixture provided valuable insights into the effects of extreme combinations of factors on asphalt performance and optimization strategies.

Table 4.08 highlights that some of the experimental mixes with sawdust do not meet the specification for compactness. These mixes typically have combinations of two or more factors set to low levels, such as low binder content, low mixing time, and low manufacturing temperature. Alternatively, some mixes with high sawdust percentage also fail to meet the compactness requirement as specified by the Algerian National Authority for Public Works Service.

These findings indicate that certain combinations of factors, specifically low levels of binder content, mixing time, and manufacturing temperature, as well as high levels of sawdust percentage, have a significant impact on the compactness of the asphalt mixtures. These factors may lead to lower density or higher void content, resulting in asphalt mixes that do not meet the desired level of compactness as per the specifications.

To ensure compliance with the specification, further adjustments to the experimental mixes are necessary, specifically considering the factors that influence compactness. Fine-tuning these factors can help achieve the required level of compactness and improve the overall performance of the asphalt mixtures in practical applications.

4.10 Conclusion

In conclusion, this chapter provides comprehensive insights into the various aspects of asphalt mix formulation and performance evaluation. The study explored the concept of formulation, the design of experiments approach, and the input of design experiments. It analyzed the compactness, Marshall Stability, Flow Value, and Marshall Quotient of the asphalt mixes with different combinations of sawdust percentage, manufacturing temperature, binder content, and mixing time.

Regarding compactness, the study revealed that higher binder content, manufacturing temperature, and mixing time contribute to increased compactness, while a lower sawdust percentage also leads to higher compactness. The investigation into Marshall Stability highlighted the significant impact of interactions between binder content and sawdust percentage, emphasizing the importance of optimizing mix design for improved stability. The Flow Value analysis showed that sawdust percentage influences flowability, but adjustments in mixing time and manufacturing temperature can mitigate its negative impact. Lastly, the Marshall Quotient results demonstrated the importance of balancing factors like binder content and sawdust percentage to optimize asphalt mix performance.

The comparison of the experimental mixes to control samples and specifications further provided valuable information on the performance of the asphalt mixtures. While some experimental mixes did not meet the specification for compactness, the findings shed light on the influence of specific combinations of factors on asphalt performance. Adjustments to these factors can enhance the overall performance of the asphalt mixes.

This chapter underscores the significance of employing the design of experiments (DOE) with the support of Minitab software. This approach allows for a systematic exploration of factors (sawdust percentage, binder content, manufacturing temperature, mixing time) and their interactions to understand their impact on asphalt mixture performance. Minitab facilitates data analysis through various plots, helping rank factors' importance and optimize their levels for desired outcomes. The chapter emphasizes the control over mixture design and the ability to explore outer ranges of factors. Overall, the use of DOE and Minitab aids researchers in making informed decisions, leading to improved asphalt mixtures that meet performance requirements.

Overall, the chapter offers valuable guidance for optimizing asphalt mixtures with sawdust as an aggregate. The study emphasizes the significance of considering and adjusting factors within their appropriate ranges to achieve desired properties and meet specification requirements. These findings are crucial for making informed decisions in designing sustainable and high-performance asphalt mixtures for various applications.

General Conclusion

In this research, we embarked on a journey to explore the uncharted territory of using sawdust as a partial replacement for asphalt aggregate, with the ambitious goal of unveiling its vast potential and the manifold benefits it offers to the realm of road construction and beyond. Our study constitutes a pioneering effort to advance sustainable practices in the construction industry and foster environmentally conscious solutions to pressing challenges. Amidst global concerns about climate change, resource depletion, and the escalating costs of road construction, the imperative to find alternative, eco-friendly materials has never been more urgent. Our findings underscore that incorporating sawdust in asphalt mixes presents a win-win scenario, harmoniously intertwining environmental, economic, and engineering advantages.

The positive impact on the environment cannot be overstated. Traditional road construction methods have been notorious for their substantial carbon footprint, largely attributed to the mining, extraction, and transportation of natural aggregates. By substituting these non-renewable resources with sawdust, we can significantly mitigate the environmental burden and contribute to conserving precious natural habitats. This transformational approach aligns perfectly with global sustainability agendas and sets a new benchmark for eco-friendly construction practices.

From an economic standpoint, the implications are equally profound. Sawdust, a by-product that has often been relegated to the realm of waste management, now emerges as a cost-effective solution to the perennial challenge of balancing the budgetary constraints of road construction projects. By repurposing this abundant and often overlooked resource, we not only reduce waste disposal costs but also curtail the expenditure associated with procuring expensive natural aggregates. In doing so, we open doors to more economically feasible infrastructure development, ultimately benefitting taxpayers and governments alike.

The engineering benefits of incorporating sawdust into asphalt mixes are nothing short of remarkable. Our research demonstrates that this innovative approach leads to enhanced Marshall Stability and Marshall Quotient, key indicators of the pavement's performance and resistance to deformation under traffic loads. The consequent improvement in rutting resistance promises longer-lasting and more durable roads, ensuring reduced maintenance costs and enhancing overall road safety.

Furthermore, the low-density mixes achieved through the incorporation of sawdust present a unique opportunity to optimize the design and construction of low-traffic roads. The adaptability of this approach to diverse road types and varying traffic conditions provides engineers and planners with a versatile toolset to tailor road designs that align with specific requirements, further elevating the efficiency and functionality of the transportation network.

Indeed, as researchers, we acknowledge that our study represents only a starting point in exploring the vast possibilities of using sawdust as a partial replacement for asphalt aggregate. To delve deeper into the potential of this innovative approach, future studies can incorporate an array of advancements and additional tests to comprehensively assess the viability and performance of sawdust-based asphalt mixes.

One crucial avenue for future research is the inclusion of the Adventist test for asphalt mixes with sawdust. The Adventist test, known for its robustness and precision in evaluating the performance of asphalt mixes under various conditions, can provide valuable insights into the long-term behavior and durability of pavements containing sawdust. This would be particularly instrumental in assessing the performance of roads subjected to heavy traffic loads and extreme weather conditions, ultimately paving the way for the widespread adoption of sawdust-based mixes in high-traffic road networks.

Additionally, future studies can seek to discover the outer limits of factors such as sawdust percentage, binder content, manufacturing temperature, and mixing time. By pushing the boundaries and testing the extremes of these factors, researchers can determine the optimal combinations that yield the highest mechanical properties, stability, and resistance to rutting. Understanding the limitations and thresholds of these factors will provide engineers with critical guidelines for designing asphalt mixes with precise sawdust ratios and manufacturing parameters, thus maximizing the benefits of sawdust usage.

To further enhance the performance of sawdust-based mixes, future research can consider the incorporation of multiple sawdust sizes. This investigation would explore how variations in sawdust particle sizes affect the overall workability, compaction, and mechanical properties of the asphalt mixes. By selecting an ideal combination of sawdust particle sizes, researchers can tailor the mix design to achieve the desired engineering properties, providing greater flexibility in road construction and adaptability to diverse environmental conditions.

Furthermore, considering the potential interplay between sawdust and other natural fibers or additives can be another intriguing dimension for future studies. Combining sawdust with other eco-friendly materials may yield synergistic effects, enhancing the performance and eco-friendliness of the asphalt mixes even further. Such explorations could uncover new possibilities for sustainable road construction and pave the way for innovative engineering solutions that embody the principles of circular economy and waste valorization.

As the journey of research continues, we recognize that collaboration with other disciplines, such as material science and environmental engineering, can enrich our understanding of the full potential of sawdust as an aggregate replacement. Interdisciplinary studies could shed light on the long-term effects of sawdust usage on the environment, as well as explore ways to enhance the durability and resistance to aging of sawdust-based asphalt mixes. Future studies hold immense promise in unlocking the true potential of sawdust as a sustainable and cost-effective alternative in road construction. By incorporating advanced tests, considering multiple factors, and exploring innovative avenues, researchers can paint a comprehensive picture of sawdust's applicability and performance across a wide range of contexts.

However, to move forward with full confidence in this innovative approach, we recognize the need for more comprehensive testing, particularly pertaining to rutting and fatigue performance. These critical tests will furnish invaluable data for optimizing mix designs, determining the longevity of the pavements, and establishing a robust set of guidelines for incorporating sawdust in road construction standards.

As we set our sights on the horizon, the future of sawdust in road construction is replete with potential avenues for exploration and refinement. The notion of coupling alternative treatment methods for sawdust opens up exciting possibilities for enhancing its performance characteristics. Moreover, delving deeper into the evaluation of sawdust surface properties to calculate binder content will elevate the precision and accuracy of mix designs, paving the way for even greater advancements in road construction technology.

With our research serving as the catalyst, we envision a promising future for sawdust in road construction. The theoretical and practical implications of our findings make a compelling case for its widespread implementation. By conducting experiments in a Quality Control laboratory under realistic working conditions, we have ensured the reliability and transferability of our conclusions to real-world scenarios.

Looking ahead, the future of sawdust in road construction is promising. Our research has unveiled numerous possibilities for improvement and expansion. Further exploration of alternative treatment methods for sawdust, coupled with the evaluation of its surface properties to calculate binder content, will refine the process of incorporating this environmentally friendly material into asphalt mixes. Moreover, running extensive tests on rutting and fatigue will yield critical data for optimizing mix designs and ensuring long-term road performance.

In summary, our extensive research on sawdust as a partial replacement for asphalt aggregate presents a compelling case for its integration into road construction practices. Not only does it offer significant environmental benefits, but it also proves to be economically viable and enhances certain mechanical properties of the pavement. As we move towards more sustainable infrastructure development, sawdust stands out as a promising additive that can revolutionize the way we build and maintain roads, ensuring a greener, more cost-effective, and long-lasting road network.

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