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The Effect of Adding Iron Powder on Self- Healing Properties of Asphalt Mixture

أثر إضافة بودرة الحديد على خاصية المعالجة الذاتية للخليط الأسفلتي

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إقـــــرار

أنا الموقع أدناه مقدم الرسالة التي تحمل العنوان:

The Effect of Adding Iron Powder on Self- Healing Properties of Asphalt Mixture

أثر إضافة بودرة الحديد على خاصية المعالجة الذاتية للخليط الأسفلتي

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أثر اضافة بودرة الحديد على خاصية المعالجة الذاتية للخليط الأسفلتي

The Effect of Adding Iron Powder on Self-healing Property of Asphalt Mixture

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DEDICATION

I am proudly dedicate this thesis to my beloved father & mother for their unlimited support ..

With love & respect …

Researcher: Mousa Alakhrass

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ABSTRACT

Asphalt Pavement needs continuous maintenance to maintain the required level of performance, especially in urban areas where the need for maintenance increases due to the exposure of huge loads that cause serious deteriorations. Therefore, the need for a stronger and less costly way to maintain asphalt has been an important issue to private and governmental organizations. This research aims to study the effect of adding iron powder on the property of the self-healing of the wearing layer in the asphalt mix. Several experiments have been conducted on aggregates such as sieve analysis, specific gravity and absorption. Other tests have been conducted to identify the different characteristics of the iron powder such as density and other physical properties. In addition, other tests were done to evaluate the binder material (bitumen) in order to check its validity as a binding agent in the asphalt mixture. Asphalt mixes have been prepared with optimum bitumen content and by adding varies contents of iron powder to asphalt mixture. Iron powder were added to asphalt mixture by various concentrations (0, 2.5, 5, 7.5 and 10%) by replacement of trabia (0/4.75) content (which have the nearest grading to iron powder), and a number of 20 samples were prepared by these concentrations (four samples for each concentration), then samples were fractured by flexural fracture machine after cooled to -20ºC, after that samples were heated by induction heating device (Microwave) for fixed time interval to each sample, temperatures of samples were recorded, and again samples were fractured after cooled, flexural forces were recorded. This operation were repeated by varying the time interval of induction heating to asphalt samples, results were recorded and analyzed. A comparison between temperatures and flexural forces of samples were made to investigate the effect of adding iron powder on self-healing properties of asphalt mixture. Results shows that adding iron powder to asphalt mix improves its self-healing properties by accelerating the heating of mixture resulting from induction heating, and samples with 7.5% iron powder concentration presented the strongest bonding among others after getting heated by induction.

ملخص البحث

تحتاج رصفات الأسفلت إلى صيانة مستمرة للحفاظ على مستوى الاداء المطلوب، وخاصـة فـي المنـاطق الحضـرية، حيث تـزداد الحاجـة إلـى الصـيانة بسبب تعـرض طبقـات الرصـف للأحمـال الضـخمة التـي تسـبب اهتراءات وتشققات للطبقة الاسفلتية. ولذلك، كانت الحاجة إلى طريقة أقوى وأقل تكلفة للحفاظ على الأسفلت مسألة هامة للهيئات الخاصة والحكومية. يهدف هذا البحث إلى دراسة تأثير إضافة برادة الحديد على خاصية المعالجة الذاتية للطبقات الاسفلتية. تم اجراء عدة تجارب على الحصويات، مثل التحليل المنخلي، والكثافة النوعية والامتصاص. كما أجريت اختبارات أخرى لتحديد الخصائص المختلفة لبرادة الحديد مثل الكثافة والخصائص الفيزيائية الأخرى. وبالإضافة إلى ذلك، أجريت اختبارات أخرى لتقييم مواد الربط (البيتومين) من أجل التحقق من فعاليتها كمادة رابطة في الخليط الأسفلتي. تم إعداد خليط الأسفلت وفقا للمواصفات القياسية متبوعة باختبار عينات الأسفلت للحصول على قيم الثبات والتدفق والكثافة النوعية. تم إضافة برادة الحديد إلى خليط الأسفلت بتركيزات مختلفة (0، 2.5، 5، 7.5، 10٪) عن طريق استبدال محتوى الترابية لخليط الأسفلت (وهو أقرب تدرج إلى برادة الحديد)، وتم تحضير 20 عينة من الأسفلت بواسطة هذه التركيزات (أربع عينات لكل تركيز)، ثم تم كسر العينات بواسطة جهاز الكسر بعد التبريد إلى درجة حرارة 20- لضمان كسر هش للعينات، بعد ذلك تم تسخين العينات عن طريق جهاز الحث الحراري (الميكروويف) لمدة زمنية ثابتة لكل عينة، وتم تسجيل درجات الحرارة للعينات ، ومرة أخرى تم كسر العينات بعد تبريدها بنفس الطريقة السابقة ، ثم تم تسجيل قوى الكسر لكل عينة. تم تكرار هذه العملية كلها من خلال تغيير المدة الزمنية للحث الحراري لعينات الأسفلت، وتم تسجيل النتائج وتحليلها. تم إجراء مقارنة بين درجات الحرارة ونتائج قوة الكسر للعينات بتركيزات الحديد المختلفة لدراسة اثر إضافة برادة الحديد على خصائص المعالجة الذاتية لخليط الأسفلت. تظهر النتائج أن إضافة برادة الحديد إلى خليط الأسفلت يحسن خاصية المعالجة الذاتية للخليط الاسفلتي عن طريق تسريع تسخين الخليط الأسفلتي بواسطة الحث الحراري، كما تظهر النتائج ان اضافة محتوى 7.5% من برادة الحديد للخليط الاسفلتي هي النسبة المثالية، والتي اظهرت ترابط اعلى من باقي العينات ذات المحتويات الحديدية الاخرى بعد تسخينها بالطريقة المذكورة سابقا.

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ABBREVIATIONS

ASTM	American Society of Testing and Materials
d_{25}	Density of bitumen at $25^{o}C$
HMA	Hot Mix Asphalt
OBC	Optimum Bitumen Content
SMA	Stone Mastic Asphalt
SSD	Saturated Surface Dry Condition
Va	Air Voids
Vb	Bitumen Volume
VFB	Voids Filled Bitumen
VMA	Voids Mineral Aggregates
ρ_A	Density of Asphalt Mix
ρ_{bit}	Theoretical Maximum Density of Asphalt Mix
ρ_{min}	Density of Aggregate in the Blend

CHAPTER 1
INTRODUCTION

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1.1 Background

Asphalt concrete is one of the most common types of pavement surface materials used in the world. It consists of a mixture of asphalt binder material, aggregates, and air voids. In good conditions and under many different climatic conditions, this material must resist all traffic loads for a long time. Asphalt concrete wearing courses should be constantly maintained and repaired, in order to maintain these characteristics during its lifetime (Garcia et al., 2011a).

As a result of different factors, such as repeated traffic loads or freeze–thaw cycles, cracks may develop in the asphalt mixture. However, asphalt concrete is considered as a self-healing material, and once a crack is take place in the pavement, if enough energy is given to the system, it will start healing, and if it has enough time to complete the process, it can even close completely. This means that under special conditions, it has the ability to repair that damage. And as its healing properties are directly linked to the rest periods and temperature, So, it can be classified as a thermally induced self-healing material (Garcia et al., 2011b).

The concept of self-healing materials is related to their inherent ability to reverse damage that might have occurred during its service life such as small crack formation. Asphalt concrete is considered a self-healing material by itself, but it only works if there is no traffic loads. Also it has some limitations: it is a slow process at low temperature and not effective if the cracks are significant (Garcia, 2012).

The objective of this study is to investigate how asphalt concrete self-healing properties can be improved through the addition of different contents of electrically conductive particles. The idea is to use this self-healing asphalt concrete as a low maintenance cost pavement in the future.

1.2 Problem Statement

During the road service life and before its end, there are many degradation processes occurs, the stiffness of asphalt concrete increases while its relaxation capacity decreases, and as result, the binder material becomes more brittle, causing a micro-cracks and in a near future the cracking on the interface between binder material and aggregates occurs (Branthaver et al., 1993).

These typical distresses of asphalt pavement are resulted from the combination of traffic loads and oxidation. The oxidation process starts during the hot mixing process and continues through its service life. During the oxidative aging of the asphalt binder, the "solid" part increases (asphaltenes) and the "liquid" part decreases (maltenes), so the ratio of asphaltenes/maltenes is reduced, causing a dry and brittle asphalt concrete pavement (Lesueur, 2009; Zhang et al., 2011).

This dry and brittle pavement will lead to pavement failures, such as surface raveling and reflection cracking. These failures increase the expense of pavement maintenance and preservation of bituminous pavements and reduce important parameters such as safety.

In order to prevent this type of pavement problems, many methods are being employed for asphalt pavement preservation. Induction heating of asphalt concrete which our study will be focused on, is considered a new and effective solution to override previously discussed asphalt problems.

Induction heating of asphalt concrete is a technique to increase the self-healing rate of the asphalt concrete material. It basically consists in adding electrically conductive fibers to the asphalt mixture. Then, with the help of an induction heating source, it is possible to heat the fibers locally, and as a result, to heat the asphalt pavement and to heal the cracks (Hassan, Aisha and Ramlawi, 2016).

But, adding steel wool (electrically conductive fibers) to the asphalt mix greater than the optimal content (4.33% by the study) causes nesting (clusters) in the mixture which reduces the stability of mix due to the higher air void percentage (Hassan, Aisha and Ramlawi, 2016).

Therefore, and to decreases the disadvantages of adding steel wool additions to asphalt mix, this research deals with studying the effects of adding iron powder (Small steel particles with diameter(0-0.60 mm) to asphalt mixture to investigate the effect of adding these iron particles on self-healing property of asphalt mix, Especially similar researches in this field are scarce, through that relationship between iron powder additions to asphalt mix and its self-healing property is investigated.

1.3 Aims And Objectives

Research Aim

The aim of this research is to investigate the possibility of using conductive materials such as iron powder to enhance the self-healing properties of asphalt.

Research Objectives

To achieve the aim of this research there is many objectives, these objectives can be summarized as bellow:

- To investigate the effect of iron powder additions to asphalt mix on self-healing property of asphalt mixtures.
- To Identify the optimal ratio of iron powder that's enhances the self-healing property of asphalt.

1.4 Importance of the Study

- Introducing an effective and economical solution for repairing cracks in asphalt concrete by improving the self-healing property of asphalt mix.
- Determining the effect of addition iron powder to asphalt mix on self-healing property of asphalt and other asphalt mix properties .
- Comparing research results with similar international research result.
- Helping asphalt industry to make decision for determining the optimum content of iron powder to the asphalt mixture that may be helpful to enhance its properties.
- Contributing in reduction of iron powder waste, resulting from factories, mills and metal workshops.

1.5 Research Contribution

From the previous studies, it should be noticed that the researchers studied the effects of using only steel wool additions to enhance the self-healing property of asphalt. This study focused on using iron powder to investigate the effect of these additions on enhancing the self-healing property of asphalt mixture.

1.6 Methodology

To achieve study goals, implementation would include the following:

1. Literature review of previous studies which include revision of scientific papers and reports in the field of self-healing asphalt, asphalt mix design, asphalt production technology, and asphalt raw contents specifications.
2. Site visits to iron workshops and investigations of the iron powder waste production to get more information and to collect samples.
3. Study of iron powder properties.
4. Identifying optimum bitumen content (OBC) using marshal mix design procedure. Four percentages of bitumen have been examined to determine the optimal content of bitumen for asphalt mixture, which represent 5.0, 5.5, 6.0 and 6.5% by the total weight of the mixture.
5. Making a number of 20 beam shape asphalt samples (16.0*4.0*4.0 cm), with different concentrations of iron powder (0.0, 2.5, 5.0, 7.5 and 10%) which have been added to asphalt mix " four samples for each concentration " .
6. Make each sample fractured after freezing samples to -20 ºC.
7. Each sample was heated at a fixed period of time by induction heating device (microwave), and the resulted temperatures were recorded.
8. Make each sample fractured again after getting cooled and breaking points forces were recorded. Healing rates of samples were calculated, this will guide to study the effect of adding iron powder on self-healing property of asphalt mix.
9. Discussion of testing results.
10. Conclusion and recommendations.

1.7 Thesis Layout

This study consists of six chapters arranged and briefly described as follows:

Chapter (1): This chapter shows General Background, Problem Statement, Research Objectives, Importance of the Study, and the Methodology of the work.

Chapter (2): This chapter summarizes the Literature Review for previous studies of self-healing asphalt.

Chapter (3): This chapter describes the evaluation processes of used materials properties such as aggregates, bitumen and iron powder. And summarizes the primary experimental work which has been done to get an optimal asphalt mixture that will be used in further experimental work.

Chapter (4): This chapter describes samples preparation method, and experimental works which has been done to achieve study aims.

Chapter (5): This chapter discusses the test results and analysis of all experimental results obtained from the testing procedures.

Chapter (6): This chapter summarizes the Conclusion and Recommendations of the research.

CHAPTER 2
LITERATURE REVIEW

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

Asphalt pavement is a composite material consisting of mineral aggregates, binder material and air voids. The load-carrying behavior and resulting failure of such material depends on many mechanisms that are mainly related to the local load transfer between aggregate particles (Sadd et al., 2004).

The increase in traffic volume in combination with an insufficient degree of maintenance and difficulties in supplying high quality materials due the siege imposed on Gaza strip has caused an accelerated and continuous deterioration to asphalt pavements in Gaza strip. To solve this, several ways may be effective, e.g., securing funds for appropriate maintenance, improved design of roadways, better control of materials quality and the use of more effective construction methods (Awwad & Shabeeb, 2007).

Asphalt pavement performance is affected by several factors, the properties of asphalt components (binder material, aggregate and additives) and the proportion of these components in the asphalt mixture. The performance of asphalt mixtures can be improved with the utilization of various types of additives, these additives include: polymers, latex, fibers and many chemical additives (Taih, 2011).

2.2 Hot Mix Asphalt

Hot-Mix Asphalt (HMA) is the most widely used paving material around the world. It's known by many different names: HMA, bituminous concrete, asphaltic concrete, bituminous mix, plant mix, and many others. It is a combination of two primary ingredients, aggregates and binder material. Aggregates include both coarse and fine materials, typically a combination of different size rock and sand. The aggregates total approximately 95% of the total weight of asphalt mixture. They are mixed with approximately 5% asphalt binder to produce HMA. By volume, a typical asphalt mixture have about 85% aggregates, 10% asphalt binder, and 5% air voids. Additives may added in small amounts to many asphalt mixtures to enhance their performance or workability. Because asphalt concrete pavement is much more flexible than Portland cement concrete pavement, asphalt concrete pavements are called flexible pavements (Advanced Asphalt Technologies, LLC. 2011).

Asphalt concrete pavements are engineered structures composed of a group of layers of specific materials that is positioned on the in-situ soil (Sub Grade). Figure (2.1) shows a vertical section of typical asphalt concrete pavement structure.

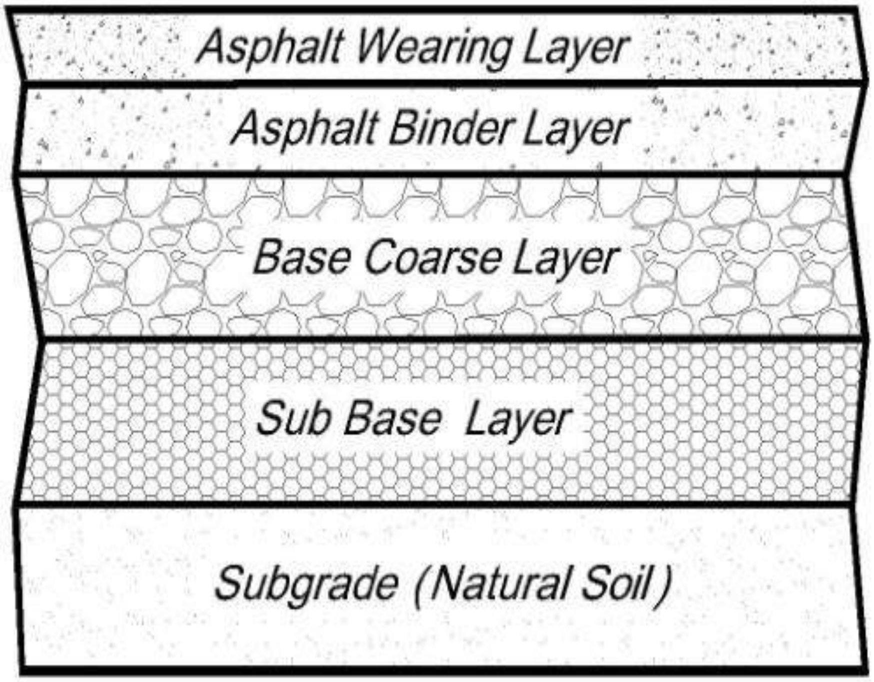

Figure (2.1): *Vertical section of asphalt concrete pavement structure*

2.2.1 Basic materials in hot mix asphalt

2.2.1.1 Aggregates

Aggregates (or mineral aggregates) are hard, inert materials such as sand, gravel, crushed stone, slag, or rock dust. Properly selected and graded, aggregates are mixed with the cementing medium asphalt to form pavements. Aggregates are the principal load-supporting components of HMA pavement. Typically they total ninety to ninety five percent of the mixture by weight and 75 to 85 percent by volume (Colorado Asphalt Pavement Association, 2015).

2.2.1.2 Asphalt binder (bitumen)

Asphalt binder (bitumen) which bonds aggregates together in HMA is thick, heavy material, remaining after refining crude oil process. Asphalt binder mostly consists of carbon and hydrogen, with small amounts of oxygen, sulfur, and different types of metals. The physical properties of asphalt binder vary considerably with temperature. At high temperatures, asphalt binder is a fluid with a low consistency similar to that of oil. At room temperature most asphalt binders will have the consistency of soft rubber. Below zero temperatures, asphalt binder can become very brittle. To improve their physical properties, many asphalt binders contain small percentages of polymers, these materials are called polymer modified binders. Most of asphalt binder specifications was designed to control changes in consistency with temperature (Advanced Asphalt Technologies, LLC. 2011).

2.2.2 Desirable properties of asphalt mixes

Mix design seeks to achieve a set of properties in the final asphalt mix product. These properties are related to some or all contents of asphalt mix which include asphalt binder content, asphalt binder characteristics, aggregate characteristics such as gradation, texture, shape and chemical composition and degree of compaction. Some of the desirable properties of asphalt mixes are listed below with brief description of each (Lee et al., 2006):

a) Resistance to permanent deformation: At high temperatures and long times of loading. the asphalt mix should not be distort or displaced when subjected to traffic loads.

b) Durability: Asphalt mix must be capable to resist weathering effects (both air and water) and abrasive action of traffic. The mix should contain sufficient asphalt cement to ensure an adequate film thickness around the aggregate particles.

c) Fatigue resistance: The asphalt mix should not cracked when it is subjected to repeated loads over a period of time.

d) Skid resistance: Particularly under wet weather conditions, the asphalt mix should have sufficient resistance to skidding. Properties of aggregates such as shape, size and texture, are all factors related to skid resistance.

e) Workability: The asphalt mix should be capable of being placed and compacted to specific density with reasonable compacting effort.

f) Resistance of moisture damage: Asphalt mix should not be degraded substantially from moisture penetrating the mix.

g) Low noise and good drainage properties: This properties of asphalt mix is important for the wearing layer of the asphalt pavement structure.

h) Resistance to low temperature cracking: This property of asphalt mix is important in cold areas.

2.3 Self-Healing of Asphalt Concrete

2.3.1 Concept of self-healing

Self-healing can be defined as the built-in ability of a material to automatically heal (repair) the damage occurring during its service life. Self-healing materials are a type of smart materials that have the ability to repair damages caused by mechanical usage (Such as traffic loading) over a period time. This inspiration comes from biological systems, which have the ability to heal after being wounded. Formation of cracks and other types of damages on has been shown to change electrical, thermal, and acoustical properties, and finally lead to large scale failure. Usually, cracks are repaired by hand, which is considered unsatisfactory because cracks are often hard to be detected by simple ways. A material that have the own ability to correct damage caused by normal usage could lower costs of different industrial processes through extension of lifetime, prevent costs incurred by material failure, as well as reduction of inefficiency over time caused by degradation (Ghosh, 2009).

2.3.2 Self-healing methods

Two effective new ideas are used to increase the self-healing rates of asphalt concrete: Induction heating of asphalt concrete and microcapsules filled with a healing agent. Both types are used to extend the lifetime of the road. Furthermore, healing by bacteria is considered a relatively old method.

2.3.2.1 Bacteria

Bacteria was first investigated to act as a self-healing agent in cement concrete. The idea to use bacteria and integrate them in the concrete matrix may seem odd at first, but it is not from a microbiological viewpoint .

Bacteria naturally virtually exist everywhere on earth, not only on its surface but also deep within. Various types of so-called extremophilic bacteria, i.e. bacteria that love the extreme, are found in highly desiccated environments such as deserts, but also inside rocks and even in ultra-basic environments which can be considered homologous to the internal concrete environment. There are some specialized cells which are characterized by an extremely low metabolic activity, are known to be able to resist high mechanically- and chemically induced stresses and are viable for periods of up to 200 years. Some published studies discussed the application of bacteria for strength improvement of cement-sand mortar and cleaning of concrete surfaces was reported. Although promising results were reported, the major obstacle of the latter studies was that the bacteria and compounds needed for mineral precipitation could only be externally applied on the structures surfaces after formation of cracks had occurred. This methodological necessity was mainly due to the limited life-time (hours to a few days) of the urease-based enzymatic activity and/or viability of the applied bacterial species (Schlangen, 2013).

Since bacteria method didn't find success in self-healing concrete production, it is more unlikely to be used in asphalt as a self-healing agent also due to the higher temperature of production in asphalt compared to concrete which causes bacteria cells to die.

2.3.2.2 Capsule method

Bitumen can be considered as a two phase material with a solid phase, called asphaltenes, and a liquid phase, called maltenes. over time, the liquid phase is to be oxidized, causing asphalt concrete to become dry and brittle. To avoid this dry resulted asphalt, and after signs of ageing start appearing, liquid bitumen (maltenes) have been traditionally added to the road surface.

This type of treatment is applied superficial, only on the first centimeters from the surface are affected, which considered fairly not effective. To solve this, it was thought that the optimum way of adding liquid bitumen (maltenes) to the road asphalt pavement would be by mixing asphalt mixture ingredients with capsules filled with maltenes. With this, aging effects over the complete depth of the pavement could be avoided. The idea is that when a crack close to a capsule containing maltenes occurs in the pavement material, the capsule will break and opened, then maltenes will flow and be in contact with the bitumen around. Then, both maltenes and damaged bitumen will be mixed by diffusion. The pavement old bitumen will be rejuvenated and the crack will close easily. With this method of using capsules, the self-healing rate of asphalt pavement is increased a lot compared to the autogenic self-healing capacity of the asphalt (Schlangen, 2013).

2.3.2.3 Induction Heating

The idea of this method that is asphalt could be heated with induction energy to increase its healing rate. The first prerequisite of induction heating is that the heated material must be conductive. In many previous studies it has been shown that it is possible to make asphalt conductive material by adding electrically conductive fibers and fillers. The second prerequisite is that these fibers and fillers should be connected in closed-loop circuits. When a micro crack occurs in the bitumen. If enough amount of conductive fillers or fibers is added to the bituminous material, A closed-loops circuits all around the micro crack will be formed. If this electrically conductive and magnetically susceptible materials is placed in the vicinity of a coil, eddy currents are induced in a closed-loops circuits, with the same frequency of the applied magnetic field. When eddy currents meet with the resistance of the conductive materials, heat is generated through the energy lost, and as a result, the bitumen is melted and the micro crack is closed (Schlangen, 2013).

2.4 Induction Heating of Asphalt Concrete

2.4.1 Induction heating technology

Induction heating technology nowadays is considered the heating technology of choice in many domestic, industrial, and medical applications because of its advantages regarding fast heating, efficiency, cleanness, safety, and accurate control. Advances in key technologies, i.e. power electronics, magnetic component design and control techniques, have allowed the development of highly, reliable and cost-effective systems, making this technology readily available and ubiquitous. (Lucía et al., 2014).

Induction heating technology provides efficient, contactless, and fast heating of electrically conductive materials. It becomes one of the preferable heating methods in domestic, industrial, and medical applications, among other methods, due to its numerous advantages when compared with other traditional heating techniques such as flame heating, resistance heating or classical ovens or furnaces. Figure 2.2 shows a typical structure of an induction heating system.

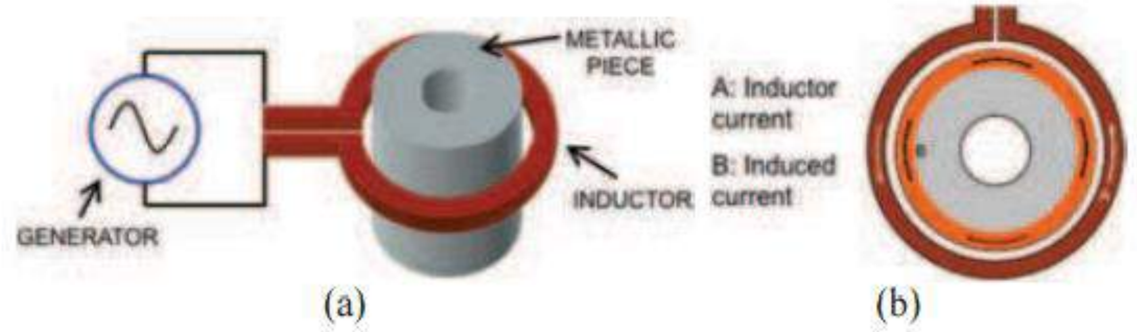

Figure (2.2): *Typical structure of an induction heating system: (a) general view and (b) top view.*

An alternating current (AC) source is used to supply the induction heating coil with an alternating voltage which generates a magnetic field, in which the induction target, i.e. the load, is immersed. Which consequently heated the induction target by means of two physical mechanisms: magnetic hysteresis and eddy currents. Eddy currents oppose to the magnetic field which applied to the induction target, and as a sequence, generate the heating by Joule effect. This is mainly considered the heat source in processes of induction heating (Lucía et al., 2014).

The followings are the commonly advantages of induction heating technology:

- **Fast heating**: at induction heating technology, induction target is directly heated, which reducing wasted heat and also reducing heating times resulted of high power densities and without any thermal inertia.
- **Efficiency and high heating temperatures**: Modern and efficient designs of the magnetic coils and the power converters guides to efficiency values upper than 90%, which significantly improving conventional heating processes. Moreover, since the induction target is only be heated, the heat loss through the ambient and surrounding elements of target is minimized and as a result high temperatures can be reached.

- **Heating control**: The location and power applied by the system of induction heating can be controlled accurately by the proper design of the magnetic coil and the power converter. Consequently, advanced features can be applied such as local heating, predetermined temperature profiles, etc.
- **Improvement of industrial process**: induction heating repeatability and consistency maximizes productivity of the process and improves quality control process. Also, since induction heating is a contactless heating process, the induction target is not affected by the heating tool, i.e. the coil, and the quality is ensured.
- **Safety and cleanness**: Induction heating directly heats the induction target, As a result, the temperature of the surroundings of the heating area is lower. Moreover, there is no local pollution unlike fossil fuel furnaces. These advantages, and the progress achieved in induction heating technology in recent years, have promoted applications of induction heating that can be categorized into domestic, industrial, and medical applications (Lucía et al., 2014).

2.4.1.2 Mechanism of induction heating process

A source of high frequency electrical current is used to supply a large alternating current (AC) through a coil. Which is known as the work coil. The alternating current passages through this coil generates a rapidly changing and very intense magnetic field in the surrounding of the work coil. The target to be heated is placed within this intense alternating magnetic field. A number of things happen depending on the nature of the target material (Kennedy et al, 2011).

The alternating magnetic field induces a current flow in the conductive target. The arrangement of the target and the work coil can be considered an electrical transformer. The work coil is like the primary where electrical energy is fed in, and the target is like a single turn secondary that is short-circuited. This will cause enormous amount of currents to flow through the target. Which is known as eddy currents. Moreover, the high frequency used in induction heating applications gives rise to a phenomenon called skin effect. Skin effect forces the alternating current to flow in a thin layer towards the target surface. This skin effect also increases the effective resistance of the metal to the passage of the large current. Thus, it greatly increases the heating effect caused by the induced current in the target (Alok & Kumar, 2011). Figure (2.3) shows a steel nut heated by induction heating coil.

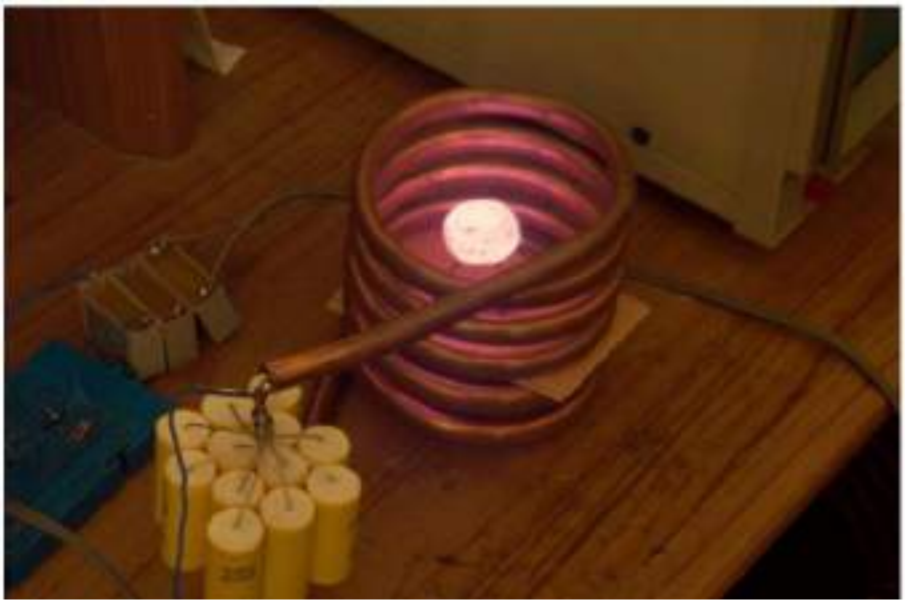

Figure (2.3): *Steel nut heated by induction heating coil*

2.4.1.3 Heating of ferrous metals

For ferrous metals like iron and some types of steel, there is an additional heating mechanism that takes place at the same time as the eddy currents. The intense alternating magnetic field inside the work coil repeatedly magnetizes and de-magnetizes the iron crystals. This rapid changing of the magnetic domains causes considerable heating and friction inside the target material. This heating mechanism is known as Hysteresis loss. This can be a large participating factor to the heat generated through induction heating process, but it takes place inside ferrous materials only. For this reason ferrous materials can more easily heated by induction than non-ferrous materials target (Alok & Kumar, 2011).

2.4.1.4 Magnetic induction heating of ferrous materials

The magnetic induction heating of ferrous materials is resulted from their power loss in alternating magnetic field. The total power loss is constitutes of three parts, eddy current loss , hysteresis loss, and residual loss. Eddy current loss is the Joule loss due to eddy current induced by the alternating magnetic field and hence depends much on the electrical resistivity of the material. Hysteresis loss is a result of the irreversible magnetization process in alternating current magnetic field. The physical origin of residual loss is more complicated. The residual loss cannot be separated straight forwardly from eddy current loss, nor even from hysteresis loss easily. However, most ferrous materials have higher electrical resistivity, leading to very low eddy current loss. For this reason, the magnetic induction heating of ferrous materials is significantly caused by the hysteresis loss and residual loss in alternating magnetic field. The residual loss is comes from various relaxation effects of magnetization in magnetic field. For that, it is also called relaxation loss. In some low loss ferrous materials, the relaxation effect shows resonance at certain high frequencies (Zhang and Zhai, 2011).

2.4.2 Using induction heating in asphalt concrete

Asphalt concrete is considered a self-healing material. This illustrated by the fact that under special conditions, it has the ability to repair its own damage. And, as its healing properties are directly linked to temperature and to the rest periods it can be classified as a thermally induced self-healing material. Damages like cracks may develop in the asphalt concrete pavement as a result of numerous factors, such as repeated traffic loads or surrounding temperature variations. However, once a crack is take place in the asphalt pavement, if enough energy is given to the system, it will start healing process, and if enough time given to the process, it may even close completely (García et al., 2012).

For this reason, induction heating of asphalt concrete is a technique used to increase the self-healing rate of asphalt concrete. It basically consists in adding electrically conductive materials like fibers or fillers to composition of the asphalt concrete mixture. Then, with the help of an induction heating source, it is possible to heat the conductive materials locally and as a result, to heat the pavement and to heal the cracks. it was discovered that there is a maximum volume of conductive materials that can be added to the mixture without damaging its properties, also it was discovered that any volume of conductive materials would contributes in increasing the temperature by induction heating mechanism, but there is a maximum volume of conductive materials that above this volume the temperature does not increase any more (García et al., 2012).

2.4.3 Laboratory studies related of induction heating of asphalt mixes

Jendia et al. (2016) added steel wool to asphalt samples with different ratios, steel wool content by 4.33% of bitumen content, showed the best thermal and electrical conductivity. The results also showed that it is possible to use steel wool in the preparation of asphalt wearing layers to enhance the self-healing property by heat induction. A comparison between the samples was held by visual inspection to assess the bonding between the fractured surfaces of the broken asphalt samples. Asphalt samples with steel wool content of 3 and 5 % presented the strongest bonding among the different percentages.

Dai et al. (2013) have evaluated the healing capacity of electroactive asphalt mastic and concrete beam samples with induction heating by adding electrically conductive steel wool fibers to the asphalt mix. The electrically conductive steel wool fibers were mixed with asphalt components to heat the surrounding binder material through induction energy. To investigate the performance of induction healing, asphalt mastic and concrete beam samples were prepared by adding steel wool fibers with an approximate length of 6.5 mm. Then, the mastic beams were tested with fracture-healing cycles under the three-point bending test and induction healing process after all samples were cooled in the freezer for 6 hours at -20 ºC. The test results presented that the healing process increases with the heating temperatures (60 C, 80 C and 100 C). The temperature distribution in the samples at the end of the healing procedure is also captured. Overall, it was found that the asphalt mixture samples still maintained at least half of the original fracture strength after six fracture-healing cycles. The experimental results indicate that the induction healing techniques have promises in elongating the pavement service life.

Garcia (2012) has studied the Self-healing of open cracks in asphalt mastic, in order to achieve this, number of asphalt mastic beams were fractured and healed at different temperatures and the time to complete the recovery was used to calculate the activation energy. It has been concluded that the asphalt mastic healing rates increase with the increase of temperature. And as a result, the mechanical resistance of asphalt mastic can be fully recovered when it is cracked. For this reason, it is necessary to heat this material for a fixed time and above certain temperature. If the heating time is less than this certain temperature, the crack will not be fully recovered, however if the heating time is too long, the mechanical resistance of the material will decrease. Besides, there is a minimum temperature bellow which material cannot be healed. It seems to coincide with the temperature when bonding material (bitumen) starts proceeding as a Newtonian fluid. Furthermore, it has been noticed that healing of asphalt beams happens when some points of both faces of a crack are in contact.

Capillary phenomena between both faces of the crack will start from these contact points and it will extend through the crack. Healing is faster in deeply buried crack, and capillary process will happen even if asphalt material is not under compression.

García et al. (2013) have added electrically conductive particles to the asphalt mixture, which is then heated with an induction heating device. Different mixtures, with different lengths, quantities and diameters of steel wool fibers have been considered. It was found that healing rates of asphalt concrete increase with the increase of temperature, and 60% of the original samples strength could be recovered.

García et al. (2011) used induction heating to increase the lifetime of asphalt concrete pavements. By the addition of conductive fibers, asphalt concrete have been made electrically conductive. Then it have been heated by induction energy. It has been found that it is necessary to add electrically conductive fibers in order to heat mastic with induction. And there is an optimum volume of fibers, above which the heating process does not increase any more, the electrical resistivity remains constant or is reduced and clusters of fibers start appearing in the asphalt mixture, which guides to non-uniform heating. This optimum volume of conductive fibers coincides with the volume needed to have the maximum conductivity in the asphalt mixture. Below this optimum value, the mixture electrical resistivity lower to that of a non-conductive material, but mixture can still be heated due to its local conductivity.

Liu et al. (2011) Made several tests to detect the healing effect of asphalt mastic and porous asphalt concrete caused by induction heating. It was concluded that the fractured mastic beams could be healed many times by induction heating process. Moreover, when induction heating was applied to the samples, the stiffness of porous asphalt concrete recovered more and faster. It was also found that by induction heating technique, lifetime of porous asphalt concrete was significantly extended.

Based on these conclusions, it was proved that the self-healing rate of porous asphalt concrete and asphalt mastic can be improved by induction heating.

2.5 Iron Modified Asphalt Mix

Asphalt Concrete mixture is exposed to to many external forces during its lifetime which may eventually lead to damages. Different types of damaged have been observed in asphalt concrete mixtures such as fatigue failure, permanent deformation (rutting), and low temperature cracking. Fatigue failure is a common damage in asphalt mixtures which appears in the form of cracking, Fatigue resistance is the ability of asphalt mixture to resist repeated forces without forming cracking and fracture (Moghaddam et al., 2012).

Iron powder and blast furnace slag can be helpful in increasing the interlocking between stone particles of asphalt concrete due to their shapeless coarse fabric structure and external characteristics. A research carried out in 2008 concluded that the use of iron powder in asphalt concrete can improve its service life noticeably by increasing interlocking between aggregates (Arabani, and Mirabdolazimi, 2011).

2.5.1 Iron Waste Problem

The vast quantities of waste (such as glass, scrap tires, steel slag, blast furnace slag, plastics, demolition and construction wastes) accumulating in landfills and stockpiles around the world are causing disposal problems that have both financial and environmental expenses. Dealing with the increasing problem of disposal of these materials is an issue that requires coordination and commitment by all parties involved. A significant solution to a portion of the waste disposal problem is to recycle and reuse these materials in the construction of highways (Arnold et al., 2008).

The reuse of waste iron powder (WIP) will partially contribute in making solutions of waste disposal problem in the world by reducing the area of stockpiles and land used for landfill. Moreover by use of basic raw materials, natural resources to modify hot mix asphalts and improves its properties (Jendia, and Tabash, 2014).

2.5.2 Laboratory studies related of iron powder utilization in asphalt mixes

Several investigations have been carried out on integrating iron powder to asphalt mixtures by replacing a portion of asphalt aggregates by iron powder. Utilizing iron powder in asphalt mixtures may improve performance of asphalt pavements, and contributes in finding solutions for iron waste accumulation.

Jendia, and Tabash (2014) also studied the effect of Crushed Waste Iron Powder as filler and coarse sand in the asphalt Binder layer, several tests were made to investigate the applicability of using the waste iron powder as an asphalt binder in road pavements. Results showed that waste iron powder content of 5 % by weight of aggregate for asphalt mix is recommended as the optimum waste iron powder content for the improvement of performance of asphalt mix. Asphalt mix modified with this percentage has approximately 23% higher stability value compared to the conventional asphalt mix.

Wu et al. (2007) indicated that volume properties of Stone Mastic Asphalt (SMA) mixture with steel slag satisfied the related specifications, and after 7 days, expansion rate was below 1%. When compared with basalt aggregate, resistance to low temperature cracking and high temperature property of the SMA mixture were improved by using steel slag as aggregate. Also, SMA pavement with steel slag presented excellent performance on porosity and roughness. It is found that the porosity of steel slag is as large as 24 times of basalt (5.76% and 0.24%, respectively), which indicates that steel slag has a porous structure.

Arabani and Mirabdolazimi (2011) discussed using waste iron powder in hot mix asphalts (HMAs) improves their dynamic properties, use 2.36mm max size of iron powder, grains number of cycles needed for the failure at 250 kpa, 400 kpa and different temperature 5, 25, 40C with Percentage of waste iron powder 0, 4, 8, 12, 16%. Arabani and Mirabdolazimi results showed that the use of waste iron powder in asphalt mixtures can improve their dynamic properties while increasing the efficiency of the asphalt pavements, thus decreasing the total cost of road networks. Furthermore, the use of waste iron powder could be a helpful solution for a better and less-polluted environment.

Therefore, this research will study the effect of adding iron powder to asphalt mixture in order to enhance the self-healing properties of asphalt mixture and its other effects on mechanical properties of asphalt mixture. Especially similar researches in this field are scarce, through that relationship between iron powder additions to asphalt mix and its self-healing property is investigated.

CHAPTER 3
MATERIALS AND ASPHALT MIXTURE PREPARATION PROCEDURE

CHAPTER 3
MATERIALS AND ASPHALT MIXTURE PREPARATION PROCEDURE

3.1 Introduction

The main objective of this study is to evaluate the effect of adding iron powder on the self-healing property of asphalt mix, and due to importance of asphalt mixture contents, this chapter have been done to evaluate required properties of used materials such as bitumen, aggregates, and iron powder, and describe experimental works requires to reach an optimum asphalt mixture.

3.2 Laboratory Test Procedure

This study mainly based on laboratory testing procedure to achieve study goals.

All the testing is conducted using equipment and devices available in the laboratories of Islamic university of Gaza.

Laboratory tests were divided into several phases, which begin with inspection of the properties of used materials as bitumen, aggregates, and iron powder. Sieve analysis for each aggregate type was carried out to obtain the aggregate gradation, followed by blending of aggregates to get asphalt wearing layer gradation curve which have been used to prepare asphalt mix compatible with standards. Numerous of asphalt mixtures with different bitumen contents were prepared, and by marshal test an optimum bitumen content was conducted. Later in chapter 5, The optimum bitumen content should be used to prepare asphalt mixes modified with addition of different percentages of iron powder. Several tests were conducted to investigate the relationship between self-healing property of asphalt mix and iron powder content. Finally, results of laboratory tests were presented and analyzed. Figure (3.1) shows the flow chart of all laboratory testing procedure.

3.2.1 Materials selection

Materials used in this study are the ingredients asphalt concrete wearing layer and iron powder, table (3.1) presents prime and local sources of these materials. Figures (3.2) shows source of iron powder used in laboratory tests.

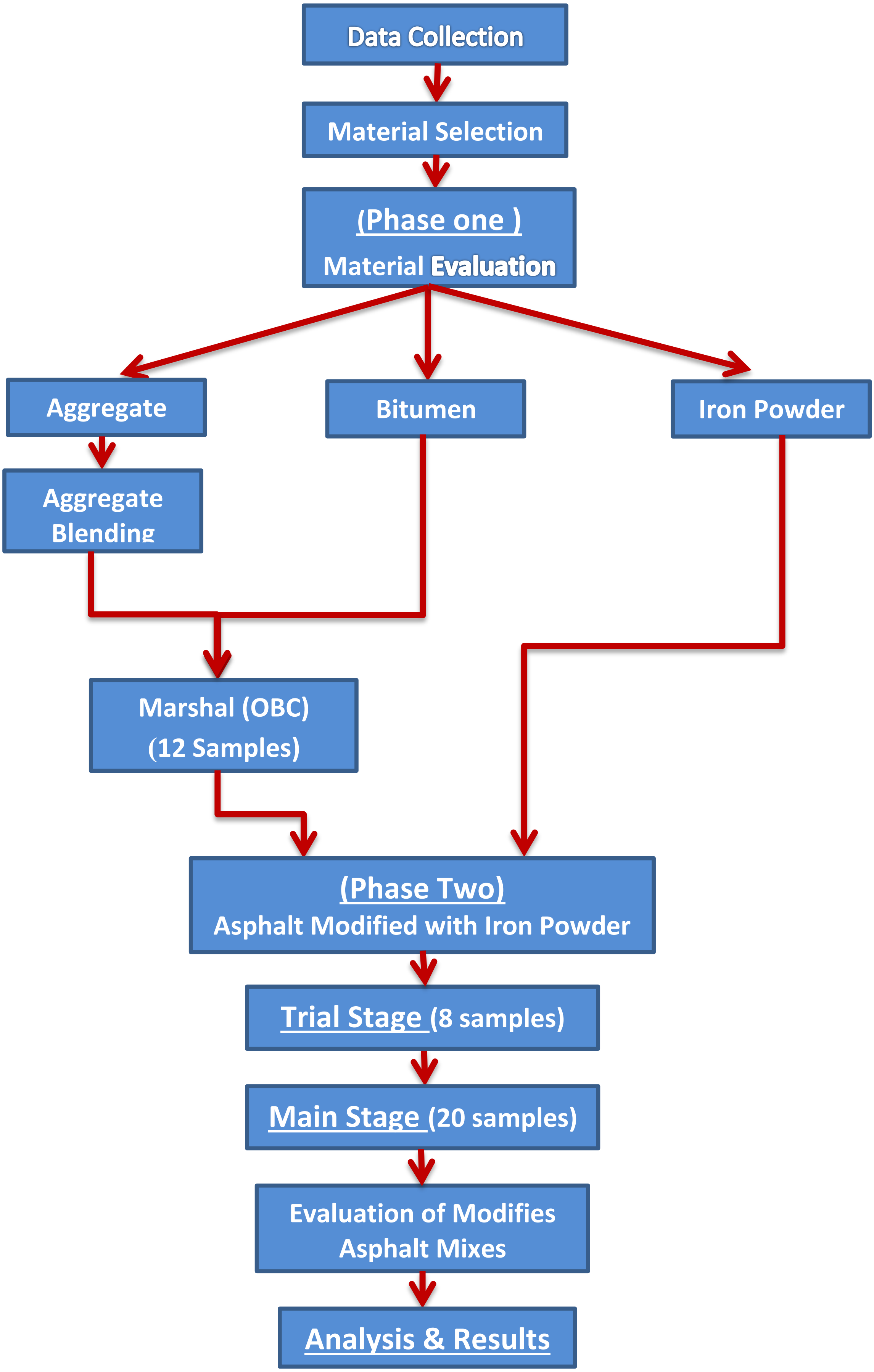

Figure (3.1): *Flow chart of laboratory testing procedure*

Table (3.1): *Prime and local sources of used materials*

Used Materials	Source	
	Prime	**Local**
Aggregate	Crushed rocks (Occupied lands)	Alqaood asphalt concrete plant (Johir El-Diek- Gaza Governorate)
Bitumen	(Pazkar factory) Occupied Lands	Alqaood asphalt concrete plant (Johir El-Diek- Gaza Governorate)
Iron powder	Occupied Lands	Bakr steel workshop (khan younis city)

Figure (3.2): Source of iron powder used in laboratory tests

3.2.2 Materials properties

3.2.2.1 Bitumen properties

Asphalt binder material (Bitumen) grade 60/70 was used. In order to evaluate bitumen properties number of laboratory tests have been performed such as: ductility, specific gravity, flash point, fire point, softening point and penetration.

- **Bitumen penetration test**

- Test specification : ASTM D5-95.
- Container dimension : 75 mm x 55mm.
- Test results is presented in Table (3.2).

Table (3.2): *Bitumen penetration test results*

	Sample No. 1			Sample No. 2		
Trial	1	2	3	1	2	3
Initial (0.1 mm)	73	74	73	70	71	71
Final (0.1 mm)	133	13	132	132	131	131
Penetration value (0.1 mm)	60	61	59	62	60	60
	60			60.67		
	Average = 60.33 (0.1 mm)					

Figure (3.3): *Penetration test for a bitumen sample*

- **Ductility test**

- Test specification : ASTM D113-86
- Test results are presented in Table (3.3).
- Figure (3.4) shows performing ductility test for samples of bitumen.

Table (3.3): *Bitumen ductility test results*

Sample	Ductility (cm)
A	151
B	150
C	151
Average	**150.33**

Figure (3.4): *Ductility test for a bitumen sample*

- **Softening point test**

- Test specification : ASTMD36-2002.
- Test results are presented in Table (3.4).
- Figure (3.5) shows performing softening point test for samples of bitumen.

Table (3.4): *Bitumen softening point results*

Sample	Softening point (C_o)
A	50.5
B	50.5
Average	**50.5**

Figure (3.5): *Softening point test for bitumen samples*

- **Flash and fire point tests**

- Test specification : ASTM D92-90
- Test results is listed in Table (3.5)
- Flash Point: The lowest temperature at which the application of test flame to the bitumen sample causes vapors from the bitumen to momentarily catch fire in the form of a flash.
- Fire Point: The lowest temperature at which the application of test flame to the bitumen sample causes the bitumen to fire and burn at least for five seconds.

Table (3.5): *Bitumen flash &fire point test results*

Flash point (Co)	311
Fire point (Co)	325

- **Specific gravity test**

- Test specification : ASTMD D70
- Test results is presented in Table (3.6).

Table (3.6): *Specific gravity test results*

Weight of sample (gm)	30
Weight of Pycnometer + water at 25ºC (gm)	1784.26
Weight of Pycnometer + Sample + water at 25ºC (gm)	1784.94

$$\text{S.G}=\frac{30}{(1784.26+30)-1784.94}= 1.023(\text{g/cm}^3)$$

- **Summary of bitumen properties**

Table (3.7): *Summary of bitumen properties*

Test	Specification	Results	ASTM specifications limits
Penetration (0.01 mm)	ASTM D5-06	60.33	60-70 (60/70) binder grade
Ductility (cm)	ASTM D113-86	150.33	Min 100
Softening point (oC)	ASTMD36-2002	50.5	(45 – 52)
Flash point (oC)	ASTM D92-02	311	Min 230o C
Fire point (oC)	ASTM D92-90	325	
Specific gravity (g/cm3)	ASTMD D70	1.023	0.97-1.06

3.2.2.2 Iron powder properties

Iron powder used in preparing modified asphalt samples was collected from residuals of mechanical cutting of iron steel members in a local industrial steel workshop.
Table (3.8), (3.9) and Figure (3.6), (3.7) display the iron powder properties such as size, gradation, density, melting point, ….etc.

Table (3.8): *Iron powder properties*

Property	Detail
Iron type	Grinded waste iron
Size (mm)	0-0.60
Density (g/cm3)	4.80
Melting point (°C)*	2750 ˚C

Table (3.9): *Iron powder sieve analysis results*

Sieve Size (mm)	Sieve #	Sample passing % Iron powder 0/ 0.60
2.00	# 10	100
1.18	# 16	100
0.600	#30	97.4
0.425	#40	91.7
0.300	#50	81.2
0.150	#100	46.5
0.075	#200	6.2

Figure (3.6): *Used gradation of Iron powder (0 – 0.60mm)*

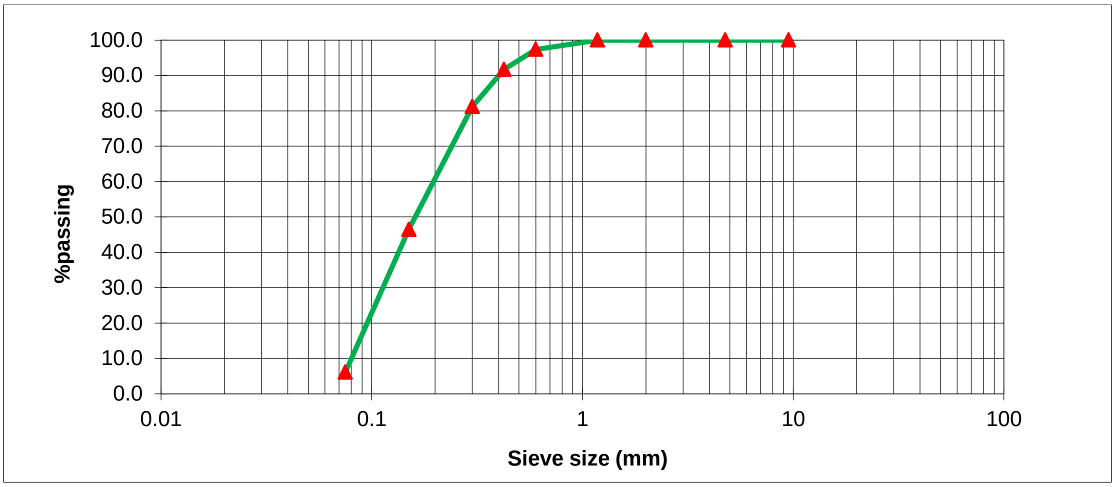

Figure (3.7): *Iron powder (0/ 0.60)*

3.2.2.3 Aggregates properties

Aggregates used in asphalt mix can be divided as shown in Table (3.10).

Table (3.10): *Types of used aggregates*

	Type of aggregate	Particle size (mm)
Course Agg.	Adasia	0/ 12.5
	Simsimia	0/ 9.50
Fine Agg.	Trabia	0/4.75
	Filler	0/1.18

In order to define the properties of used aggregates, number of laboratory tests have been done, these tests include:

a. Sieve analysis (ASTM C 136).

b. Specific gravity test (ASTM C127).

c. Water absorption (ASTM C128).

d. Los Angles abrasion (ASTM C131).

Table (3.11) present aggregate tests results.

Table (3.11): *Results of aggregates tests*

Test	Adasia 0/ 12.5	Simsimia 0/ 9.50	Trabia 0/4.75	Filler 0/1.18	Designation No.	Specification limits
Bulk dry S.G	2.54	2.57	2.58	--	ASTM : C127	--
Bulk SSD S.G	2.60	2.63	2.64	--		
Apparent S.G	2.70	2.74	2.74	--		
Effective S.G	2.62	2.66	2.66	--		
Absorption (%)	2.35	2.43	2.29	--	ASTM : C128	**< 5**
Abrasion value (%)	17.54	--	--	--	ASTM : C131	**< 40**

- **Sieve analysis**

- Specification (ASTM C 136).
- Table (3.12) and figures (3.8 - 3.11) show aggregates sieve analysis results.

Table (3.12): *Aggregates sieve analysis results*

Sieve Size (mm)	Sieve #	Sample passing %			
		Adasia 0/ 12.5	Simsimia 0/ 9.50	Trabia 0/4.75	Filler 0/1.18
19	**3/4''**	100.0	100.0	100.0	100.0
12.5	**1/2''**	91.4	100.0	100.0	100.0
9.5	**3/8''**	30.7	99.5	100.0	100.0
4.75	**#4**	0.4	56.1	98.6	100.0
2.00	**# 10**	0.2	4.8	92.2	100.0
1.18	**# 16**	0.2	1.1	67.1	99.7
0.600	**#30**	0.2	1.0	48.2	99.4
0.425	**#40**	0.2	0.9	38.7	98.9
0.300	**#50**	0.2	0.9	29.5	98.2
0.150	**#100**	0.2	0.8	15.9	94.2
0.075	**#200**	0.2	0.8	10.7	85.0

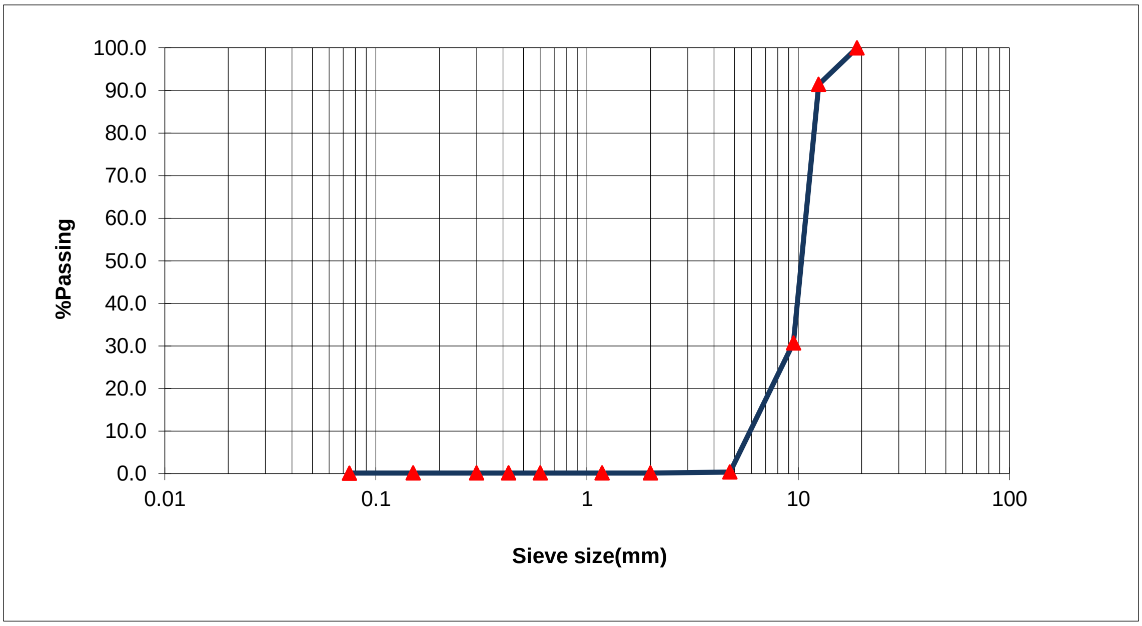

Figure (3.8): *Adasia (0/ 12.5)*

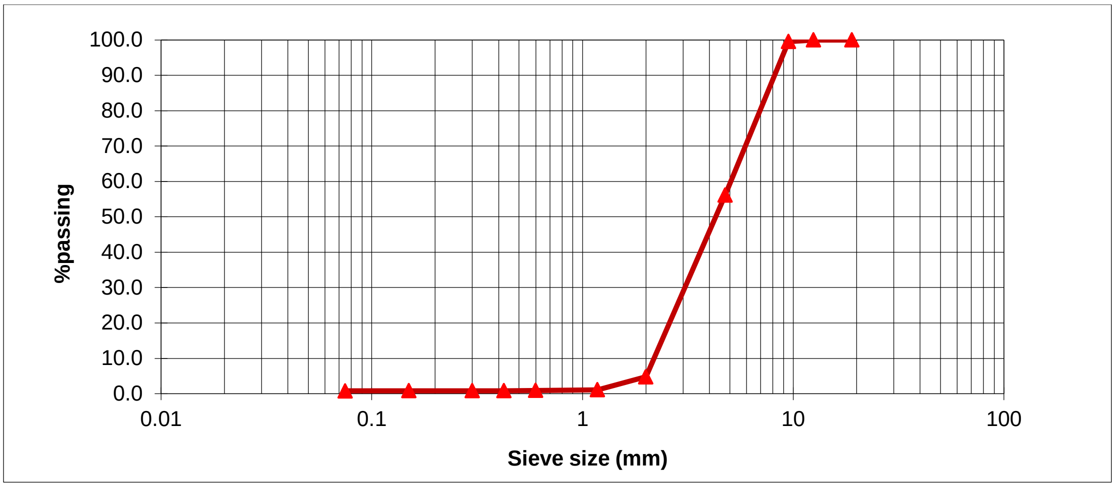

Figure (3.9): *Simsimia (0 / 9.5)*

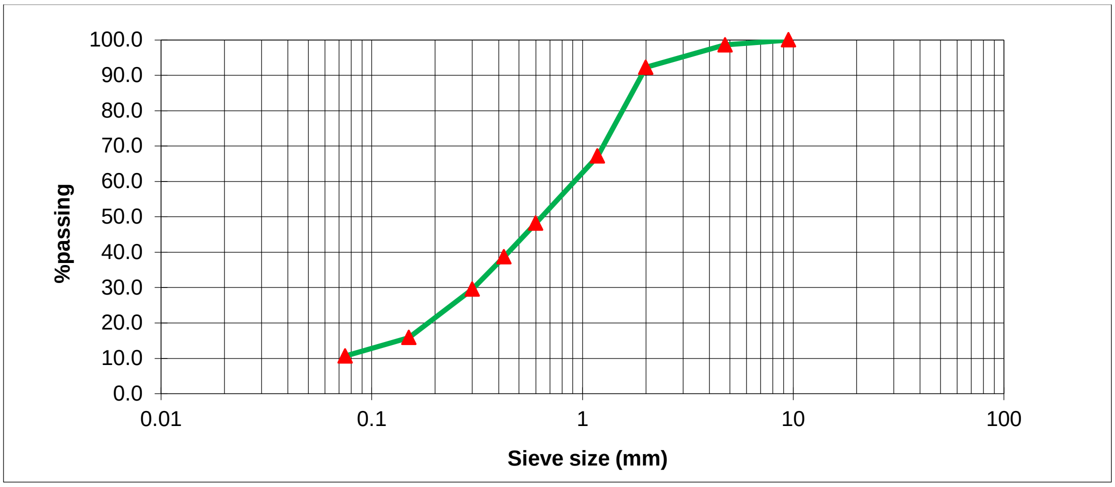

Figure (3.10): *Trabia (0 / 4.75)*

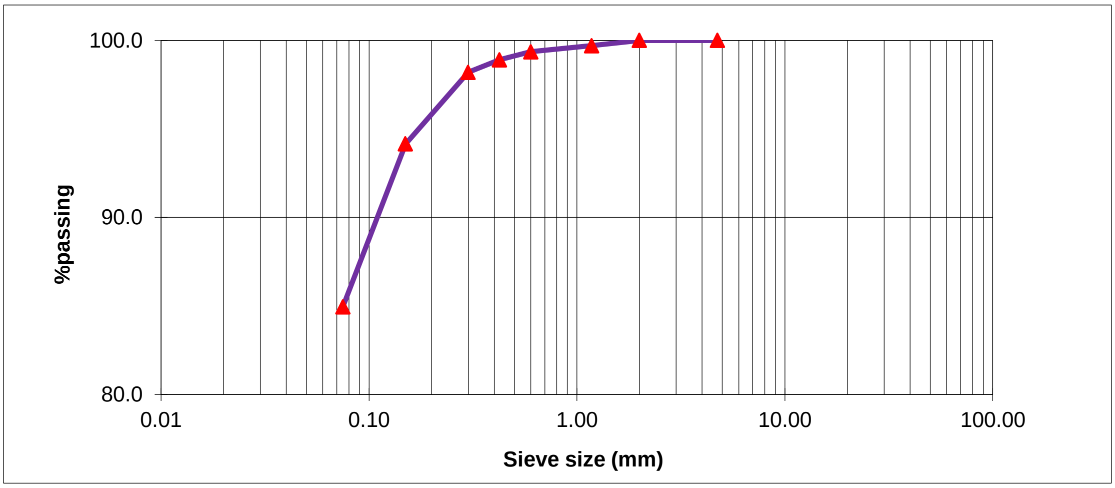

Figure (3.11): *Filler (0 / 1.18)*

3.3 Asphalt Mixture Preparation Procedure

3.3.1 Blending of aggregates

To produce an aggregate blend that meets gradation specifications for a particular asphalt concrete mix, asphalt mix requires the combining of two or more aggregate types, having different size gradations,.

Available aggregate size gradation (0/12.5), (0/9.5), (0/4.75) and Filler (0/1.18) are combined in different percentages in order to get the proper size gradation within the allowable limits according to ASTM specifications using mathematical trial method. This mathematical trial method depends on suggesting different trial proportions for aggregate materials from whole gradation. The percentage of each aggregate size is to be computed and compared to limits of ASTM specifications. If the calculated gradation is within the allowable specification limits, no more adjustments need to be performed; if not, an adjustment in the proportions must be performed and the calculations should be repeated. The trials are continued until the percentage of each size of aggregate are within allowable specification limits (Jendia, 2000). Aggregates blending results are presented in chapter (5) and in more detail in Appendix (B).

3.3.2 Marshal test

Marshall Method is a method of designing hot asphalt mixtures, which is used to determine the optimum bitumen content to be added to specific aggregate blend resulting a mix that met the desired properties of durability and strength. Marshal method were applied at standard 75-blow, according to (ASTM D 1559-89). a number of 12 samples each of 1200 gm in weight were prepared using four different bitumen contents (from 5 – 6.5% with 0.5 % incremental). Three samples were prepared for each bitumen content to get an average value of bulk density, flow, marshal stability and other properties.

Marshall Properties such as density, flow, stability, air voids in total mixture, and voids filled with bitumen percentage are obtained and calculated for asphalt mixtures of different bitumen contents. Then, the following graphs are plotted:

a) Bulk Specific Gravity vs. bitumen Content.

b) Stability vs. Bitumen Content.

c) Flow vs. Bitumen Content.

d) Air voids (Va) vs. Bitumen Content.

e) Voids Filled with Bitumen (VFB) vs. Bitumen Content.

These graphs are used to obtain an optimum bitumen content for asphalt mixture.

3.3.2.1 Determination of optimum bitumen content (OBC)

In order to determine the optimum bitumen content (OBC) needed for a proposed asphalt mix, three values of bitumen content, should be utilized (Jendia, 2000), as follows:

a) Bitumen content at the highest value of bulk density $(\%\ m_b)_{bulk\ density}$

b) Bitumen content at the highest stability $(\%\ m_b)_{Stability}$

c) Bitumen content at the median of allowed percentages of air voids (Va = 3-5%) $(\%\ m_b)_{Va}$

To obtain these three values, Marshal graphs should be used.

Optimum bitumen content (OBC) % =

$$\frac{(\%\boldsymbol{mb})_{\boldsymbol{stability}} + (\%\boldsymbol{mb})_{\boldsymbol{bulk\ density}} + (\%\boldsymbol{mb})_{\boldsymbol{v_a}}}{\mathbf{3}}$$

In Chapter five of this research (Results and data analysis) , Characteristic of the asphalt mix using optimum bitumen content such as bulk density, stability, flow, Va, and VMA are obtained and checked against specifications.

CHAPTER 4
SAMPLING AND TESTING PROGRAM

CHAPTER 4
SAMPLING AND TESTING PROGRAM

4.1 Introduction

The main objective of this chapter is to investigate how asphalt concrete can be heated through the addition of different contents of electrically conductive particles (Iron Powder). The idea is to use this electrically conductive asphalt concrete for healing purposes.

To achieve this goal, a modified asphalt mixes were prepared with addition of different percentages of iron powder, and a measurable tests were done to evaluate the self-healing behavior of asphalt mixture, data analysis of test results in chapter five should guide to investigate the effect of adding iron powder on self-healing property of asphalt mixture which is the main objective of this study.

4.2 Healing of asphalt mixture

Healing of asphalt is the ability of asphalt sample to recover its strength by refilling the cracks with bonding bitumen material.

Garcia (2012) defined the healing level of asphalt mixture as the relationship between the ultimate force of asphalt beam samples during a three point bending test, and the ultimate force measured in the beams after some time healing.

4.3 Testing methodology and sampling

Asphalt mixture were prepared with the optimum percentages of aggregate and bitumen contents which was obtained in study primary tests, mixture components were mixed to have uniform grading, In addition, Iron powder were added to the mixture with different percentages, and then, modified asphalt samples with iron powder were prepared and tested as will discussed later.

4.3.1 Samples preparation

As discussed earlier, our study will focused on study the self-healing property of asphalt mix for wearing layer, and to obtain a representative sample of a section of asphalt layer, which will be tested later by three-point bending, a rectangular beam shape samples were made with dimensions 16.0 *4.0*4.0 cm, Figure (4.1) shows samples shape and dimensions. This samples were prepared using prefabricated steel molds which was manufactured exclusive for research tests, samples were compacted with process similar to standard 75-blow Marshal Method, also by prefabricated rectangle steel compactor Figure (4.2) shows steel molds used in preparing asphalt beams.

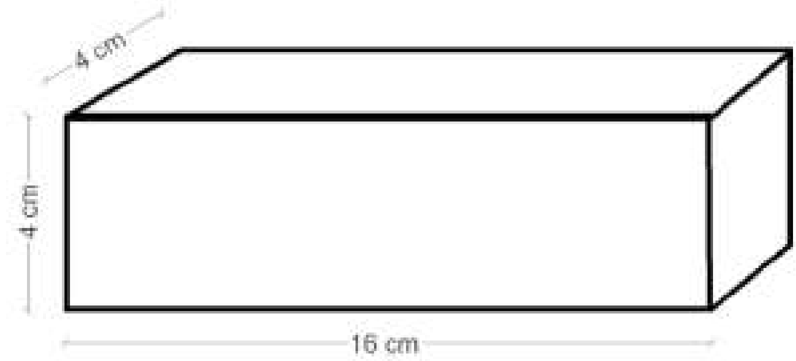

Figure (4.1): *Shape and dimensions of asphalt sample*

Figure (4.2): *Steel molds used in preparing asphalt beams*

4.3.2 Healing Level quantification method

To quantify healing process, asphalt samples were tested under three-point bending, always at temperature of -20 ºC, to avoid creeping, The load was applied at the middle top face of sample, with two pillars rested 12 cm wide at the bottom face of sample, this was enough to produce a crack crossing the sample from the load application point to the bottom face of sample, which similar to cracks developed in real life asphalt layer. Then, maximum loads causing samples fractured were recorded and after that, each sample was heated during a period of time (will be discussed later) by induction heating device (Microwave), and samples were tested again under three-point pending device after getting cooled to -20 ºC. The healing level of asphalt mixture should be concluded from the relationship between the ultimate force of the asphalt beams during a three point bending test, and the ultimate force measured in the beams after some time healing. Figures (4.3) shows location and dimension of three-point bending loading, and (4.4) shows using three-point bending in testing samples.

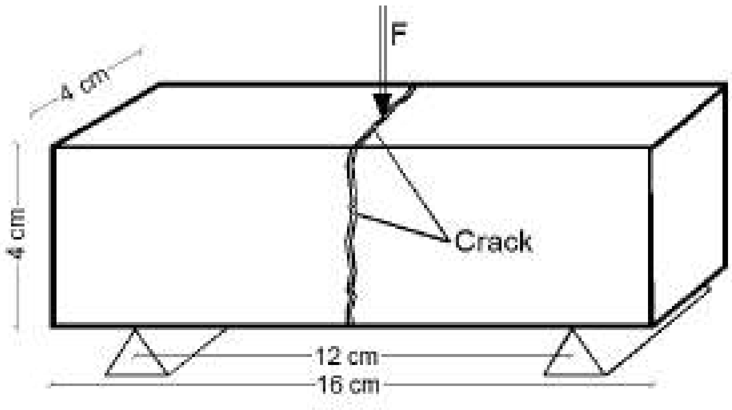

Figure (4.3): *Location and dimensions of three-point bending loading*

Figure (4.4): *Using three-point bending in testing samples*

4.4 Testing Program

To get accurate results for this research and to override any obstacles faces testing procedure, a testing program of two stages were performed as follows:

4.4.1 First stage (Trial stage)

This trial stage has performed to get primary results about investigation the effect of adding iron powder to asphalt samples, and to explore for any obstacles faces the future testing procedure, also to get solutions about overtaking these obstacles, toward executing the second testing stage without any obstacles.

After obtaining OBC (as discussed in chapter 3), eight samples were prepared at OBC to evaluate the thermal effect of adding Iron powder to asphalt samples by considering two proportions of Iron powder, (0.0 and 5.0% by the weight of total mix). The 5.0% Iron powder content was chosen according to (Jendia, and Tabash 2014) that's concluded that the 5.0% is the optimum iron content which improves the physical characteristics of asphalt mixture.

The procedure of trial stage can be summarized as follows:

a. Iron powder was sieved to get a granular size (0 - 0.60 mm).
b. Obligatory amount of bitumen according to optimum bitumen content was heated until it reaches 150 °C.
c. Iron powder and coarse aggregates were mixed with fine aggregates followed by addition of hot bitumen at OBC. All component were mixed dynamically to form a homogeneous asphalt mixture.
d. After preparing asphalt mixes, 16.0*4.0*4.0 cm beam shape samples were prepared and compacted as discussed earlier in this chapter.
e. Samples were cooled to the room temperature at 25 ºC.
f. Samples were fractured by three-point bending testing machine after getting cooled to -20 ºC for 24hours to insure brittle fracture.
g. Make every sample heated by microwave device (900 watt, 2450MHz) for 90 seconds. and samples temperature were recorded.
h. After that, Samples were cooled to the room temperature at 25 ºC, and again every sample was heated by microwave device for 120 seconds.

i. After samples getting heated two times by microwave, samples temperatures were recorded for each time, shape and mass of samples were checked visually for any variations, all observations were recorded.
j. Results of samples temperature guided to primary investigation about the effect of adding Iron powder on self-healing property of asphalt mix.
k. Other recorded observations leaded to investigate obstacles that faced testing procedure at second main stage of research testing program.
l. Obstacles and observations were discussed, and solutions were made to next main testing stage.

4.4.2 Second stage (Main stage)

After getting results of trial stage, and obstacles were overtaken by innovative solutions (will be discussed later in chapter 5), Second stage was performed to widely investigate the effect of adding iron powder to asphalt samples, results were analyzed to study the feasibility of adding iron powder to asphalt mixture.

After obtaining OBC (as discussed in chapter 3), 20 samples were prepared at OBC to study the effect of adding iron powder to asphalt samples by considering five proportions of iron powder (0.0, 2.5, 5.0, 7.5, and 10.0% by the weight of total mix).

The procedure of main stage can be summarized as follows:

a. Iron powder were sieved to get a granular size (0 - 0.60 mm).
b. Obligatory amount of bitumen according to optimum bitumen content was heated until it reaches 150 °C.
c. Iron powder and coarse aggregates were mixed with fine aggregates followed by addition of hot bitumen at OBC. All component were mixed dynamically to form a homogeneous asphalt mixture.
d. After preparing asphalt mixes, 16.0*4.0*4.0 cm beam shape samples were prepared and compacted as discussed earlier in this chapter.
e. Samples were cooled to the room temperature at 25 ºC.
f. Samples were fractured by three-point bending testing machine after getting cooled to -20 ºC for 24hours to insure brittle fracture.
g. Fracture load for each sample were recorded.
h. Samples were rested for 24hours to get room temperature at 25 ºC.

i. Every sample was heated by microwave device (900 watt, 2450MHz) for 140 seconds, and samples temperature were recorded.
j. Samples were fractured again by flexural testing machine after getting cooled to -20 ºC, and fracture load for each sample were recorded.
k. After samples getting cooled to room temperature, every sample was heated again by microwave device for 180 seconds, and samples temperature were recorded for the second time.
l. Samples were fractured for the third time by flexural testing machine after getting cooled to -20 ºC for 24hours.
m. Fracture point load for each sample was recorded for the second time.
n. Recorded results for each iron powder proportion were compared, analyzed and discussed to made a deep study about the effect of adding iron powder on self-healing property of asphalt mix.

4.5 Summary of Testing Samples

As discussed earlier in research chapters, number of samples were prepared to achieve study goals, marshal cylindrical samples were prepared to get the OBC, and a parallel rectangles beam shape samples were prepared to investigate effect adding iron powder on self-healing property of asphalt mix. Table (4.1) presents summary of samples which were made in this research.

Table (4.1): Summary of samples which were made in this research

Purpose	No. of Samples	Sample Structure	Picture
Marshal (OBC)	12	Cylinder	
Modified Asphalt (Trial Stage)	8	Parallel Rectangles Beam	
Modified Asphalt (Main Stage)	20	Parallel Rectangles Beam	

CHAPTER 5

RESULTS AND DATA ANALYSIS

CHAPTER 5
RESULTS AND DATA ANALYSIS

5.1 Introduction

Results of laboratory work had been obtained and analyzed with the purpose of achieve study objectives that includes studying the effect of adding different percentages of iron powder on the self-healing properties of asphalt mix.

Laboratory work results were presented at this chapter in two phases. First phase handles with results of blending aggregates to obtain asphalt binder coarse gradation curve, then marshal test was carried out with different percentages of bitumen in the purpose of obtaining the optimum bitumen content (OBC).

Later than identifying OBC, the second phase handles with test results which was made to study the effect of adding different percentages of iron powder on self-healing properties of asphalt mix. Temperature recordings and flexural force results for modified asphalt mixes were analyzed and finally the relationship between iron powder additions and self-healing property of asphalt mix were obtained.

5.2 Phase One (Asphalt mixture preparation)

5.2.1 Blending of aggregates

The final proportion of each aggregate material in asphalt wearing layer is shown in Table (5.1). The proposed gradation curve of blended aggregates is found to be satisfying ASTM specification for asphalt wearing layer gradation. The gradation of final aggregate mix with ASTM limits is presented in Table (5.2) and Figure (5.1).

Table (5.1): *Proportion of each aggregate material from proposed mix*

Aggregates type	Size (mm)	Proportion from proposed mix (%)
Adasia	0/12.5	25.4
Simsimia	0/9.5	20.1
Trabia	0/4.75	51.9
Filler	0/1.18	2.6
Sum		**100**

Table (5.2): *Gradation of proposed mix (wearing layer) with ASTM specifications limits*

Sieve size (mm)	% Passing	ASTM D3515-D5 specification limits (%)	
		Min	Max
19	**100**	100	100
12.5	**98**	90	100
9.5	**82**		
4.75	**65**	44	74
2.00	**51**	28	58
1.18	**38**		
0.600	**28**		
0.300	**18**	5	21
0.150	**11**		
0.075	**8**	2	10

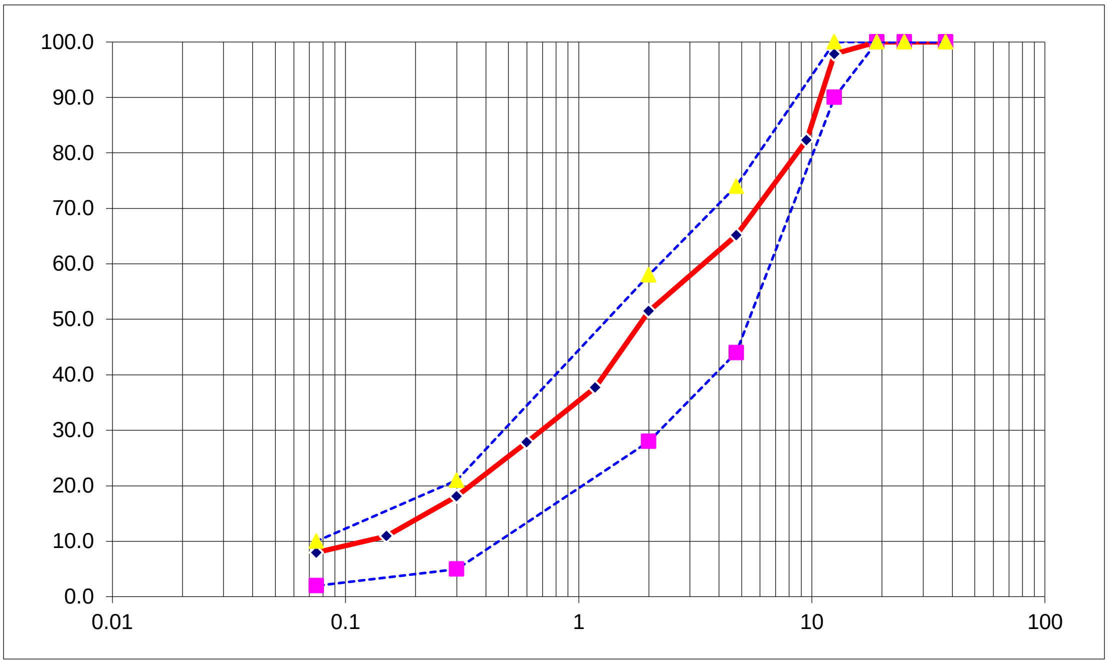

Figure (5.1): *Gradation of final aggregates mix with ASTM specification range.*

5.2.2 Marshal Test

As discussed in chapter (3). A number of 12 samples each of 1200 gm in weight were prepared using four different bitumen contents (from 5 – 6.5% with 0.5 % incremental) in order to obtain the optimum bitumen content (OBC). Table (5.3) and Figures (5.2–5.7) show summary of Marshal Test results. Further details are presented in Appendix D.

Table (5.3): *Summary of Marshal Test results*

Bitumen % (By total weight)	Sample No.	Corr. Stability (Kg)	Flow (mm)	ρ_A (g/cm3)	Va (%)	VMA (%)	VFB (%)
5	1	1914.9	2.70	2.34	5.25	15.5	66.1
	2	1887.7	2.60	2.34	5.20	15.4	66.2
	3	1836.0	2.50	2.34	5.29	15.5	65.9
	Average	**1879.53**	**2.60**	**2.34**	**5.25**	**15.5**	**66.1**
5.5	1	1999.2	3.20	2.35	4.60	15.5	70.2
	2	2099.8	3.04	2.35	4.60	15.5	70.1
	3	2136.6	3.15	2.35	4.60	15.5	70.3
	Average	**2078.53**	**3.13**	**2.35**	**4.60**	**15.5**	**70.2**
6	1	2369.1	3.36	2.36	3.15	15.5	79.7
	2	2244.0	3.90	2.36	3.27	15.6	79.1
	3	2050.9	3.60	2.35	3.64	16.0	77.2
	Average	**2221.3**	**3.62**	**2.36**	**3.35**	**15.7**	**78.67**
6.5	1	2061.8	3.87	2.35	2.25	16.6	86.4
	2	2026.4	3.80	2.33	2.73	17.0	83.9
	3	2098.5	3.84	2.35	2.28	16.6	86.3
	Average	**2061.9**	**3.84**	**2.35**	**2.42**	**16.7**	**85.5**

ρ_A: Bulk Density

$V_a\%$: Percentage of air voids in total mix.

VMA% : Percentage of voids in Mineral Aggregates

VFB%: Percentage of Voids Filled with Bitumen

5.2.2.1 Stability – bitumen content relationship

Stability is the maximum load required for the asphalt specimen to produce failure when the load is applied to specimen at constant rate 50 mm / minute (Jendia, 2000). Figure (5.2) presents the stability results for different percentages of bitumen content. Stability of asphalt mix increases as the bitumen content increase until it reaches the maximum value at bitumen content 5.90% then it started to drops gradually at higher bitumen content.

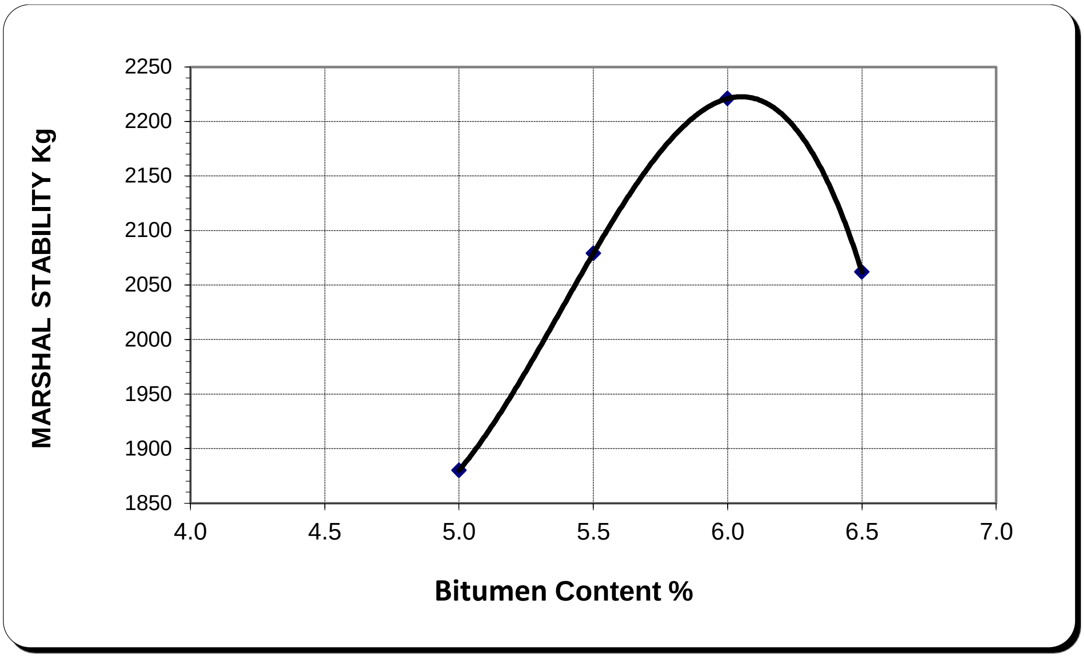

Figure (5.2): *Stability vs. bitumen content*

5.2.2.2 Flow – bitumen content relationship

Flow is the total amount of deformation obtained for asphalt specimen which occurs at maximum load (Jendia, 2000). Figure (5.3) presents Flow results for different bitumen contents. Flow of asphalt mix increases as the bitumen content increase until it reaches the maximum value at the maximum bitumen content 6.5 %.

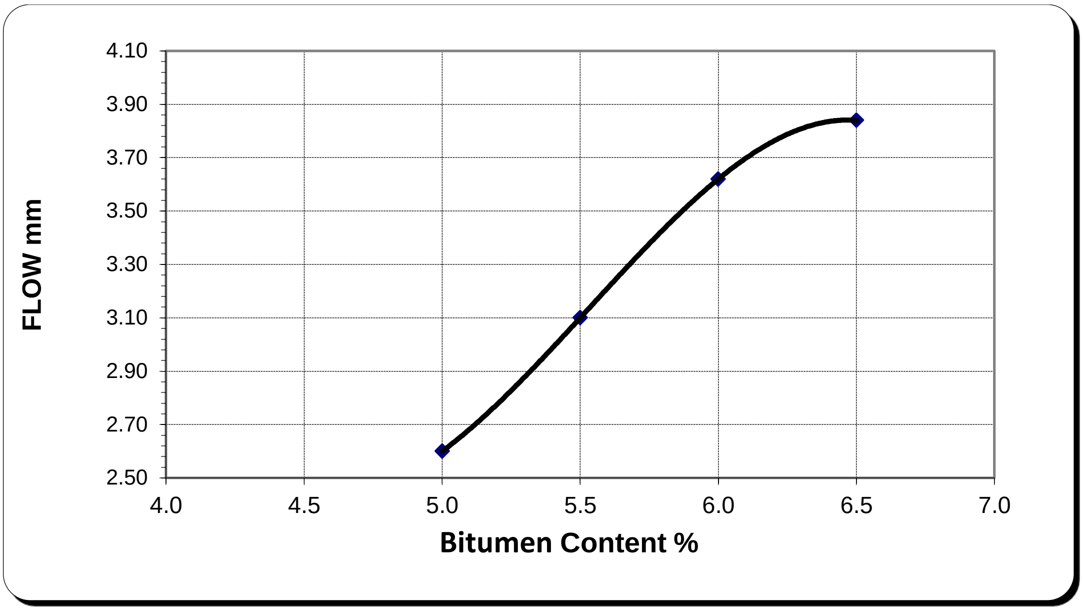

Figure (5.3): *Flow vs. bitumen content*

5.2.2.3 Bulk density – bitumen content relationship

Bulk density is the actual density of the compacted asphalt mix. Figure (5.4) presents results of Bulk density for different bitumen contents. Bulk density of asphalt mix increases as the bitumen content increase until it reaches the maximum value (2.36 g/cm3) at bitumen content 5.90 % then it started to decline gradually at higher bitumen content.

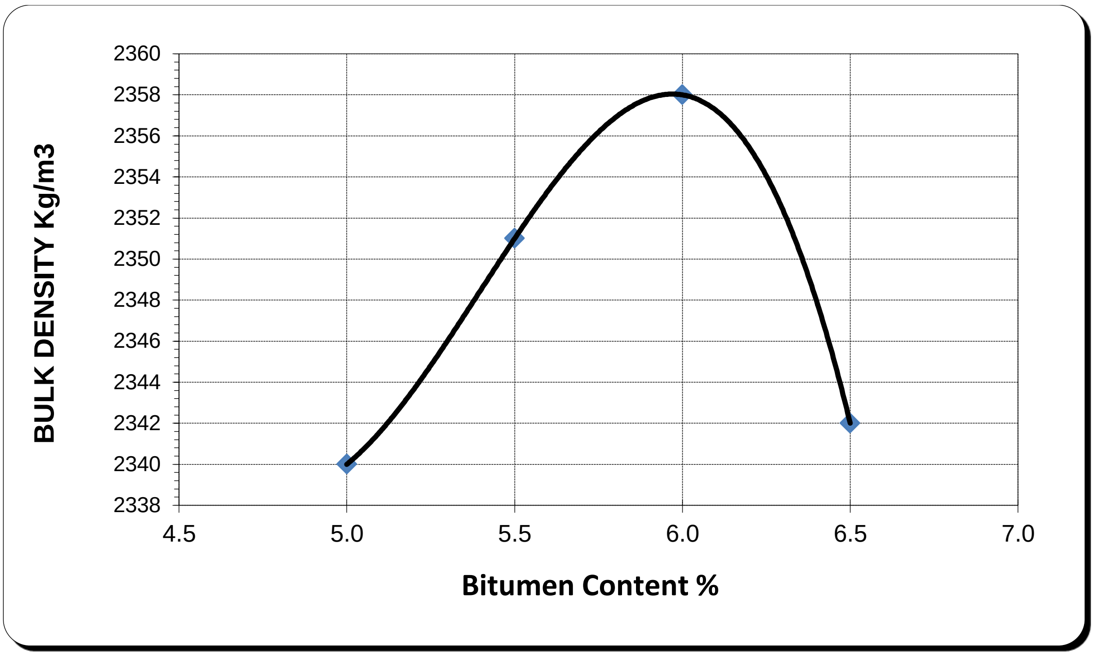

Figure (5.4): *Bulk density vs. bitumen content*

5.2.2.4 Void ratio (Va%) – bitumen content relationship

Void ratio (Va %) is the percentage of air voids by volume in asphalt specimen or compacted asphalt mix (Jendia, 2000). In Figure (5.5) Va% results for different bitumen contents are represented. Maximum value of air voids is at the lowest bitumen content (5%). Va% decrease gradually as bitumen content increase, this was because of the increase of voids filled with bitumen in the asphalt mix.

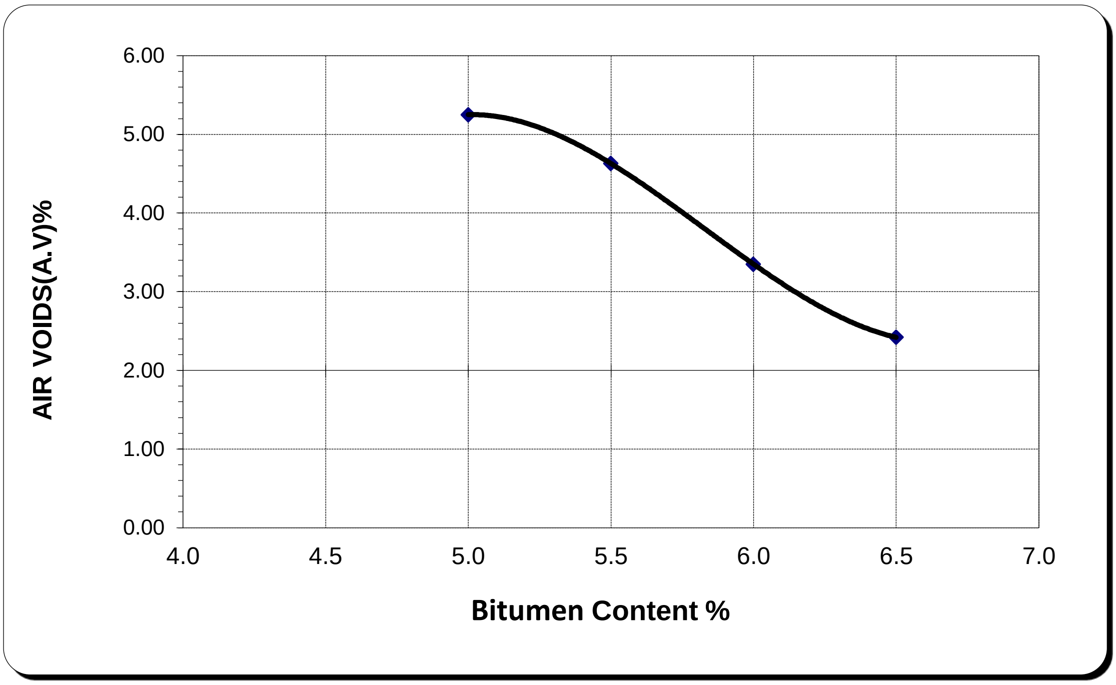

Figure (5.5): *Mix air voids proportion vs. bitumen content*

5.2.2.5 VFB% – bitumen content relationship

Voids Filled with Bitumen (VFB) is the percentage of voids in mineral aggregates filled with bitumen (Jendia, 2000). In Figure (5.6) VFB% results for different bitumen contents are represented. Minimum VFB content value is at the lowest bitumen percentage (5%), VFB% value increase gradually as bitumen content increase.

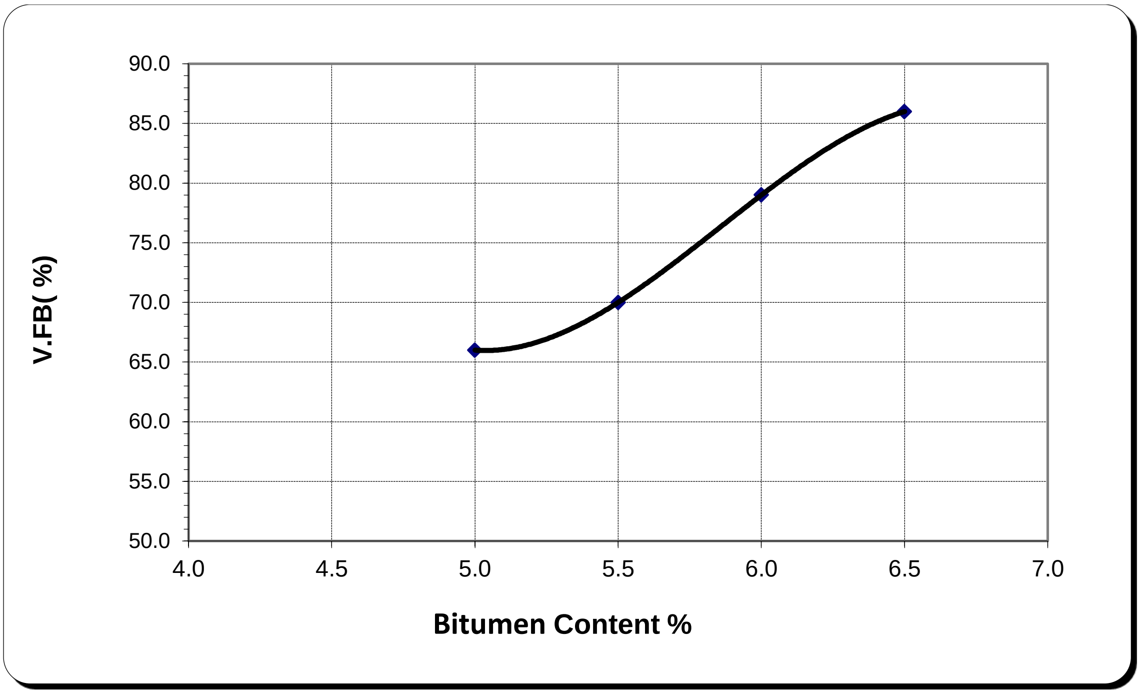

Figure (5.6): *Voids filled bitumen proportion vs. bitumen content*

5.2.2.6 VMA% – bitumen content relationship

Voids in Mineral Aggregates (VMA) is the percentage of voids volume in the aggregates before adding bitumen or the sum of the percentage of voids filled with bitumen and percentage of air voids remaining in asphalt mix after compaction (Jendia, 2000). In Figure (5.7) VMA% results for different bitumen contents are represented. Maximum percentage of VMA is obtained at the higher bitumen percentage (6.5%), VMA% decrease gradually as bitumen content decrease.

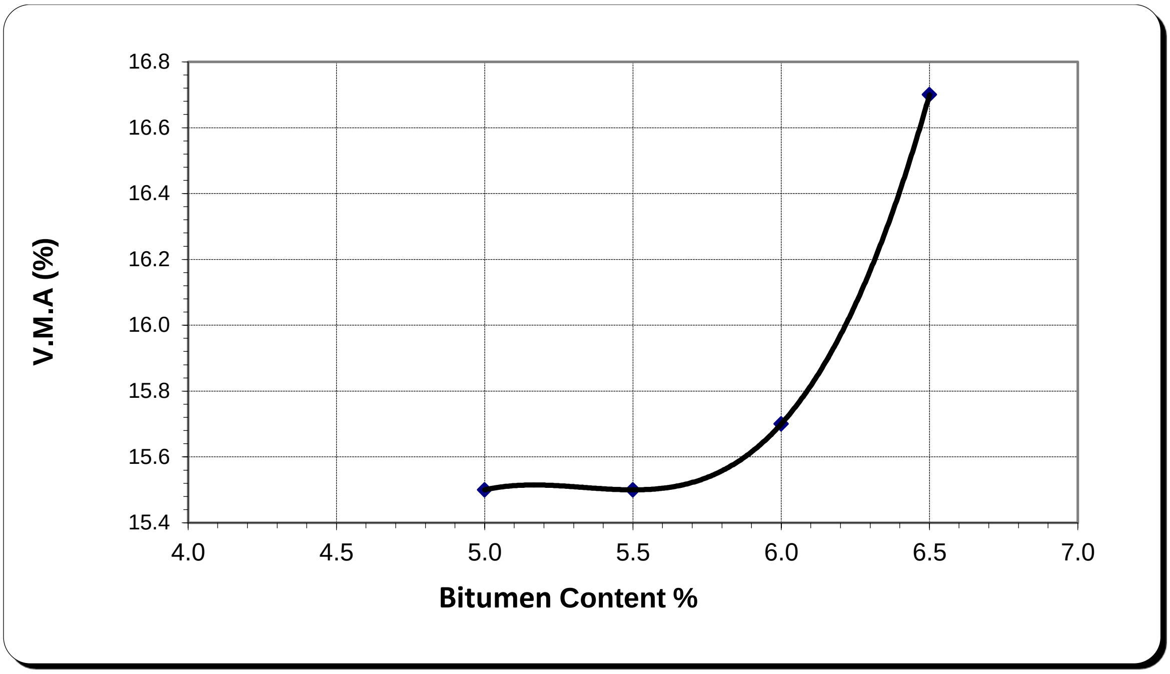

Figure (5.7): *Voids of mineral aggregates percentage vs. bitumen content.*

5.2.2.7 Determination of optimum bitumen content (OBC)

Figures (5.2, 5.4 and 5.5) are used to find three values of bitumen contents in order to be utilized in determining of OBC. These values are:

- Bitumen content at the highest stability $(\% \, m_b)_{Stability}$ = 5.90%
- Bitumen content at the highest value of bulk density $(\% \, m_b)_{bulk\ density}$ = 5.90%
- Bitumen content at the median of allowed percentages of air voids (at 4% air voids), $(\% \, m_b)_{Va}$ = 5.70%.

$$\textbf{Optimum bitumen content (OBC)} \cong \frac{\mathbf{5.90+5.90+5.70}}{\mathbf{3}} \cong \mathbf{5.8}$$

5.3 Phase Two (Effect of iron powder on self-healing properties of asphalt mix)

As discussed in chapter (4). In this phase, two test stages were performed, the first stage was a trial stage which was made to explore any obstacles faces the future testing procedure, also, to get solutions about overtaking these obstacles toward executing the second testing stage without any obstacles. The second stage was made to widely investigate the effect of adding iron powder to asphalt mixture that is the main study objective.

5.3.1 First stage (Trial stage)

As discussed in chapter (4). Eight samples were prepared at OBC by considering two proportions of iron powder , (0 and 5.0% by the weight of total mix), The 5.0% Iron powder content was chosen referred to (Jendia, and Tabash. 2014) that's concluded that the 5.0% is the optimum iron content which improves the physical characteristics of asphalt mixture. and after each sample has been heated in microwave separately for 90 and 120 seconds respectively as a trial heating duration, samples temperature were recorded, shape and mass of samples has checked visually for any variations, all observations were recorded. Tables (5.4), (5.5) shows temperature recordings results. Figure (5.8) shows using Laser thermometer to measure sample temperature.

Table (5.4): *Temperature recordings results*

Sample No.	**Iron powder content (%)**	Initial Temp. ºC - (A)	Temp. ºC after 90 seconds heating (B)	Temp. ºC increase after 90 seconds heating (B-A)	**Average increase of temp. (ΔT) after 90 seconds heating**	Temp. ºC after 120 seconds heating (B)	Temp. ºC increase after 120 seconds heating (B-A)	**Average increase of temp.(ΔT) after 120 seconds heating**
1	**0.00 %**	25	70.6	45.6	**45.1**	112.2	87.2	**84.7**
2		25	67.9	42.9		104.3	79.3	
3		25	71.4	46.4		114.5	89.5	
4		25	70.3	45.3		107.6	82.6	
1	**5.00%**	25	98.1	73.1	**78.4**	135.0	110.0	**111.7**
2		25	104.8	79.8		135.2	110.2	
3		25	103.7	78.7		134.1	109.1	
4		25	107.0	82.0		142.5	117.5	

Table (5.5): *Summary of Temperature recordings results*

Iron powder content (%)	Initial Temp. ºC – **(A)**	Average increase of temp. (ΔT) after 90 seconds heating **(C)**	**Temp. increase Percentage after 90 seconds heating (C/A)**	Average increase of temp. (ΔT) after 120 seconds heating **(C)**	**Temp. increase Percentage after 120 seconds heating (C/A)**
0.00 %	25	45.1	**180%**	84.7	**339%**
5.00%	25	78.4	**314%**	111.7	**447%**

Figure (5.8): *Using Laser thermometer to measure sample temperature*

5.3.1.1 Temperature increase – Iron powder content relationship

In Figure (5.9) Results of temperature increases for different iron powder contents are represented. At 90 seconds heating time interval, temperature of asphalt mixture was 45 ºC for 0.0% iron content, while it was 78 ºC at 5.0% content. Also at 120 seconds heating, temperature of asphalt mixture was 85 ºC at 0.0% iron content, while it was 112 ºC at 5.0% iron content. That's means that temperature of asphalt mixture increases as iron powder content increase while heating time interval is fixed.

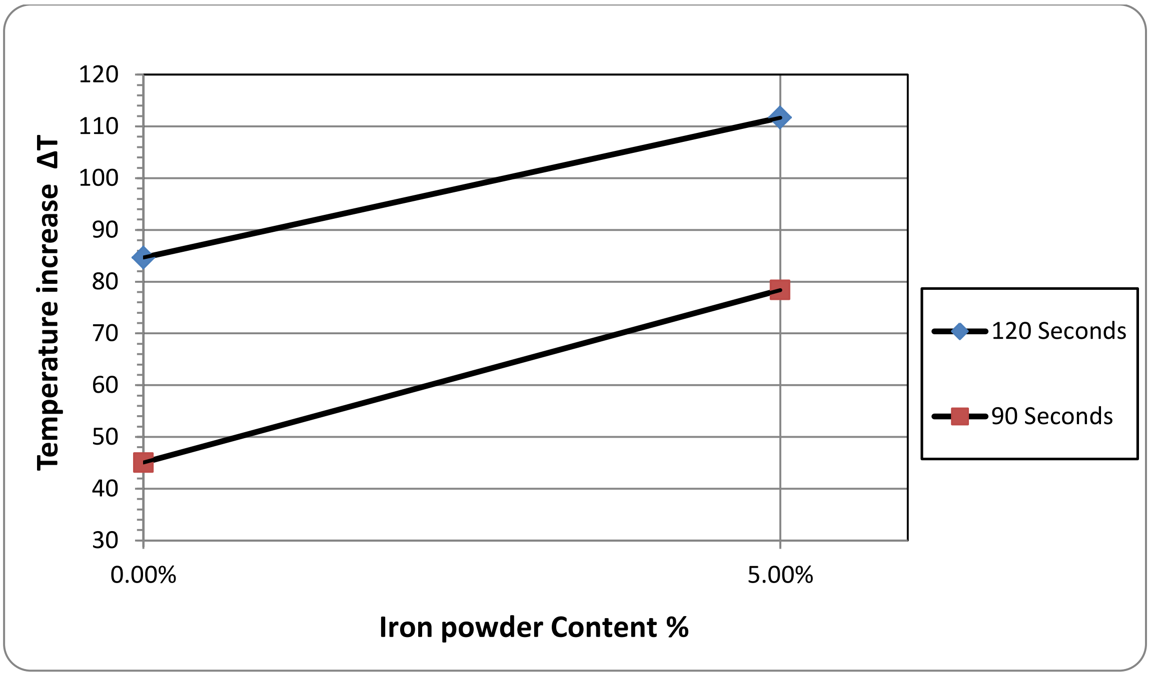

Figure (5.9): *Temperature increase vs. Iron powder content*

5.3.1.2 Temperature increase – Induction time interval relationship

In Figure (5.9) Results of temperature increases at different induction heating time intervals are represented. At 0.0% iron content, temperature increase was 45 ºC for 90 seconds heating while it was 85 ºC at 120 seconds, also at 5.0% iron content, temperature increase was 78 ºC for 90 seconds heating while it was 112 ºC at 120 seconds. That means temperature of asphalt mixture increases as the induction heating time intervals increases while samples content of iron powder is fixed.

5.3.2 Trial stage obstacles and observations

As discussed earlier, trial stage was made to investigate any obstacles that may faces later test procedure, and to find solutions to override these obstacles. These obstacles will be presented and discussed as follows:

1- Number of samples

As temperature results shows, temperature of samples increases as the iron powder content increase, and a progress in crack healing of samples is expected as temperature increases, and to proof this, two contents of iron powder (0.0% and 5.0%) is not enough, thus, the iron powder content percentages should be widening from 0.0% to 10.0% instead of 5.0%.

2- Iron powder percentage determination

At 90 seconds heating time interval, the difference between temperature increasing at 0.0% and 5.0% iron content s was 39.6 ºC (from 45.1 ºC to 84.7 ºC), and at 120 seconds heating the difference was 33.3 ºC (from 78.4 ºC to 111.7 ºC), these temperature differences was large enough to be divided to two steps, by dividing the iron powder content percentage, and a 2.5% step between each iron powder content percentages will guide to more accurate and detailed results, thus, later tests should deals with iron powder contents (0.0 , 2.5, 5.0, 7.5 and 10.0%).

3- Failure of sample mass due to temperature rising

At 5.0% iron powder content, and after samples were heated for 120 seconds, temperature reading was near 135 ºC, and failure in samples was observed clearly by forming a gap in the middle of the sample, this is due to the decrease of bitumen viscosity as temperature of samples rising, which weak bonding between mixture contents, and also due to lack of supporting to sample edges. Figure (5.10) shows failure comparison between samples of 0.0% and 5.0% iron powder content.

Non-Cracked sample (0.0% Iron Content)

Cracked sample (5.0% Iron Content)

Figure (5.10): *Failure comparison between samples of 0.0% and 5.0% iron powder content*

To solve this issue, samples edges should be supported by a samples container during heating in microwave, and to minimize its impact on test results, the container should be made of a low inductive material. A wooden identical containers was made to protect samples from failure during heating period, and to save the internal stresses in the sample within the sample only. Figure (5.11) shows wooden containers which was made to support sample edges.

Figure (5.11): *Wooden containers of asphalt samples.*

As a result of the above, a loss of temperature is expected to be happen due to using these containers, because wood is containing a reasonable amount of moisture that will leads to wood temperature rising during microwave heating. This guides to increase the heating time intervals, from (90s, and 120s), to (140s, and 180s), to compensate the loss of temperature resulting from using wooden containers in testing procedure.

Note that, at the last discussed observation at samples of 5.0% Iron powder content, Iron powder content has contributed in temperature rising of bitumen, which makes it less viscous enough to help in refilling cracks in asphalt maintenance operations.

5.3.3 Second stage (Main stage)

After obstacles and test procedure problems of trial stage were solved, twenty samples of asphalt mixture were prepared at OBC by considering five proportions of iron powder, (0.0, 2.5, 5.0, 7.5 and 10.0% by the weight of total mix). Then, samples were fractured by three-point bending testing machine after getting cooled to -20ºC. Failure load for each sample was recorded. After that, samples were heated in microwave for 140 seconds and samples temperatures were recorded. Then, samples were fractured again by three-point bending testing machine after getting cooled to -20ºC and failure load for each sample was recorded again for the second time.

The whole last operation was repeated with varying the heating time to 180 seconds, then temperatures and failure loads results were recorded. Tables (5.6) and (5.7) shows temperature recording results, Tables (5.8) and (5.9) shows fracture loads recording results. Figure (5.12) shows using three-point bending testing machine to measure fracture point load for each sample.

Figure (5.12): *Using three-point bending testing machine to measure fracture point load*

Table (5.6): *Temperature recordings results*

Sample No.	**Iron powder content (%)**	Initial Temp. ºC - (A)	Temp. ºC after 140 seconds heating (B)	Temp. ºC increase after 140 seconds heating (B-A)	**Average increase of temp. (ΔT) after 140 seconds heating**	Temp. ºC after 180 seconds heating (B)	Temp. ºC increase after 180 seconds heating (B-A)	**Average increase of temp.(ΔT) after 180 seconds heating**
1	**0.00 %**	25	96.4	71.4	**68.4**	116.7	91.7	**91.1**
2		25	94.2	69.2		114.7	89.7	
3		25	92.7	67.7		113.5	88.5	
4		25	90.4	65.4		119.4	94.4	
1	**2.50%**	25	102.9	77.9	**81.1**	131.2	106.2	**103.5**
2		25	109.8	84.8		127.1	102.1	
3		25	107.6	82.6		126.3	101.3	
4		25	104.2	79.2		129.5	104.5	
1	**5.00%**	25	116.3	91.3	**91.5**	140.2	115.2	**117.5**
2		25	115.9	90.9		141.2	116.2	
3		25	116.7	91.7		143.4	118.4	
4		25	117.2	92.2		145.3	120.3	
1	**7.50%**	25	130.0	105.0	**104.7**	159.8	134.8	**132.4**
2		25	129.1	104.1		155.8	130.8	
3		25	131.1	106.1		158.7	133.7	
4		25	128.7	103.7		155.2	130.2	
1	**10.0 %**	25	139.2	114.2	**117.4**	170.6	145.6	**147.6**
2		25	144.2	119.2		174.2	149.2	
3		25	143.5	118.5		175.2	150.2	
4		25	142.7	117.7		170.3	145.3	

Table (5.7): *Summary of Temperature recordings results*

Iron powder content (%)	Initial Temp. ºC – **(A)**	Average increase of temp. (ΔT) after 140 seconds heating **(C)**	**Temp. increase Percentage after 140 seconds heating (C/A)**	Average increase of temp. (ΔT) after 180 seconds heating **(C)**	**Temp. increase Percentage after 180 seconds heating (C/A)**
0.00 %	25	68.4	**274%**	91.1	**364%**
2.50%	25	81.1	**324%**	103.5	**414%**
5.00%	25	91.5	**366%**	117.5	**470%**
7.50%	25	104.7	**419%**	132.4	**530%**
10.0%	25	117.4	**470%**	147.6	**590%**

Table (5.8): *Fracture loads results*

Sample No.	**Iron powder content (%)**	Initial Fracture load. (N) at -20 ºC	**Average Initial Fracture load. (N)** at -20 ºC	Fracture load at -20 ºC after 140 seconds heating (N)	**Average Fracture load at -20 ºC after 140 seconds heating. (N)**	**Healing Level (%)**	Fracture load a -20 ºC after 180 seconds heating (N)	**Average Fracture load at -20 ºC after 180 seconds heating. (N)**	**Healing Level (%)**
1	**0.00 %**	2080	**2048**	578	**610**	**30%**	1234	**1069**	**52%**
2		1954		703			903		
3		2166		610			998		
4		1992		547			1139		
1	**2.50%**	2257	**2159**	901	**832**	**39%**	1148	**1296**	**60%**
2		2066		855			1591		
3		2126		768			1197		
4		2187		802			1246		
1	**5.00%**	2250	**2193**	988	**1086**	**49%**	1393	**1511**	**69%**
2		2262		1221			1578		
3		2061		1017			1433		
4		2198		1117			1641		
1	**7.50%**	1954	**2029**	1191	**1260**	**62%**	1660	**1575**	**78%**
2		2009		1362			1378		
3		2054		1278			1567		
4		2100		1209			1696		
1	**10.0 %**	2067	**2055**	1424	**1430**	**70%**	1328	**1485**	**72%**
2		2054		1388			1473		
3		2113		1412			1608		
4		1987		1497			1532		

Table (5.9): *Summary of Fracture loads results*

Iron powder content (%)	Average Initial Fracture load. (N) at -20 ºC)	Average Fracture load at -20 ºC after 140 seconds heating (N)	**Healing Level (%)**	Average Fracture load at -20 ºC after 180 seconds heating (N)	**Healing Level (%)**
0.00 %	2048	610	**30%**	1069	**52%**
2.50%	2159	832	**39%**	1296	**60%**
5.00%	2193	1086	**49%**	1511	**69%**
7.50%	2029	1260	**62%**	1575	**78%**
10.0%	2055	1430	**70%**	1485	**72%**

5.3.3.1 Temperature increase – Iron powder content relationship

In Figure (5.13) Results of temperature Increases for different iron powder contents are represented. Temperature of asphalt mix increases as the iron powder content increase while heating time interval is fixed.

This relationship proofs that iron powder content accelerating the temperature rising of asphalt mixture resulting from induction heating, which is contributing in making the bitumen bonding material less viscous enough to help in refilling cracks in asphalt maintenance operations.

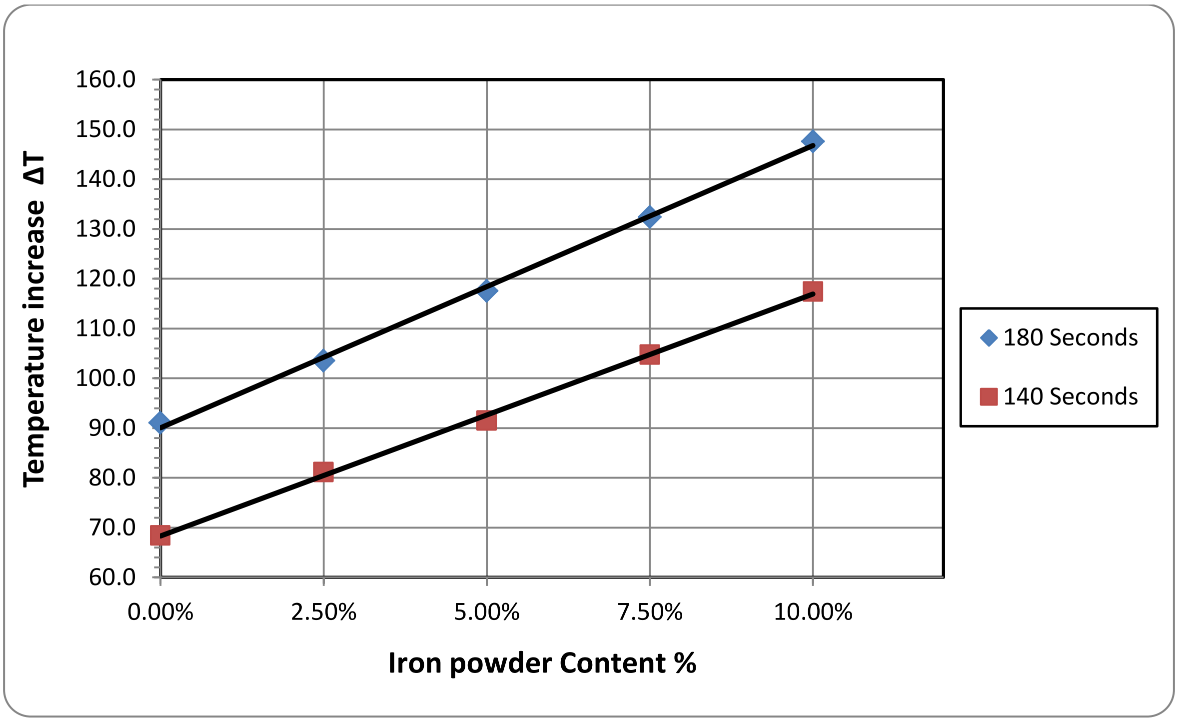

Figure (5.13): *Temperature increase vs. Iron powder content*

5.3.3.2 Temperature – Induction time interval relationship

Figure (5.13), Also represented that, for each content of iron powder, temperature recordings after 180 seconds were higher that which after 140 seconds, that's means that temperature of asphalt mix increases as induction heating time interval increase while samples content of iron powder was fixed.

5.3.3.3 Iron powder content – Healing of asphalt mixture relationship

As discussed earlier in chapter (4), Healing of asphalt is the ability of asphalt sample to recover its strength by refilling the cracks with bonding bitumen material.

Garcia (2012) defined the Healing level of asphalt mixture as the relationship between the ultimate force of the asphalt beams during a three point bending test, and the ultimate force of beams measured after some time healing.

García et.al. (2013) Stated that healing of open cracks in asphalt mix will happen when some of the points in both faces of a crack are in contact. Phenomena of Capillary Flow will start from these contact points and bitumen will spread through the crack if the asphalt temperature is high enough for bitumen to proceed as a Newtonian fluid. Healing will happen faster in cracks deeply buried in the pavement. So, an appropriate healing level is reached when bitumen is heated for a sufficient time above the temperature at which it behaves as a Newtonian fluid. Figure (5.14) shows the behavior of bitumen in filling cracks of asphalt mixture.

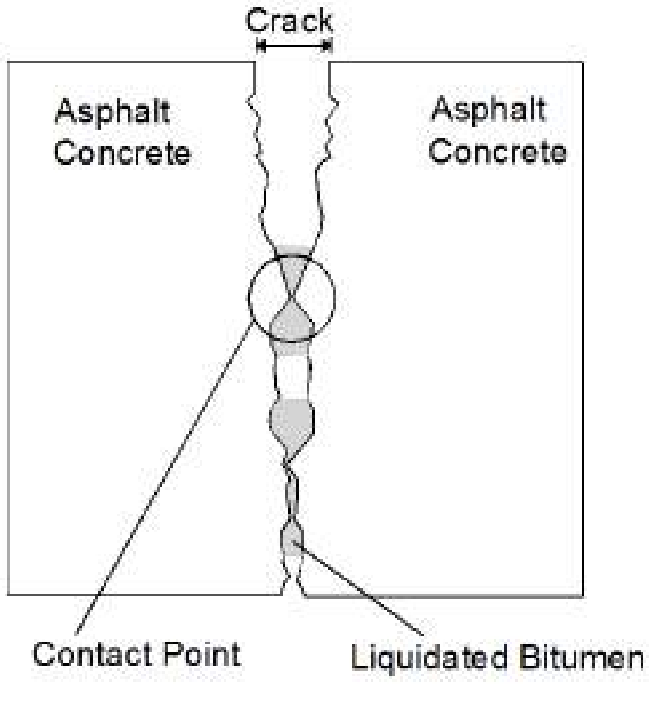

Figure (5.14): *Bitumen behavior in filling cracks of asphalt mixture*

Figure (5.15) shows Healing levels of asphalt mixture, at different Iron powder contents and after different heating times, it can be observed that healing level increases as Iron powder content increase. It can be also observed that after 180 second heating, 7.5% is an optimum Iron powder content, at which asphalt mixture healing level is maximum, and if the Iron powder is above the optimum value, the healing level decreases. Also, at 140 seconds heating it can be observed that healing level acceleration begins to lower after 7.5% iron powder, In addition, it's expected that as iron powder content increases, it would have to affect other physical properties of asphalt mixture like stability, density and void ratio, which guides to preferring increasing the heating time instead of increasing iron powder content above 7.5%.

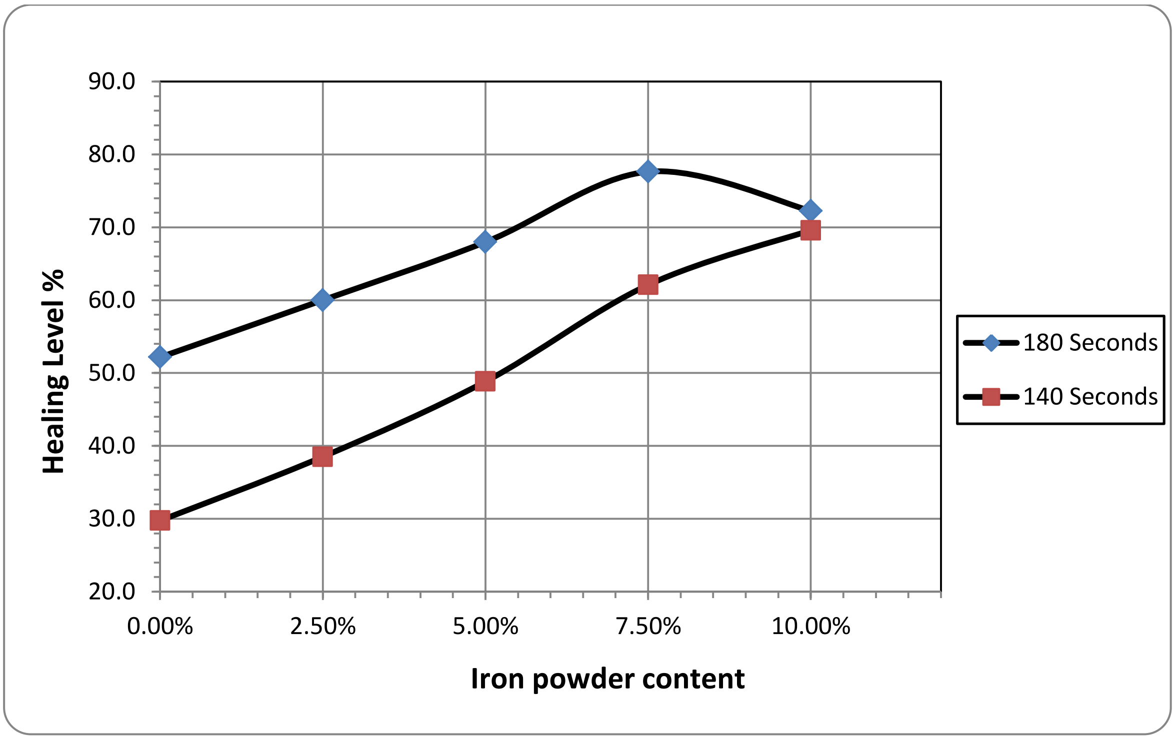

Figure (5.15): *Iron powder content vs. Healing Level*

This phenomenon is explained by the fact that after sample temperature reaches an appropriate point, the sample will be subjected to internal pressures as a result of the expansion of mixture components resulting from heating, which causes swelling and distortions of the sample, that's increases the void ratio within the sample during cooling of mixture without re-compact the mixture, and then causes weakness and lowering the healing level of mixture.

Figure (5.16) shows the surface deformities of the sample with iron powder content 10%, which was visually observed after samples getting heated for 180 seconds and reaches temperature above 170 ºC.

Figure (5.16): *Visually observed deformities for sample surface with 10.0% iron content, after getting heated above 170* ºC

CHAPTER 6
CONCLUSION AND RECOMMENDATIONS

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6.1 Conclusion

Based on results of experimental work for iron powder modified asphalt mixtures compared with conventional asphalt, the following conclusions can be drawn:

a) This research explains how asphalt mixture can be heated with induction heating. It has been proved that in order to accelerate heating of asphalt with induction, it is necessary to add electrically conductive materials (Iron powder) to asphalt mixture.

b) This research shows the effect of adding electrically conductive materials (Iron powder) on self-healing property of asphalt mixture. It has been found that by induction heating, the healing level of asphalt mixture increases with increasing the iron powder content of asphalt mixture.

c) The strength (fracture resistance) recovery of asphalt beams was used to evaluate its self -healing effect. It was found that completely fractured asphalt beams modified with addition of iron powder can be healed many times due to induction heating and asphalt beams strength could be recovered up to 78% at 7.5% iron content and 180 seconds heating.

d) It is concluded that the durability of asphalt pavements will be improved with induction heating as a result of increasing the self-healing and fatigue resistance of road pavements. The direct effect of this is less maintenance-activity on the road.

6.2 Recommendations

Based on the experience obtained from this study, the following aspects of applying induction heating technology are recommended for further research:

- While temperature of asphalt samples with 10% iron content was the higher after induction heating, the recovered strength (fracture resistance) at 10% iron content was less than at 7.5% content, this was explained because the test samples at high temperatures were deformed during induction heating. In order to reach a better healing level, it is recommended to re-compact asphalt locally using asphalt compactors or rollers.

- Future work will be performed to consider the healing effects with different mixture design of asphalt concrete samples, heating time-periods, volume and dimension parameters of iron powder, since these parameters are very important factors affecting the electrical conductivity and induction heating speed of asphalt.

- Application of this study tests on real life asphalt road sections may be helpful to obtain more real and accurate results and conclusions.

- The unavailability of heating induction machine and the complexity of its manufacturing should be overcome to bring the self-healing asphalt study to a real-life application in Palestine.

- Studying the effect of induction heating on different crack widths and different types of bitumen on the healing rates of asphalt mixtures requires more investigation.

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THE END

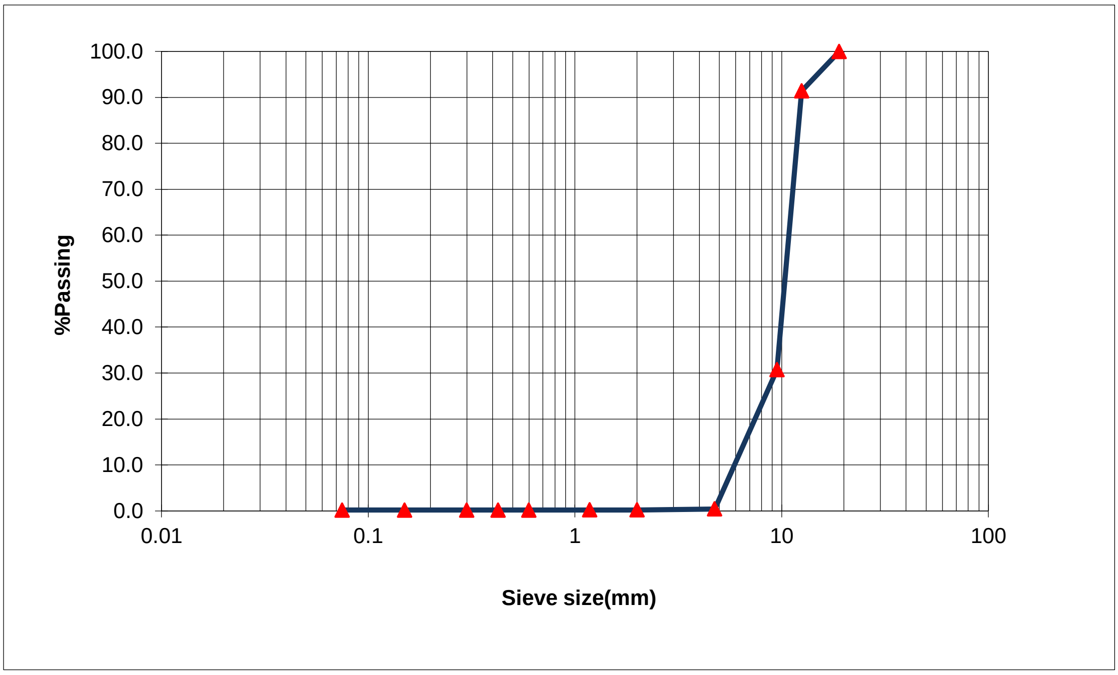
APPENDICES

Appendix (A)

Aggregates sieve analysis (ASTM C 136)

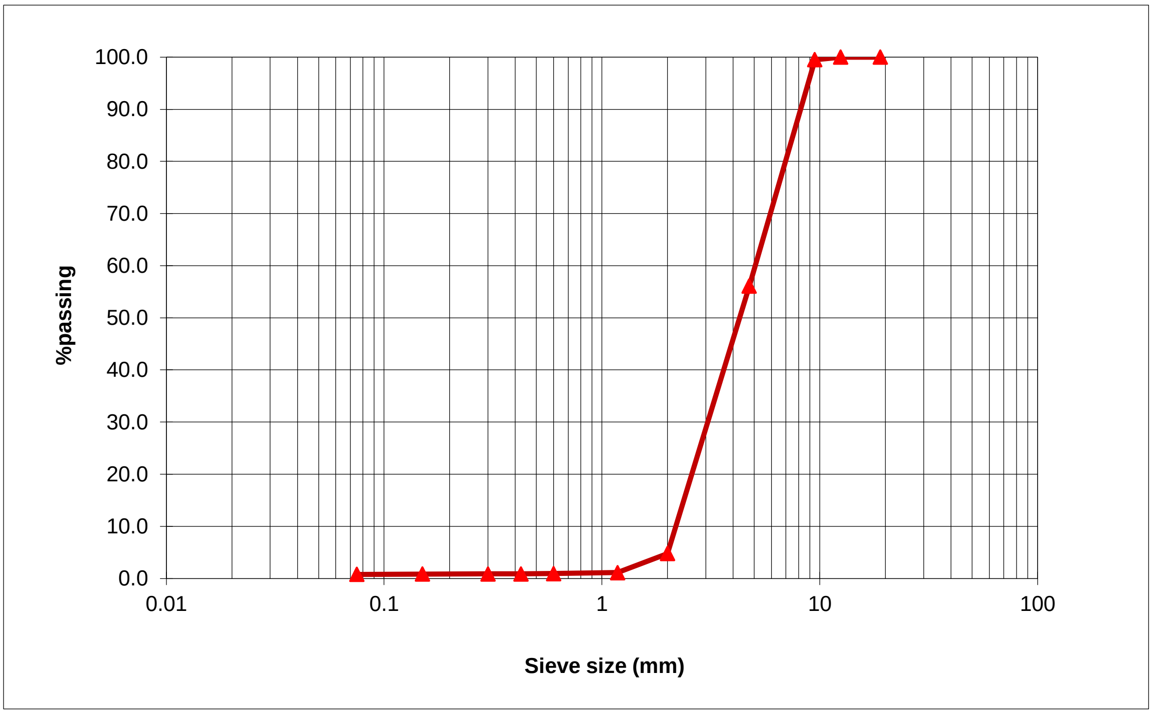
Sieve analysis Adasia (0/12.5)

Sieve size (mm)	Sieve #	Cumulative retained(g)	Cumulative retained(%)	Sample passing(%)
19	**3/4"**	0.0	0.0	**100.0**
12.5	**1/2"**	129.0	8.6	**91.4**
9.5	**3/8"**	1039.0	69.3	**30.7**
4.75	**#4**	1494.0	99.6	**0.4**
2.00	**#10**	1497.0	99.8	**0.2**
1.18	**#16**	1497.0	99.8	**0.2**
0.6	**#30**	1497.2	99.8	**0.2**
0.475	**#40**	1497.3	99.8	**0.2**
0.3	**#50**	1497.3	99.8	**0.2**
0.15	**#100**	1497.4	99.8	**0.2**
0.075	**#200**	1497.5	99.8	**0.2**
Pan	**Pan**	1500.0	100.0	**0.0**



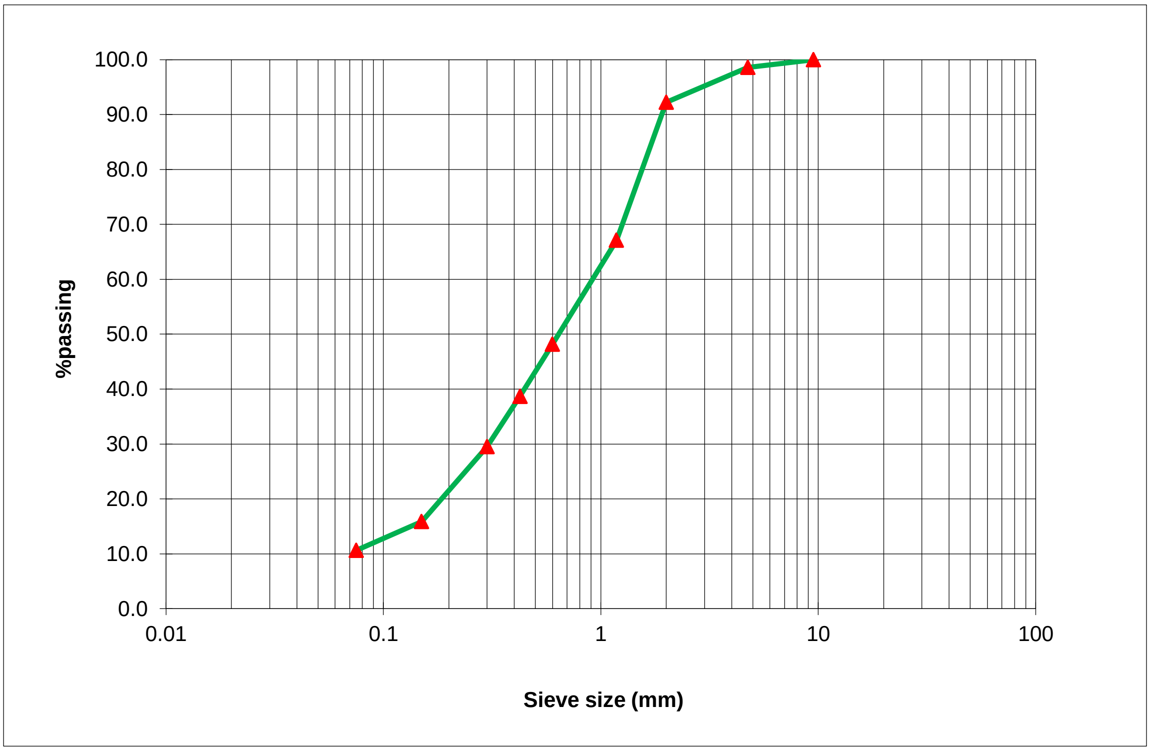
Sieve analysis Simsimia (0/9.5)

Sieve size (mm)	Sieve #	Cumulative retained(g)	Cumulative retained(%)	Sample passing(%)
19	**3/4"**	0	0.0	**100.0**
12.5	**1/2"**	0	0.0	**100.0**
9.5	**3/8"**	6	0.5	**99.5**
4.75	**#4**	540	43.9	**56.1**
2	**#10**	1172	95.2	**4.8**
1.18	**#16**	1217	98.9	**1.1**
0.6	**#30**	1219	99.0	**1.0**
0.475	**#40**	1220	99.1	**0.9**
0.3	**#50**	1220	99.1	**0.9**
0.15	**#100**	1220.3	99.2	**0.8**
0.075	**#200**	1220.9	99.2	**0.8**
Pan	**Pan**	1230.7	100.0	**0.0**



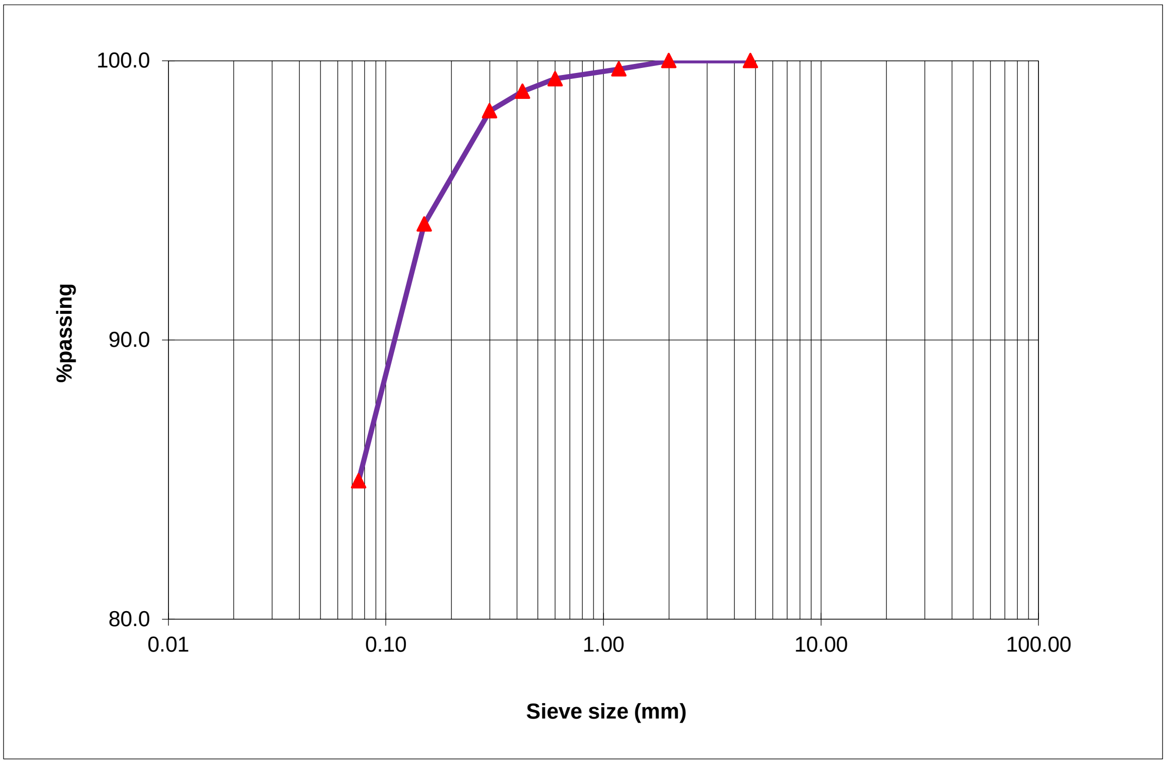
Sieve analysis Trabia (0/4.75)

Sieve size (mm)	Sieve #	Cumulative retained(g)	Cumulative retained(%)	Sample passing(%)
12.5	**1/2"**	0	0.0	**100.0**
9.5	**3/8"**	0	0.0	**100.0**
4.75	**#4**	14	1.4	**98.6**
2	**#10**	77.7	7.8	**92.2**
1.18	**#16**	328.7	32.9	**67.1**
0.6	**#30**	517.9	51.8	**48.2**
0.475	**#40**	613	61.3	**38.7**
0.3	**#50**	704.7	70.5	**29.5**
0.15	**#100**	841.2	84.1	**15.9**
0.075	**#200**	893.5	89.3	**10.7**
Pan	**Pan**	1000	100	**0.0**



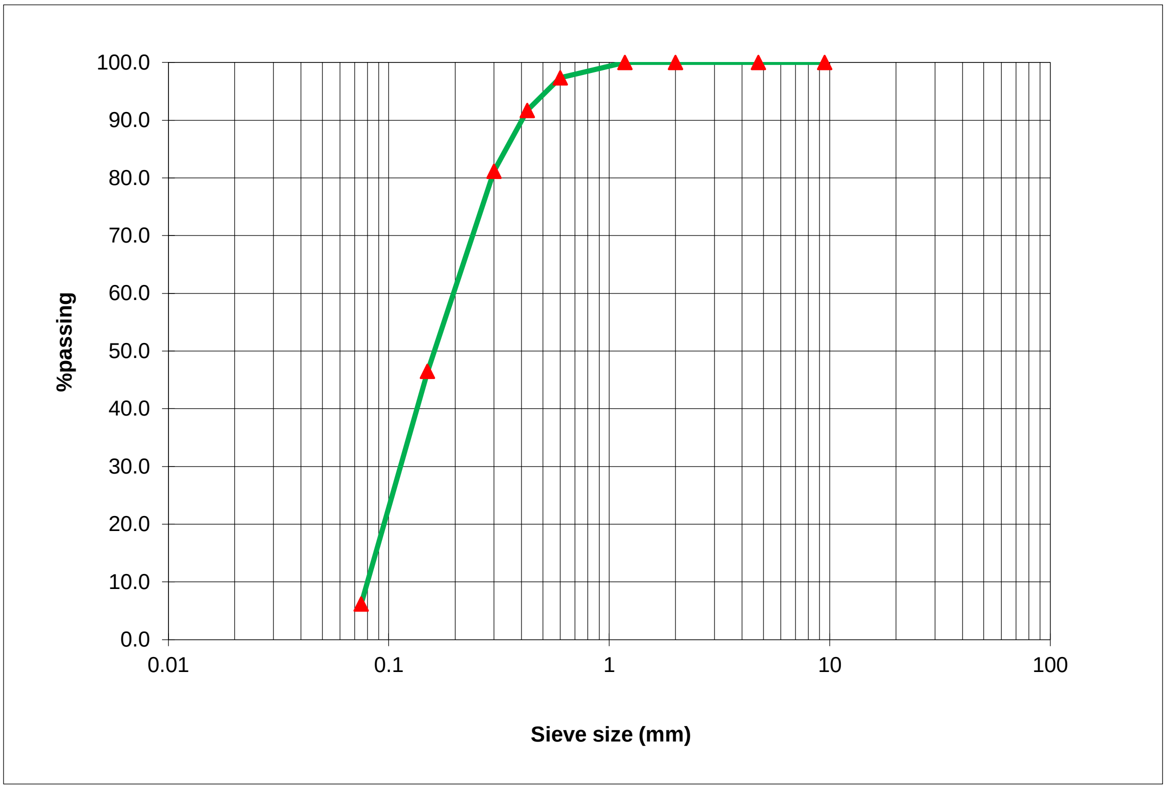
Sieve analysis Filler (0/1.18)

Sieve size (mm)	Sieve #	Cumulative retained(g)	Cumulative retained(%)	Sample passing(%)
9.5	**3/8"**	0	0	**100.0**
4.75	**#4**	0	0.0	**100.0**
2	**#10**	0	0.0	**100.0**
1.18	**#16**	0.6	0.3	**99.7**
0.6	**#30**	1.3	0.6	**99.4**
0.475	**#40**	2.2	1.1	**98.9**
0.3	**#50**	3.6	1.8	**98.2**
0.15	**#100**	11.7	5.8	**94.2**
0.075	**#200**	30.1	15.0	**85.0**
Pan	**Pan**	200	100	**0.0**



Sieve analysis Iron powder (0/0.60)

Sieve size (mm)	Sieve #	Cumulative retained(g)	Cumulative retained(%)	Sample passing(%)
2	**#10**	0	0.0	**100**
1.18	**#16**	0	0.0	**100**
0.6	**#30**	5.3	2.6	**97.4**
0.475	**#40**	16.6	8.3	**91.7**
0.3	**#50**	37.7	18.8	**81.2**
0.15	**#100**	107	53.5	**46.5**
0.075	**#200**	187.7	93.8	**6.2**
Pan	**Pan**	200	100	**0.0**



Appendix (B)

Aggregate Blending

Suggested percentages for binder course aggregate mix

Aggregate mix	Grain size (mm)											Suggested percents for final agg. Mix
	0.075	0.15	0.3	0.6	1.18	2	4.75	9.5	12.5	19	25	
Filler (0/1.18)	84.95	9.20	4.05	1.15	0.35	0.30	0.00	0.00	0.00	0.00	0.00	2.6
	2.21	0.24	0.11	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.00	
Trabia (0/4.75)	10.65	5.23	13.65	18.68	18.92	25.10	6.37	1.40	0.00	0.00	0.00	51.9
	5.53	2.71	7.08	9.69	9.82	13.03	3.31	0.73	0.00	0.00	0.00	
Simsimia (0/9.5)	0.80	0.05	0.02	0.08	0.16	3.66	51.35	43.39	0.49	0.00	0.00	20.1
	0.16	0.01	0.00	0.02	0.03	0.74	10.32	8.72	0.10	0.00	0.00	
Adasia (0/12.5)	0.17	0.01	0.01	0.01	0.01	0.00	0.20	30.33	60.67	8.60	0.00	25.4
	0.04	0.00	0.00	0.00	0.00	0.00	0.05	7.70	15.41	2.18	0.00	
Folia (0/19)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Sum	7.94	2.97	7.20	9.74	9.86	13.77	13.68	17.15	15.51	2.18	0.00	100
Σ% passing	7.94	10.91	18.10	27.85	37.71	51.48	65.16	82.31	97.82	100.00	100.00	
Sieve size (mm)	0.075	0.15	0.3	0.6	1.18	2	4.75	9.5	12.5	19	25	
Wearing 0/ 12.5 (min)	2		5			28	44		90	100	100	ASTM Specifications D3515 – D-5
(max)	10		21			58	74		100	100	100	

Appendix (C)

Calculations of physical properties of aggregates

1- <u>**Specific gravity and absorption** (ASTM C127 - C128)</u>

- **Coarse aggregate (Adasia 0/12.5)**

A= Weight of oven-dry sample in air, grams = 1566.1 gr

B=weight of saturated - surface -dry sample in air = 1602.9 gr

C= weight of saturated sample in water = 985.4 gr

- Bulk dry S.G = $\frac{A}{B-C} = \frac{1566.1}{1602.9-985.4} = 2.54$
- SSD S.G =$\frac{B}{B-C} = \frac{1602.9}{1602.9-985.4} = 2.60$
- Apparent S.G =$\frac{A}{A-C} = \frac{1566.1}{1566.1-985.4} = 2.70$
- Effective S.G = $\frac{Bulk(dry)+Apparent}{2} = \frac{2.54+2.70}{2} = 2.62$
- Absorption = $\frac{B-A}{A} * 100 = \frac{1602.9-1566.1}{1566.1} * 100 = 2.35\%$

- **Coarse Aggregate (Simsimia 0/9.5)**

A= Weight of oven-dry sample in air, grams = 1099.0 gr

B=weight of saturated - surface -dry sample in air = 1125.7 gr

C= weight of saturated sample in water = 697.4 gr

- Bulk dry S.G = $\frac{A}{B-C} = \frac{1099}{1125.7-697.4} = 2.57$
- SSD S.G =$\frac{B}{B-C} = \frac{1125.7}{1125.7-697.4} = 2.63$
- Apparent S.G =$\frac{A}{A-C} = \frac{1099}{1099-697.4} = 2.74$
- Effective S.G = $\frac{Bulk(dry)+Apparent}{2} = \frac{2.57+2.74}{2} = 2.66$
- Absorption = $\frac{B-A}{A} * 100 = \frac{1125.7-1099}{1099} * 100 = 2.43\%$

2- Pycnometer method

- **Fine Aggregate (Iron 0/2.00)**

(W_{P+W}) = Weight of Pycnometer filled with water = 1785.68gr

(W_S) = Weight of the Iron sample dry and SSD = 425.73gr

(W_{S+P+W}) =Weight of Pycnometer filled with water and the Iron sample = 2122.41 gr

$$\rho_{Iron} = \frac{W_S}{W_S - (W_{S+P+W} - W_{P+W})}$$

$$\rho_{Iron(Dry\ \&SSD)} = \frac{425.73}{425.73-(2122.41 - 1785.68)} = 4.80(g/cm^3)$$

- Apparent S.G $= \frac{Dry}{Dry - in\ water} = \frac{425.73}{425.73-336.73} = 4.80$
- Absorption $= \frac{SSD-Dry}{Dry} * 100 = \frac{425.73-425.73}{425.73} * 100 = 0.00\%$

Fine Aggregate (Trabia 0/4.75)

(W_{P+W}) = Weight of Pycnometer filled with water = 1796.7gr

(W_S) = Weight of the crushed sample SSD = 500.1gr

(W_S) = Weight of the crushed sample Dry = 488.9 gr

(W_{S+P+W}) =Weight of Pycnometer filled with water and the crushed sample = 2107.2 gr

$$\rho_{trabia} = \frac{W_S}{W_S - (W_{S+P+W} - W_{P+W})}$$

- $\rho_{trabia\ SSD} = \frac{500.1}{500.1-(2107.2-1796.7)} = 2.64(g/cm^3)$
- $\rho_{trabia\ Dry} = \frac{488.9}{500.1-(2107.2-1796.7)} = 2.58(g/cm^3)$
- Apparent S.G $= \frac{Dry}{Dry - in\ water} = \frac{488.9}{488.9-310.5} = 2.74$
- Effective S.G $= \frac{Bulk(dry)+Apparent}{2} = \frac{2.58+2.74}{2} = 2.66$
- Absorption $= \frac{SSD-Dry}{Dry} * 100 = \frac{500.1-488.9}{488.9} * 100 = 2.29\%$

3- **Abrasion value** (ASTM C131)

- **Grade (C)**

Passing 9.5mm , Retained on 6.3 mm = 2500 gr

Passing 6.3mm , Retained on 4.75mm = 2500 gr

A= Original sample weight = 5000 gr

B=Weight retained on the 1.7mm sieve = 4123 gr

A.V= $\frac{A-B}{A} * 100 = \frac{5000-4123}{5000} * 100 = 17.54\%$

Appendix (E)
Photos

Figure (F1): *Loss Angeles abrasion Test*

Figure (F2): *Preparation of Bitumen specimens*

Figure (F3): *Softening point Test*

Figure (F4): *Flash point Test*

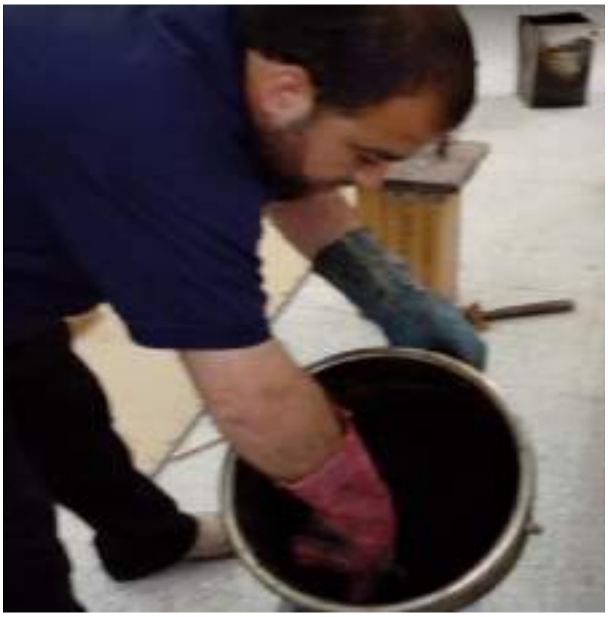


Figure (F5): *Preparation of asphalt mixture*

Figure (F6): *Asphalt samples compaction*

Figure (F7): *Samples fracture with three point bending machine*

Figure (F8): *Using Freezer in Cooling samples to -20 C*

Figure (F9): *Using Microwave in heating samples*

Figure (F10): *Using laser thermometer for measuring Temperature*

Figure (F11): *Iron powder modified asphalt samples*

Figure (F12): *Using wooden containers in stabilizing asphalt samples*