PERFORMANCE EVALUATION OF STEEL SLAG AND MILL SCALE UTILIZATION AS PARTIAL AGGREGATE REPLACEMENT IN HOT MIX ASPHALT

SAAD RABBANI

(00000104370)

A thesis submitted in partial fulfillment of
the requirements for the degree of

Master of Science

In

Transportation Engineering

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING (SCEE)
NATIONAL UNIVERSITY OF SCIENCES & TECHNOLOGY (NUST)
SECTOR H-12, ISLAMABAD, PAKISTAN
(September, 2020)

THESIS ACCEPTANCE CERTIFICATE

Certified that final copy of MS thesis written by **Mr. SAAD RABBANI (Registration No.00000104370)** of **(SCEE)**, has been vetted by undersigned, found complete in all respects as per NUST Statutes / Regulations, is free of plagiarism, errors, and mistakes and is accepted as partial fulfillment for award of MS degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have also been incorporated in the said thesis.

Signature: ________________________________

Name of Supervisor: **Dr. ARSHAD HUSSAIN**

Date: ____________________________________

Signature **(HOD)**: _________________________

Date: ____________________________________

Signature **(Dean/Principal)**: ________________

Date: ____________________________________

PERFORMANCE EVALUATION OF STEEL SLAG AND MILL SCALE UTILIZATION AS PARTIAL AGGREGATE REPLACEMENT IN HOT MIX ASPHALT

By

SAAD RABBANI

(00000104370)

A Thesis

Of

Master of Science

Submitted to

Department of Transportation Engineering

School of Civil and Environmental Engineering (SCEE)

National University of Sciences and Technology (NUST)

Islamabad

In partial fulfillment of the requirements for the degree of

Master of Science Transportation Engineering

September, 2020

DEDICATED

TO

MY PARENTS, TEACHERS AND COLLEAGUES

ACKNOWLEDGEMENTS

I am greatly thankful to **Almighty Allah**, who gave me the strength and patience to complete my research. I would like to express my sincere gratitude to Dr. Arshad Hussain, being the advisor for this study, whose countless inspiration and guidance made it possible to complete my research work. Also, Dr. Kamran Ahmed and Engr. Mansoor Ahmed Malik in the capacity of committee members gave me guidance and feedback throughout the thesis process. I am thankful to Dr. Bilal Khurshid for providing guidance and motivation to complete this research. I acknowledge and extend my thanks to the staff of the transportation lab, Iftikhar Ali Shah, Hidayat Ullah, and Mahmood Hussain, for their help throughout this research journey. I also thank my colleague Mr. Ahmer hameed for his help and moral support.

I would like to pay gratitude to the academic members of SCEE who provided a lot of knowledge during the postgraduate program. In the end, I pay my earnest gratitude with a sincere sense of respect to my parents for their encouragement, sincere prayers, and good wishes for the successful completion of my research work.

(Engr. Saad Rabbani)

Table of Contents

LIST OF ACRONYMS

AASHTO	- American Association of State Highway and Transportation Officials
ASTM	- American Society for Testing and Materials
BS	- British Standard
HMA	- Hot Mix Asphalt
LVDTs	- Linear Variable Differential Transformer
UTM	- Universal Testing Machine
VMA	- Voids in Mineral Aggregates
VFA	- Voids Filled with Asphalt
IF	- Induction Furnace
ITS	- Indirect Tensile Strength
MR	- Resilient Modulus
Gmb	- Bulk Specific Gravity
Gmm	- Maximum Specific Gravity
MS-2	-Manual Series (Asphalt Institute)
NHA	- National Highway Authority
NMAS	- Nominal Maximum Aggregate Size

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Roads are valuable assets of a country and with the increase in road traffic and the emergence of trade through CPEC routes; the need for proper roads has significantly increased in Pakistan. Roads serve a very important role in the functioning of a country. In Pakistan, the majority of the roads are built using asphalt concrete. The technique of using waste/ alternative materials was though introduced earlier in the twentieth century, it's use has significantly increased in the last couple of decades. Waste products are produced in steel making processes which can be utilized in road pavement as aggregate. The past two decades have seen an increase in the production of waste products in the steel industry, considerably. The steel industry's goal of zero-waste is becoming achievable because of ground-breaking technology developments and collaborations with other industries. This prevents the coverage of areas due to landfills, helps preserve natural resources, and reduces the emission of CO2 in the environment. The depletion of natural resources and energy use in the production phase is reduced by substituting natural resources with waste products. If steel slag and mill scale is disposed of in a landfill, then it has hazardous effects on the environment and it engages valuable land which can otherwise be used for important purposes. Therefore the analysis is done on the use of Induction Furnace steel slag as coarse aggregate and mill scale as fine aggregate in hot mix asphalt. The materials that were used in this research comprised of aggregate from Margalla quarry, Induction Furnace steel slag and mill scale from Pak Iron steel mill Islamabad, plus binder from Parco (Pak Arab refinery limited) having a penetration grade of 60/70. Different percentages i.e. 5%, 10%, and 15% of IF slag whereas 3%, 6%, and 9% of mill scale by weight of total aggregate, were replaced. Performance tests were carried out, i.e. resilient modulus and moisture susceptibility of asphalt samples were investigated. Moisture damage was measured using the Universal Testing Machine (UTM) by performing the Indirect Tensile Strength (ITS) test. The addition of IF steel slag gave promising results as far as Indirect tensile strength, tensile strength ratio, and resilient modulus are concerned. Mixes with 15% steel slag gave better indirect tensile strength and resilient modulus results than the rest of the mixes, whereas TSR values for steel slag are almost similar and comparable to that of the conventional mix, with a very minute decrease. For mixes with mill scale, ITS (dry) increased at 6% from that of 3% and then decreased at 9%. Whereas ITS(wet) slightly decreased with an increase in the percentage of mill scale from 3 % to 6%, therefore this resulted in a minor decrease in TSR values comparatively, whereas a significant decrease in TSR occurs at 9% mill scale because of a decrease in ITS(wet) values but, still the value is quite above than the minimum requirement. This depicted that mixes with 9% mill scale are more moisture susceptible and sensitive in comparison to mixes with 3%, 6% mill scale, steel slag, and conventional mixes. Whereas in resilient modulus tests steel slag showed better performance but replacing mill scale with conventional aggregate resulted in a gradual decrease in resilient modulus although 6 % showed optimum result for resilient modulus. Mixes with 9% mill scale gave comparatively the least value for resilient modulus. Low percentages replacement was carried out in this research study for the IF steel slag and mill scale. IF steel slag showed quite promising results and mill scale results were satisfactory as for as these two performance testing parameters were concerned. But small percentages of mill scale up to 6% showed good results. This seems that these materials can show some interesting behavior in other performance tests and for practical applications, trial sections can be beneficial as they will show on-ground results of using these materials, within the indigenous environmental factors and situations of Pakistan.

Key words: Steel slag, resilient modulus, hot mix asphalt, tensile strength ratio, indirect tensile strength.

Chapter 1

INTRODUCTION

1.1 BRIEF DESCRIPTION/ BACKGROUND

Every year nearly 400 million tons of slag is produced. Advanced countries are using steel slag efficiently and it is used in road construction worldwide. Steel production in Pakistan is nearly 5 million tons therefore a reasonable amount of slag is produced which should be utilized instead of disposing of it in landfills (http://www.pakalumni.com). According to previous studies and physical survey of steel mills, steel slag produced is 10%-15% of total steel production Steel slag is produced when scrap metal is melted at high temperature to obtain steel which is then cast in the form of steel billets bars. Oxidation of the steel surface during reheating, conditioning, hot rolling, and hot forming operations causes the formation of mill scale. Descaling is done to remove it from the steel surfaces. It is then recovered by gravity separation techniques.

In Pakistan research on blast furnace slag is carried out where BF slag is used as aggregate in HMA and its suitability is justified through lab experiments. But not much research is done on steel slag especially steel slag produced in Induction Furnaces.

In the early ’70s, almost 15 arc furnaces were installed in Pakistan and these furnaces are playing their part in producing steel in our country. More than 140 steel induction furnaces are installed in different areas of Pakistan. As induction furnaces are less expensive and have less production time than arc furnaces so private sector in Pakistan has shifted to induction furnaces. The private sector is almost producing 30 million tons of steel and steel products annually (abad.com.pk).

In this research, we will investigate the suitability of the use of induction furnace steel slag and mill scale waste as partial replacement of aggregate in Hot mix asphalt. Performance evaluation will be carried out by laboratory testing which includes resilient modulus and moisture damage through tensile strength ratio. Different percentages of steel slag would be used as a replacement for coarse aggregate and likewise, three different percentages mill scale will be utilized as fine aggregate replacement having the aim of synthesizing research findings on the use of steel slag and mill scale in HMA (wearing course).

1.2 REASONS / JUSTIFICATION FOR SELECTION OF THE TOPIC

Over the past years, the world is heading to attain the Millennium Development Goal (MDG) where sustainability is of great importance. The key purpose of this goal is to use all the natural resources without deterring the needs and not causing difficulties for future generations. With the time world is progressing and there is more and more demand for natural resources as construction industries are booming but the irony is that natural resources are limited. Pakistan also has limited natural sources utilized as aggregate sources. Therefore, waste materials/ alternative materials must be used in road construction. In this way, the hazardous effects of steel by-products i.e. steel slag and mill scale on the environment are eliminated. Steel slag from induction furnaces in Pakistan is disposed of in landfills which causes pollution, damages the environment, and even pollutes groundwater as metals and other chemicals get to mix with groundwater through leaching.

1.3 OBJECTIVES

- To investigate the effect of using steel slag as coarse aggregate on properties of hot mix asphalt i.e. tensile strength ratio and Resilient Modulus.
- To investigate the effect of mill scale as fine aggregate, on properties of hot mix asphalt.
- To compare the results and find suitable percentages of steel slag and mill scale to be used in asphalt concrete mixtures.

1.4 SCOPE OF THE THESIS

To achieve the above-mentioned objectives following methodologies are implemented. Literature review about steel slag and mill scale utilization was carried out. It was deducted that induction furnace slag and mill scale are not utilized in wearing course of flexible pavement.

Therefore these materials were used in the hope of promising results. Literature review about marshall mix design, resilient modulus, and moisture susceptibility was also carried out.

This study involved NHA-B gradation, limestone aggregate from Margalla quarry and Parco bitumen grade 60/70.

Aggregate and bitumen laboratory characterization was done. Marshall mix design using the MS-2 manual was used to find out optimum bitumen content at 50 blows simulating medium level traffic.

Marshall samples of 4in dia. were used for performance testing i.e. resilient modulus and TSR. Samples conditioning was carried out according to ALDOT-361. Testing of unconditioned and conditioned specimens was conducted, for indirect tensile strength through test equipment UTM-25 according to ASTM D 6931-07. Resilient modulus test was done confirming to ASTM D 4123.

Test matrix for performance testing is mentioned below

Table 1. 1: Test matrix for performance testing

S.No	**Material**		**Performance Tests**		
		%age of total agg replaced	**Resilient Modulus**	**TSR**	**Total**
1.	HMA		2	4	6
2.	HMA + steel slag (coarse agg replaced)	5%	2	4	18
		10%	2	4	
		15%	2	4	
3.	HMA + mill scale(fine agg replaced)	3%	2	4	18
		6%	2	4	
		9%	2	4	
	Total		14	28	42

1.5 RELEVANCE TO NATIONAL NEEDS

Pakistan is a developing country, with the passage of time the construction industry will flourish more and steel demand is increasing day by day. With time steel production in Pakistan is increasing according to statistics. So there will be more production of steel slag. In Pakistan, mostly steel furnaces are installed which uses scrap to produced steel. In Pakistan research on blast furnace slag is carried finding its suitability of using it in road construction but not much work done on steel slag from induction furnace and mill scale. In developed countries, steel slag has its utilization as aggregate for road construction on a large scale therefore protecting the environment. In Pakistan induction furnace steel slag is mostly disposed of in landfills therefore having long-term detrimental effects on the environment. By utilizing such waste materials/ by-products, we will help in conserving the natural resources of our country.

1.6 AREAS OF APPLICATION

The area of application this research is to find out the suitability of using alternative materials i.e. steel slag and mill scale in road pavement in transportation field and determination of moisture damage of steel slag and mill scale containing mixes used in the road network of Pakistan. It will help in achieving sustainability goals as it will help in conserving natural resources as expected with time steel production in Pakistan will increase. This research will also help in conserving the environment from the harmful effects of steel industry by-products as slag decreases the fertility of soil. The suitability of mill scale in HMA is to be assessed. As it has high metal content therefore it is expected that its use will be beneficial in induction heating/ induction healing of roads. Use of these materials is beneficial for sustaining environment and also have associated economic benefits.

1.7 ORGANIZATION OF THE THESIS

This thesis is comprised of 5 chapters which are briefly summarized below

Chap 1 highlights the use of steel industry's wastes in the asphalt paving mixtures and emphasizes its suitability. An overview of the objectives, problem statement scope of the research, and tests performed is also stated.

Chap 2 comprises of literature review about the findings of past researches carried on the use of steel slag and mill scale. It also includes a literature review of resilient modulus and moisture susceptibility.

In Chap 3 the methodology adopted for attaining the research objectives is been discussed. It encompasses the material selection, characterization, determination of OBC, and volumetric analysis of mixes and performance tests and their procedures.

Chap 4 experimental outcomes and analysis of the results obtained from resilient modulus and TSR are discussed.

Chap 5 comprises of outcomes and results. Recommendations about future researches are also stated.

Chapter 2

LITERATURE REVIEW

2.1 INTRODUCTION

Because in construction a lot of aggregate is used, which is gradually depleting the natural resources. The use of these materials has threefold advantages which are conserving natural resources, disposing of waste materials which are the cause of unsightliness, and clearing valuable land for other uses. It is common practice in some countries to make use of waste materials and industrial by-products in road construction. Examples of this are:

a. Bulk fill for embankment construction e.g. colliery shale.

b. Base and sub-base construction e.g. burnt colliery shale, blast furnace slag

c. Aggregate for bituminous mixtures e.g. steel slag, blast furnace slag.

d. Hydraulic binder e.g. Fly ash together with lime or cement.

2.2 BACKGROUND

Waste management and the use of mining, metallurgical, and industrial by-product have become an important aspect of national policies aimed at reinforcing present trends regarding the conservation of natural resources, environmental protection, and energy savings. These three vital concerns have made it highly desirable to systematically promote known uses, and develop new uses for various types of wastes and by-products in highway construction. With the shortage of land available for waste disposal, the restrictions on dumping, and the increased generation of wastes and by-products, it is imperative that increased use of these materials be developed. waste materials and by-products can be used in road construction for solving the problem of disposal of waste material economically.

While exploring new materials, waste materials should be given first preference. There are certain waste materials either agro waste or industrial waste that can be used in asphalt concrete

(AC) wearing course, amongst them are steel slag and mill scale. The use of waste byproducts in place of virgin conventional materials would relieve some of the burdens on the ailing economy of Pakistan. Slag is a waste by-product of the metallurgic industry.

This study is not only aimed at using two waste products i.e. induction furnace slag and mill scale as road construction materials but also to see how these can impact the properties of asphalt mix at high moisture. Pakistan is a developing country and needs to develop road networks throughout the country. There is an issue of drainage of roads even in big cities like Karachi. The poorly drained retained water damages the pavement structure, therefore, moisture damage is been evaluated in this study

Coarse aggregate at 5%, 10% and 15% replacement levels with induction furnace steel slag and fine aggregate at 3%, 6% and 9% replacement levels with mill scale was studied. Marshall asphalt mix was designed for medium-level traffic therefore optimum bitumen content was obtained at 50 blows. Pakistan is a developing country most of the underdeveloped areas need to develop road networks. Pakistan is an agricultural country so farm to market roads are necessary, roads connecting towns to towns and towns to cities are a dare need for the development of population masses. Tests were carried out according to ASTM and AASHTO specifications. Marshall mix design properties, resilient modulus and moisture damage using the indirect tensile test of the various mixes were evaluated.

2.3 TYPES OF SLAG

Slags are formed during the refining and processing of metals. There are two types of slags

1. Ferrous slags
2. Non-ferrous slags

Ferrous slags are formed during the refining and processing of iron and steel while non-ferrous slags are produced during the refining and extraction of non-ferrous metals like copper, lead, aluminum, etc. the utilization of iron and steel is much more than non-ferrous metals therefore ferrous slags are produced in large quantities. Slag is formed when the metal is separated from unwanted elements in raw material (ore or scrap used). Flux material is added during the melting process in the furnace which facilitates the separation of unwanted elements from metal.

There are different types of slags generated in iron and steel making industries. Ferrous slags are mainly divided into two types

I. iron slag
II. steel slag

2.3.1 Iron slag (blast furnace slag):

Blast furnace slag is actually iron slag. In blast furnace, iron ore extracted from natural resources is used and after processing in furnaces iron is obtained. A blast furnace slag is a molten material, which appears above the pig iron at the bottom of the furnace. It is formed from the gangue derived from the iron ore, the combustion residue of the coke, the limestone and other materials that have to be added. Its temperature is close to that of iron that is between 1400 °C and 1600 °C. Slow curing of slag leads to a stable solid, which is crystalline and has mechanical properties similar to basalt. If they are quenched from the melt, slags are obtained as glass materials higher in energy than the crystalline material. These slags, which are called granulated slags, have latent hydraulic properties.

- **Historical background**

The earliest known use of slag was in the days of the Roman Empire when slag from Catalan forges was used as a base material for Roman roads. The first sustained use was in the manufacture of armaments. Some ammunition makers in the 16th century thought of making cannonballs from slag instead of the more costly iron. Other small volume uses that developed over the years included cast concrete building blocks, slag lime mortars and cement, slag wool, ballast, road base, and finally concrete aggregate. The true potential of the blast furnace slag was recognized after World War 2.

The changes in blast furnace practice in the mid-1950s led to the production of slag that had lower bulk density. However, there was evidence that it could be used successfully for road making. The road research laboratory in collaboration with the British Slag Federation investigated the concern.

A survey of examples of surfacing of various types where the lighter-weight slag had been used was made in London, the southern countries and South Wales. Some 80 sites were visited and the performances of the material in bituminous mixtures were assessed. It became clear from this survey that slag, provided an increased binder content was used, the lighter weight slags could give performance comparable with that from a conventional dense blast furnace slag (Rojer Hosting, 1992).

Blast furnace slag is a by-product of iron making industry. At the time of production, its temperature is between 1400^0C and 1600^0C. It may take several forms based on methods used for cooling processes. The slag used in this study is from Karachi Steel Mills and is called granulated blast furnace slag due to its -production process.

- **Use of blast furnace slag in road construction**

The use of granulated slag, as a hydraulic binder in pavement courses, is today a proven technique having both economic and technical advantages.

This technique has seen widespread development, especially in France, where its use has become so extensive that there are fears that the resources of slag will no longer will meet the needs of road construction. In 1974, 48 percent of the French granulated slag production went to road construction, while the cement industry accounted for some 50 percent. Its use in pavement has now been taken up by several countries including Luxembourg, Italy, Hungary, Algeria and Tunisia.

- **Use in asphalt concrete pavements**

Blast furnace slag can be used only as fine aggregate because of its size gradation (0-4mm) in the wearing course. The earliest research on use of blast furnace slag as fine aggregate in asphalt pavements was carried out in 1950's. The full-scale road experiments on the Great North Road A.1, and the Yaxley-Farcet road B 1091, in Huntington-Shire were begun in 1954 to test the laboratory findings on the effect of changing the types of fine aggregates in dense bituminous surfacing mixtures. These roads carried about 3,500 and 4,000 tons of traffic per day respectively in 1955. It was concluded that both on heavily and on lightly trafficked roads, satisfactory results were obtained over a period of five years with rolled asphalt made with either crushed-rock or slag fine aggregate. For the dense tar surfacing, it was found that good results were obtained with blast furnace aggregate over a range of binder contents considerably wider than can be used with sand, as the fine aggregate (Rojer Hosting, 1992).

Now a day granulated blast furnace slag is not being utilized much in AC wearing course and its use should be studied in the Asphalt wearing course keeping in view the climatic conditions prevailing in tropical climates.

- **Use in base and sub-base**

  Nearly all developed countries use granulated BF slag to replace natural aggregates, either for blanket courses, base or sub-bases. Following laboratory tests going back to 1961, the use of granulated slag as binder for gravel slag and sand slag has been under development in France since 1965 and has shown that granulated slag in association with a basic catalyst (lime or soda) sets by a hydration process.

Granulated blast furnace slag is used in various countries in base and sub-base construction. The different types of mixes with different proportions of granulated slag are produced for utilization of slag in road construction like gravel slag, sand slag, ready mixed gravel slag, pre crushed granulated slag etc.

Gravel slag is produced in mixing plants; it consists of a mixture of natural or artificial gravel with 15 to 20 percent granulated slag together with I percent of basic activator (generally hydrated lime), and a water content of about 10 percent. The mechanical characteristics of gravel slags are unaffected by temperature (once cured) or by speed of load application. The relatively high tension/ compression ratio is important to prevent cracking. The amount of granulated slag added will depend on the pavement layer for which the gravel slag is to be used, less is employed in the sub-base than the base course.

Ready-mixed gravel slag is similar to gravel slag in composition and the only distinction is that of transportation. Ready-mixed gravel slag is manufactured in a fixed plant where the aggregates are produced and subsequently transported by train to a neighborhood of the road construction, often over a haul of some hundreds of kilometers and this is only because of the slow setting time of these gravel slags.

All slag gravel slag is already used regularly in Northern and Eastern France. The sharp and angular properties of slag and its freedom from foreign material give the moisture an immediate mechanical stability and make it impervious to the effects of water. Hence, whatever the weather conditions, all-slag gravel-slag will ensure excellent behavioral characteristics. Pre crushed granulated slag is obtained by lightly crushing the whole mass of granulated slag to obtain 0-2 mm material with 10 percent fine material (minus 90 micron). When used in base and sub base construction, it gives greater degree of compaction. As compared to normal gravel slags mixtures and for the same strengths, less pre crushed granulated slag may be required.

2.3.2 Steel Slag

Steel slag is produced in the formation of steel. Mostly in steel mills steel scrap is used and pure steel is extracted as scrap is melted at high temperature. Scrap steel may be of varying quality from poor quality to good quality if imported scrap is used therefore steel slag produced has variations in composition and properties. Metallic components present in steel slag can be separated by magnetic separation.

Steel slag is further divided into different types on the basis of the furnaces which are used in steel industries, which are; i) electric arc furnace slag ii) basic oxygen furnace slag iii) induction furnace slag iv) ladle slag

Slag composition is dependent upon composition of flux and additives, procedure used for its generation, the cooling speed and the type of steel been produced. Methods of cooling are air cooled , cooling by using large quantity of water, cooling by sprinkling little water. Crystalline slag is formed in air cooling. Crystalline slag has porous structure due to the formation of air bubbles in melted mass so it is normal weight/ density aggregate(Barišić et al., 2010).

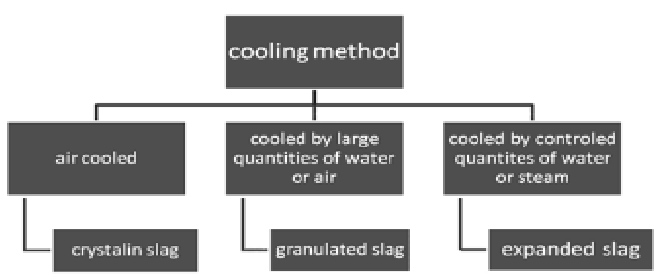


Figure 2. 1: Cooling process of slag

Steel slag has different types that depend on the procedure used to make steel. When oxides of iron, manganese aluminum, magnesium, and calcium combine with calcium ferrites and silicates in a furnace a non-metallic material is produced which floats on molten steel. It is the impurity present in the raw material that is charged in the furnace. Furnaces can be of different types like basic oxygen furnace, electric arc furnace, or induction furnace. (National Slag Association).Steel slag can be used as aggregate in the base, sub-base, and wearing course of flexible pavements, ballast for the railroad, in cement production, and agricultural uses.

Three main types of furnaces are electric arc furnace (EAF), basic oxygen furnace (BOF), and induction furnace (IF). So the slag is named after the type of furnace used.
As different types of scrap and additives are used in different steel mills so the chemical and physical composition can vary from one mill to another mill.

(Tiwari et al., 2016) mentioned that sometimes steel slag can exhibits expansion so becomes a bit unstable due to the presence of a large amount of free lime and free magnesia so therefore it can be used in roads especially in the wearing course but cannot be used as fill under different structures.

(Ameri et al., 2013) The construction of asphalt concrete pavement has environmental effects and economical costs, heat sources are needed for the processing of paving materials and natural resources are utilized. Therefore using steel slag as an alternative material is a good option.

2.3.2.1 Basic Oxygen Furnace Slag

In BOF iron, metal scrap, a fluxing agent like lime, and chemicals are used
Molten iron from the blast furnace process is combined with scrap metals and a fluxing agent like dolomite or lime in basic oxygen furnace. Seel is produced along with basic oxygen furnace slag. Oxygen is blown through the molten iron which lowers down the carbon content.

High-quality steel is produced as a result and the by-product steel slag is also generated.
Robert Durrer developed this process in 1948, it became commercial in 1952 (A Steel, Grade, 2011). It is also referred as converter slag

2.3.2.2 Electric Arc Furnace Slag

Electric arc furnace uses Cold steel or scrap steel to produce new alloy steel. After putting scrap steel in the furnace, the graphite electrodes are put in place. For regulating the chemical composition of the mixture proper monitoring is done and contents are carefully charged into the furnace. Flux material is added in the furnace to ease the process of removing impurities and its amount differs from furnace to furnace. Elements like silicon, magnesium and aluminum are some of the elements which are added. Electric arc furnace slag is also known as black slag due to its color (Polanco et al., 2011).

During the processing of the slag, some ferrous metal can be recovered by magnetic separation, large magnets can be used. In the end, slag is produced at a rate of 0.1 to 0.15 ton per ton of crude steel.

2.3.2.3 Induction furnace slag

The slag that formed in Induction furnace melting, is the result of complex reactions between silica, oxide of iron from steel scrap, other oxidation by-products from melting, and reactions with refractory linings. A large amount of induction furnace slag is considered as waste (Joseph & Sridhar, 2020).

The induction furnace was patented by Edward Allen Colby in 1890 for melting metals. Kjellin from Sweden used it practically in 1900.

As compared to the electric arc furnace, induction melting is more sensitive to the quality of charge materials, limiting the types of scrap usage. Some of the largest commercial units are capable of melting at nearly 60 tons per hour. In a study, it was found that the induction furnace consumes less power as compared to an electric arc furnace. The induction furnace does not use the combustion process and generates heat cleanly. The induction power unit generates an alternating electric current which flows into a furnace and through a coil made of hollow copper tubing. This creates an electromagnetic field that passes through the refractory material and couples with conductive metal charge inside the furnace. This process produces an electric current which flows inside the metal charge itself, producing heat quite fast for melting metal. (Gandhewar et al., 2011)

The induction furnace needs good quality scrap. Environmental protection requirements are well catered by induction furnace. Whereas high energy consumption, noise, waste residue, and exhaust gas is associated with electric arc furnace. (*On the Advantage and Disadvantage of Electric Arc Furnace and Induction Furnace*, n.d.)

2.3.3 World Steel Production

China is leading the front in steel production. India and Japan are also contributing significantly to the production of steel (World Steel Association, 2011).

With time the production of steel is increasing especially in Asia. Global steel production is **1,869.9 million tones (Mt)** for the year 2019, up by 3.4% compared to 2018. Asia manufactured 1,341.6 Mt of steel in 2019, an increase of 5.7% as compared to 2018 (worldsteel.org).

Table 2. 1: World steel production (worldsteel.org)

Rank	**Country**	**2019 (Mt)**
1	China	996.3
2	India	111.2
3	Japan	99.3
4	United States	87.9
5	Russia	71.6
6	South Korea	71.4
7	Germany	39.7
8	Turkey	33.7
9	Brazil	32.2
10	Iran	31.9

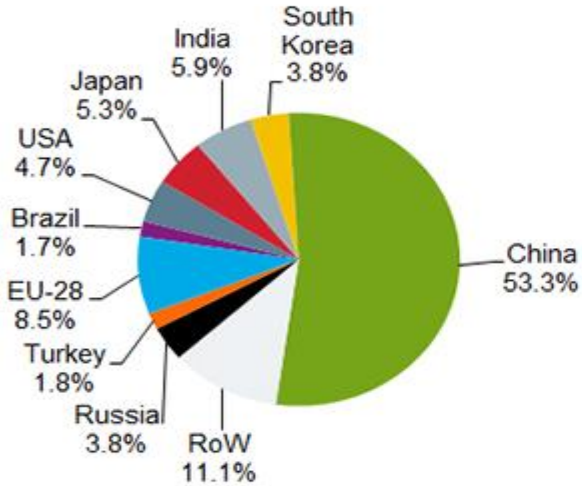


Figure 2. 2: World steel production (worldsteel.org)

Worldwide slag recovery rate is 80% and recovery of iron making slag is nearly 100%(*FACT SHEET Steel Industry Co-Products*, 2018)

2.3.4 Scenario of Pakistan

The steel demand may increase in the future because of CPEC, dams construction, and because of the domestic construction industry. Currently, the domestic steel consumption of Pakistan is 9 million tons according to an online source. It is estimated that over the next 5 years the consumption trend will increase up to double the present which is 18 million tons (pakistangulfeconomist.com). Pakistan's domestic steel production is roundabout 5 million tons. So there is potential to expand domestic production to meet domestic needs instead of importing steel from other countries.

Pakistan as being a developing country does not have proper facilities to ensure safe disposal and recycling of slag. Hence, new and innovative ways of recycling slag are a necessity for Pakistan to move towards technological advancement. Although Iran is not a developed country, its steel production is quite large as compared to Pakistan, which is playing the part in flourishing the economy of the country.

2.4 MARSHALL MIX DESIGN COMPACTIVE EFFORTS

With the increase in binder content air voids present in the mix decreases. With the increase in the percentage of fine particles in the mix bitumen requirement increases. Lower bitumen content in the mix can result in loss of bond between aggregate and bitumen which can lead to stripping issue that reduces resistance to moisture damage and can lower fatigue resistance. Too much bitumen content can cause a lowering in skid resistance, bleeding, and lowering of resistance to permanent deformation (Shahid, 2019).

Higher marshal stability and lower bitumen content are obtained from 75 blows. 75 blows simulate heavy traffic while 50 blows simulate medium traffic. 75 blows result in lower VMA and VFA as compared to 50 blows (Boulbibane, n.d.).

Compaction effort has a relation with VTM (air voids). Marshal compaction with 50 blows has higher air voids than 75 blows compaction (Salifu et al., 2009).

The research was done on compaction effort of 50 blows and 75 blows. The lower the number of blows the higher is optimum bitumen content. The higher OBC causes a thick layer of bitumen coating around the aggregate particles therefore samples with 50 blows showed higher TSR value in the moisture susceptibility test. Stripping potential is decreased by the increase in optimum bitumen content. It is rather not easy to pinpoint the causes of stripping. Because of stripping the pavement loses its integrity and strength. Air void criteria is very important. Air voids prevent bleeding but excessive air voids cause moisture damage and oxidation of mix (Subramaniam, 2006). By providing a thick asphalt coating to the aggregate, expansive characteristics of steel slag can be prevented (Noureldin & RS McDaniel, 1990).

Sometimes steel slag has variability even of the same furnace and same plant. Sometimes steel slag has expansive nature because of the presence of magnesium and calcium oxides. If in some occasions expansion occurs then it has minimum effects in HMA because of the coating film thickness of bitumen over the aggregates, but it can create a problem if such steel slag is used in PCC and in base, sub-base, and subgrade. Asphalt coating minimizes this phenomenon (I. Ahmed, n.d.). The expansion of steel slag is limited because of the bitumen coating.

Steel slag utilization in wearing course has been researched upon but there is not much literature on the use of induction furnace slag, in hot mix asphalt. Researches have been carried about IF slag use in concrete, in bricks, etc. but not in hot mix asphalt.

2.5 PREVIOUS STUDIES CARRIED ON USING STEEL SLAG

(Xu et al., 2020) analyzed the utilization of steel slag as fine and coarse aggregate and studied the effects of induction healing of asphalt concrete. With the process of induction heating asphalt concrete can be healed. The investigation was carried out as healing property, natural cooling speed, induction heating speed, and thermal properties were evaluated. It was concluded that using steel slag in self-healing induction heating asphalt concrete is practicable. Steel slag has better heat storage capacity as it has longer cooling time. Sometimes the presence of free CaO impacts negatively to the resistance to moisture damage.

(Nguyen et al., 2018) investigated the use of steel slag in the surface course of flexible pavements. Mineral aggregates were replaced by steel slag. In developing countries technology used in steel industries is not as much advance as compared to developed countries so the by-products may contain elements that are harmful to the environment. Chemical analysis showed that it is not harmful to use steel slag as mineral aggregate. Promising stability and flow results were obtained. Skid resistance and the result of modulus also fulfilled the standard requirements.

(Liu et al., 2017) investigated the use of steel slag and steel fiber in hot mix asphalt for induction heating and healing properties. The results were promising as stability improved. Cooling of steel slag is slow so it helps in crack healing properties asphalt mixes. Steel fibers increased thermal conductivity and toughness of samples. Induction heating speed is enhanced.
(Maharaj et al., 2017) concluded that steel slag of 6 to 15% showed satisfactory results in marshal stability test and volumetric analysis. Addition of 15% steel slag showed similar results and properties as 0% control samples. Steel slag addition reduced stability but within the acceptable limits.

(Oluwasola et al., 2015) investigated the use of copper mine tailings and electric arc furnace as aggregate in hot mix asphalt. Four different proportions of both materials were taken. Overall the performance of asphalt mixtures was improved. Different tests like dynamic creep, resilient modulus, marshall stability, and moisture susceptibility through TSR. EAF slag and CMT samples depict lower TSR values but within the limits. While resilient modulus increased with the use of these materials.

(Ameri et al., 2013) conducted a research study on the utilization of Arc Furnace slag in warm mix asphalt and did performance evaluation. four different proportions of aggregates were used for HMA and WMA samples were also prepared.

In WMA samples when steel slag was introduced it resulted in less resilient modulus because of lower aggregate binder adhesion as steel slag has lesser CaO/SiO2 rate than limestone aggregate. The same reason is mentioned for the higher indirect tensile strength value of samples with limestone aggregate. it was concluded that the use of coarse aggregate steel slag increased marshall stability, flow, and better MQ parameter. It was deducted that the use of steel slag is feasible.

(Behnood & Ameri, 2012) investigated the use of steel slag in stone mastic asphalt. Positive results were obtained about resistance to permanent deformation and resistance to moisture damage.

(Hainin et al., 2012) studied the usage of steel slag in dense asphalt mix as aggregate. samples with steel slag showed higher resilient modulus and better rutting resistance.

In a study steel slag and recycled concrete aggregate were used in asphalt mixtures and the properties of these asphalt mixtures were analyzed. Overall three types of aggregates were used which were steel slag, recycled concrete, and dacite. Different tests like resilient modulus, dynamic creep, and indirect tensile fatigue tests were performed. The results were positive(Arabani & Azarhoosh, 2012).

In this study, electric arc furnace slag was used as aggregate and performance analysis was carried out. Indirect tensile tests, fatigue tests, and stiffness modulus at different temperatures were carried out. Steel slag in the wearing course reduces the chances of permanent deformation. Therefore electric arc furnace steel slag has comparable properties to that of natural aggregate(Pasetto & Baldo, 2011).

With time due to great advancement in industrial production waste materials are also increasing. There is pressure on the HMA industry to incorporate more and more feasible waste materials instead of virgin resources. In a study, steel slag was used as coarse aggregate. Limestone and steel slag was used as aggregate. Marshall stability, creep stiffness, and indirect tensile strength tests were carried out. Asphalt concrete mixes with steel slag showed better results than asphalt mixes with limestone. Electrical sensitivity tests were also carried out. It was analyzed that electrical conductivity was improved by the introduction of steel slag in mixes. It is easy to remove ice by melting it from more thermo electrical roads, highway bridges and airports, etc.(Ahmedzade & Sengoz, 2009).

In this study, steel slag was used in stone mastic asphalt. Resistance to low-temperature cracking and high-temperature properties of SMA were enhanced by the usage of steel slag as coarse aggregate(Wu et al., 2007).

In this study, different percentages of steel slag were used as a replacement of coarse aggregate in the asphalt mix. Performance evaluation was carried out comprising of stripping resistance, fatigue life, rutting resistance, resilient modulus, and indirect tensile test of asphalt concrete mixes. 25% of the replacement came out to be optimum. Up to 75% replacement showed feasible results. Toxicity and chemical analysis showed that steel slag can be used in road construction(Asi et al., 2007).

In a study, the investigation was done on the utilization of basic oxygen furnace steel slag in the asphalt mix. Modified lottman, rutting, soaked wheel track test, and indirect tensile test were performed. It was concluded that it is feasible to use BOF slag in asphalt concrete. Limestone is used as a flux in BO Furnace to form steel slag. It was found that the characteristic of fine slag aggregate with asphalt binder is rather poorer than those natural fine aggregates(Xue et al., 2006).

In a study, it was mentioned that steel slag generation is 10-15% of steel output(Proctor et al., 2000).

In a study, it was summarized that roads built with steel slag as aggregate in bituminous mixes did pose a threat to the environment by leaching(Motz & Geiseler, 2000).

A study was carried out in Saudi Arabia for optimizing the use of steel slag in asphalt mixes. It is been mentioned that a good quantity of slag is put to waste which should not be done. Steel slag was used as fine aggregate and different performance tests including resilient modulus test were carried out. Tensile strength was improved. 100% used of steel slag is discouraged as it did not produce good results(U. Bagampadde, 1 H. I. Al-Abdul Wahhab, 1999). Substituting 100% steel slag is liable to high void space and bulking problems due to the angular shape of steel slag aggregate(Ahmedzade & Sengoz, 2009).

In a study, steel slag was used in hot mix asphalt as fine aggregate. Swell potential and moisture damage were analyzed and no significant problem was detected. Steel slag showed satisfactory performance in the moisture-induced damaged test. It was also discussed that steel slag in HMA showed promising results in marshall stability, wear resistance, and stripping resistance(Kandhal & Hoffman, 1997).

Good quality of steel slag can be achieved by proper slag processing and stockpiling. Different flux elements also have an impact on slag expansion (Farrand & Emery, 1995).

The roads which are constructed with steel slag has higher road surface temperature than conventional roads with other types of aggregates. The specific heat of steel is quite low. It keeps the surface of pavement warmer so the formation of ice on roads can be reduced(Noureldin & RS McDaniel -, 1990).

2.6 PAST STUDIES ON INDUCTION FURNACE SLAG

Not much research has been done on induction furnace slag. In Pakistan, there are a lot of induction furnaces in the private sector. Its set up is economical as compared to the electric arc furnace. The induction furnace slag is of less weight as compared to other steel slags.

(Joseph & Sridhar, 2020) investigated the use of silica fume and induction furnace slag in black cotton soil and analyzed the strength and compaction characteristics. Different percentages of IF slag were used up to 20% replacement. The optimum moisture content of soil decreased. The maximum dry density and strength of soil increased due to the inclusion of these waste products in soil.

(Saha et al., 2019) analyzed the use of induction furnace slag for making non fired bricks. Bricks were made using lime, cement, gypsum, and induction furnace slag. Two slag percentages of 25% and 50% were used. Non fired slag bricks showed better compressive strength results as compared to conventional burnt bricks.

(M. L. Ahmed et al., 2018) investigated the use of induction furnace slag as the replacement of cement in concrete. It was a case study of Pakistan. The steel industry of Pakistan comprises of public and private sectors. The private sector of Pakistan comprises of almost 140 induction furnaces in different areas of Pakistan. There is a difference in the chemical composition of blast furnace slag and induction furnace slag. Different percentages of IF slag were used as replacement. It was estimated that the cost per kg of grinding, transporting and other miscellaneous expenses of slag were about PKR 1.15. The results concluded that with the increase in slag percentages split tensile, flexural, and compressive strength decreases.

(Ahmad & Rahman, 2018) investigated durability and mechanical properties of concrete having induction furnace slag as partial replacement of recycled aggregate. Different percentages of IF slag were incorporated. Tensile strength and compressive strength results were satisfactory up to 50% replacement. Durability properties decrease with the replacement of more than 50%. The induction furnace is a comparatively old system and relatively less expensive as compared to an arc furnace.

(Qurishee et al., 2017) analyzed the use of slag in concrete by varying its proportions as aggregate. As analyzed specific gravity of slag was 2.56 which is less than the steel slag obtained from electric arc furnace and basic oxygen furnace. The research concluded that by replacing aggregate with steel slag compressive strength increases comparable to normal concrete.

(Rezaul et al., 2017) conducted a comparative study of electric arc furnace slag and induction furnace slag in which mechanical properties were analyzed as steel slags were incorporated in concrete as coarse aggregate replacement. Arc furnace slag produced better results as compared to the induction furnace slag. Compressive strength of 2418-3578 psi was achieved with induction furnace slag while compressive strength of 5076-5850 psi was achieved by using electric arc furnace slag. While as far as splitting tensile strength is concerned, values of 183-298 psi for IF slag and 297-449 psi for EAF slag were obtained. Steel slags were initially in boulder form and were crushed, sieved, and graded. Unit weight of IF slag was less than that of EAF slag. Different percentages of IF slag did not cause much variation in the compressive strength of samples. It was concluded that both types of slags can be used as they fulfill the requirements and criteria. The composition of slags through X-Ray Fluorescence (XRF) results is as follows (Rezaul et al., 2017).

Table 2. 2: composition of IF slag and EAF slag (Rezaul et al., 2017)

	SiO_2	Fe_2O_3	MnO	Al_2O_3	CaO
IF slag sample	40.01	23.29	9.73	7.85	12.80
IF slag [7]	48.54	25.89	7.62	8.45	3.91
IF slag [8]	55.82	13.09	-	16.35	2.86
EAF slag sample	19.9	19.9	5.1	6.3	35.5
EAF slag [9]	16.1	16.1	4.5	7.6	29.5
EAF slag [10]	14.1	14.1	5	6.7	38.8

According to a research study chemical composition of IF steel slag is analyzed on the basis of different type of scrap used, and results are as below

Table 2. 3: Composition of IF slag (Rezaul et al., 2017)

Chemical Component	Slag-1 (scrap-1st class)	Slag-2 (scrap-2nd class)
$\%SiO_2$	33.627	55.823
$\%Al_2O_3$	27.025	16.345
$\%Fe_2O_3$	6.744	13.088
%S	0.09	0.11
%MgO	2.457	5.193
%CaO	1.271	2.864

The slag produced from good quality scrap especially imported scrap has comparatively better properties.

Figure 2. 3: Manually crushed induction furnace slag

For a long time in the past, steel slag was considered a harmful waste material and was mostly dumped into the landfills. But later on, through researches and risk assessments, it was concluded that iron and steel slag are not harmful for the environment and humans when used in the construction industry especially in the road wearing coarse as slag aggregates get coated with bitumen, therefore, minimizing any leaching potential.

(Mohammed et al., 2016) investigated the use of IF slag and brick aggregate in concrete. According to this study, slag was distinguished as mixed weight, lightweight, and heavyweight slag. The slag was produced in lump form after cooling which was then manually broken in the laboratory. The variation might be due to the cooling process of slag aggregate. Concrete with lightweight slag depicted less compressive strength and tensile strength compared to mix weight and heavyweight slag concrete. Lightweight slag concrete produced a higher modulus of elasticity.

Figure 2. 4: Steel Slags with different densities

(M V Deshmukh, 2015) did an analysis of the induction furnace slag. Metal content in IF slag is about 10%-15%. Some industries ignore this. By breaking the slag and with magnetic separation some metal can be extracted. Six samples were collected from three steel mills. There were mineralogical and chemical variations in slag samples mostly because of variation in operating temperature, refractory furnace lining, additives, furnace charge, and quality of scrap. Induction furnace produces well-controlled and energy efficient metal melting but less refining of metal occurs as compared to arc furnace. The composition of slag varies dependent on the type of scrap, quality of iron or steel used, and the process that is used.

(John & John, 2013) conducted a study on IF slag utilization in concrete by using different percentages of slag as fine aggregate replacement. 30% replacement showed better results for compressive strength.

In a study, mineralization and chemical characterization of induction furnace slag were carried out. From three different steel foundries, six samples were collected and their mineral and chemical composition was determined. The calcium oxide limit was low which limits their use as cement however as a roadbed material it is feasible. The induction furnace and cupola furnace are analyzed in this study. When analyzed there was variation in the chemical composition of the same type of slag obtained from two different furnaces. The difference can be a result of the following factors; quality of scrap used in the furnace, quality, and type of fluxing agent, quality, and type of coke used. Rusted scraps and poor energy efficiency furnace result in a large amount of slag production(Andrews et al., 2012)

Table 2. 4 Chemical composition of IF slag(Andrews et al., 2012)

Na_2O	0.48
MgO	1.68
Al_2O_3	8.45
SiO_2	48.54
P_2O_3	0.06
SO_3	0.37
Cl	0.08
K_2O	0.32
CaO	3.91
TiO_2	2.82
MnO	7.62
Fe_2O_3	25.89
LOI	16.80

There is a variation in the chemical composition of steel slag as analyzed by reviewing past studies, different factors can be involved for example type of furnace used, type of scrap used, and fluxes used for refining for the type of steel grade to be produced.

Figure 2. 5: Lump of steel slag

2.7 MILL SCALE

Mill scale is a waste product of the steel industry. It has a flaky structure and even powder-like consistency which is usually less than 1mm in size. It is formed on the surface of steel products like steel billets when they are casted. The formation of mill scale occurs due to the process of oxidation which occurs on the steel surface mostly during reheating and hot rolling processes when the molten steel is casted into different steel members. It is formed on the surface of these steel members gradually when they are cooled. It initially forms a coating on the surface and gradually cracks start appearing, some of it breaks and fell off while the rest is removed by different techniques, notable techniques are gravity separation and shot blasting. Mill scale is produced on steel surfaces as a residual due to the side effects of the production process. Hot-rolled steel and iron products are exposed to the formation of mill scale. It chips off easily on contact. In the conditions where corrosion is likely to occur, the presence of mill scale can be detrimental. Its removal is a must before the protective coating can be given to a steel piece. Paints and coatings cannot be applied in the presence of mill scale. Therefore the pre-coating process requires scale removal.

Hot steel surface forms into a flaky mill scale. It is one of the wastes generated in steel plants and is produced around 4 % of the produced steel (Akhinesh et al., 2016). It is a hard breakable coating of iron oxide which is manually composed of iron oxide plus some other oxides, elements, and compounds. It flakes off the steel easily.

Different types of waste materials are produced in steel making processes in steel mills for example steel slag, mill scale, sludge, dust, etc. whereas most widely produced is steel slag. Sometimes high-quality mill scale is used in refining processes by steel industries and rest is disposed of. Steel mill waste products have variations in composition and properties because of different types of scrap steel used for making steel even based on the flux material used and types of steel furnace used. Iron is a major component of the mill scale. Through complex processes, metal extraction can be done.

So this material has potential properties of fine aggregate which is backed by some of the tests which are done to identify the potential properties of the material.

According to test results, this material can be used as a partial substitution of fine aggregate. A relatively small amount is used in the cement industry. Overall globally with time steel production is increasing so as steel waste products therefore instead of disposing mill scale in landfills which causes environmental degradation because of its metal content, it should be utilized. Developed countries are discovering different avenues while developing countries need to have research and utilization of these waste materials as alternative materials in ways that are beneficial and also don't pose damage and have harmful consequences by dumping in landfills.

Figure 2. 6: A stockpile of mill scale

Source: (https://www.google.com/search?q=mill+scale)

2.7.1 Utilization of Steel mill scale

Mill scale is a waste product produced in hot rolling step during the formation of steel in the steel industry. Some potential uses of mill scale are discussed below

Mill scale can be used to prepare glass-ceramics. Electrical characteristics of glass-ceramic materials produced from mill scale were evaluated in a study(Montedo et al., 2015)
Another study was carried out about utilizing mill scale in the preparation of sustainable bricks. The results were satisfactory(Baghel et al., 2020).
It can also be used in the process of forming cement clinker (United States Patent 2004).
Mill scale has been used for the stabilization of expansive soil. Properties like CBR, permeability, and plastic limit were evaluated. prominent changes in permeability and plasticity properties were resulted in mixing 15% of mill scale to black cotton soil. Thus, a mill scale stabilized black cotton soil can be used as an embankment or subgrade layer for the road (Murthy, 2012).

Mill scale can be used in concrete. The study of the Compressive Strength of concrete was carried out in which the steel mill scale was used as fine aggregate. Different proportions of mill scale were taken. Optimum results were obtained by replacing 15% sand with mill scale in concrete. The compressive strength of concrete having mill scale was satisfactory(Akhinesh et al., 2016). Therefore the option of mill scale utilization in concrete is researched but its application in road construction is rarely explored although it has the potential to be used as fine aggregate. Its specific gravity is more than natural aggregate so it results in a more dense compact structure.
Another study was carried out in Pakistan about the use of mill scale as fine aggregate in concrete. Concrete specimens with mill scale were tested for compressive strength and results came out to be promising. The flow and density of concrete were also increased(Hussain et al., n.d.). This is also mentioned in this previous study that a small fraction of steel mill scale is used in Pakistan rest is been dumped in landfills although it was exported to China in the past. As it composes of metallic oxides so some portion of it leaches into the ground over time and can pollute groundwater as well as the surrounding environment therefore landfilling is not an option at all. This study showed that up to 40% replacement of fine aggregate with mill scale waste is viable(Hussain et al., n.d.).

According to an online source mill scale can be used in roads because the road surface and tire will have greater adhesion and even greater abrasion resistance. As mill scale has metal content so it can have greater conduction of surface heat. Therefore heat induction process may be carried out easily facilitating induction healing of pavement and de-icing roads, parks and airports, etc. durability, quality, and safety of road may be increased because of adding mill scale. **(https://millscale.org/).**

2.8 MOISTURE DAMAGE

This section contains a literature review and theory associated with water damage and the response of bituminous mixtures to it when subjected to performance testing. An overview of the previous findings on the moisture susceptibility obtained through TSR following ALDOT-361 and resilient modulus is discussed.

The durability of asphalt pavement is profoundly affected by environmental factors such as existence of water, high temperature, and high air void content. Among these water is the worst enemy of asphaltic mixtures. It substantially erodes and damages the flexible pavement and causes premature and durability related failures.

The presence of water often causes premature failure of the pavement due to the de-bonding between aggregate surface and binder or because of fatigue cracking due to the reduced strength of the asphalt mixture (Hamzah et al., 2015).

Moisture susceptibility is considered a major mix design criterion because it can be a cause of cracking, rutting, and raveling (Huang et al., 2010).

Because of moisture adhesion and integrity between aggregate and binder is compromised. Heavy traffic and moisture saturation in asphalt mixtures cause distresses. It can be evaded by considering it in the pavement design, mix design, and construction-related factors causing moisture damage. Moisture sensitivity also depends upon the material characteristics and is affected by the type and ratio of aggregates, fines, and binder used in the mix. To construct a durable pavement with a long life span and to safeguard it against distresses the detrimental effects of moisture should be reduced to an acceptable limit.

2.8.1 Effect of moisture on road pavements

The surface layer of the pavement is exposed to saturation by water from precipitation which causes the deterioration of cohesion bond in the binder, reduction in shear strength of the asphalt layer and rutting of the wearing course layer particularly in moisture susceptible mix, in the excessive rainfall area and under heavy traffic loading. This loss of bond propagates top-down cracking. It is also a major cause of raveling of the surface where vertical stresses and horizontal forces are induced in combination by the repeated traffic.

Water being a universal solvent can solve anything in it no matter how hard it is over the time a constant sprinkle of water can solve that thing, even an asphaltic pavement can't withstand the effect of water. Although pavements are made with great care so that water may not come in contact with it, but it is impossible to keep pavement away from water. So a pavement should be designed such that it can bear the effect of moisture without any major damage. Generally, there are two major types of failure which are caused by moisture, stripping, and raveling because the bond between bitumen and aggregates is broken due to the intrusion of moisture. Asphalt is a viscoelastic material having flow characteristics due to which it tends to heave up under intense loadings or repeated cyclic loadings. To minimize this effect and enhance the serviceability different additives are used in asphalt.

2.8.2 Sources of moisture

During the service life of a pavement, it is exposed to several precipitation cycles. Moisture can be present in asphalt pavement either internally or it can enter the pavement from external sources.

Internally moisture is present if the aggregate is not properly dried before the construction (Santucci, 2002). If this water interacts with the hot binder it converts into steam and the volume of water particles is increased and as a result over boiling and foaming of bitumen takes place (The Shell Bitumen Handbook, 5th Edition). This can be reduced by using warm mix asphalt.

Externally the water can enter the pavement surface due to poor drainage, less compaction of layers, and mix design having high air voids which makes the pavement surface permeable. Moisture can also enter from beneath the subgrade primarily because of high water table and low quality and poor drainage characteristics of subbase and base course material(Caro et al., 2008).

2.8.3 Types Of Moisture Damage

The existence of moisture in the asphaltic mixtures causes certain types of premature distresses and also intensifies the amount and severity of already present distresses. Different types of distresses caused my moisture is given below:

- ***Stripping and Raveling:***

The adhesive failure among the aggregate surface and bituminous film which causes de-bonding is called stripping. Stripping generally begins at the lowermost portion of the asphalt layer where the tensile stresses due to heavy traffic loading are the greatest. It then gradually progresses upwards and reduces the strength of asphalt pavements. When it occurs in an isolated spot, it quickly produces potholes. When stripping is caused at the surface of pavement, it is called raveling.

- ***Potholes:***

The bowl shaped depressions in the pavement where the material has been broken and removed are called potholes. The moisture helps in bond breakage amongst the asphalt binder and aggregate which causes the removal of aggregates from its place.

- ***Fatigue cracking/ Permanent Deformation:***

Fatigue cracking is a series of interconnected cracks. It is a load associated mechanism and is caused by the failure of the surfacing layer or the stabilized base course. It commences at the lowest portion of the asphaltic layer and under heavy traffic loading, it forms a web-like pattern and is called web cracking or alligator cracking.

Permanent deformation in the surfacing layer is caused by material movement under traffic. Rutting causes depressions on the road along the wheel path. Moisture existence in the pavement reduces its structural capacity and weakens the cohesion and adhesion bonds between bitumen and aggregate which aids cracking and rutting of the pavement under repetitive cyclic loading of the traffic. Additionally, cracking helps penetration of moisture which results in other distresses mechanisms.

Figure 2. 7: Moisture-induced damage (online source)

2.9 PREVIOUS STUDIES ABOUT MOISTURE DAMAGE

(Kakar et al., 2016)stated that bitumen is the key component to bind the aggregate in asphaltic mixtures which transmit the stresses due to traffic loading throughout its service life. Therefore, the adhesion bond amongst aggregate and bitumen is of key importance. Anything which diminishes this adhesion decreases the lifespan of the asphaltic layer.

(Baldi-Sevilla et al., 2017) and (Hamzah et al., 2015)reported that damage induced due to water is one of the chief reasons for distress in flexible roadways causing fatigue, stripping, raveling, permanent deformation, and loss of strength. As the moisture damage takes place due to several different processes therefore a single test is unreliable, impractical and difficult to evaluate the moisture sensitivity of widespread range of aggregate materials and conditions.

(Varveri et al., 2015) investigated the short and long term effects of moisture damage by combining two methods for conditioning and used them as a single protocol. The strength reduction was given by ITS. He concluded that reduction in the strength of the mixture chiefly depends upon the type of conditioning and the time for which the samples are conditioned. Reduced strength values were observed for higher bath conditioning. The mixtures with sandstone and polymer modified binder performed well against moisture. The mixtures with soft modified binder were more damaged as compared to that of hard modified binders which performed well.

(Martin et al., 2014)proposed methods to estimate susceptibility to moisture with the help of laboratory-mixed and compacted in laboratory or plant-prepared and compacted in the lab. samples, after examining various field projects in which they explored the moisture susceptibility of asphalt mixes. The tests recommended included the Hamburg Wheel Tracking Device test, T-283 and the resilient modulus test. The criteria used for evaluation include ITS and Minimum TSR of 80%, resilient modulus, striping slope and inflection point of stripping (SIP obtained from HWTDT). They observed in most cases, that after sufficient aging the resistance of the asphalt to rutting could be very much enhanced.

(Moraes et al., 2011) found that the damages due to moisture result in permanent deformation, stripping, raveling, cracking of the pavement and failures like potholes. It has also been found that the high viscosity asphalt is better to resist damages by moisture as compared to the low viscosity asphalt.

(Bausano & Williams, 2009) tested 16 mixes to cover a wide range of traffic levels and materials types. AASHTO T-283 (TSR), flow number and dynamic modulus tests were performed to evaluate HMA moisture susceptibility. He found that the effect due to moisture is highly dependent on the loading conditions, raised temperatures, and/or lower frequencies.

According to (Shrum, 2010) reduced temperature used for compaction while producing Warm Mix Asphalt (WMA) can escalate moisture damage potential. The reduced temperatures cause insufficient aggregate drying, thus making it more water damage susceptible due to trapped moistness in the coated aggregate. For WMA adequate moisture susceptibility tests must be accomplished to make certain that it will perform just like HMA.

(Grenfell et al., 2015) used Saturation Ageing Tensile Stiffness (SATS) protocol to quantify the water damage of different asphalt mixes used in the United Kingdom (UK). In comparison with Modified Lottman test, the SATS protocol was found to be very aggressive and suitable to find field performance of asphalt against moisture. Specimens of 60mm thickness and 100mm diameter were aged at high pressure and raised temperature. The vessel used in SATS can hold five samples at different saturation levels. Airey found that with the reduction of air voids from 10-4% or the increase of bitumen from 4-5% there is an insignificant influence on the stiffness values (retained) of the acidic and basic Dense Bituminous Macadam (DBM) mixes. Also, the decrease in stiffness moduli shows a reduction in resistance to water damage.

(Lu & Harvey, 2005) evaluated the effectiveness of liquid anti-stripping agents and hydrated lime, by fatigue beam test and TSR (Tensile Strength Ratio), to improve asphalt paving mixtures resistance to moisture damage. He concluded that even after one year of moisture conditioning both the treatments were found effective in reducing the moisture damage which causes the damage of bond strength and composite stiffness of the mixture.

2.9.1 Universal testing system

The Universal Testing System also known as Materials Testing Machine (System) is used to test different properties of materials. It can be used to test resilient modulus, tensile strength, dynamic modulus, permanent deformation, fatigue etc. of asphalt concrete. The Universal Testing System consists of following parts.

- A hydraulic or, pneumatic axial and pneumatic confining stress loading system.
- A Control and Data Acquisition System (CDAS).
- A personal computer (PC) with the Microsoft Windows operating system.
- A suite of UTS software applications and support files.

The CDAS provides both the servo-feedback loading control electronics and transducer data acquisition and timing functionality. Overall system control is managed by the PC under the direction of the application software. Also, data gathered by the CDAS during specimen testing is processed, displayed, reported, and archived on the PC. A PC-based pendant provides axis jogging operations together with power-pack control for hydraulic loading systems.

2.10 RESILIENT MODULUS OF BITUMINOUS PAVING MIXES

The material’s resilient modulus is an estimate of its modulus of elasticity (E). Resilient modulus is stress divided by strain for dynamically applied loads, like those experienced by pavements.

The elastic modulus obtained from the ratio of repeated stress (loads) to the recoverable strain is called the resilient modulus MR, defined as

$$M_R = \frac{\sigma_d}{\varepsilon_r}$$

Where, is the stress applied axially repeatedly. The binder used in the surface course materials i.e. bitumen is assumed to be completely elastic in theory but in practice, it was found that it is not the case and small deformations are observed every time a load is applied. But if the bitumen used has higher strength and the applied load is small then and repeated many times then ultimately the deformations after every load application becomes almost recoverable and the binder can be regarded as elastic. Figure depicts the stress-strain behavior under a repeated stress test. The figure illustrates that at first the material is experiencing permanent deformation due to plastic strain but as the process continues and more stress repetitions are applied, the deformations start to decrease until the number of cycles reach 100 to 200, after which the material behaves elastic and deformation is recoverable (Huang 2003).

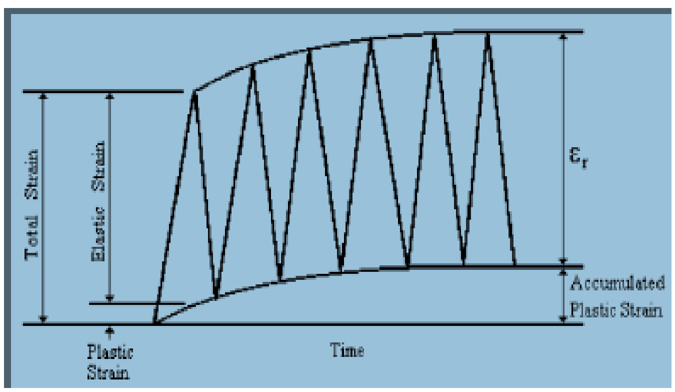


Figure 2. 8: Recoverable strain under cyclic loading (Huang 2003)

In the laboratory, indirect tension test can be used to measure resilient modulus. Other tests can also be used to measure resilient modulus. But the indirect tension test is non-destructive and easy to perform, therefore it is suitable.

2.10.1 Indirect Tension Test

The indirect tensile strength test standardized as ASTM D6931 is used to evaluate the comparative quality of paving binding materials and mixes and determining its potential for cracking and rutting. This test is performed by applying a pointed compressive on a 4-inch diameter of a cylindrical sample at a constant deformation rate of 50 mm/min at a temperature of 25 C. This loading arrangement is selected because it helps in reasonable homogeneous tensile stresses distribution along the vertical plane and applied load is perpendicular to the induced stresses (Yoder & Witczak, 1975). The ultimate result is the splitting of the specimen. The stress distribution is shown in Figure.

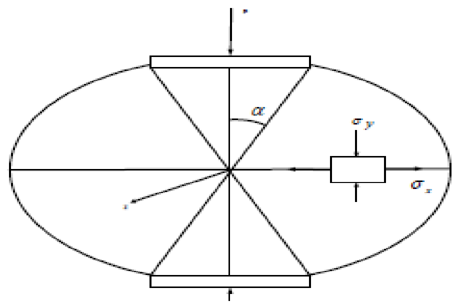


Figure 2. 9: Schematic for the Indirect Tension Test (Yoder 1975)

2.10.2 Resilient Modulus Test

Resilient modulus test can be performed on cores, obtained from the field or on the laboratory compacted specimens. The resilient modulus of bituminous paving mixes prepared in the laboratory depends on the following factors:

I. The test setup used. (indirect tension vs. triaxial)
II. Level of compaction (number of gyration or number of blows).
III. Temperature. (high or low)
IV. Loading factor (Loading duration and rest period, waveform, strain level).
V. Geometry (diameter and thickness)
VI. Binder

The test method for measurement of resilient modulus using indirect tension test (ASTM D4123), and it recommends that the load should be applied in the form of alternate loading and unloading form also known as haversine load form. This test procedure is divided into three stages which are, ITS determination on one specimen, conditioning for 100 load pulses and finally determining the actual resilient modulus.

- **Pretest Tensile Strength Determination**

It is recommended by the ASTM D6931 that before the commencement of the actual resilient modulus test, the ITS on one of the specimens should be performed that is representative of other specimens in size and material properties. The purpose of performing an indirect tensile strength test is to select the baseline for the preconditioning peak loading force.

- **Preconditioning**

The preconditioning of specimens shall be conducted while the specimen is located in a temperature-controlled cabinet. The selection of applied loads for preconditioning is based on the indirect tensile strength of the bituminous paving mix in accordance with the test method ASTM D6931. The peak loading force during preconditioning shall be 10 to 20% of the peak load found by the indirect tension test at 25 C. Pre-conditioning involves no. of load applications. In this research preconditioning cycles were 100.

- **Resilient Modulus Determination**

Following the ITS and conditioning procedures, the resilient modulus is determined by applying five load pulses with nearly constant deformation. The equation is used to determine the resilient modulus of asphalt concrete is as follows although the UTM machine is advanced tech equipment that automatically calculates and displays resilient modulus for the last 5 pulses after preconditioning and calculate the mean resilient modulus.

$$E = \frac{P(\upsilon + 0.27)}{Ht}$$

Where,

E = Resilient Modulus (MPa)

P = Peak loading force (N)

v = Poisson ratio (0.4) assumed

H = Recovered horizontal deformation of sample (mm)

t= Thickness of specimen (mm)

Some factors that affect resilient modulus are load duration, aggregate gradation, bitumen content, temperature, diameter of specimen.

(ASTM D4123), recommends that the tests shall be conducted on 4-inch or 6-inch diameter specimens with 2.5-inch thickness.

2.11 SUMMARY

From the foregoing literature review, it can be seen that steel slag is used in different fields ranging from agriculture, building block construction, and cement manufacture to roads construction. However, there is little evidence of using especially induction furnace slag and mill scale as a partial replacement of coarse and fine aggregate used in asphalt concrete wearing course.

The incorporation of materials like induction furnace slag and mill scale may be of some benefit in this respect. The literature review does not show any evidence of using these materials for wearing course of pavements. This allows us to make an experimental study by incorporation of these steel industry waste products.

Chapter 3

RESEARCH METHODOLOGY

3.1 INTRODUCTION

The research methodology for this research is discussed in this chapter to achieve research objectives that were introduced in Chapter 1. The laboratory characterization of aggregates and bitumen used in bituminous mixtures is presented in detail. This chapter contains the devised methodology for accomplishing the defined objectives of this research aforementioned in chapter one which includes the acquisition of required material, sample preparation for Marshall mix design, and performance testing. (OBC) for Hot Mix Asphalt (HMA) mixes used in this study is determined using marshall mix design. Resilient modulus and TSR test on the bituminous paving mixes using indirect tension test setup are discussed.

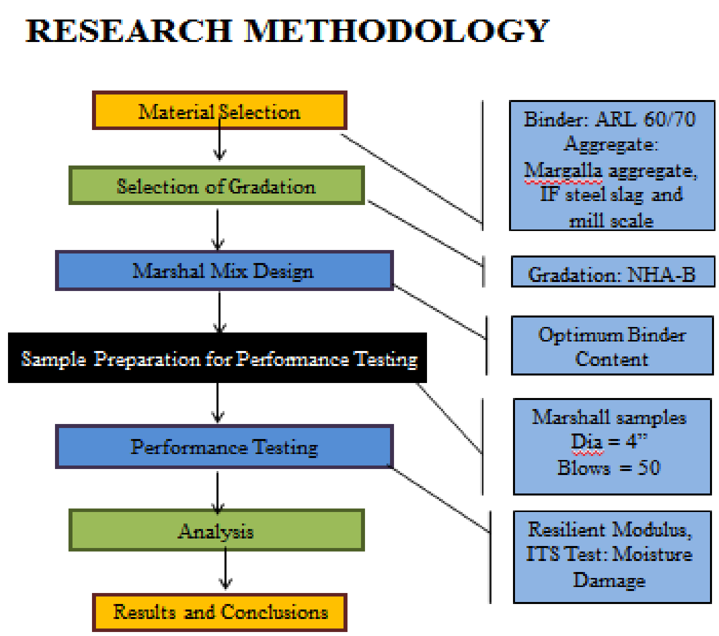


Figure 3. 1: Research Methodology

The study was carried out on asphalt concrete specimens prepared with aggregate from Margalla quarry and a partial aggregate replacement was done by incorporating IF steel slag and mill scale. Samples were prepared using gradations of wearing course NHA-B, and binder Parco 60/70. Optimum binder content was found out by using different percentages of the binder with an increment of 0.5%. Using the optimum binder content Marshall samples incorporating waste materials were prepared to find the moisture damage. The testing was done at control conditions and specified temperature for each test. For TSR, four Marshall samples were prepared at OBC (two tested unconditioned and two tested after conditioning) and then tested with Universal Testing Machine (UTM). For TSR, samples were conditioned according to ALDOT-361. Two samples for each percentage of IF slag and mill scale were prepared for the resilient modulus test. This chapter also discusses the detailed procedures of tests mentioned above, testing equipment, and the input parameters used during these tests. The use of IF slag and mill scale is investigated by comparing the results of these samples with control samples

3.2 CHARACTERIZATION OF SELECTED MATERIALS

3.2.1 Material Selection

For this research fine and coarse aggregate were brought from Margalla quarry and 60/70 penetration grade binder was acquired from Parco. 60/70 grade Binder was selected because it is largely used in asphalt mixes in Pakistan. Also, it is appropriate for use in moderate to colder temperature regions.

The asphaltic mixture is the composition of aggregates, bitumen, and air. Usually, the aggregate is 95% by weight as it provides the main portion of confrontation to permanent deformation and the remaining 5% is the weight of the bitumen. Air being weightless has no percentage in the mix. Concerning volume, asphaltic mix is composed of 85% aggregate, 10% Bitumen, and the air occupy the remaining 5% volume. To meet the required standards of asphaltic mixtures, detailed laboratory testing of selected materials, the aggregate, and bitumen is required.

Figure 3. 2: Margalla crush

The steel slag and mill scale source was Pak Iron steel mills, Islamabad. Few pictures are as followed as data was collected by a physical survey.

Figure 3. 3: Pictures from on site visit of Pak Iron steel mill, Islamabad

3.2.2 Aggregate Testing

The term aggregate is largely used for mineral materials such as sand, crushed stone, and gravel. They can occur naturally or be manufactured. Large rock formation from which natural aggregates are mined is called quarry. These rocks are then crushed into suitable and usable sizes. Aggregate provides the skeletal structure of the mix and is responsible for the load-bearing capacity of the pavement by transferring the moving load to the under laying layers. The basic strength properties of asphaltic mixtures are influenced by the size, the shape, the texture of the surface, and aggregate gradation for which it needs to be strong, durable, tough, hard, properly graded with low porosity. It must be clean, rough, and have hydrophobic surfaces. Many tests have been performed on the selected aggregate in the laboratory. Table 3-1 shows all the tests carried out on both fine and coarse aggregate to find their properties and suitability. The standards are also mentioned in the table below.

Table 3. 1: Aggregate testing

S. No.	**Test**	**Standard**
1	Fractured Particles	ASTM D 5821
2	Flat and Elongated Particles	ASTM D 4791
3	Resistance to Degradation Los Angeles Abrasion test	ASTM C 131
4	Aggregate Impact Value Test	BS 812
5	Crushing Value Test of Aggregate	BS-812
6	Specific Gravity Test	ASTM C 127 & ASTM C 128

3.2.2.1 Fractured Particles

. The surface of an aggregate particle that is angular, rough, and has been broken because of crushing by artificial or natural means is called fractures face. This test helps to find the proportion, by counting or mass, of a course aggregate specimen that contains fractures particles meeting the aforementioned criteria. It is required to provide maximum shear strength to bound or unbound mixtures of aggregate by increasing the friction between the particles. It also offers aggregate stability in surface treatment and increases aggregate friction which is used in surface of the pavement. This test is conducted only on coarse aggregate according to ASTM standard D 5821. The minimum criteria for coarse aggregate to pass this test are having a percentage of more than 90%. The result of coarse aggregate of Margalla quarry was 100% which is in an acceptable range.

3.2.2.2 Flat and Elongated Particles Test

The workability and strength of asphaltic mixtures mainly depend on the shape of the particles. It also affects the bound and unbound aggregate mix properties. The required effort for compaction is also influenced by the shape of aggregate particle which is necessary to achieve the desired density. This test provides a criterion to check the compatibility of aggregate and to find the properties and characteristics of the relative shape of the coarse aggregate. It determines the percentage of elongated and flat particles or both present in the sample of the aggregate.

This examination is performed by following ASTM D 4791 which categorizes particles as flaky if their lesser dimension is smaller than 0.6 of their mean sieve size while the particles are called elongated if their length is greater than 1.8 of their mean sieve size. During the compaction practice, these flat and elongated particles can lock up more swiftly making the process more problematic. Also during the process of compaction, the aggregate particles reorient while these particles tend to break under compaction consequently making the aggregate gradation finer which helps to reduce the Voids in Mineral Aggregates (VMA). According to specifications of the ASTM, the percentage of elongated and flat particles must be fewer than or equal to 15%. Results of test performed on selected aggregates are within an acceptable range. Table shows the result of flat and elongated particles test.

Figure 3. 4: Flat and Elongated Particle Test Apparatus

3.2.2.3 Los Angeles (LA) Abrasion Test

Los Angeles (LA) Abrasion Test is commonly used to find the degradation resistance of aggregate. This experiment confirms the toughness as well as abrasion characteristics of the aggregate i.e. the resistance to wear due to heavy traffic loads. The property of resistance to abrasion is important to check because the aggregate present in the mix undergoes high repeated load levels which cause fragmentation, degradation, and crushing. The apparatus used for this test includes LA Abrasion machine, weight balance, set of sieves, and steel balls known as charge. Testing methodology or grading B was adopted for this procedure. 2500 g of aggregate retained on ½" and 3/8" sieves each, which is a total of 5000g (W1) of aggregate along with 11 steel balls or charges were placed in the Los Angeles abrasion instrument. It was then given rotation of 500 revolutions with 30 – 33 rpm speed. After that, the material was sieved through a 1.7mm sieve. The weight of the sample passing through it (W2) was noted down. The abrasion value was found out by = W2/W1× 100. According to NHA specifications 30% or less abrasion value is acceptable for coarse aggregates. This test has been performed following ASTM C 131 Standard. Table shows the results of the LA Abrasion test.

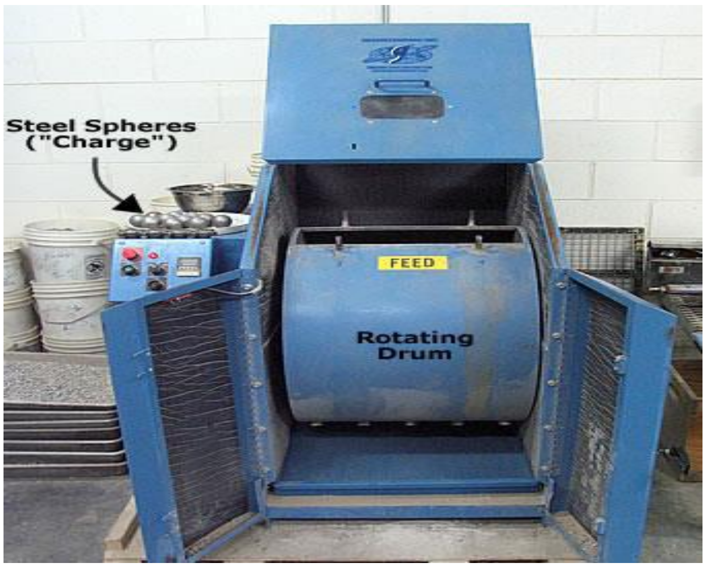


Figure 3. 5: Angeles Abrasion Machine

3.2.2.4 Impact Value Test of Aggregate

The resistance of an aggregate to a sudden shock is measured by the impact value of the aggregate. This procedure is performed according to BS 812 standard. The apparatus required for measuring impact value included impact testing machine, a cylindrical mold of 75mm diameter and 50mm depth, tamping rod of 10mm circular section and 230mm long and sieves of sizes 1/2”, 3/8” and #8 (2.36mm.) Around 350g of aggregate passing through 1/2” sieve and retaining on 3/8” sieve was taken and filled in the mold of the Impact Testing Machine in three (3) layers, with tamping of 25 times given to each layer. The sample was transferred into the larger mold of the machine and 15 number of blows were given from a 38cm height with the hammer of 13.5 to 14kg weight. The resulting aggregate was removed and passed from sieve #8. The impact value was measured by the percentage of aggregate passing through 2.36mm sieve. The table shows the results of this test.

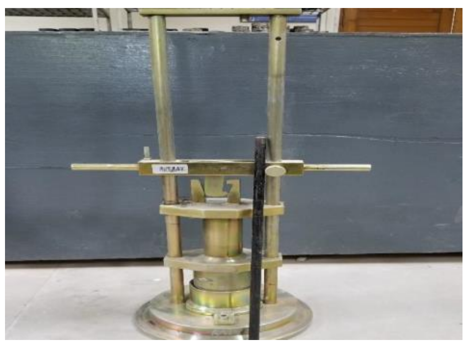


Figure 3. 6: Impact Value Test Apparatus

3.2.2.5 Crushing Value Test

To achieve a pavement with higher quality and strength, the aggregates must have enough strength to sustain traffic loads. The apparatus used for this test was a steel cylinder having open ends, base plate, plunger with a piston diameter of 150 mm, and a hole provided across it, so that a rod could be inserted for lifting it, cylindrical measure, balance, tamping rod, and a compressive testing machine. Aggregates were passed through a set of sieves and that passing through ½” and retaining on 3/8” were selected. The sample of aggregate was washed, oven-dried, and weighed (W1) and then added in three (3) covers into that cylindrical measure, by giving 25 number of tamping to each layer. The specimen was then shifted into the cylinder made of steel with a base plate and the plunger was inserted. Then it was placed in a compressing machine and tested. 4tons/minute load was applied at a uniform rate until 40tons total load was achieved. Crushed aggregate was then isolated from the steel cylinder and was passed through a sieve of 2.36mm. The passed material was collected and weighed (W2). The crushing value of aggregate was calculated by = W2/W1 x 100. The outcomes are given in Table

3.2.2.6 Specific Gravity and Water Absorption Test

Fine and coarse aggregate specific gravity is of major importance in the production of asphalt paving mixtures. It is frequently used by engineers in the design of pavement and construction too. The amount of binder absorbed and VMA is evaluated based on bulk specific gravity. Relative density is also the term used for specific gravity representing the weight volume characteristics of aggregate material. It is the mass to volume ratio of a material at a persistent temperature. The coarse aggregates are those which retain on sieve No. 4 while passing from No. 4 sieve are termed as fine aggregate. Specific gravities of coarse and fine aggregate were determined separately.

- **Coarse Aggregate Specific Gravity**

ASTM standard procedure C 127 was followed to determine the specific gravity and water absorption of coarse particles of aggregate. The aggregates were first passed from sieve #4 and the aggregates that retained on sieve #4 were firstly dried in an oven and then soaked for 24 hours in water. The aggregates were then rolled on a towel and its weight in the saturated state was noted. After this, the submerged weight of aggregates was determined and its specific gravity and water absorption were calculated. The oven-dried sample does not have any water in it while in the saturated surface-dry condition water fills the aggregate pores.

- **Fine Aggregate Specific Gravity**

This test was conducted by following the C-128 standard procedure of ASTM. Aggregates passing sieve #4 were dipped in water for approximately 24 hrs. The aggregates were then dried up to the extent of the saturated surface condition by spraying it in a tray. The cone was placed on a level surface, filled with the fine aggregate, and compacted with a tamping rod by delivering twenty-five (25) blows. After removing the cone, the aggregates were observed. If they possessed the mold's shape and then the particles were not SSD. After drying the aggregate again, the same technique was performed until the aggregate slightly slumped with the cone removal. A pycnometer was weighted after filling it up with water to a specified mark. The sand was put in the flask and weighed again after saturated surface drying. The specific gravity and absorption were calculated after oven drying of sand at a temperature of 110oC.

The results of laboratory tests on aggregate are as below

Table 3. 2: Aggregate test results

Description of test	**Specification standard**		**Results**	**Specification limit**
Fractured Particles	ASTM D 5821		100%	More than 90%
Los Angles Abrasion	ASTM C 131		22.9%	≤ 40 %
Elongation Index	ASTM D 4791		3.52%	≤ 15 %
Flakiness Index	ASTM D 4791		12.78%	≤ 15 %
Impact value	BS 812		18.5%	≤ 30%
Crushing value	BS 812		23.6%	≤ 30%
Water absorption	Fine agg	ASTM C 128	2.39%	≤ 3%
	Coarse agg	ASTM C 127	0.81%	≤ 3%
Specific Gravity	Fine agg	ASTM C 128	2.59	
	Coarse agg	ASTM C 127	2.64	

Test done on steel slag are as follows

Table 3. 3: Steel slag test results

Test	**Results**
Specific Gravity	2.75
Los Angles Abrasion	25.5%
Elongation Index	3.2%
Flakiness Index	8.9%

3.2.3 Binder Testing:

Bitumen is used as a binder in asphalt mixtures. It is blackish or dark brownish and is produced from residues distillation of petroleum. It occurs naturally is asphalt lakes or produced in petroleum refineries from the residue of crude oil. Consistency, safety, and purity of bitumen are the properties that are necessary for engineering and construction purposes (MS-4 Manual 2003). These properties chiefly affect the asphalt mixture performance. As these properties change significantly over time therefore the age of the binder is an important factor to know about its behavior. A new system is developed by the Strategic Highway Research Program (SHRP) to predict the physical properties of bitumen in the field. This system is called the Performance Grading (PG) system. It stresses to control viscosity at low temperature but it is not a concern in our country due to the temperature of the environment. A variety of tests were performed to check the suitability of binders for HMA. Tests on binders are usually performed at 25oC temperature to compare consistencies of asphalt binders as consistency changes with temperature. The table below mentions tests and their standards performed on these binders.

Table 3. 4: Tests performed on the binder

Test Performed on Binders S. No.	Test	Standards
1	Penetration Test	In accordance with ASTM D 5
2	Flash and Fire Point	In accordance with ASTM D 92
3	Softening Point	In accordance with ASTM D 36
4	Ductility	In accordance with ASTM D 113
5	Viscosity	In accordance with ASTM D 88
6	Specific Gravity	In accordance with ASTM D 70

3.2.3.1 Penetration Test:

Penetration test was performed on both the binders according to ASTM D 5 and AASHTO T 49-03. To find the consistency of asphalt binders, it is one of the oldest tests. It measures the softness and hardness of binder to classify them in different standard grades. A higher penetration value shows a soft and thin binder. Binder having low penetration value is used in hot regions while binder of high penetration is desirable in colder climates. First of all, the binder is heated to a suitable temperature to make it flow and not to trap any air but it should not be heated too much otherwise binder properties are affected. The binder is then poured into a test container and maintained at a standard temperature of 25C by insertion in a temperature-controlled water bath. After the standard temperature is attained the container is taken out and tested in a penetrometer by applying a 100g load through a needle for 5 seconds. Penetration test was performed on two samples of each bitumen and the penetration readings were noted at five points of each specimen. The results of the penetration test are mentioned in Table.

3.2.3.2 Softening Point Test

ASTM D 36 is the standard followed to perform this test by using the apparatus of ring and ball. With the rising temperature, the bitumen becomes softer progressively and its viscosity decreases although it is a visco-elastic material. The temperature point at which the sample of the asphalt binder cannot resist the steel ball’s weight of 3.5g when immersed in water. Therefore, it is the average of temperatures when two bitumen disks become adequately soft to allow balls of steel for a 25mm fall. First of all, the binder was heated to a temperature so that it can flow and its properties are not lost. Then it was transferred to a mold to form horizontal disks. Once placed in the apparatus, the balls were positioned on the disks. The temperature was increased to a point where the binder allowed the balls to fall through above-mentioned distance. The results are stated in Table.

3.2.3.4 Ductility Test

It is performed according to the D 113 Standard of ASTM which shows the stretching ability and adhesion property of the binder. Ductility is considered an important and significant physical property of bitumen. It shows the bitumen behavior concerning the change in temperature. The standard temperature used to conduct this test is 25oC. Ductility is the distance to which a standard-sized specimen of binder (placed in briquette of 1 in2 cross-sectional area) lengthens without breaking when its two ends are dragged apart at a rate of 5cm/minute and a specified 25 ± 0.5°C temperature. The minimum length criterion of the specimen to pass the ductility test is 100cm. The asphalt mixtures produced from less ductile bitumen are cracked under heavy and repeated traffic loads. Table 3 gives the result of the ductility test performed on both the binders.

3.2.3.5 Viscosity Test

T-316 standard procedure of AASHTO is adopted to find the binder's viscosity through rotational viscometer at raised temperatures. The viscosity at high temperature is essential as pumping, workability, mixing ability, and compaction are controlled by it. It can be performed at a range of temperatures but for Performance Grade bitumen it is performed at 135°C and 160°C because of similar production temperature, irrespective of the environmental conditions.

For this purpose, the Brookfield RV apparatus was used as per ASTM D 4402 and AASHTO T 316. First of all, the sample chamber, the spindle, and the environmental chamber were heated to 135oC and 160oC. The bitumen sample was then heated so that it can flow easily and then it was poured properly in the sample chamber after stirring it so that no air bubbles are entrapped in it. The sample was then inserted into a temperature controller unit and a spindle No. 27 was carefully lowered into the sample. It was then brought to the chosen temperature (135 C or 160 C) within thirty minutes and then it was permitted to equilibrate at that temperature for ten minutes. Rotate spindle at 20 revs/min, so that percent torque is between 2 and 98 percent. Take three readings as the sample has reached temperature and equilibrated, permitting one minute between each reading. The average of the three readings will report viscosity. The results obtained are mentioned in the table below.

3.2.3.3 Flash and Fire Point Test

The Flashpoint of a binder is the temperature at which the fumes of bitumen sample in COC suddenly produce flash in presence of flame. The surface of binder catches fire and gives flames for at least 5 seconds this basically corresponds as fire point. A brass cup was filled with bitumen up to a certain volume. It was then heated at a constant rate and a test flare 30 as passed above it at definite intervals. When the above mentioned conditions were attained, the temperature at which flash and fire occurred was noted. Three different trials were carried out to note these temperatures for each of the binder.

According to the specifications flash point should always be greater than 232 C. these results are also given in table below

Table 3. 5: Results of tests performed on bitumen

S No.	Tests	Specifications	Results
1	Penetration test@25°C	ASTM D 5	69
2	Flash Point(°C)	ASTM D 92	268
3	Fire Point(°C)	ASTM D 92	299
4	Softening point(°C)	ASTM D 36	48
5	Viscosity Test (Pa.sec)	ASTM D 88	0.2529
6	Ductility Test(cm)	ASTM 113	111
7	Specific Gravity	ASTM D 70	1.02

3.3 GRADATION

NHA grad**a**tion B was selected for surface course mix according to NHA specifications. The nominal maximum size of gradation is 19mm (3/4”) according to MS2. The gradation selected is shown in the table.

Table 3. 6: Gradation used for testing

S.NO	Sieve Size (Passing mm)	NHA specification range (%)	Selection	Retention (%)
1	19	100	100	0
2	12.5	75 to 90	82.5	17.5
3	9.5	60 to 80	70	12.5
4	4.75	40 to 60	50	20
5	2.38	20 to 40	30	20
6	1.18	5 to 15	14	16
7	0.075	3 to 8	4	10
8	Pan	….	….	4

Coarse aggregate of sieve size 1/2 in (12.5mm) is replaced by steel slag in three percentages i.e. 5%, 10% and 15% by weight of total aggregate and as proper mill scale is mostly less than 1mm in size therefore 3%, 6% and 9% replacement of fine aggregate retained on sieve No. 200(0.0075mm) by mill scale is been done.

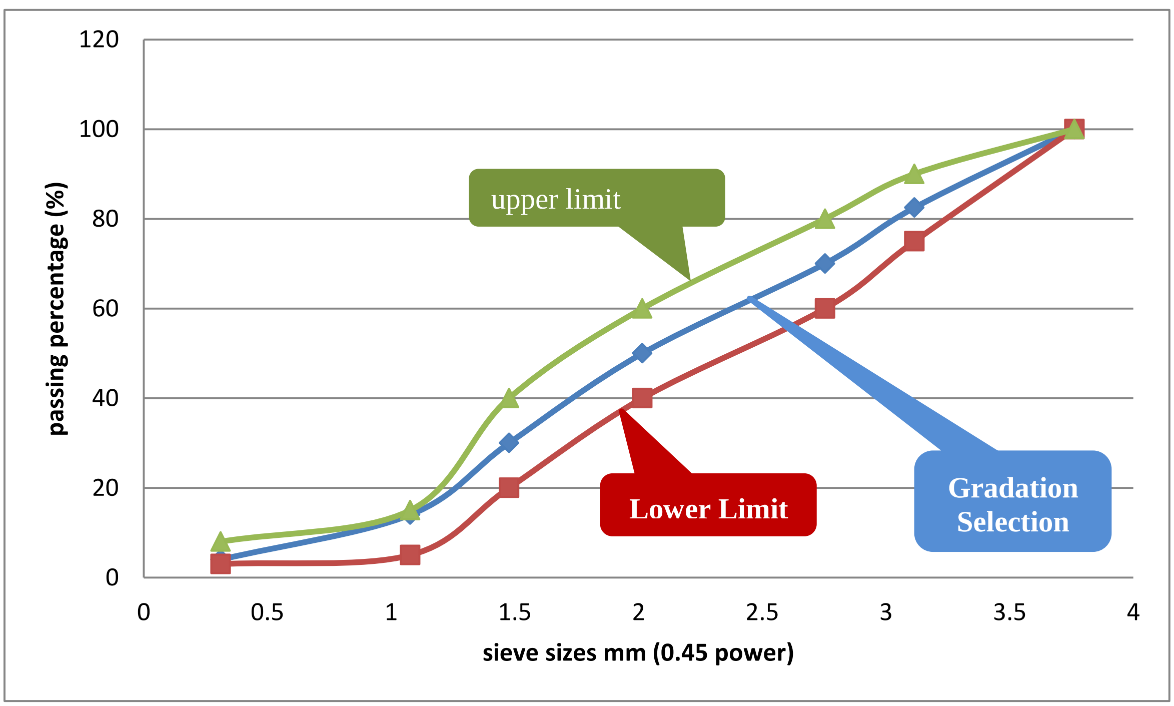


Figure 3. 7: Gradation curve (Sieve sizes vs % passing)

3.4 ASPHALT MIXTURE PREPARATION

The best combination of aggregate and binder is the basic concept for design of asphalt mixtures because the pavement constructed such combination will have high performance and long life span. The structure of aggregate plays an important role in the prevention of deformation therefore mix design should provide such a mix that can resist densification under traffic load and very little change in the air voids occur after construction. Asphalt mixture should have high shear and tensile strength, flexibility and should provide better resistance to moisture damage. A good quality aggregate following a suitable gradation can increase the shear strength of the mixture. Air voids are one of the most important factors in the selection of mix design. Adequate air voids should be provided in the mix so that the pavement is durable and does not rut due to fewer air voids. The total air voids depend on VMA, aggregate structure, amount of fines, level of compaction, binder content, and nominal maximum aggregate size. Different procedures have been developed to find the best percentages of materials for the mix in the laboratory but the Marshall Method is mostly preferred and adopted for asphalt mixture design. It was developed by Bruce G. Marshall of the Mississippi Department of Highway in 1939. The standard specification followed for this test is ASTM D 6926. It is only appropriate for asphalt paving mixtures having a MAS up to 1 inch (25 mm). If the mix has aggregate size of more than 1 inch, then modified method is used.

3.4.1 Aggregate and Bitumen Preparation

First of all, the acquired aggregates were sieved through a set of sieves mentioned in the gradation chart and placed in separate buckets. After performing sieve analysis aggregates were dried to constant weights at 105 C to 110 C. The effect of gradation of the aggregate on the performance of hot mix asphalt is an issue which many agencies around the world cater by using different gradations keeping in consideration the maximum aggregates size. Even if different hot mix asphalt mixtures use the same source of aggregate, then physical and chemical properties remain the same, but changing the gradation can alter the performance of aggregate and bitumen blend under the same loading and conditions. Out of the three gradations used NHA-B gradation is coarser with NMAS of 19 mm whereas the other two gradations, Superpave-2 and MS-2, are on the finer side having maximum nominal size of aggregate 12.5 mm.

1200gm of material is required for a 4-inch sample The amount of binder requisite to prepare the specimen was calculated as a portion of the weight of the total asphalt mix.

Figure 3. 8: Aggregate preparation

3.4.2 Aggregate and Binder Mixing

According to ASTM D 6926 proper mixing to bitumen and aggregate should be done in a mechanical mixer. After removing from the oven, heated aggregate and asphalt were transferred in the mixer. The temperature of mixing should be such that it gives a binder viscosity of 0.22 – 0.45 Pa.sec which is specified by Superpave mix design (SP-2). Therefore, a temperature range of 160C to 165C was selected that resembles with temperature for bituminous mixtures preparation in NHA Specifications (Pakistan).

3.4.3 Bituminous Mix Compaction Procedure

Compaction was carried out by using Marshall Compactor as Marshall mix design was adopted. A mechanical compactor was used having a drop of 18 in. Marshall mix design was carried out for medium traffic criteria using 50 blows on both sides of the specimen. It was used as IF slag has comparatively less strength than electric arc furnace slag and 50 blows compaction has more air voids and slightly high OBC as compared to 75 blows therefore a better asphalt film coating occurs on steel slag aggregates. As motorways and highways are heavily trafficked and overloaded so there is a probability for failure, therefore using IF steel slag mix design for medium traffic volume is carried. Secondly, it reduced the overall compaction cost, and mix design was carried out for inter-district roads, farm to market roads, and urban roads that constitute the majority of the road network in Pakistan.

3.4.4 Conditioning and Compaction of Mixture

It has been recommended by ASTM D 6926 that the mixtures should be conditioned for about two hours before compaction. Therefore, after mixing the bituminous mix was transferred to a metal tray for conditioning. After two hours of conditioning, the mix was compacted at 135℃ using an automatic Marshall Compactor. The mold cylinder, base plate and extension collar are parts of mold assembly. The height of the cylinder is 3 inch while its internal diameter is 4 inch. The collar is exchangeable with both ends of the mold. The mold assembly was thoroughly cleaned and heated to a temperature between 95 °C and 150 °C and a piece of filter paper was placed in it. The mix was then placed in the mold with the help of a scoop and spatula and the mold was packed after piece of filter paper was placed over it. On the compaction pedestal, the mold assembly was placed in the mold holder. The hammer was correctly placed on the mold. The selected design criteria for wearing course for this research was medium traffic conditions resulting in a 20-year Design ESAL between 10^4 and 10^6.

Therefore, for compaction purposes, 50 blows were applied mechanically on the face of the sample to simulate medium traffic volume conditions. Blows were applied on both sides of the specimen.

Figure 3. 9: Automatic Marshall Compactor

3.4.5 Specimen Extraction

After compaction of both the faces, the assembly was removed and the sample was allowed to cool to a suitable temperature so that it can be removed. The specimen was then removed from the mold using a manual marshall compactor. These extracted specimens were placed on a flat surface and permitted to cool down to the ambient temperature of the room. These specimens were prepared at different bitumen contents at an increment of 0.5% to find the optimal performing mix at minimum content of binder at air voids of 4%.

3.5 MARSHALL MIX DESIGN CRITERIA FOR MEDIUM TRAFFIC VOLUME (50 BLOWS)

Mix Design Method in accordance with Asphalt Concrete (MS-2 manual) is as below

Table 3. 7: Marshall Mix Design Criteria

Marshall method Mix Criteria	**Medium Traffic**	
Compaction, No. of blows	50	
	Min	**Max**
Stability (N)	5338 N	-
Flow (mm)	2mm	4mm
Air Voids (%)	3	5
Minimum VMA (%)	13% (for design air voids 4% & NMAS 19mm)	-
VFA (%)	65	78

Marshall mix design was carried out for medium level traffic.

3.6 STABILITY, FLOW AND VOLUMETRICS DETERMINATION

Every specimen after compaction was tested for bulk specific gravity, stability and flow and density to find the optimum binder content for each combination of aggregate and bitumen. Marshall testing machine was used to perform the testing which conforms to ASTM D 1559.

3.6.1 Bulk Specific Gravity

According to ASTM D 1188 bulk specific gravity test was performed on freshly prepared samples when they cooled down to room temperature. First of all, dry weight of the specimen was taken, then it was submerged in the water for a time till the voids were filled with water and then weighed. Finally, the sample was taken out from the water, dried with a cloth and weight of the saturated surface dry sample was noted. The test was performed on every sample of the combination and their bulk specific gravities were calculated.

3.6.2 Stability and Flow

Stability is the maximum load that a Marshall sample can resist at a temperature of 60oC. For this purpose, as the bulk specific gravity is a non-destructive test, the same samples were placed in a water bath at 60oC ± 1oC for almost 30 to 40 minutes before the test. The samples were taken out from the water bath, placed in the Marshall testing machine and load was applied at a rate of 50.8mm/minute until maximum load is achieved. At the point where load just start to decrease, the value is recorded and is called as Marshall Stability. Before the performance of the test, a displacement gauge is also attached to the sample frame and the deformation in the vertical direction is recorded in an increment of 0.25 mm. The deformation at the maximum load is recorded and is called flow value. The stability depends upon friction and cohesion between aggregates in asphalt mixture provided by the binding force of bitumen and can affect resistance to shear and rutting. This test was performed by following ASTM D 6927

3.6.3 Maximum Theoretical Specific Gravity

The combined specific gravity of aggregate and bitumen in an asphaltic mixture when the air voids are excluded is called maximum theoretical specific gravity (Gmm). It is one of the major characteristics of asphalt mixtures as air voids are calculated with the help of Gmm which is greater than or equals to Gmb. This test was performed according to ASTM D 2041 and AASHTO T 209. The loose mix sample prepared in the laboratory was first weight in dry condition. Then it was placed in the vacuum container and the container was filled with water. A vacuum of 25 – 27 mm Hg was applied to the pycnometer to remove the entrapped air. The pycnometer was agitated through an agitator. Its weight was recorded after the agitation. Then the Gmm of the sample was calculated as the ratio of mass of the sample and volume of water displaced by it.

Figure 3. 10: Maximum Theoretical Specific Gravity (Gmm)

3.6.4 Volumetrics:

The pavement performance can also be indicated up to some extent by the volumetric properties, density and void percentages. Aggregate can absorb water or bitumen up to a certain level and this can vary with the type of aggregate used. These details can be found with the help of Gmb and Gmm. The volumetric properties used are defined as follows:

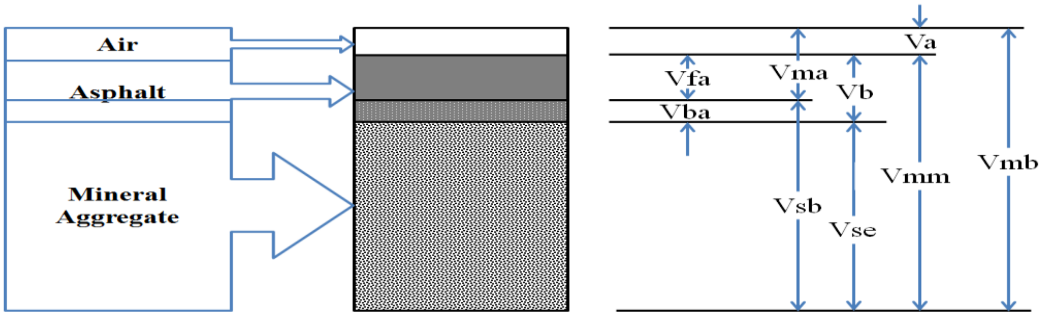


Figure 3. 11: Volumetrics of asphalt mix

3.6.4.1 Air Voids

The total volume of the air present in the small gaps between the coated aggregate particles in a compacted mix. The percentage of air voids calculated by the weight of the compacted mix is as follows:

$$Va = 100 \text{ x} \frac{Gmm - Gmb}{Gmm}$$

Where:

Va = Percentage of air voids in compacted mix by total volume

Gmm = Maximum theoretical specific gravity (ASTM D 2041)

Gmb = Bulk specific gravity of compacted mix

3.6.4.2 Voids in Mineral Aggregate

Voids between aggregate particles in a compacted mix occur which includes the air voids and the bitumen that is not absorbed in the porous voids of the aggregates. The percentage VMA expressed concerning the bulk volume of the compacted mix is calculated using the bulk specific gravity of aggregate as following:

$$VMA = 100 - \frac{Gmb \text{ x } Ps}{Gsb}$$

Where:

VMA = % age of voids in mineral aggregate by bulk volume

Ps = % age of aggregate by total weight of mix

Gsb = Aggregate's bulk specific gravity

Gmb = Compacted mixture's bulk specific gravity

3.6.4.3 Voids Filled with Asphalt

The voids filled with asphalt consists of the part of the volume the void space in between the aggregates that is filled with bitumen only, not including the air and the absorbed bitumen in aggregates. The formula used to calculate these void percentage is as follows:

$$VFA = \frac{VMA - Va}{VMA} \text{ x } 100$$

Where:

VFA = Voids filled with bitumen (Percentage)

VMA = % age of voids in mineral aggregate by bulk volume

Va = % Air voids in compacted mix

3.6.5 Determination of OBC

The OBC should be determined to prepare samples for performance testing. For this purpose, all the samples were rigorously tested to find their stability, flow, density, Gmb, Gmm, air voids, VMA and VFA. The results of these tests were compiled to make it meaningful data. Graphical plots and curves were developed using this data.

These results show the sensitivity of mix to the bitumen content. According to the graphs, air voids and voids in mineral aggregate decreases with increasing bitumen content while VFA and flow increase with an increase of bitumen in the mix. Stability first increases with increasing bitumen, reaches to a maximum value and then starts decreasing. This research was carried out for wearing course gradation of medium traffic road (50 blows) for which the Asphalt Institute recommends minimum stability of 5338 N, flow value between 8 and 16, air voids can vary from 3 to 5 percent and VFA between 65 to 78. The OBC is determined as the bitumen content that produces 4 percent air voids. Other properties are then read from the graphs directly.

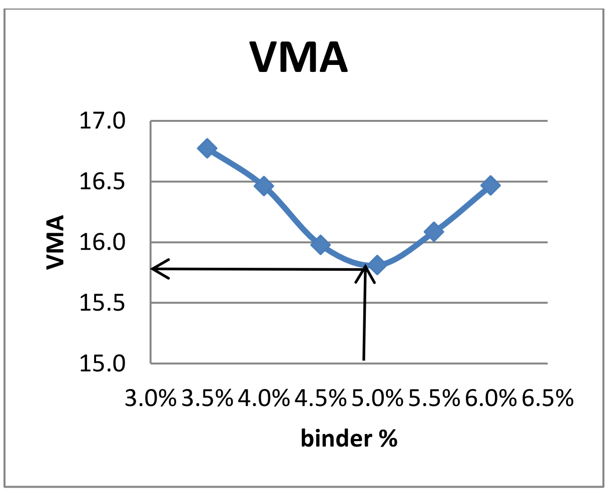
3.6.6 Volumetric properties of mix

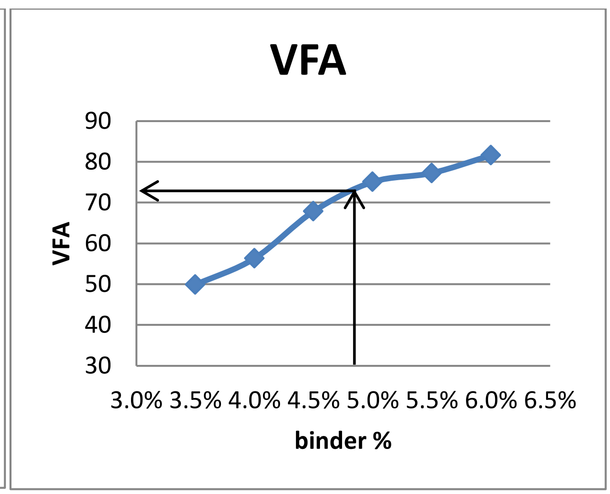
The stability, flow and volumetric properties of mix are given. Volumetric Properties of NHA-B with Parco are displayed

Table 3. 8: Stability, flow and volumetric properties

Volumetric properties of mix								
S.No	Binder %	Flow (mm)	Stablilty (KN)	Gmb	Gmm	Air Voids (VA)	VMA	VFA
1.	3.5%	2.0	10.63	2.255	2.463	8.41	16.77	49.85
2.	4.0%	2.5	12.88	2.276	2.452	7.19	16.46	56.32
3.	4.5%	2.88	12.91	2.301	2.425	5.13	15.98	67.86
4.	5.0%	3.25	12.86	2.317	2.413	3.94	15.81	75.05
5.	5.5%	3.33	12.25	2.322	2.410	3.66	16.08	77.24
6.	6.0%	4.5	11.70	2.324	2.397	3.03	16.47	81.58

Graphical representation of volumetric properties of mix design for medium level traffic using 50 blows of marshall compactor is also given





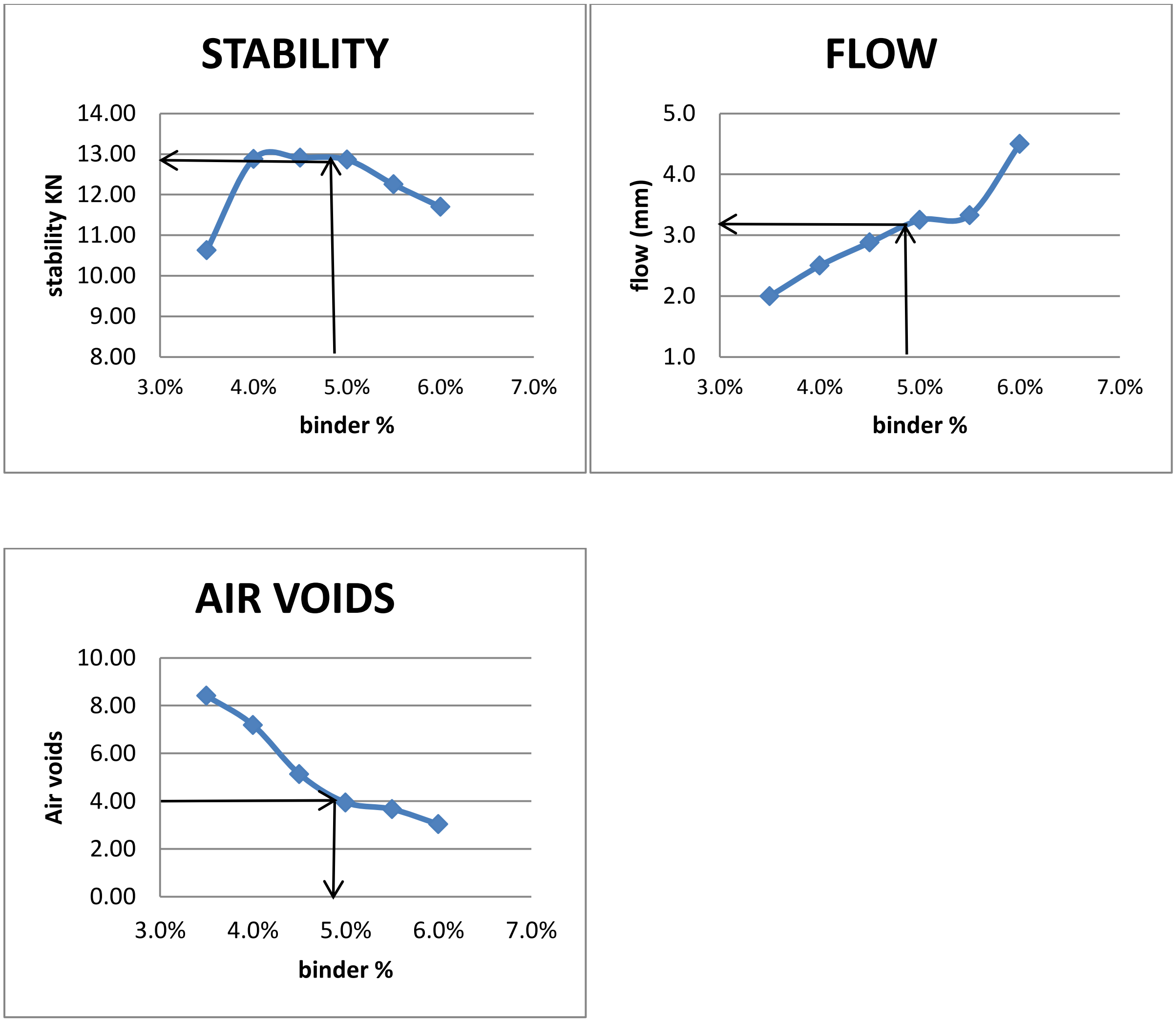


Figure 3. 12: Plot of bitumen content vs stability, flow and volumetrics

The optimum bitumen content came out to be 4.9%. The volumetric properties at OBC are fulfilling the criteria according to the MS-2 manual.

3.7 SAMPLE PREPARATION FOR PERFORMANCE TESTS

After finding out OBC, samples for performance tests were prepared i.e. for Moisture susceptibility and resilient modulus test. For this research, resilient modulus and moisture susceptibility test were selected as performance tests to characterize and analyze the use of mill wastes in asphalt mixtures. Laboratory prepared and laboratory compacted specimens were used to evaluate the performance of these mixes. After the determination of OBC, samples were prepared using Marshall Compactor. The process of manual mixing was carried out.

3.7.1 ITS Test

To find resilient modulus marshall samples of 4-inch diameter and 2.5-inch height were made. For each mix, aggregate and bitumen were mixed using OBC at 160 ± 5 ℃ and then aged for about 2 hours. After aging they were compacted at a temperature of 135℃ and then permitted to cool down to room temperature.

Also for TSR using ITS, four marshall specimens (half tested dry and half tested after conditioning) were prepared in the laboratory.

Figure 3. 13: Sample cracks under ITS test

3.8 PERFORMANCE TESTING

The resilient modulus test and moisture susceptibility test through indirect tensile strength test are selected as performance tests.

3.8.1 Moisture susceptibility testing

The moisture susceptibility test was carried out in accordance with ASTM D 6931-07, (Resistance of Compacted Hot-Mix Asphalt to Moisture Induced Damage). Two specimens per mix were tested unconditioned. These unconditioned specimens were placed in a water bath at 25±1°C (77±1.8°F) one hour prior to testing. Another set of two specimens per mix were tested conditioned.

The Samples for Moisture Susceptibility were prepared according to ALDOT 361, for which Marshall sample having 2.5” height and 4” diameter were prepared.

Specimens were saturated and then placed in a 60±1°C (140±1.8°F) water bath for 24 hours followed by one hour in a water bath at 25±1°C (77±1.8°F). No freeze-thaw conditioning cycles were performed on the conditioned specimens. Both unconditioned and conditioned specimens were loaded diametrically at a rate of 50 mm/minute. For each specimen, the tensile strength was then calculated using specimen dimensions and failure load. The tensile strength ratios were then calculated by dividing the average conditioned tensile strength by the average unconditioned tensile strength. The acceptable value for the tensile strength ratio employed was 80% (minimum).

The tensile strength of each subset was determined by Equation

$$St = \frac{2000P}{\pi D t}$$

Where:

St = Tensile strength, kPa

P = Maximum load, N

t = Specimen height before tensile test, mm

D = Specimen diameter, mm

The TSR indicate the potential for moisture damage which is the ratio of the tensile strength of the conditioned subset to that of the unconditioned subset. The TSR for each mixture is calculated by Equation 3.4.

$$TSR = \left[\frac{S2}{S1}\right]$$

Where:

S1 = Average tensile strength of dry subset, and

S2 = Average tensile strength of conditioned subset.

Figure 3. 14: Performing ITS test

3.8.2 Resilient modulus

Resilient modulus simulates the elastic property of HMA mixtures, it is an important parameter to take into account in pavement structural design. It is basically stress divided by strain for dynamic loads.

The test was performed in accordance with ASTM D 4123. The indirect tension test setup was used for the resilient modules test of hot mix asphalt mixtures because it is a simple method and was available in the laboratory. Universal Testing Machine (UTM-25) was used for testing. Indirect tensile strength of hot mix asphalt mixtures was acquired earlier to resilient modulus testing.

20% of indirect tensile strength peak force was used for resilient modulus. For performing the test, the metallic fixtures for LVDTs (linear variable differential transformer) were installed in the jig. The LVDTs are used for measuring the linear displacement. The specimen was then loosely fitted into the jig on the bottom loading platen. The yoke support cross-arm was raised by lifting then turning the support spacers. The height of the support cross-arm was adjusted in such a way that the displacement transducers remain exactly in line with the horizontal center of the specimen. The displacement transducer yoke was then placed and adjusted with the help of screws then the clamps were tightened. The top loading platen was then placed and lowered it onto the specimen.

After the jig set up, the jig was transferred for resilient modulus testing into universal testing machine. The LVDTs were installed through the fixtures and adjusted to operate within their range as shown in Figure 3.15. The levels display view helped to adjust the LVDTs. The virtual pendant window containing the functionality controlled the hydraulic power pack and service manifold of the machine. Therefore; by using axis jog control, the loading ram was lowered to such a level that it just a made contact with the jig but without application of load. The value of Poisson ratio assumed was 0.4. Sample was subjected to sine loading after inputting factors like load pulse width, target temperature, pulse repetitional period and conditioning pulse count. Force and displacement were displayed by the software as the test proceeds.

Deflection and load readings were recorded by the software for the last 5 pulses after conditioning pulses of the test. The readings were averaged to determine the resilient modulus.

Chapter 4

RESULTS AND ANALYSIS

4.1 INTRODUCTION

The behavior of utilization of low percentages of steel slag and mill scale is investigated with comparison to control mixes with conventional aggregate from margalla quarry, for roads designed according to medium level traffic volume. Binder used was Parco 60/70, Induction Furnace steel slag and mill scale from Pak-Iron steel mill, and NHA-B gradation was used. NHA – B gradation is a bit coarser than other gradations like MS-2. The objectives of this research were to characterize the HMA mixtures with different percentages of industrial wastes, to analyze the relative performance of the asphalt mixtures.

4.2 MOISTURE SUSCEPTIBILITY TEST

After completion of mix design, moisture susceptibility test was carried out on the asphalt mixtures according to ASTM D 6931 (Resistance of compacted hot-mix asphalt to moisture-induced damage) while conditioning was done according to ALDOT 361 standard procedure. The freeze-thaw cycle was not incorporated. Marshall samples of dia 4”(in) and thickness 2.5”(in) were prepared for performance testing. Samples were prepared for each percentage of steel slag and mill scale separately. A total of 28 samples were prepared, 4 for each mix, out of which 2 were tested unconditioned, and 2 were tested after conditioning. Conditioned samples were soaked in water for 24 hrs at 60 C then for one hour at 25 C before testing. All samples fulfilled the minimum TSR criteria of 80%. Samples with different percentages of induction furnace steel slag showed better results as compared to samples with conventional aggregate, this can be attributed to the better aggregate structure of steel slag. While the results of samples with mill scale of 3% and 6% are better than that of 9% mill scale. There was a minute difference of TSR values for steel slag whereas for 9% mill scale the TSR value was relatively lower than other samples due to a decrease in conditioned ITS, but it didn't appear to be a threat as it's above the minimum requirement. Therefore it can be concluded that with good binder coating steel slag is less susceptible to moisture damage. Sometimes free lime content if present, can cause some variable behavior with long-lasting exposure to moisture but proper binder coating cover up this concern. Steel slag behaved sometimes equal but mostly better than conventional aggregate as indirect tensile strength and resilient modulus is concerned. 6% mill scale showed the optimum result as far as this material is concerned resulting in a little bit higher unconditioned indirect tensile strength and comparable TSR value with the control sample with a small difference. 9% mill scale showed lower indirect tensile strength, both conditioned and unconditioned. Overall mixes with 15% of steel slag depicted better results for tensile strength. So these samples were tested for indirect tensile strength and their TSR was calculated. Steel slag depicted slightly high water absorption as compared to conventional aggregate, this is because of a bit more porous structure of steel slag than coarse aggregate from margalla quarry, this can be a cause of a slight reduction in TSR value.

Table 4. 1: Test parameters for ITS test

Test Parameters	**Specifications**
Specimen size	2.5”× 4”
Compaction temperature	150˚C- 160˚C
Water soaking (conditioning)	60˚C for 24 hours proceeded by 25˚C for 1 hour
Compaction method	Marshall
Strength property	Indirect tensile strength @ 25 ˚C

4.2.1 Unconditioned Indirect Tensile Strength

ITS test results depict the intensity of tensile stresses that asphalt concrete can bear. ITS value is obtained from the peak force displayed by UTM that a sample bears before it cracks. Results obtained in this research are quite satisfactory, results are displayed in the table.

Table 4. 2: Unconditioned ITS test results

S. No.	Alternative aggregate as replacement (%)	Height (mm)	Indirect tensile strength Unconditioned		Average ITS (S1)
			N	KPa	KPa
1	Control sample 1	67	4547	427.768	423.39
	Control sample 2	66.7	4434	419.013	
2	IF steel slag 5% 1	67	4497	423.064	426.36
	IF steel slag 5% 2	67	4567	429.649	
3	IF steel slag 10% 1	67	4631	435.670	440.29
	IF steel slag 10% 2	66.7	4708	444.906	
4	IF steel slag 15% 1	66.7	4779	451.616	459.74
	IF steel slag 15% 2	66	4899	467.866	
5	Mill scale 3% 1	66.7	4422	417.879	423.92
	Mill scale 3% 2	66	4502	429.951	
6	Mill scale 6% 1	67	4528	425.980	430.14
	Mill scale 6% 2	65.5	4513	434.292	
7	Mill scale 9% 1	65	4372	423.960	422.02
	Mill scale 9% 2	64.7	4312	420.080	

The results of dry conditioned ITS for both materials are quite promising.

4.2.2 Conditioned Indirect Tensile Strength

Conditioned ITS is used to find moisture susceptibility of asphalt concrete samples. induced moisture damage can be evaluated by using conditioned ITS to find out the tensile strength ratio. Test results are displayed in the table below

Table 4. 3: Conditioned ITS results

S. No.	Alternative aggregate as replacement (%)	Height mm	Indirect tensile strength Conditioned N	Indirect tensile strength Conditioned Kpa	Average ITS (S2) Kpa
1.	Control sample 1	66.7	4312	407.484	412.54
	Control sample 2	66.7	4419	417.596	
2.	IF steel slag 5% 1	66.5	4372	414.397	414.73
	IF steel slag 5% 2	67	4412	415.067	
3.	IF steel slag 10% 1	66.7	4507	425.912	423.54
	IF steel slag 10% 2	66	4410	421.165	
4.	IF steel slag 15% 1	66.3	4663	443.312	434.35
	IF steel slag 15% 2	65.7	4434	425.391	
5.	Mill scale 3% 1	66.7	4415	417.218	411.20
	Mill scale 3% 2	67	4307	405.189	
6.	Mill scale 6% 1	66.7	4321	408.335	409.54
	Mill scale 6% 2	66	4301	410.755	
7.	Mill scale 9% 1	65.3	3897	376.162	381.35
	Mill scale 9% 2	65	3986	386.529	

Conditioned ITS increases with the incorporation of steel slag percentages. For 9% mill scale, it reduces significantly.

4.2.3 Tensile Strength Ratio

The results obtained by performing ITS on mixes with steel slag and mill scale are shown in the table as below

Table 4. 4: TSR results

Aggregate replaced (%)	Average ITS unconditioned	Average ITS conditioned	TSR (%)
0% (control mix)	423.39	412.54	97.44
5% steel slag	426.36	414.73	97.27
10% steel slag	440.29	423.54	96.2
15% steel slag	459.74	434.35	94.18
3% mill scale	423.92	411.2	97
6% mill scale	430.14	409.54	95.21
9% mill scale	422.02	381.35	90.36

Steel slag displayed better ITS results than other mixes. Both conditioned and unconditioned ITS increased for mixes with steel slag and has an increasing trend with the increase in percentage. As TSR is a ratio of ITS conditioned and unconditioned, although conditioned ITS increased but, according to proportion with unconditioned ITS, it is slightly less at 15%, hence small reduction in TSR occurred. Secondly, maybe the presence of free lime is slightly interfering by interacting with water, but this phenomenon has fewer chances to occur as steel slag is coated with the binder, but still, this can be a cause of this slight reduction in TSR with increasing steel slag percentages.

There is a reduction in TSR with an increase in mill scale percentage due to the reduction in conditioned ITS value. Although of no threat but this indicates that the mill scale is susceptible to moisture. This may be due to the chemical composition of, mill scale as it comprises of metal oxides, maybe this factor is responsible for the reduction of TSR especially at 9% replacement.

4.2.4 RELATIVE PERFORMANCE PLOTS

Obtained Results of indirect tensile strength and tensile strength ratio are displayed graphically in the form of bar charts.

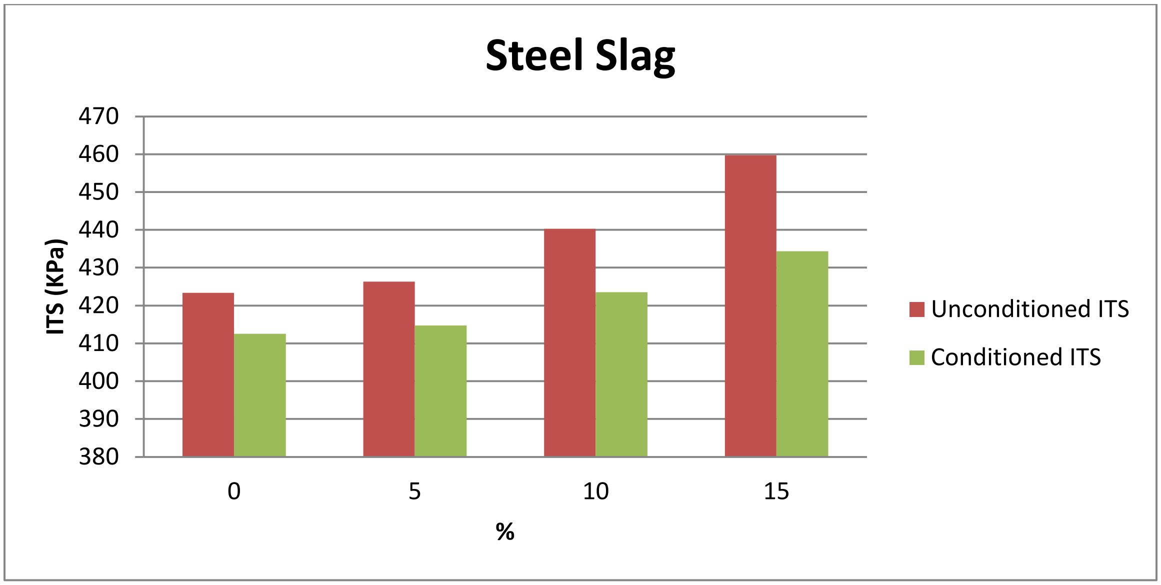


Figure 4. 1: Indirect Tensile Strength results

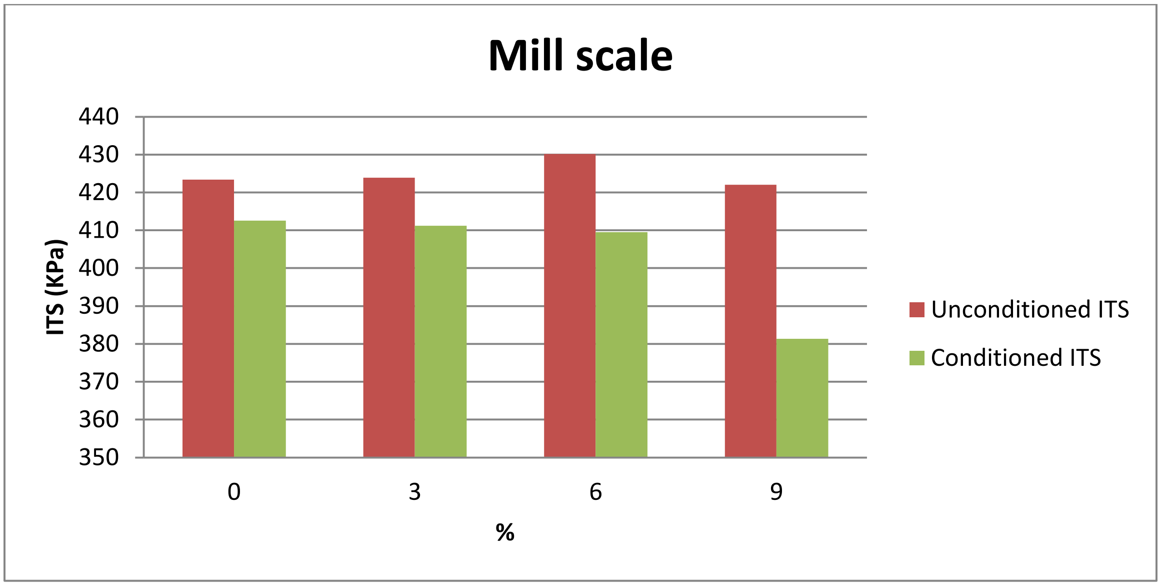


Figure 4. 2:Indirect Tensile Strength results

Comparative analysis of results shows that conditioned indirect tensile strength significantly decreases when 9% mill scale is used. This led to lower TSR value as compared to other mixes. TSR values are shown below in bar charts against each percentage of steel slag and mill scale separately. Induction furnace slag displayed an increasing trend in tensile strength with an increasing percentage whereas 6% mill scale shows the optimum result in terms of tensile strength.

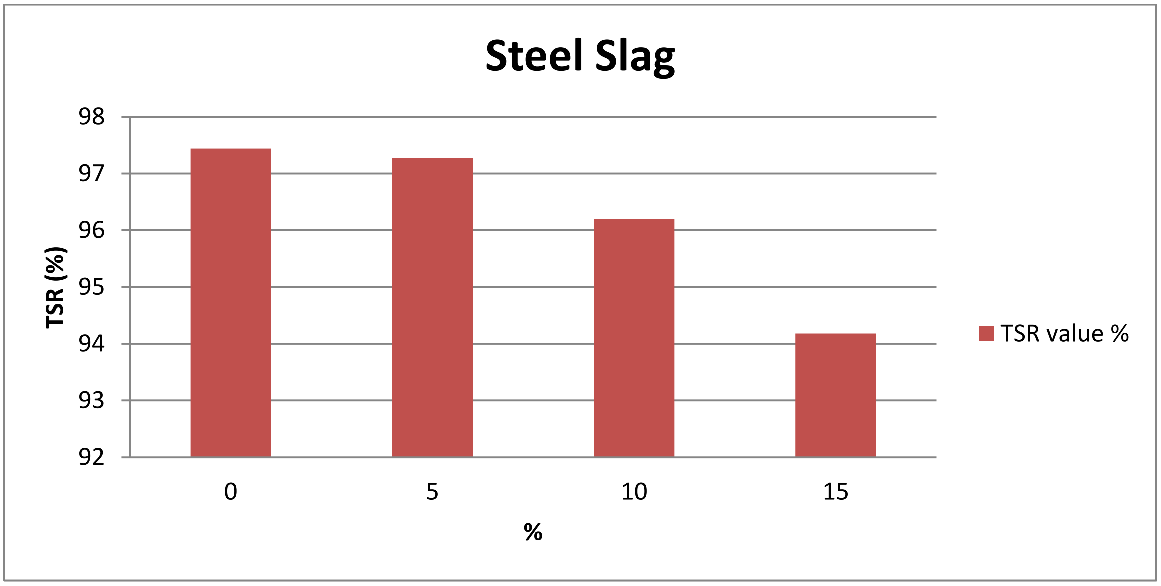


Figure 4. 3: Tensile Strength Ratio results

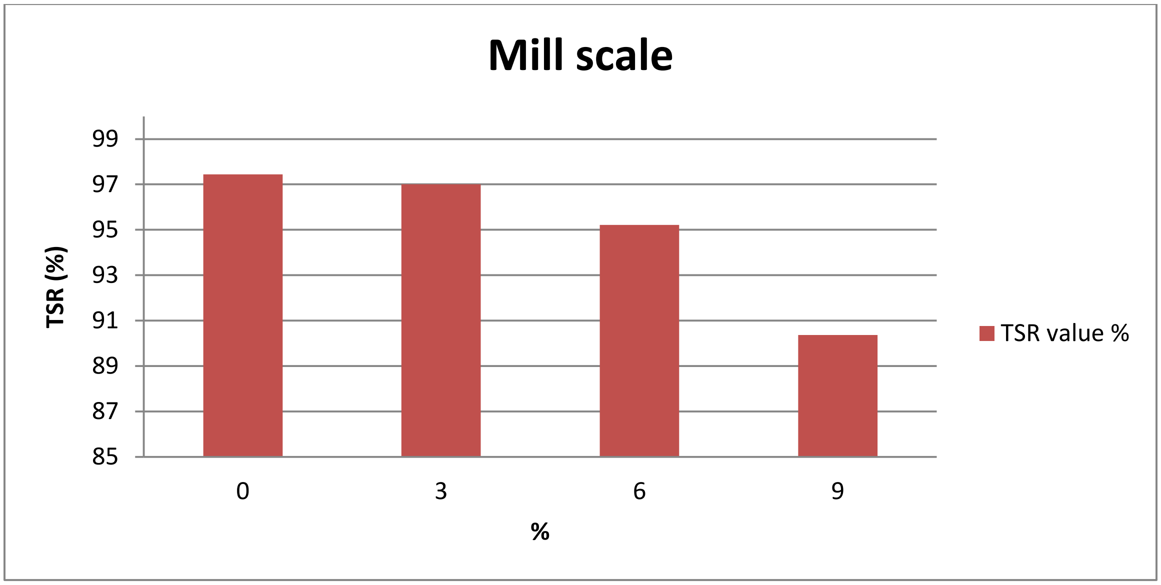


Figure 4. 4: Tensile Strength Ratio results

Relative plots of different percentages of steel slag for ITS are displayed in figures below

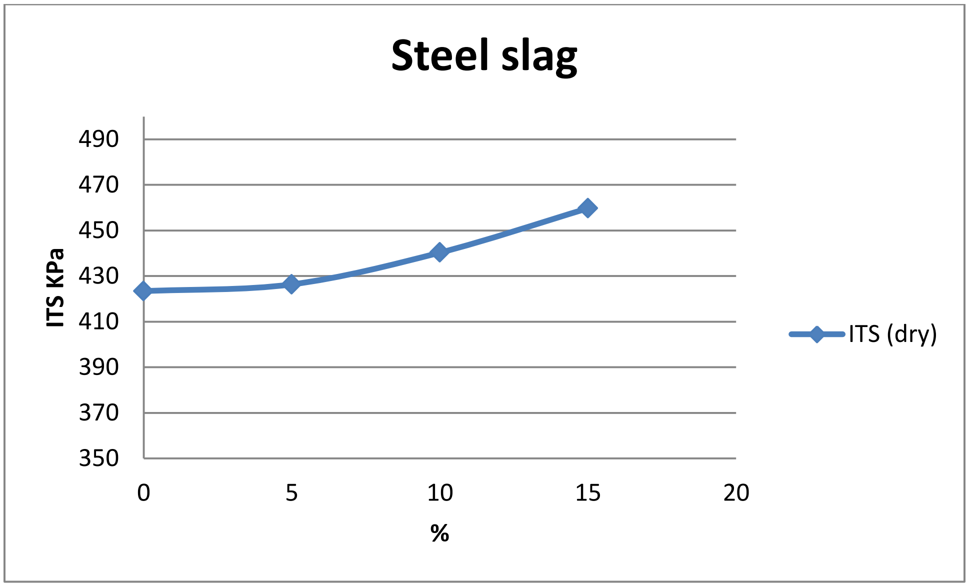


Figure 4. 5: Unconditioned ITS

Conditioned ITS results for steel slag are shown in figure below

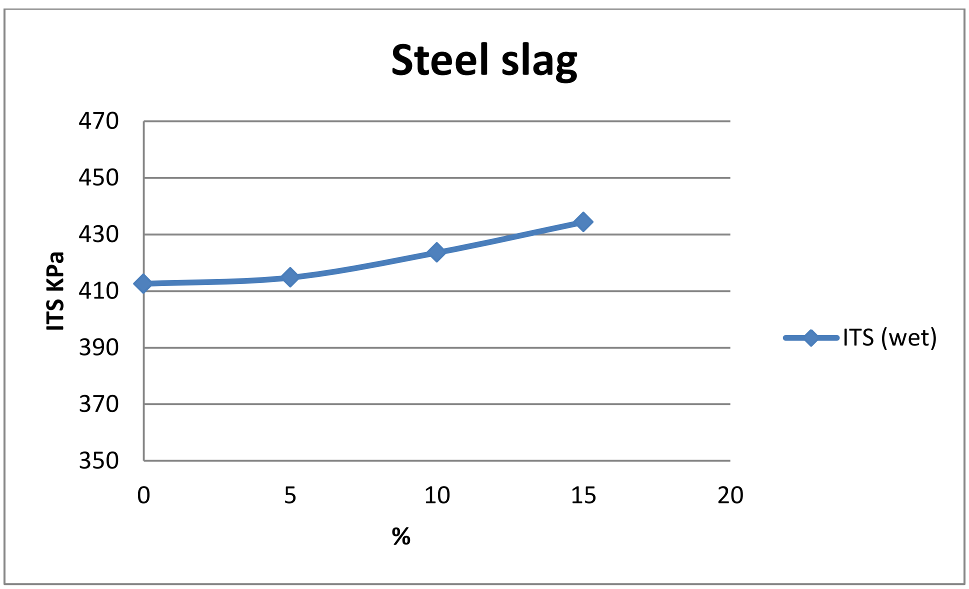


Figure 4. 6: Conditioned ITS

Results of ITS test for mill scale are displayed in figures below

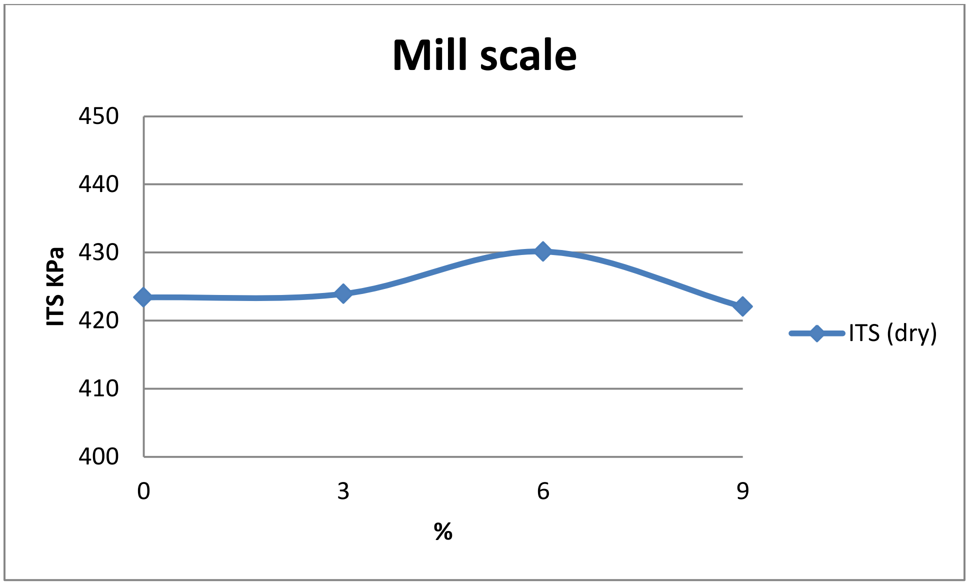


Figure 4. 7: Unconditioned ITS Results

Indirect tensile strength increases at 6% mill scale and then decreases.

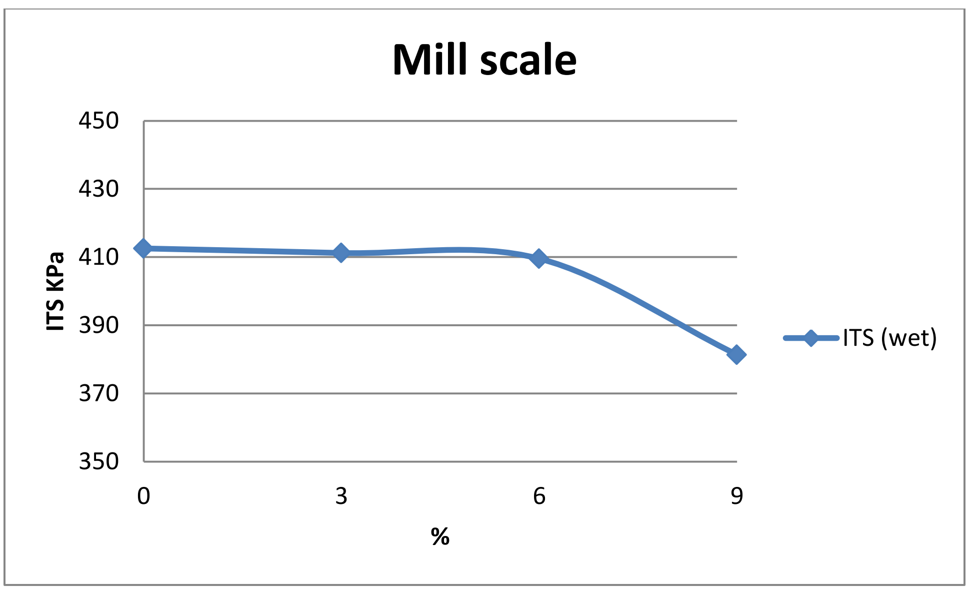


Figure 4. 8: Conditioned ITS Results

ITS for conditioned mill scale mix at 9% decreases significantly relative to other mixes.

Replacement with15% steel slag results in 3.04% reduction in TSR as compared to control sample. Replacement with 9% mill scale results in 7.27% reduction in TSR as compared to the control sample.

4.3 RESILIENT MODULUS TEST

IF Steel slag was used as coarse aggregate whereas mill scale was used as fine aggregate and replacement percentages used were of total aggregate by weight. **ASTM D 4123** is been followed. NMAS was 19 mm, marshall samples of dia 4"(in) and thickness 2.5"(in) were prepared for Resilient modulus and load pulse duration was 100ms. Virgin control sample, 3 different percentages of steel slag, and 3 percentages of mill scale were taken. A total of 14 sample mixes were prepared. Deflection and load readings were recorded by the software for the last 5 pulses after conditioning pulses of the test. The readings were averaged by UTM to determine the resilient modulus. 20% of indirect tensile strength is used as a peak loading force and the seating force is used as 10 % of peak loading force. The Poisson ratio was taken as 0.4, a loading strip of 0.5 in was used and the tests were performed at 25 C.

Angular shape, good structure, high specific gravity, and other properties of steel slag can be attributed to higher resilient modulus values.

Table 4. 5: Factors used in Resilient modulus testing

1	Temperature	**°C** 25	Condition Based Factors
2	Load Pulse Duration	**ms** 100	
3	Diameter of Specimen	**Inches** 4	

These parameters affect resilient modulus, by varying values of these parameters change occurs in resilient modulus of asphalt concrete.

The results obtained are shown in the table below

Table 4. 6: Resilient modulus test results

% of aggregate replaced	Resilient Modulus (MPa)		
	Sample 1	Sample 2	Average
(control)0%	3453	3463	3458
Steel slag 5%	3277	3649	3463
Steel slag 10%	3401	4080	3740.5
Steel slag 15%	3735	3905	3820
Mill scale 3%	3177	3102	3139.5
Mill scale 6%	3503	2992	3247.5
Mill scale 9%	2208	2471	2339.5

Mixes with steel slag displayed better results than other mixes. Mixes with 3% and 6% mill scale showed almost similar results with a minute reduction in value, as compared to control mixes. Mixes with 9% mill scale have the least value of resilient modulus comparatively.

Mill scale has a high specific gravity, it is the outer layer on steel billets or other steel rolled produced, which gradually wear out and chips off with time. So it is flaky in shape. Most of its percentage size is less than 1 mm as small flakes break down in further small size. Its has a slightly smooth outer texture when observed visually, maybe flaky structure and slightly smooth surface can be the cause of gradually lower resilient modulus value at 9% replacement.

6% mill scale is displaying optimum results, higher than 3%, and 9% replacement. This may be due to the high density of mill scale that and its adjusting and suitable behavior with asphalt mix. This can lead to further research that why it is behaving in such a manner.

4.3.1 RELATIVE PERFORMANCE PLOTS

Two samples were prepared for resilient modulus for each percentage and the average value of both samples is been plotted against each percentage of steel slag and mill scale separately.

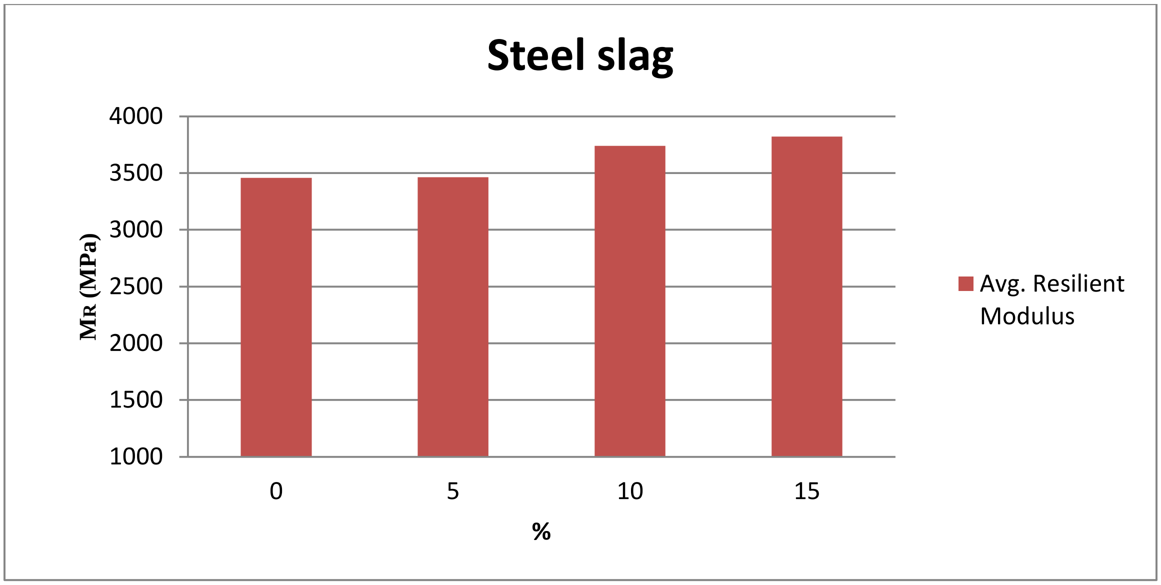


Figure 4. 9: Average Resilient Modulus values

Steel slag showed an increase in resilient modulus.

Bar chart for average resilient modulus of mill scale mixes is displayed below.

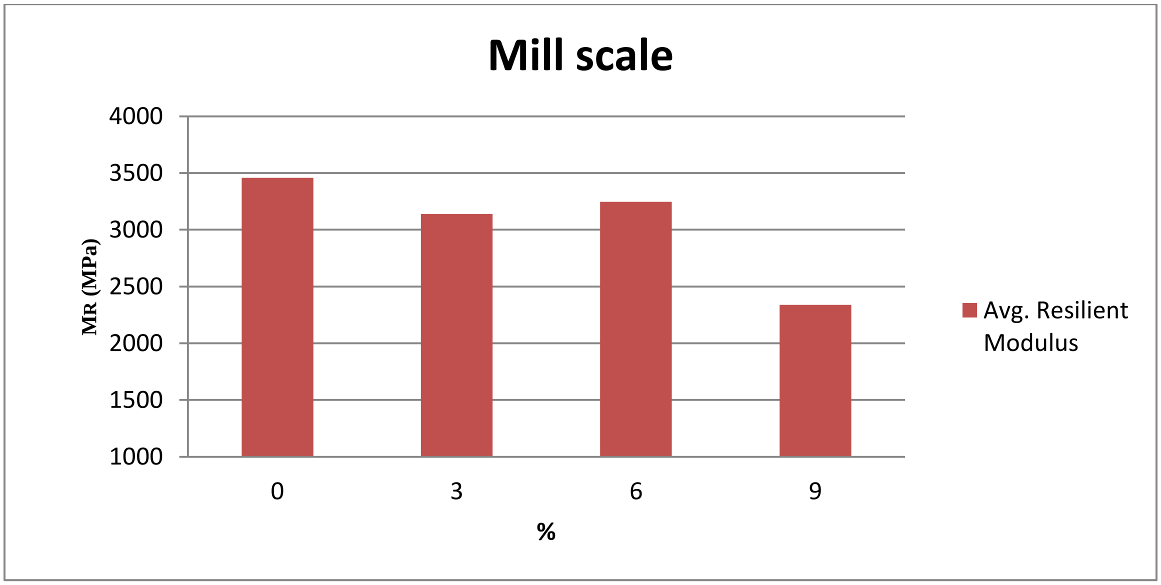


Figure 4. 10: Average Resilient Modulus values

The resilient modulus of mill scale is less than that of steel slag and control mix. Resilient modulus gradually increases with steel slag percentages. Replacement with 15% slag results in a 10.47% increase in MR as compared to the control sample

4.4 SUMMARY

In this chapter the detailed analysis of the results obtained after laboratory testing has been discussed. The results obtained from UTM are discussed about ITS values, TSRs and resilient modulus. The data analysis carried out was presented in the form of tables, bar charts, and graphs. The results of ITS tests for controlled specimens and specimens containing different percentages of IF steel slag and mill scale were presented in the form of bar charts. A comparison of results for these materials while increasing their percentages, is done and discussed in detail, which shows that steel slag has a greater resilient modulus as compared to the controlled specimens while with the mill scale replacement the value of resilient modulus comparatively decreased. ITS values for steel slag increase with the increasing percentage of steel slag whereas 3% mill scale showed almost the same result as the control sample, 6% mill scale showed better results than 3% mill scale and while ITS results of 9% mill scale both conditioned and unconditioned, were lower than that of control samples as well as all other samples. Resilient modulus gradually and slightly decreased with the addition of mill scale, as compared to control samples. From research outcomes, 15% steel slag and 6% mill scale are displaying optimum results. Steel slag is displaying an increase in tensile strength and resilient modulus, so further research should be carried out at higher percentages of steel slag.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 SUMMARY

This research aimed to study characteristics of asphalt mixtures containing steel slag and mill scale produced locally, by using performance tests i.e. finding resilient modulus and moisture damage using indirect tensile strength. NHA-B gradation was adopted for this study. Limestone aggregate from the margalla quarry was used as a conventional aggregate. Induction furnace slag and mill scale were obtained from Pak Iron steel mill Islamabad, bitumen grade 60/70 was of PARCO. Samples with 4 in diameter were prepared through Marshall mix design and compacted using marshal compactor. Marshal mix design was carried out for medium traffic volume. Indirect tensile strength was performed at temperature 25 C. Resilient modulus test was also carried out at 25 C, Poisson ratio was assumed as 0.4. the number of load pulses was 100, load duration was 100ms. After conditioning, 5 pulses were applied for obtaining resilient modulus and the average value is calculated by the UTM machine.

5.1 CONCLUSIONS

The compatibility of using industrial waste such as steel slag and mill scale as an aggregate was checked by performance tests and the results showed that they can be incorporated into HMA mixes. The results are quite satisfactory and according to this research low percentages of both materials can be incorporated in HMA. And this research can be further carried on by incorporating relatively high steel slag percentages. All the mixes have passed the TSR test with relation to the minimum specified limit. Resilient modulus results are also satisfactory.

The key findings and conclusions of results are established as follows:

5.1.1 Conclusions about using Steel slag

1. The same asphalt aggregate ratio for steel slag asphalt mix and conventional aggregate asphalt mix shows nearly comparable moisture susceptibility and better resilient modulus value up to 15% replacement, so it can be deducted that asphalt mixes using induction furnace steel slag can work as good as asphalt mixes incorporating conventional aggregate without further asphalt addition for low percentage replacement, and the cost of more binder can be reduced, so this has an economic benefit.
2. By incorporating steel slag indirect tensile strength of mixes increased. There is a slight reduction in Tensile Strength Ratio, but of no threat as its way above the minimum limit established by standard. This slight reduction may be the result of the occurrence of free lime (CaO) present in steel slag that may be interacting with water.
3. The resilient modulus of mixes increases with the replacement of conventional aggregate with different percentages of steel slag. It increased with increasing percentages. 15% of steel slag showed better tensile strength and resilient modulus. Therefore 15% of steel slag is expressing optimum results. Angular shape, good structure, high specific gravity, and other properties of steel slag can be attributed to higher tensile strength and resilient modulus values.
4. Overall, the results of the experiments showed an enhanced performance of asphalt mixtures with the use of steel slag.

5.1.2 Conclusions about using Mill scale

1. Mill scale exhibited quite satisfactory results but is slightly less compatible when compared with steel slag especially as far as conditioned indirect tensile strength and resilient modulus are concerned.
2. Tensile strength and resilient modulus slightly increased at 6% but then reduced at 9% mill scale. Comparatively 3% and 6% mill scale displayed good results. 9% mill scale displayed a reduction in the Tensile strength ratio as ITS (wet) reduced significantly and resilient modulus was also relatively less. 3% and 6% mill scale behaved almost similar to that of mixes with conventional aggregate in tensile strength and TSR.

3. Resilient modulus values were a bit less than that of the control mix. 6% mill scale replacement showed optimum results in tensile strength and resilient modulus test out of the three percentages used.
4. Mill scale has high density but it is flaky in shape and has a slightly smooth surface this can be the factor for reduction in resilient modulus as it is the ratio of dynamic stress to strain. Samples with mill scale are showing slightly more horizontal deformation hence resulting in low resilient modulus than steel slag. But still, the results are satisfactory.
5. The performance of mill scale is satisfactory hence; it can be incorporated as fine aggregate in HMA and further research exploring other performance parameters needs to be carried out.

5.2 RECOMMENDATIONS

Based on the results of the research the recommendations are as follows

1. Additives, rejuvenating agents and anti-stripping agents with steel slag and mill scale can be studied in combination with induction heating and induction healing techniques to develop a synergy between these techniques.
2. In future studies, proper economic cost-benefit analysis of using the induction furnace steel slag and mill scale can be researched, comparative analysis of the chemical composition, mineralogical composition and mechanical properties of indigenous IF slags from different steel mills can be carried out. And even locally produced induction furnace slag, electric arc furnace, and blast furnace slag can be compared to find feasibility for use in wearing course of bituminous pavements.
3. As steel slag is displaying better results on percentages up to 15% so high percentages of IF slag as aggregate can be investigated and steel slag in a combination with other waste materials can be used. Some of these materials are china clay wastes, demolition wastes (concrete, masonry materials), slate waste, and crushed brick, etc. And other gradations like NHA-A, SP-2, MS-2 along with these waste products, can be investigated.
4. Steel slag and mill scale have good induction heating, according to research done in the past. Therefore in colder areas having high altitudes where ice freezes on road pavements and airport runways, induction heating process can be carried out for melting ice, research

should be carried out on this aspect while simulating the cold climatic conditions of Pakistan. Resilient modulus of mixes incorporating steel slag and mill scales at lower temperatures i.e. 0 C or 5 C can be carried out while incorporating lower penetration grade bitumen. Other performance tests can be carried out to fully assess the behavior of the utilization of these industrial wastes.

5. Further research on different factors and variable parameters of a resilient modulus test can be carried out at different levels to assess the variation in the resilient modulus values of laboratory compacted specimens with steel slag and mill scale. The resilient modulus test was performed following ASTM D4123 standard in which two LVDTs located 180 degrees apart, were used to measure horizontal deformation. Poisson ratio was assumed to be 0.4 as it could not be calculated because deformation was taken in one direction, thus recommendation is for using ASTM 7369 standard for performing resilient modulus test with measurement of both horizontal and vertical deformations.
6. HMA containing these materials met the criteria for adequate resistance to moisture and displayed good stiffness under dynamic loading as simulated by the resilient modulus test, so the trial sections can be laid in on-going projects in Pakistan after carrying out the other performance tests.

REFERENCES

Ahmad, S. I., & Rahman, S. (2018). *Mechanical and Durability Properties of Induction-Furnace-Slag-Incorporated Recycled*. *2018*.

Ahmed, I. (n.d.). *Use of Waste Materials in Highway Construction : State of the Practice and Evaluation of the Selected Waste Products*.

Ahmed, M. L., Javed, M. A., & Qureshi, A. S. (2018). Benefits of Incorporating Induction Furnace Slag in Concrete as Replacement of Cement: A Case Study of Pakistan. *Mehran University Research Journal of Engineering and Technology*, *37*(4), 701–714. https://doi.org/10.22581/muet1982.1804.20

Ahmedzade, P., & Sengoz, B. (2009). Evaluation of steel slag coarse aggregate in hot mix asphalt concrete. *Journal of Hazardous Materials*, *165*(1–3), 300–305. https://doi.org/10.1016/j.jhazmat.2008.09.105

Akhinesh, K., Francis, J. G., Junaid, K. T., Jishnulal, K., Joseph, J. N., & Neelancherry, R. (2016). *Study of the Compressive Strength of Concrete with Various Proportions of Steel Mill Scale as Fine Aggregate Study of the Compressive Strength of Concrete with Various Proportions of Steel Mill Scale as Fine Aggregate*. *April*, 104–109.

Ameri, M., Hesami, S., & Goli, H. (2013). Laboratory evaluation of warm mix asphalt mixtures containing electric arc furnace (EAF) steel slag. *Construction and Building Materials*, *49*, 611–617. https://doi.org/10.1016/j.conbuildmat.2013.08.034

Andrews, A., Gikunoo, E., Ofosu-Mensah, L., Tofah, H., & Bansah, S. (2012). Chemical and Mineralogical Characterization of Ghanaian Foundry Slags. *Journal of Minerals and Materials Characterization and Engineering*, *11*(02), 183–192. https://doi.org/10.4236/jmmce.2012.112015

Arabani, M., & Azarhoosh, A. R. (2012). The effect of recycled concrete aggregate and steel slag on the dynamic properties of asphalt mixtures. *Construction and Building Materials*, *35*, 1–7. https://doi.org/10.1016/j.conbuildmat.2012.02.036

Asi, I. M., Qasrawi, H. Y., & Shalabi, F. I. (2007). Use of steel slag aggregate in asphalt concrete mixes. *Canadian Journal of Civil Engineering*, *34*(8), 902–911. https://doi.org/10.1139/L07-025

Baghel, R., Pandel, U., & Vashistha, A. (2020). Manufacturing of sustainable bricks: Utilization of mill scale and marble slurry. *Materials Today: Proceedings*, *26*(xxxx), 2136–2139. https://doi.org/10.1016/j.matpr.2020.02.460

Baldi-Sevilla, A., Aguiar-Moya, J. P., Vargas-Nordcbeck, A., & Loria-Salazar, L. (2017). Effect of aggregate–bitumen compatibility on moisture susceptibility of asphalt mixtures. *Road Materials and Pavement Design*, *18*, 318–328. https://doi.org/10.1080/14680629.2017.1304248

Barišić, I., Dimter, S., & Netinger, I. (2010). Possibilities of application of slag in road construction. *Tehnicki Vjesnik*, *17*(4), 523–528.

Bausano, J., & Williams, R. C. (2009). Transitioning from AASHTO T283 to the Simple Performance Test Using Moisture Conditioning. *Journal of Materials in Civil Engineering*, *21*(2), 73–82. https://doi.org/10.1061/(ASCE)0899-1561(2009)21:2(73)

Behnood, A., & Ameri, M. (2012). Experimental investigation of stone matrix asphalt mixtures containing steel slag. *Scientia Iranica*, *19*(5), 1214–1219. https://doi.org/10.1016/j.scient.2012.07.007

Boulbibane, M. (n.d.). EFFECT OF ASPHALT MIXTURE COMPACTION ON STABILITY AND VOLUMETRIC PROPERTIES OF ACW14. *(5)2*(2), 285–299.

Caro, S., Masad, E., Bhasin, A., & Little, D. N. (2008). Moisture susceptibility of asphalt mixtures, Part 1: Mechanisms. *International Journal of Pavement Engineering*, *9*(2), 81–98. https://doi.org/10.1080/10298430701792128

FACT SHEET Steel industry co-products. (2018).

Farrand, B., & Emery, J. (1995). Recent improvements in quality of steel slag aggregate. *Transportation Research Record*, *1486*, 137–141.

Gandhewar, V. R., Bansod, S. V., & Borade, A. B. (2011). Induction furnace - A review. *International Journal of Engineering and Technology*, *3*(4), 277–284.

Grenfell, J., Apeagyei, A., & Airey, G. (2015). Moisture damage assessment using surface energy, bitumen stripping and the SATS moisture conditioning procedure. *International Journal of Pavement Engineering*, *16*(5), 411–431. https://doi.org/10.1080/10298436.2015.1007235

Hainin, M. R., Yusoff, N. I. M., Mohammad Sabri, M. F., Abdul Aziz, M. A., Sahul Hameed, M. A., & Farooq Reshi, W. (2012). Steel Slag as an Aggregate Replacement in Malaysian Hot

Mix Asphalt. *ISRN Civil Engineering*, *2012*, 1–5. https://doi.org/10.5402/2012/459016

Hamzah, M. O., Kakar, M. R., & Hainin, M. R. (2015). An Overview of Moisture Damage in Asphalt Mixtures. *Jurnal Teknologi*, *73*(4). https://www.academia.edu/21147122/An_Overview_of_Moisture_Damage_in_Asphalt_Mixtures

Huang, B., Shu, X., Dong, Q., & Shen, J. (2010). Laboratory evaluation of moisture susceptibility of hot-mix asphalt containing cementitious fillers. *Journal of Materials in Civil Engineering*, *22*(7), 667–673. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000064

Hussain, M. S., Mehtab, F., & Nawaz, A. (n.d.). *Use of Steel Mill Slag in Concrete as Fine Aggregates*. 1–6.

John, A., & John, E. (2013). *Open Access Study on the partial replacement of fine aggregate using induction furnace slag Recent Advances in Structural Engineering , RASE2013*. 1–5.

Joseph, W., & Sridhar, R. (2020). Effect of silica fume and induction furnace slag in the compaction and strength characteristics of black cotton soil. *IOP Conference Series: Materials Science and Engineering*, *872*(1). https://doi.org/10.1088/1757-899X/872/1/012114

Kakar, M. R., Hamzah, M. O., Akhtar, M. N., & Woodward, D. (2016). Surface free energy and moisture susceptibility evaluation of asphalt binders modified with surfactant-based chemical additive. *Journal of Cleaner Production*, *112*(4), 2342–2353. https://doi.org/10.1016/j.jclepro.2015.10.101

Kandhal, P. S., & Hoffman, G. L. (1997). Evaluation of steel slag fine aggregate in hot-mix asphalt mixtures. *Transportation Research Record*, *1583*, 28–36. https://doi.org/10.3141/1583-04

Liu, Q., Li, B., Schlangen, E., Sun, Y., & Wu, S. (2017). Research on the mechanical, thermal, induction heating and healing properties of steel slag/steel fibers composite asphalt mixture. *Applied Sciences (Switzerland)*, *7*(10). https://doi.org/10.3390/app7101088

Lu, Q., & Harvey, J. T. (2005). *(PDF) Investigation of Conditions for Moisture Damage in Asphalt Concrete and Appropriate Laboratory Test Methods*. https://www.researchgate.net/publication/46439820_Investigation_of_Conditions_for_Moisture_Damage_in_Asphalt_Concrete_and_Appropriate_Laboratory_Test_Methods

M V Deshmukh, N. R. V. (2015). Analysis of Induction Furnace Slag of Ferrous Foundry.

International Journal for Scientific Research & Development, *2*(11), 590–593. http://www.ijsrd.com/articles/IJSRDV2I11284.pdf

Maharaj, C., White, D., Maharaj, R., & Morin, C. (2017). Re-use of steel slag as an aggregate to asphaltic road pavement surface. *Cogent Engineering*, *4*(1), 1–12. https://doi.org/10.1080/23311916.2017.1416889

Martin, A. E., Arambula, E., Yin, F., Cucalon, L. G., Chowdhury, A., Lytton, R., Epps, J., Estakhri, C., & Park, E. S. (2014). Evaluation of the Moisture Susceptibility of WMA Technologies. In *Evaluation of the Moisture Susceptibility of WMA Technologies*. Transportation Research Board. https://doi.org/10.17226/22429

Mohammed, T. U., Rahman, M. N., Mahmood, A. H., Hasan, T., & Apurbo, S. M. (2016). Utilization of steel slag in concrete as coarse aggregate. *Sustainable Construction Materials and Technologies*, *2016-Augus*(August). https://doi.org/10.13140/RG.2.1.3804.4404

Montedo, O. R. K., Alves, I. T., Faller, C. A., Bertan, F. M., Piva, D. H., & Piva, R. H. (2015). Evaluation of electrical properties of glass-ceramics obtained from mill scale. *Materials Research Bulletin*, *72*, 90–97. https://doi.org/10.1016/j.materresbull.2015.07.040

Moraes, R., Velasquez, R., & Bahia, H. U. (2011). Measuring the Effect of Moisture on Asphalt–Aggregate Bond with the Bitumen Bond Strength Test. *Transportation Research Record: Journal of the Transportation Research Board*, *2209*(1), 70–81. https://doi.org/10.3141/2209-09

Motz, H., & Geiseler, J. (2000). Products of steel slags an opportunity to save natural resources. *Waste Management Series*, *1*(C), 207–220. https://doi.org/10.1016/S0713-2743(00)80033-1

Murthy, Y. I. (2012). Stabilization of Expansive Soil Using Mill Scale. *International Journal of Engineering Science and Technology*, *4*(02), 629–632.

Nguyen, H. Q., Lu, D. X., & Le, S. D. (2018). Investigation of using steel slag in hot mix asphalt for the surface course of flexible pavements. *IOP Conference Series: Earth and Environmental Science*, *143*(1). https://doi.org/10.1088/1755-1315/143/1/012022

Noureldin, A., & RS McDaniel -. (1990). Evaluation of surface mixtures of steel slag and asphalt. *Transportation Research Record*, *1269*. https://trid.trb.org/view/348923

Oluwasola, E. A., Hainin, M. R., & Aziz, M. M. A. (2015). Evaluation of asphalt mixtures incorporating electric arc furnace steel slag and copper mine tailings for road construction. *Transportation Geotechnics*, *2*, 47–55. https://doi.org/10.1016/j.trgeo.2014.09.004

On the Advantage and Disadvantage of Electric Arc Furnace and Induction Furnace. (n.d.). Retrieved August 10, 2020, from https://www.linkedin.com/pulse/advantage-disadvantage-electric-arc-furnace-induction-kerri-zhang

Pasetto, M., & Baldo, N. (2011). Mix design and performance analysis of asphalt concretes with electric arc furnace slag. *Construction and Building Materials*, *25*(8), 3458–3468. https://doi.org/10.1016/j.conbuildmat.2011.03.037

Proctor, D. M., Fehling, K. A., Shay, E. C., Wittenborn, J. L., Green, J. J., Avent, C., Bigham, R. D., Connolly, M., Lee, B., Shepker, T. O., & Zak, M. A. (2000). Physical and chemical characteristics of blast furnace, basic oxygen furnace, and electric arc furnace steel industry slags. *Environmental Science and Technology*, *34*(8), 1576–1582. https://doi.org/10.1021/es9906002

Qurishee, M. A., Iqbal, I. T., Islam, M. S., & Islam, M. M. (2017). *Use of Slag As Coarse Aggregate and Its Effect on Mechanical Properties of Concrete*. *December 2016*, 1–7.

Rezaul, R. M., Atahar, R., Tasnim, T. Bin, & Kurny, A. S. W. (2017). *Comparison of Mechanical Properties of Induction Furnace Steel Slag and Electric Arc Furnace Steel Slag as a Replacement of Coarse Aggregate in Construction Materials*. *2017*(December), 28–30.

Saha, U., Hossain, M. A., & Gulshan, F. (2019). Making Non-fired Brick Using Locally Produced Induction Furnace Steel Slag. *5th International Conference on Computer, Communication, Chemical, Materials and Electronic Engineering, IC4ME2 2019*, 1–4. https://doi.org/10.1109/IC4ME247184.2019.9036557

Salifu, A., Berthelot, C., Marjerison, B., & Anthony, A. (2009). Compaction sensitivity of saskatchewan SPS-9A asphalt mixes. *TAC/ATC 2009 - 2009 Annual Conference and Exhibition of the Transportation Association of Canada: Transportation in a Climate of Change*.

Shahid, K. (2019). *Effect of Binder Content on Volumetric Properties of Asphalt Mix*. *5*(1).

Shrum, E. D. (2010). *Evaluation of Moisture Damage in Warm Mix Asphalt Containing Recycled Asphalt Pavement*.

Subramaniam, s. A. (2006). *Evaluation of the compactive effort on the stripping characteristic of hot mix asphalt (hma) mixtures*. *May*.

Tiwari, M., Bajpai, D. S., & Dewangan, D. U. (2016). Steel Slag Utilization — Overview in Indian Perspective. *International Journal of Advanced Research*, *4*(8), 2232–2246.

https://doi.org/10.21474/ijar01/1442

U. Bagampadde, 1 H. I. Al-Abdul Wahhab, 2 and S. A. Aiban. (1999). *Optimization of Steel Slag Aggregates for Bituminous Mixes in Saudi Arabia*. 30–35.

Varveri, A., Avgerinopoulos, S., & Scarpas, A. (2015). Experimental evaluation of long- and short-term moisture damage characteristics of asphalt mixtures. *Road Materials and Pavement Design*, *17*(1), 168–186. https://doi.org/10.1080/14680629.2015.1066705

Wu, S., Xue, Y., Ye, Q., & Chen, Y. (2007). Utilization of steel slag as aggregates for stone mastic asphalt (SMA) mixtures. *Building and Environment*, *42*(7), 2580–2585. https://doi.org/10.1016/j.buildenv.2006.06.008

Xu, H., Wu, S., Li, H., Zhao, Y., & Lv, Y. (2020). Study on recycling of steel slags used as coarse and fine aggregates in induction healing asphalt concretes. *Materials*, *13*(4). https://doi.org/10.3390/ma13040889

Xue, Y., Wu, S., Hou, H., & Zha, J. (2006). Experimental investigation of basic oxygen furnace slag used as aggregate in asphalt mixture. *Journal of Hazardous Materials*, *138*(2), 261–268. https://doi.org/10.1016/j.jhazmat.2006.02.073

Yoder, E. J., & Witczak, M. W. (1975). Principles of Pavement Design. In *Principles of Pavement Design*. John Wiley & Sons, Inc. https://doi.org/10.1002/9780470172919

Zuno-Silva, J., Bedolla-Jacuinde, A., Martínez-Vázquez, J., Pérez-Perez, A., Quintero-Azuara, T., Rosas Guanajuato, J., & La Salle Bajío Zuno-Silva, D. (2013). *Laboratory scale study of uncommon degradation SiO2 refractories used on induction furnaces*. https://repository.uaeh.edu.mx/bitstream/handle/123456789/15332

(12) United States Patent. (2004). *1*(12).

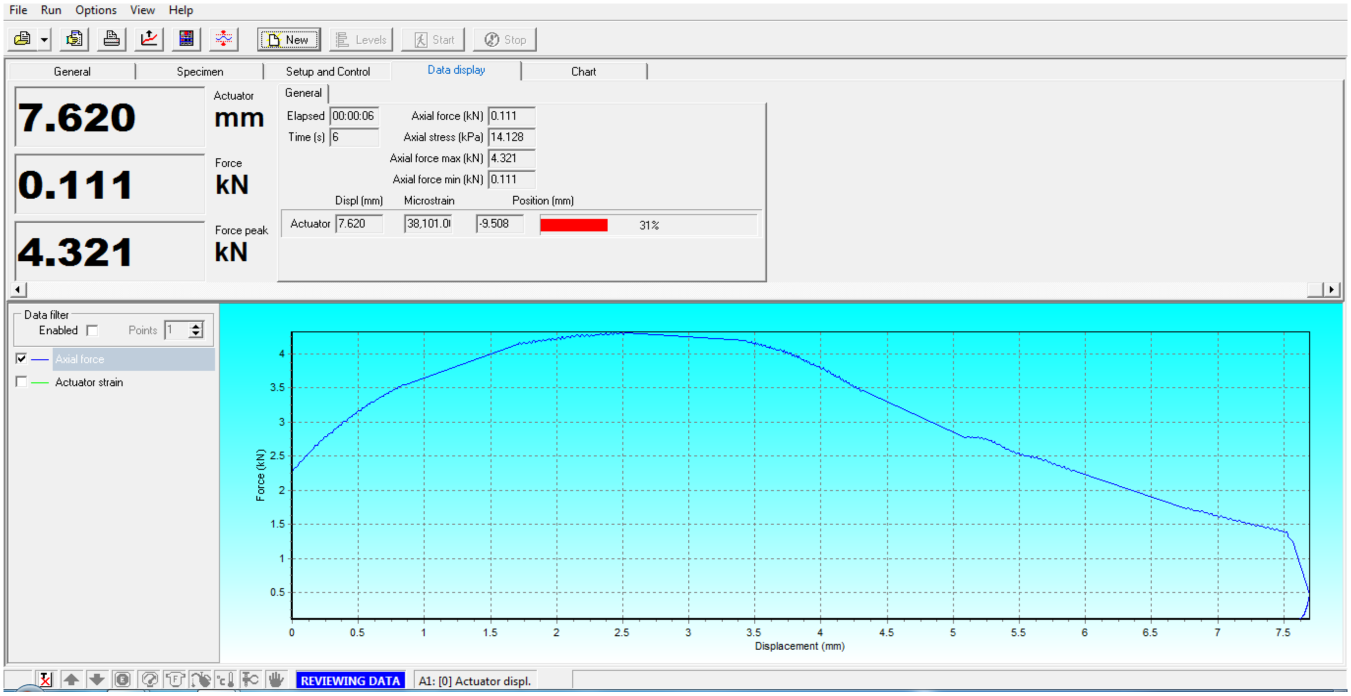
http://www.pakalumni.com/profiles/blogs/pakistan-is-the-world-s-fastest-growing-steel-producer

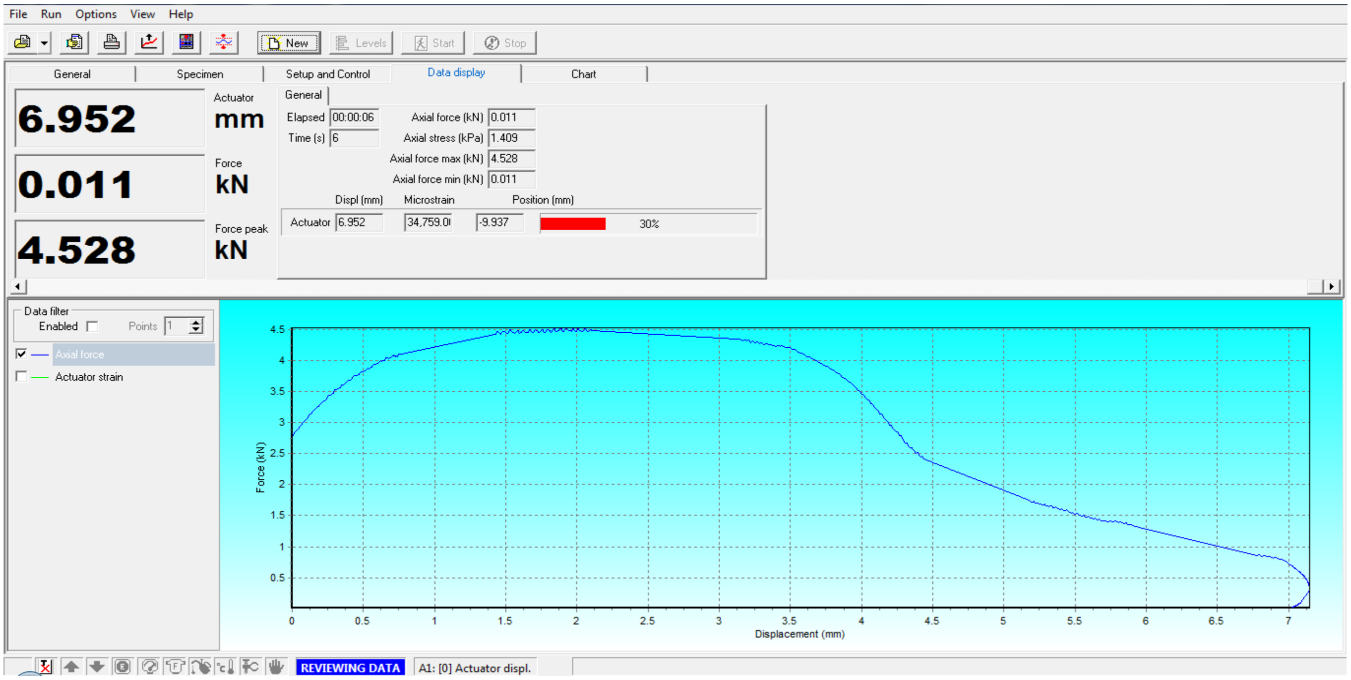
Rojer Hosting (1992). "Road Aggregates and Skidding". FWSO, London, UK

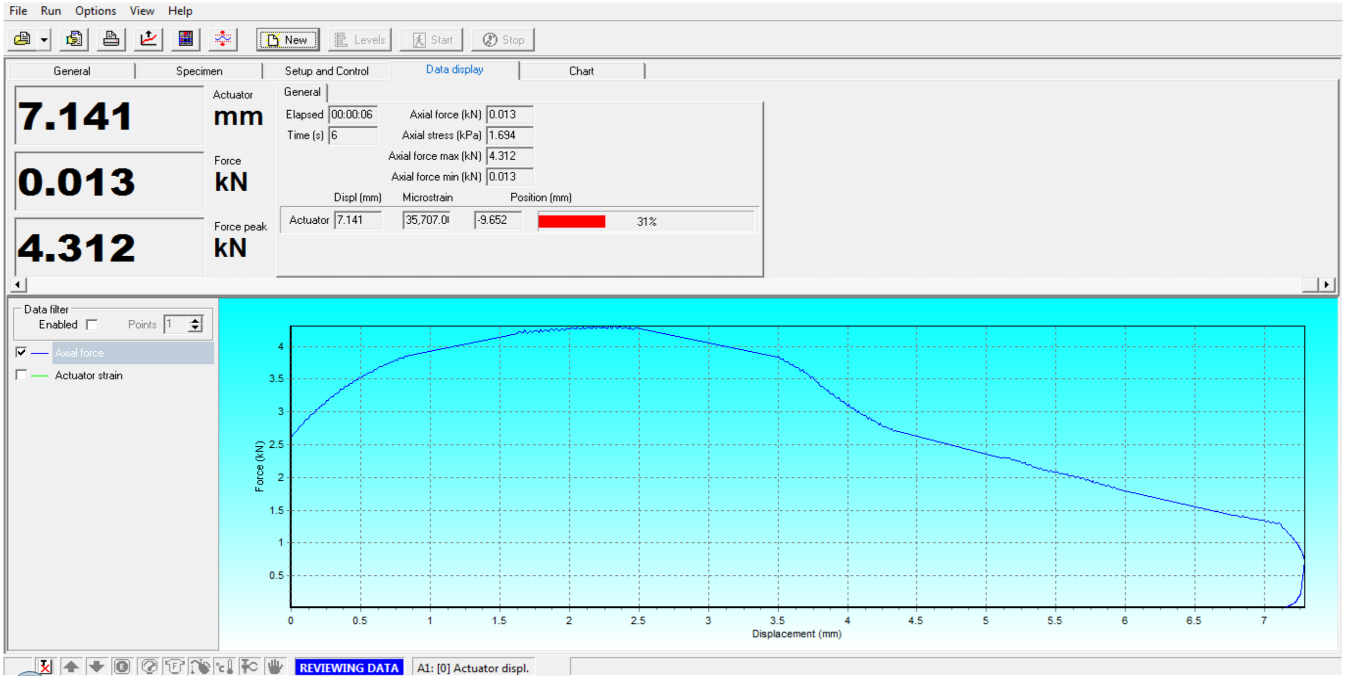
APPENDIX I: MARSHALL MIX DESIGN

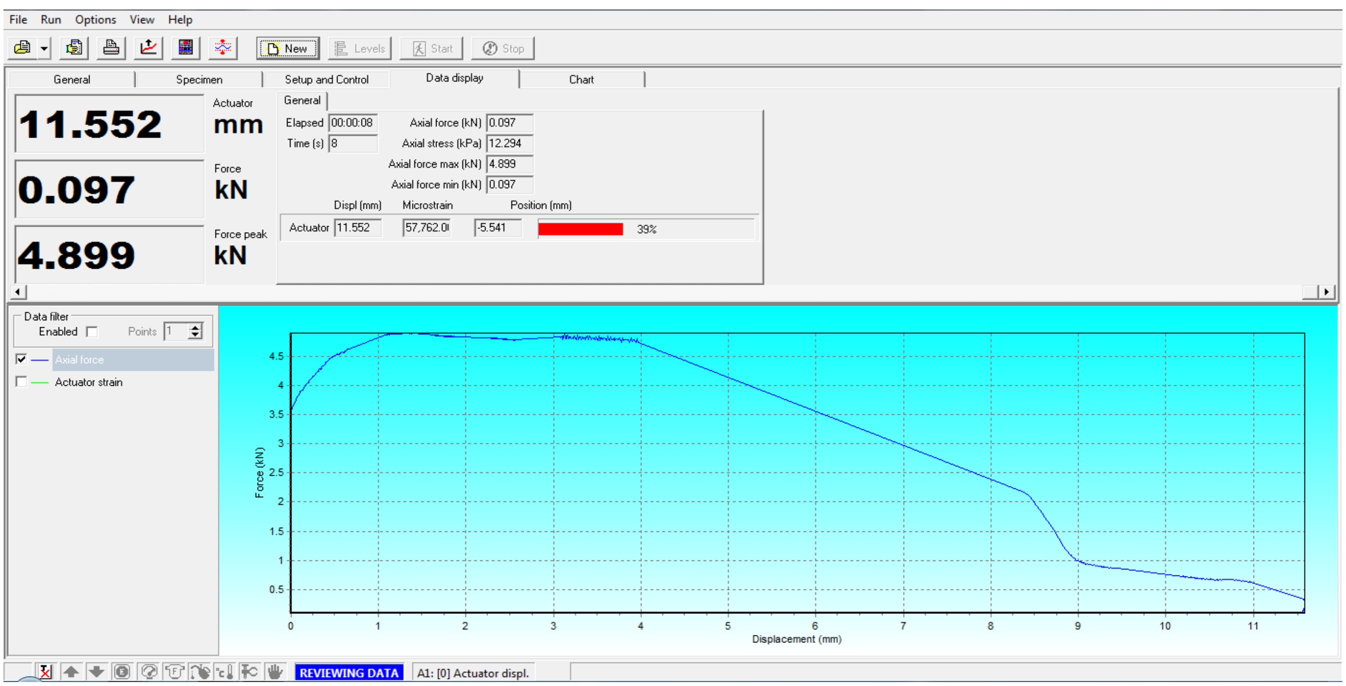
							Saad Rabbani											
			Virgin HMA Marshall				**Bitumen:PARCO 60/70**											
							Aggregate: Margalla											
		Stability Flow				**Gmb**					**Gmm**							
S.No	**Binder %**	**Flow (mm)**	**Stablilty (KN)**	**Stability (Avg)**	**Flow (Avg)**	**a (Wt in Air)**	**b (SSD Wt)**	**c (Submerged Wt)**	**Gmb Values**	**Average Gmb**	**A**	**B**	**sample+water + pycnometer+lid**	**Gmm Values**	**Average Gmm**	**Air Voids (VA)**	**VMA**	**VFA**
1	3.5%	3	10.632	12.127	3.05	1177.3	1196.5	675	2.258	2.255	1174	6340	7035.5	2.4535	2.463	8.41	16.77	49.85
2	3.5%	3.1	13.622			1187.2	1206	679	2.253		1187	6340	7047	2.4729				
1	4.0%	2.5	12.975	13.3	2.83	1136.2	1151.9	655	2.287	2.276	1126.4	6340	7015.5	2.4981	2.452	7.19	16.46	56.32
2	4.0%	3	13.625			1158.4	1177.1	666.8	2.270		1201	6340	7046.5	2.4287				
3	4.0%	3	11.11			1155.3	1172	663.4	2.272		1152.7	6340	7018	2.4283				
1	4.5%	2.5	14.673	13.3545	2.33	1160.5	1176.2	669.8	2.292	2.301	1172.5	6340	7021	2.3856	2.425	5.13	15.98	67.86
2	4.5%	2	12.036			1178.3	1190.2	679.4	2.307		1179	6340	7036	2.4410				
3	4.5%	2.5	10.901			1177.3	1190.9	680	2.304		1183.6	6340	7040	2.4475				
1	5.0%	3.5	11.109	12.0735	3.17	1132.5	1142	649.8	2.301	2.317	1147.5	6340	7011	2.4082	2.413	3.94	15.81	75.05
2	5.0%	3.5	13.038			1202	1208.5	693.5	2.334		1200	6340	7042	2.4096				
3	5.0%	2.5	15.572			1164.1	1173.5	671	2.317		1157	6340	7019	2.4205				
1	5.5%	3.5	13.625	13.3105	3.33	1174.3	1181.9	676.2	2.322	2.322	1172.4	6340	7026	2.4104	2.410	3.66	16.08	77.24
2	5.5%	3.5	12.996			1192.1	1197	683	2.319		1184	6340	7037	2.4312				
3	5.5%	3	14.063			1169.4	1174.4	671.4	2.325		1166.4	6340	7018	2.3882				
1	6.0%	4.5	15.7	14.66	4	1128	1132.4	649	2.333	2.324	1142.6	6340	7005	2.3924	2.397	3.03	16.47	81.58
2	6.0%	3.5	13.62			1189.5	1192.4	678.3	2.314		1186	6340	7032	2.4008				

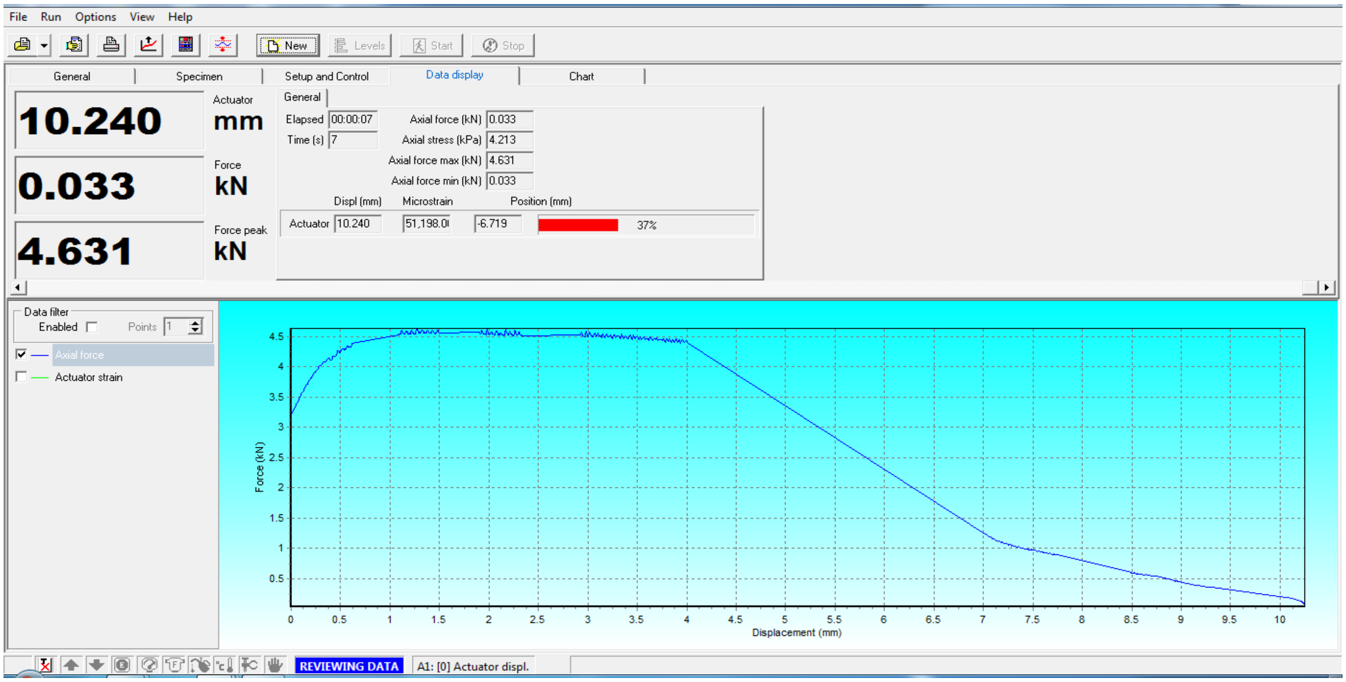
APPENDIX II: ITS TEST RESULT

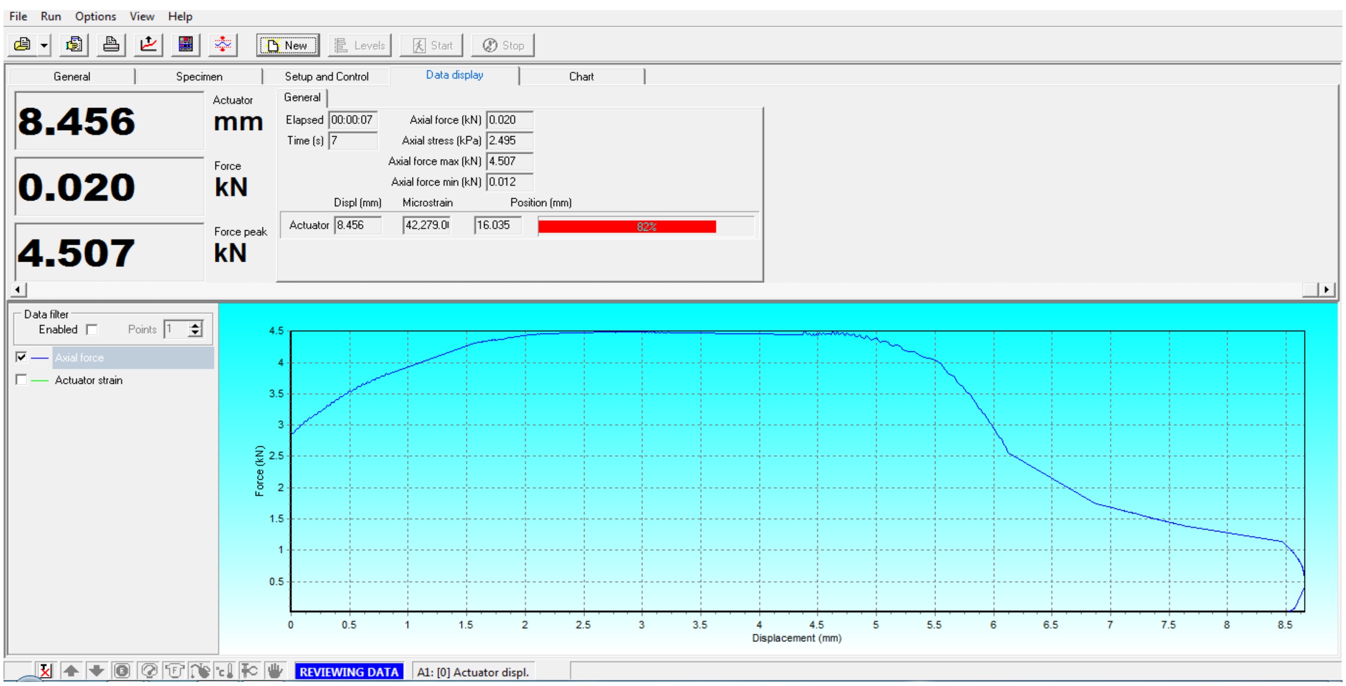


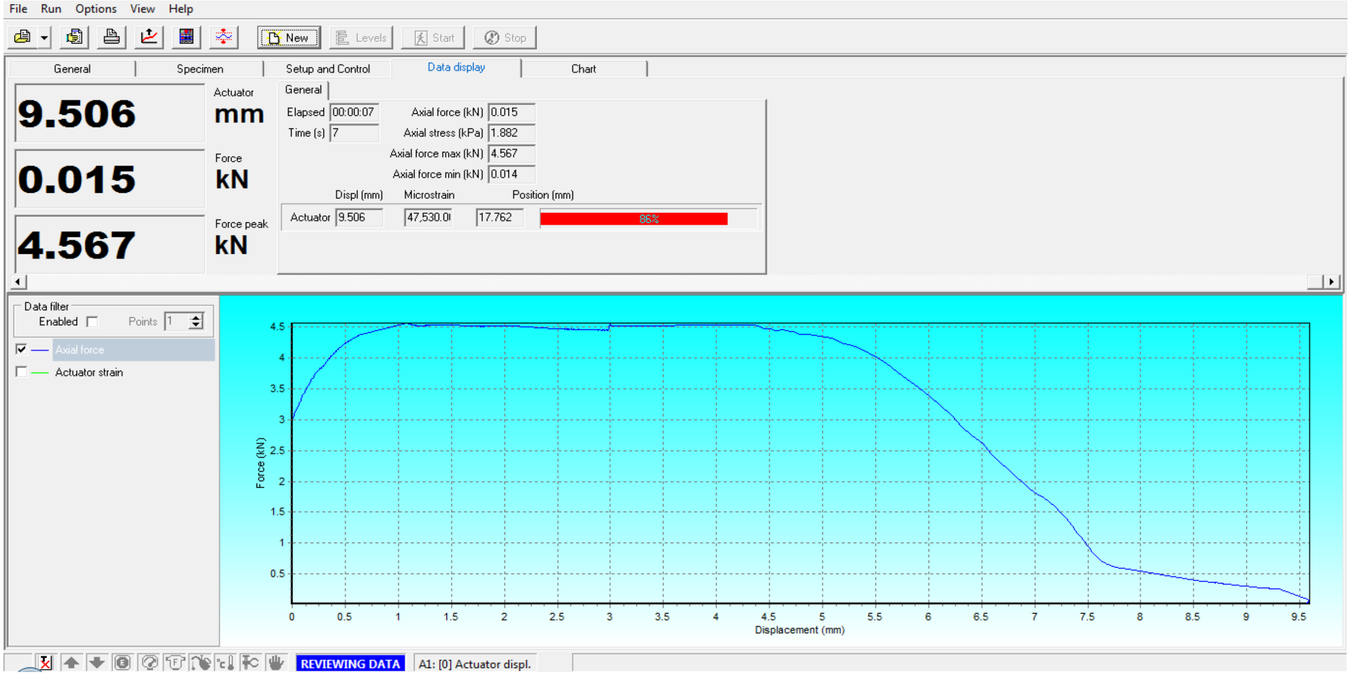



File Run Options View Help
New Levels Start Stop
General Specimen Setup and Control Data display Chart
7.141 Actuator mm
0.013 Force kN
4.312 Force peak kN
General
Elapsed 00:00:06 Axial force (kN) 0.013
Time (s) 6 Axial stress (kPa) 1.694
Axial force max (kN) 4.312
Axial force min (kN) 0.013
Displ (mm) Microstrain Position (mm)
Actuator 7.141 35,707.0 -9.652 31%
Data filter
Enabled Points 1
Axial force
Actuator strain
Force (kN)
Displacement (mm)
REVIEWING DATA
A1: [0] Actuator displ.

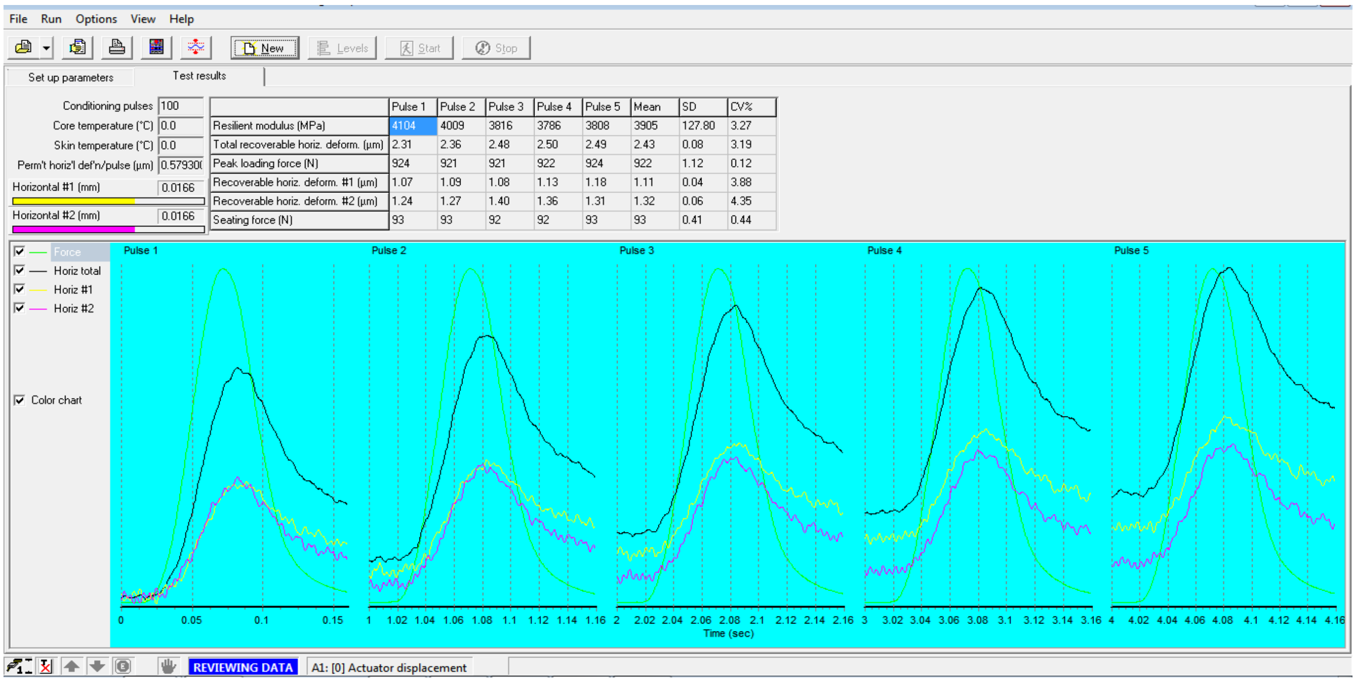

File Run Options View Help
New Levels Start Stop
General Specimen Setup and Control Data display Chart
11.552 Actuator mm
0.097 Force kN
4.899 Force peak kN
General
Elapsed 00:00:08 Axial force (kN) 0.097
Time (s) 8 Axial stress (kPa) 12.294
Axial force max (kN) 4.899
Axial force min (kN) 0.097
Displ (mm) Microstrain Position (mm)
Actuator 11.552 57,762.0 -5.541 39%
Data filter
Enabled Points 1
Axial force
Actuator strain
Force (kN)
Displacement (mm)
REVIEWING DATA
A1: [0] Actuator displ.


File Run Options View Help
New Levels Start Stop
General Specimen Setup and Control Data display Chart
10.240
Actuator
mm
0.033
Force
kN
4.631
Force peak
kN
General
Elapsed 00:00:07
Time (s) 7
Axial force (kN) 0.033
Axial stress (kPa) 4.213
Axial force max (kN) 4.631
Axial force min (kN) 0.033
Displ (mm) Microstrain Position (mm)
Actuator 10.240 51,198.0 -6.719 37%
Data filter
Enabled Points 1
Axial force
Actuator strain
Force (kN)
Displacement (mm)
REVIEWING DATA
A1: [0] Actuator displ.

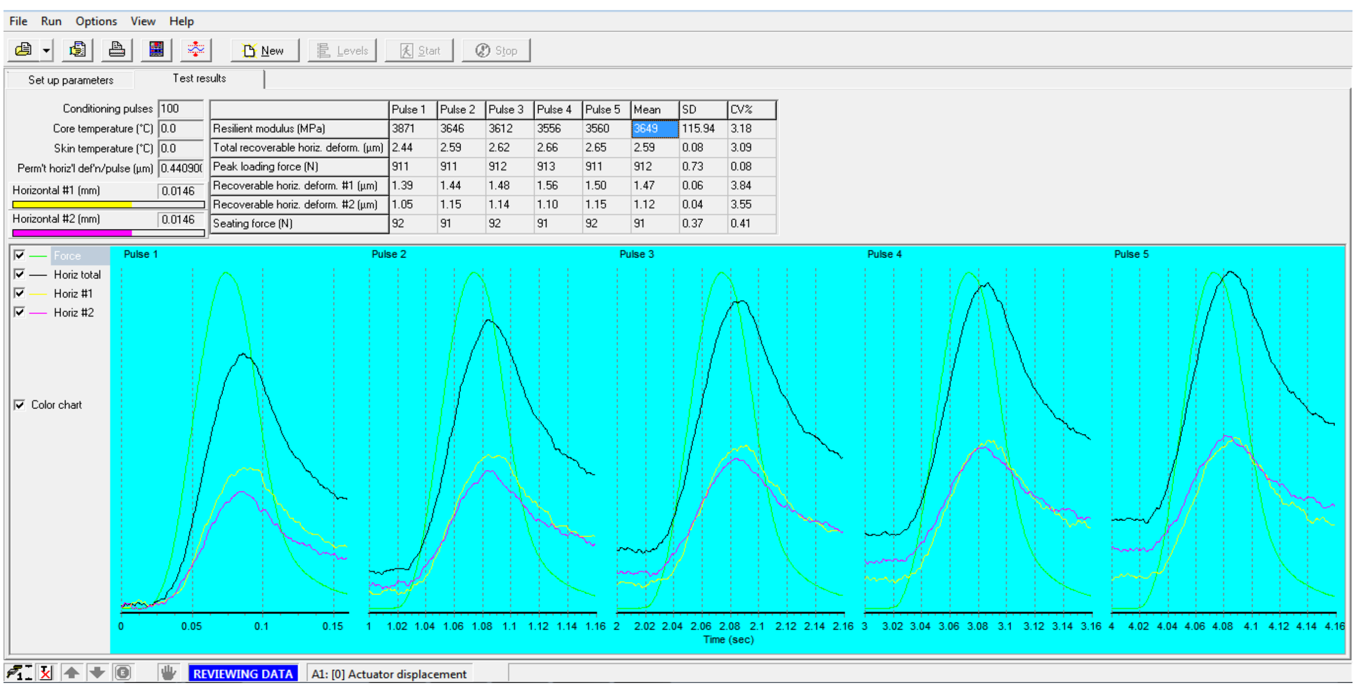

File Run Options View Help
New Levels Start Stop
General Specimen Setup and Control Data display Chart
8.456
Actuator
mm
0.020
Force
kN
4.507
Force peak
kN
General
Elapsed 00:00:07
Time (s) 7
Axial force (kN) 0.020
Axial stress (kPa) 2.495
Axial force max (kN) 4.507
Axial force min (kN) 0.012
Displ (mm) Microstrain Position (mm)
Actuator 8.456 42,279.0 16.035 82%
Data filter
Enabled Points 1
Axial force
Actuator strain
Force (kN)
Displacement (mm)
REVIEWING DATA
A1: [0] Actuator displ.


File Run Options View Help
New Levels Start Stop
General Specimen Setup and Control Data display Chart
9.506
Actuator
mm
0.015
Force
kN
4.567
Force peak
kN
General
Elapsed 00:00:07
Time (s) 7
Axial force (kN) 0.015
Axial stress (kPa) 1.882
Axial force max (kN) 4.567
Axial force min (kN) 0.014
Displ (mm) Microstrain Position (mm)
Actuator 9.506 47,530.0 17.762
Data filter
Enabled
Points 1
Axial force
Actuator strain
Force (kN)
Displacement (mm)
REVIEWING DATA
A1: [0] Actuator displ.

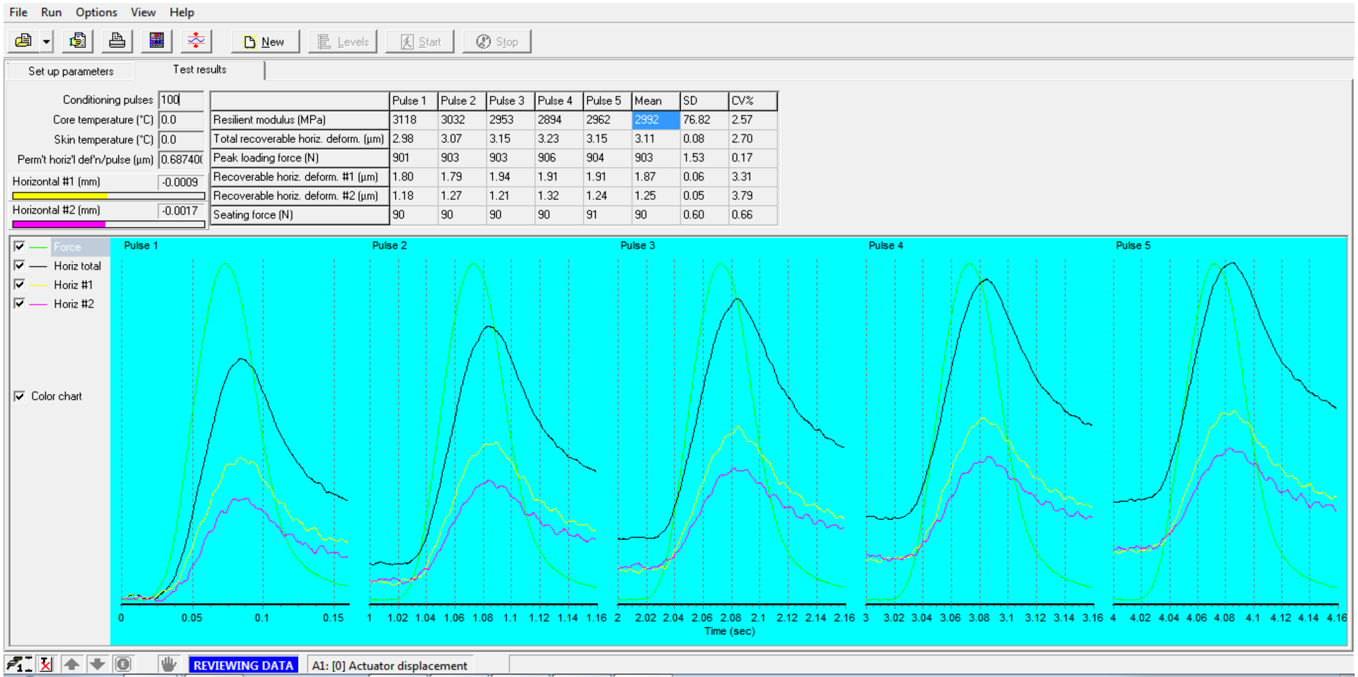
APPENDIX III : RESILIENT MODULUS TEST RESULTS

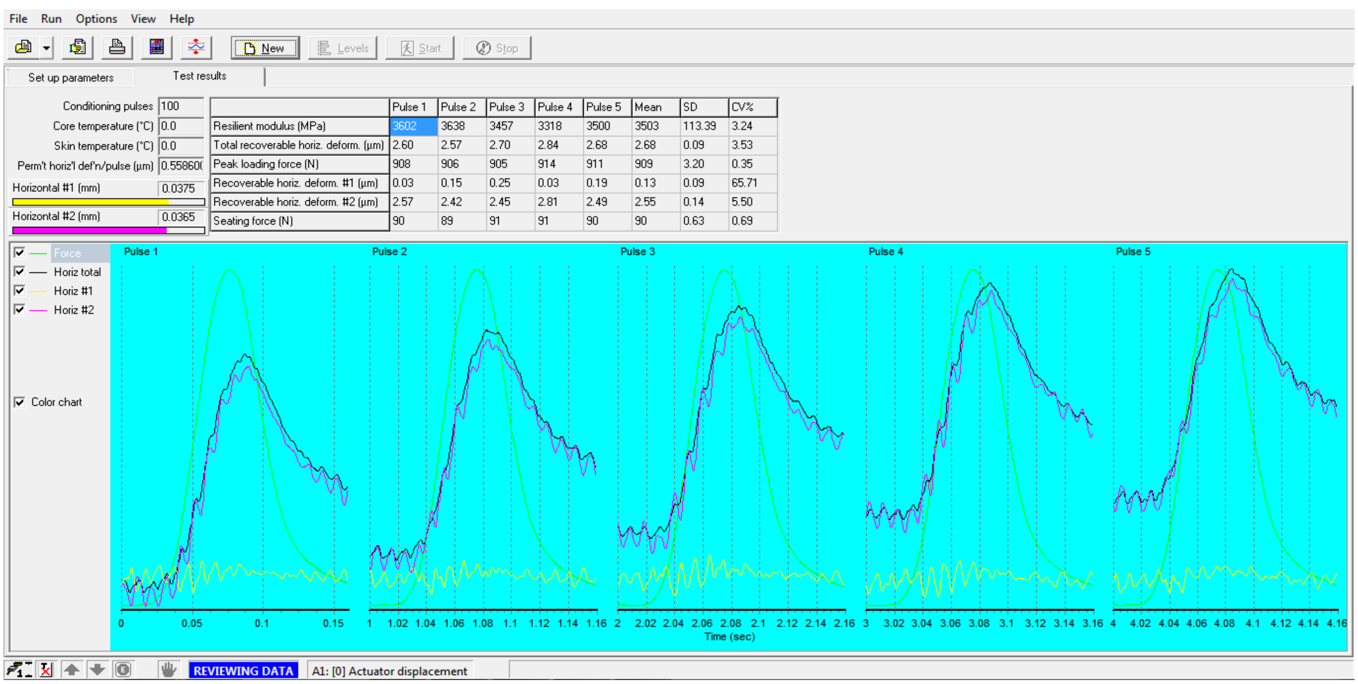


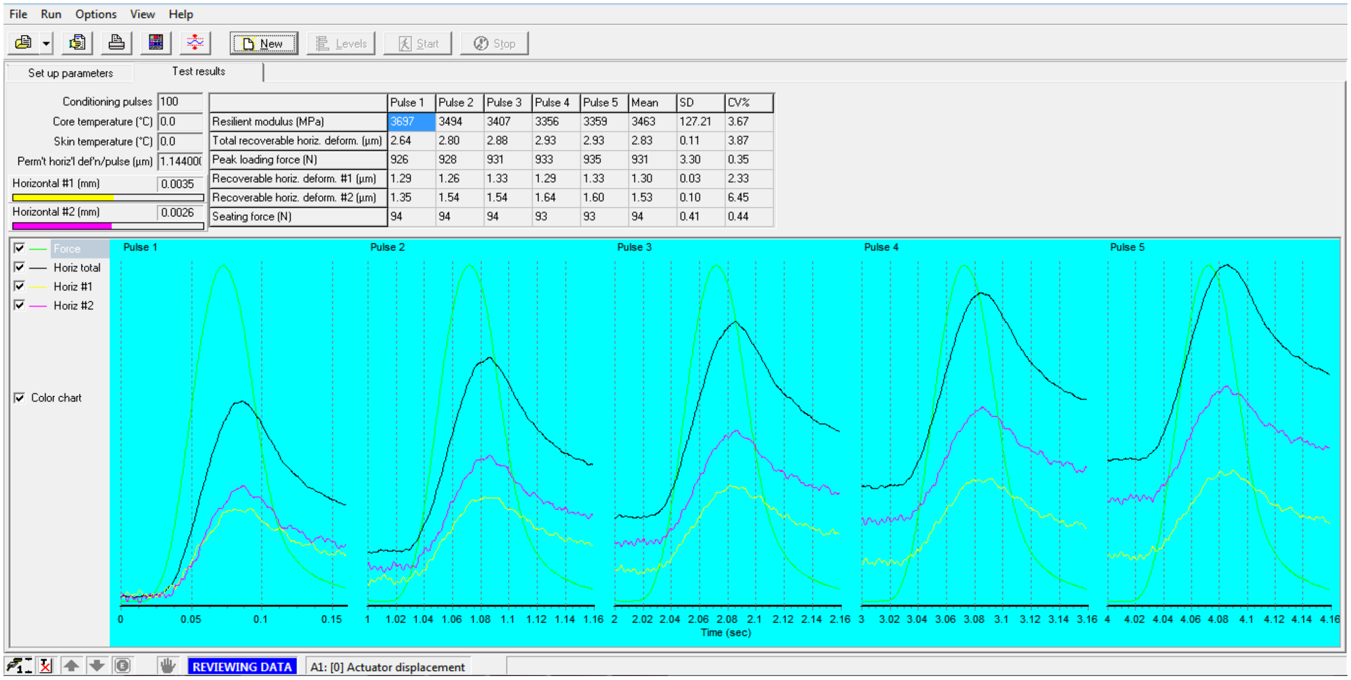
	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	SD	CV%
Resilient modulus (MPa)	4104	4009	3816	3786	3808	3905	127.80	3.27
Total recoverable horiz. deform. (µm)	2.31	2.36	2.48	2.50	2.49	2.43	0.08	3.19
Peak loading force (N)	924	921	921	922	924	922	1.12	0.12
Recoverable horiz. deform. #1 (µm)	1.07	1.09	1.08	1.13	1.18	1.11	0.04	3.88
Recoverable horiz. deform. #2 (µm)	1.24	1.27	1.40	1.36	1.31	1.32	0.06	4.35
Seating force (N)	93	93	92	92	93	93	0.41	0.44



	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	SD	CV%
Resilient modulus (MPa)	3871	3646	3612	3556	3560	3649	115.94	3.18
Total recoverable horiz. deform. (µm)	2.44	2.59	2.62	2.66	2.65	2.59	0.08	3.09
Peak loading force (N)	911	911	912	913	911	912	0.73	0.08
Recoverable horiz. deform. #1 (µm)	1.39	1.44	1.48	1.56	1.50	1.47	0.06	3.84
Recoverable horiz. deform. #2 (µm)	1.05	1.15	1.14	1.10	1.15	1.12	0.04	3.55
Seating force (N)	92	91	92	91	92	91	0.37	0.41


File Run Options View Help
New Levels Start Stop
Set up parameters
Test results
Conditioning pulses 100
Core temperature (°C) 0.0
Skin temperature (°C) 0.0
Perm't horiz'l def'n/pulse (μm) 0.687400
Horizontal #1 (mm) -0.0009
Horizontal #2 (mm) -0.0017
Pulse 1 Pulse 2 Pulse 3 Pulse 4 Pulse 5 Mean SD CV%
Resilient modulus (MPa) 3118 3032 2953 2894 2962 2992 76.82 2.57
Total recoverable horiz. deform. (μm) 2.98 3.07 3.15 3.23 3.15 3.11 0.08 2.70
Peak loading force (N) 901 903 903 906 904 903 1.53 0.17
Recoverable horiz. deform. #1 (μm) 1.80 1.79 1.94 1.91 1.91 1.87 0.06 3.31
Recoverable horiz. deform. #2 (μm) 1.18 1.27 1.21 1.32 1.24 1.25 0.05 3.79
Seating force (N) 90 90 90 90 91 90 0.60 0.66
Force
Horiz total
Horiz #1
Horiz #2
Color chart
Pulse 1
Pulse 2
Pulse 3
Pulse 4
Pulse 5
Time (sec)
REVIEWING DATA
A1: [0] Actuator displacement


File Run Options View Help
New Levels Start Stop
Set up parameters
Test results
Conditioning pulses 100
Core temperature (°C) 0.0
Skin temperature (°C) 0.0
Perm't horiz'l def'n/pulse (μm) 0.558600
Horizontal #1 (mm) 0.0375
Horizontal #2 (mm) 0.0365
Pulse 1 Pulse 2 Pulse 3 Pulse 4 Pulse 5 Mean SD CV%
Resilient modulus (MPa) 3602 3638 3457 3318 3500 3503 113.39 3.24
Total recoverable horiz. deform. (μm) 2.60 2.57 2.70 2.84 2.68 2.68 0.09 3.53
Peak loading force (N) 908 906 905 914 911 909 3.20 0.35
Recoverable horiz. deform. #1 (μm) 0.03 0.15 0.25 0.03 0.19 0.13 0.09 65.71
Recoverable horiz. deform. #2 (μm) 2.57 2.42 2.45 2.81 2.49 2.55 0.14 5.50
Seating force (N) 90 89 91 91 90 90 0.63 0.69
Force
Horiz total
Horiz #1
Horiz #2
Color chart
Pulse 1
Pulse 2
Pulse 3
Pulse 4
Pulse 5
Time (sec)
REVIEWING DATA
A1: [0] Actuator displacement



	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	SD	CV%
Resilient modulus (MPa)	3697	3494	3407	3356	3359	3463	127.21	3.67
Total recoverable horiz. deform. (µm)	2.64	2.80	2.88	2.93	2.93	2.83	0.11	3.87
Peak loading force (N)	926	928	931	933	935	931	3.30	0.35
Recoverable horiz. deform. #1 (µm)	1.29	1.26	1.33	1.29	1.33	1.30	0.03	2.33
Recoverable horiz. deform. #2 (µm)	1.35	1.54	1.54	1.64	1.60	1.53	0.10	6.45
Seating force (N)	94	94	94	93	93	94	0.41	0.44