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CHARACTERIZING A SEMI-FLEXIBLE MIXTURE INCORPORATING MODIFIED CEMENT –EMULSION GROUT

A Thesis Submitted to the Department of Civil Engineering, University of Kerbala in Partial Fulfillment of the Requirements for the Degree of Master of Science in Civil Engineering

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بسم الله الرحمن الرحيم

أقْرَأْ بِاسْمِ رَبِّكَ الَّذِي خَلَقَ ﴿١﴾خَلَقَ الْإِنسَانَ مِنْ عَلَقٍ ﴿٢﴾اقْرَأْ
وَرَبُّكَ الْأَكْرَمُ ﴿٣﴾الَّذِي عَلَّمَ بِالْقَلَمِ ﴿٤﴾عَلَّمَ الْإِنسَانَ مَا لَمْ يَعْلَمْ ﴿٥﴾

صدق الله العلي العظيم

سورة العلق

Dedication

I dedicate this thesis to a precious soul that crossed the world to heaven in peace. To the soul of my grandmother in gratitude for her grace and loyalty to her covenant, to my family and to my friends who supported me during my studies.

Acknowledgment

I thank Almighty Allah for his bounty, as he made it possible for me to complete this work by his grace. Praise be to Almighty Allah first and foremost.

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Abstract

Early distresses such as "rut, cracking, fatigue, etc." are common on traditional asphalt roads as traffic flow and traffic loads increase dramatically. Therefore, extensive research efforts have been conducted to offer pavement mixture alternatives that show better performance than tradition mixtures. Semi-flexible pavement (SFP) with open-graded matrix asphalt mixture, constructed with (25-35) % air voids filled with special cementitious grout materiel, has been proposed as one of the best alternatives, whereas pavement performance under such mixtures shows extended life of roadways. SFP is widely utilized in many countries because of its superior mechanical qualities, high temperature resistance, and great fatigue resistance, It is characterized by the flexibility of asphalt concrete pavement and the rigidity of cement concrete pavement, It reducing early distresses produced by increased traffic flow and traffic loads.

The primary aim of this research is to develop SFP performance by balancing the rigidity and flexibility of the developed mixtures. The developed SFPs were designed from local materials, including an assessment of the contribution of cementitious grout components and their effect on SFP performance. Ordinary Portland cement (OPC), silica fume (SF), emulsion (EM), superplasticizer (SP), and water were used to make the grout mixtures.

Results show that “flow time” decreases with increasing water percentage, while it is increased with an increase in the emulsion percentage. The compressive strength increases with the increase in age, and the highest compressive strength is associate to 40% Water/binder (W/B) ratio. Also, the flexural strength decreases with the increase in the percentage of EM. Furthermore, low density polyethylene polymer was used to prepare the cylindrical and slab samples using an amount equal to 3%under an air voids content of about 32% within the range of allowed values. The cementitious grout mixes were made and applied to the porous asphalt mixture specimens, with cementitious grout materials completely penetrating all of them.

However, indirect tensile strength (ITS), creep compliance test (CCP), wheel track test (WTT), dynamic stability (DS), Cantabro loss test (CLT), skid resistance, and durability tests in terms of water sensitivity (TSR) and ageing were conducted to assess SFP mixtures performance. Results show that the (ITS), for example, increases with the increase age, where optimum mix ingredients can achieve such increment with no EM. Almost similar results were recognized for the tensile examination of the creep compliance test, the dynamic stability, Cantabro loss% and the wheel track test. Inversely, the skid resistance test is associated with the mixture that contains 20% EM, whereas TSR highest value is associated with 60% of EM, reaching up to 88.7%.

Finally, as a main conclusion, using a small amount of emulsion up to 20% with optimum other SFP ingredients plays a vital role in improving the SFP mixture and suggests high performance material in roads construction.

Table of Contents

List of Figures

List of Tables

List of Plates

Abbreviations and Symboles

AASHTO	*American Association of State Highway and Transportation Officials*
ASTM	*American Society for Testing and Materials*
AV	*Air Voids*
BD	*Bulk Density*
BPN	*British Pendulum Number*
BS	*British Standards*
CCT	*Creep Compliance Test*
CLT	*Cantabro Loss Test*
CM	*Control Mixture*
CMF	*Conventional Mineral Filler*
D	*Ductility*
DRT	*Draindown Test*
DS	*Dynamic Stability*
$CC_{(t)}$	*Creep Compliance at time t*
EM	*emulsion*
EP	*Effective Porosity*
Gmb	*Bulk Specific Gravity of Compacted Mixture*
Gmm	*Maximum Theoretical Specific Gravity*
γ_s	*Bulk Density of The Coarse Aggregate Fraction in The Dry-Rodded Condition*
γ_w	*Density of Water*
HL	*Hydrated Lime*
HMA	*Hot Mix Asphalt*
ITS	*Indirect Tensile Strength*
K	*Permeability*
LDPE	*Low Density Polyethylene*
MB	*Modified Binder*
MM	*Modified mixture*
NB	*Neat Binder*
OAC	*Optimum Asphalt Content*

OGFC	*Open Grade Friction Course*
OPC	*Ordinary Portland cement*
PA	*Porous Asphalt*
PAI	*Penetration Aging Index*
Pb	*Percent of Asphalt Content by Total Weight of Mixture*
PCA	*Percent Coarse Aggregate in Total mixture*
Pen.	*Penetration*
PFC	*Permeable Friction Course*
PI	*Penetration Index*
ρ_w	*Water Density*
RD	*Rut Depth*
SPI	*Softening Point Index*
SRT	*Skid Resistance Test*
VFA	*Voids Filled with Asphalt*
VIS	*Viscosity*
VMA	*Voids in Mineral Aggregate*
VT	*Total Volume of The Compacted Sample*
Wdry	*Dry Weight of Compacted Sample*
Wsub	*Submerged Weight of Compacted Sample in Water*
WTT	*Wheel Track Test*
SF	*Silica fume*
SFP	*Semi-flexible pavement*
SP	*Super-plasticizer*
TSR	*Tensile strength ratio*
w-LDPE	*waste -Low-Density Polyethylene*
W/B	*Water/Binder*

Chapter One

Introduction

1.1 Background

Generally, there are two-main traditional pavement types that have been extensively used for road building and reconstruction of pavement layer systems namely; flexible and rigid pavements. Flexible pavements are defined by their ease of maintenance, high ride quality, and lack of joint, whereas rigid pavements made of Portland cement are known for their high bearing capacity and a longer life. Pavement failures related to flexible pavements' is reflected to abrasive loads, fuel spillage, and stripping, as well as rigid pavement failures related to joints and lack of strains, prompted the hunt for a material that combines the benefits of both Portland cement concrete and hot-mix asphalt (Al-Qadi et al., 1994a). However, extensive research works have been spent on overcoming the observed failure forms, mainly through offering developed mixture preparation techniques and benefit from the characteristics of existing techniques.

One of the developments in this regard is constructing highly porous asphalt concrete and filling the voids with a cementitious grout. It is usually called semi flexible pavement (SFP). However, it has got different names such as resin modified pavement (RMP), grouted macadam and other brand names; its success is being reported (Setyawan, 2013, Hlail et al., 2021) However, in recent years, a new type of pavement has been used, which is the focus of this thesis. It is called SFP because the surface course is made of a semi-flexible material that can incorporate good features of both flexible and rigid pavements, such as the free of joints, long life, and high bearing capability. It also provides good protection against water ingress to the foundation since it has an impermeable surface.

SFP was developed during the 1950s, in France (Van de Ven et al., 2004). It is a composite pavement material with open-graded matrix asphalt mixture of 25–35% air void content, filled with high performance cement mortar (Afonso et al., 2016b, Hirato et al., 2014). SFP has many advantages; it has high strength, high durability, fuel resistance, impermeability and joint less construction, so it can be used in construction and reconstruction of areas subjected to high traffic loads such as factory floors, airports, bus stations, harbors, parking areas, etc. (Zarei et al., 2020).

One of the disadvantages of SFP is that it arises in two phases, which are carried out over a period of two days. First is the construction of the porous asphalt layer, and secondly, the grout is poured on the porous layer (Dias et al., 2005). In terms of construction time, this is preferable to rigid pavement, but in terms of flexible pavement, the opposite is true.

1.2 Problem statement

Flexible pavement is widely used in road due to its low cost, high slip resistance, ease of maintenance, and high ride quality. However, it is exposed to many problems such as cracks and permanent deformation due to the increasing heavy traffic and severe environmental conditions that can affect its service life and performance. Instead, the rigid pavement is more durable and environmentally friendly than flexible pavement. Moreover, it also has other restrictions such as construction time and the necessity of joints to allow the thermal movement of the concrete layers. One of these alternatives is the semi flexible which combines the high strength of Portland cement compounds with the flexibility of asphalt materials. It has high strength, impermeability, high durability and fuel resistance, it has high crack resistance and better moisture stability than conventional asphalt mixture, as well as reduces cracking resistance at low temperatures due to the brittleness of the hardened cement paste. Therefore, SFP can be applied for the construction and renovation of heavy traffic areas, such as industrial floors, bus terminals, parking areas, loading platforms and other areas, but the global experience of such mix characteristics is somehow limited. Also, optimizing its ingredients is in high demand, furthermore, balancing the flexibility and rigidity of SFP using more flexible grout is needed.

1.3 Aim and objectives of the research

The aim of this research is to develop a SFP mixtures and evaluate the achievements related to the application of the grout and by referring to the porous mixtures in this way, the cementitious grout will be understood in a better way. To achieve the aims of this research, the objectives or tasks below are followed: -

1. Determining the optimum cementitious grout material from ordinary Portland cement (OPC), emulsion (EM), silica fume (SF), superplasticizer (SP), and water.
2. Designing a porous HMA with air voids of 25-35%, using neat and modified waste-Low-Density Polyethylene (w-LDPE) bitumen.
3. Designing SFP mixtures, consist of porous HMA and cementitious grout material.
4. Characterizing the volumetric, mechanical, functional, and durability properties of SFP in terms of: -

a. Volumetric properties (bulk density, voids in mineral aggregate, voids filled with asphalt, air voids, porosity and draindown).

b. Mechanical & functional properties (permeability, indirect tensile strength, creep compliance, and skid resistance).

C. Durability (Cantabro abrasion (aged and unaged), water damage (TSR)).

1.4 Scope of work

The scopes of the work followed in this research are summarized below:

1. The raw material used in this research were local and non-local materials. Local materials are fine and coarse aggregates, asphalt binders and cement. Non-local materials are silica fume, super-plasticizer and asphalt emulsion.
2. The modifier material used in this research is w-LDPE, it was nominated to study the effect of recycled materials on the performance of semi-flexible mixtures.
3. The tests in this research are laboratory tests that were conducted at the University of Kerbala laboratories.

1.5 Thesis layout

This thesis consists of five chapters explaining the components and result of the study as listed below:

Chapter one:	Introduces the background of the research, its problem statement, aim and objectives, scope of work and thesis layout.
Chapter two:	Describes a review about the type of pavement, review of the semi-flexible pavement, its performance, influence of material properties on SFP and properties.
Chapter three:	Describes the materials used in this study, preparation of the grout, preparation of the porous asphalt mixtures, preparation of the semi-flexible mixture, laboratory tests and methodology followed in this research.
Chapter four:	Shows laboratory tests results about cementitious grouts and semi-flexible mixture, and discuss them in detail.

Chapter five: Shows the conclusions and recommendations for future work.

Chapter Two

Literature Review

2.1 Introduction

flexible layers at the top of a road or paved area are exposed to heavy and slow loads, mostly canalized traffic, such as bus lanes, airport aprons and taxiways, or distribution centers, the pavement structure is susceptible to permanent deformation. As a result, rigid pavements are often recommended in these regions. In contrast to flexible pavements, rigid pavements have many significant drawbacks. The key drawbacks of rigid pavements over flexible pavements are construction time and the need for joints to allow for thermal movements of the concrete layer in order to prevent dispersed cracks from forming in the pavement due to the constraint of such movements. Therefore, a different form of material has been developed to produce a semi-flexible, rut-resistant surface layer that is free of joints and cracks. Accordingly, this chapter displays the previous studies that accommodate the identification of paving techniques, pavement structures, and current context in develop pavement industry, and recent trend in develop SFP. Finally, this chapter will include the gap in the knowledge for increase the performance of SFP.

2.2 Pavement Structures

A highway pavement is a structure consisting of various layers of processed materials above the subgrade soil, whose primary function is to distribute the applied vehicle loads to the subgrade soil. The pavement structure should be able to provide a surface of acceptable riding quality, adequate skid resistance, favorable light reflecting characteristics, and low noise pollution (Akhter, 2018).

The widely used pavements in the world are: flexible and rigid pavements, or it might be developed as a composite pavement. It is worth mentioning that there are other types of pavements, but not commonly used such as block pavement (Yasuhisa et al., 2006).

2.2.1 Flexible Pavement

The flexible pavement consists of bituminous materials in the upper layers. There are several types of bituminous mixtures that can be used in those layers, depending upon the function of the layer. About 95% of world's roads are made of flexible pavements(Aziz et al., 2015).

2.2.2 Rigid Pavement

Rigid pavements (or concrete pavements) normally consist of two structural layers, the concrete slab and the sub-base. The slab may be laid in composite form using different aggregates in the upper and lower layers. (Croney et al., 1991) (Manna et al., 2021), Plate (2-1) shows the general forms of flexible and rigid pavements.

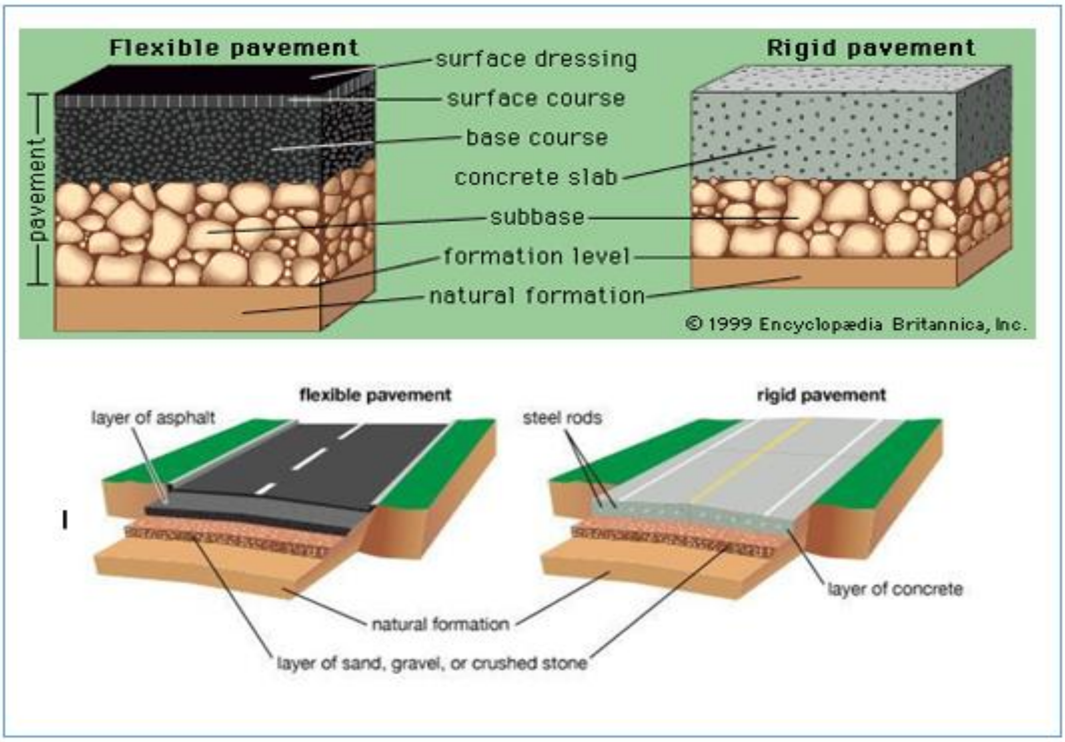


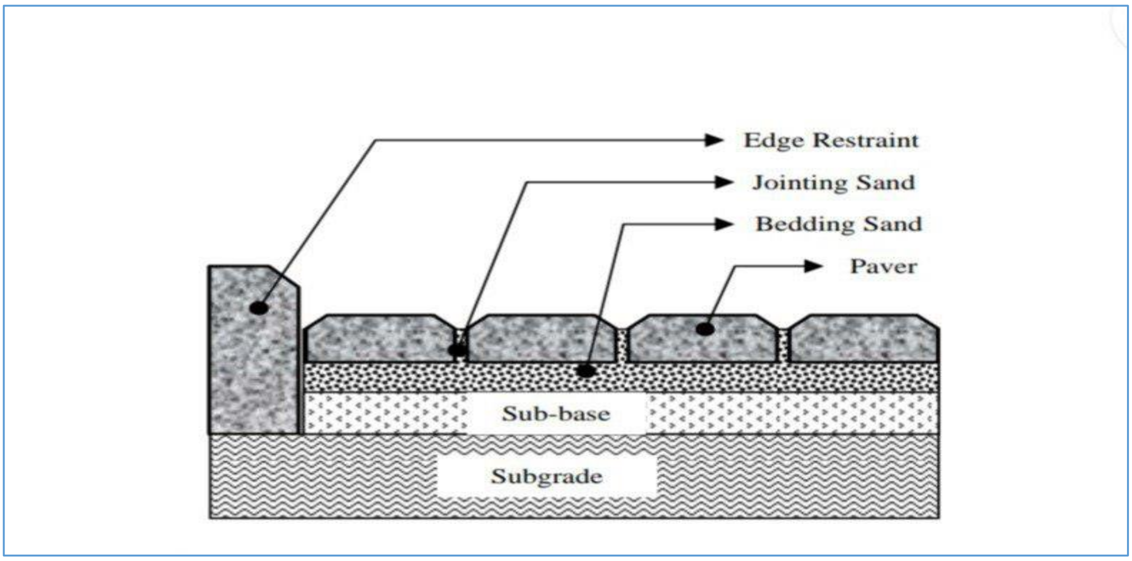
Plate (2-1): General forms of flexible and rigid pavement (M. Gkovedarou, 2019).

2.2.3 Composite Pavement

A composite pavement is one that is made up of two layers: commonly, a rigid pavement on the bottom and a flexible pavement surfacing or wearing course on top, the inverse sequence is used in limited region when the asphalt concrete is used as a base layer for rigid slabs (Yoon et al., 2018). Asphalt layer is designed to provide special functions such as frictional resistance, wear resistance, thermal insulation, and protection against adverse environmental effects (Paveen et al., 2013).

2.2.4 Block Pavement

Block pavements differ from other forms of pavement in that the wearing surface, they are made from small paving units bedded and jointed in sand rather than continuous paving. Beneath the bedding sand, the substructure is similar to that of a conventional flexible pavement(Panda et al., 2002), as shown in Plate (2-2).



Plate(2-2): Structure of concrete block pavement (Mudiyono et al., 2006)

2.3 Semi-flexible pavement Mixture (SFP)

SFP is an open-graded asphalt mixture with (25–35) % air void content that is packed with high performance cement mortar (CM) as demonstrated in Plate (2-3). SFP described by its lack of joints, high strength, impermeability, high endurance, and fuel resistance, which are all advantages. Additionally, SFP can be used to construct and renovate high-traffic areas like industrial floors, bus terminals, parking lots, loading platforms, and other heavy duty areas (Zarei et al., 2020).

Plate (2- 3): Formation of semi-flexible pavement

Many reports on the efficiency of semiflexible materials have been conducted by various researchers. The effects of various factors on damage were studied, and a relationship between loading times and damage was developed using cyclic wheel load tests (Yang et al., 2015a).The performance variations using compressive strength, indirect tensile stiffness, and dynamic creep tests of both cool-mixed and conventional hot-mixed methods have been investigated (Sun et al., 2018a).

Recently, studies on semi-flexible material design methods have been carried out in China(Sun et al., 2018b). The effects of different types of asphalt mixtures and porosity on the efficiency of SFP materials have been investigated (LING et al., 2010). A study was performed to determine the amount of compound mortar needed to fulfill the construction specifications. (Wei et al., 2017).The optimization configuration of the cement mortar to cement injection ratio was investigated, whereas the effect of various factors on the fluidity of cement mortar has also been investigated (Sun et al., 2018b).

Nowadays, SFP research has primarily concentrated on the differences between SFP and other conventional pavements in terms of mixture designs, structures, and mechanical efficiency (Sun et al., 2018a, Wu et al., 2011, Bang et al., 2017, Bonicelli et al., 2019, Zarei et al., 2020, Yang et al., 2015a) , but the effects of grouting materials have received less attention. Cement mortar studies in China have so far followed the technical requirements in the Technology Guide for Application of Semi-Flexible Pavement (Wu et al., 2011), and the strengths of cement mortars at 7 and 28 days have been investigated, but no further research has been done on the low-age strength of cement mortars. Anther work stated that, the grouting material's strength was slow, curing was sluggish, and significant shrinkage cracking’s were common, resulting in a lengthy construction time and a negative impact on road performance (LING et al., 2009b).

2.4 Performance of Semi-Flexible Pavement

The performance of SFP is classified into functional performance and durability performance.

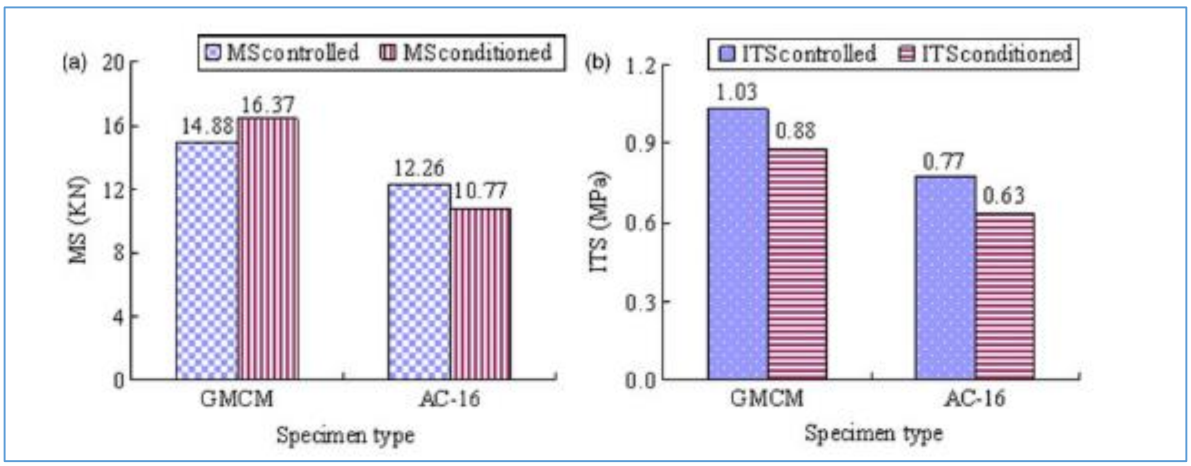
2.4.1 Functional performance

2.4.1.1 Traffic loading

SFPs were first used in France and Japan in the early 1960s.(Zarei et al., 2020, Cihackova et al., 2015, Luo et al., 2020, Mayer et al., 2001). Following that, the United States and the United Kingdom experimented with SFPs as an alternative to asphalt pavements for freeways, airports, bus stations, and bridge deck pavement (Al-Qadi et al., 1994a). Their research focused on the use of SFP as an overlying layer on bridge deck pavement to reduce the rate of rutting distress. In addition, tests for indirect tensile strength, Marshall Stability, and moisture sensitivity were performed (Hassani et al., 2020, Al-Qadi et al., 1994a).

The results indicated that the strength and durability of SFPs are greater in comparison with flexible pavements. Additionally, one-day moist curing is recommended after the application of grouting material to accomplish the hydration to improve performance of SFP (Hassani et al., 2020). The durability and stability of semi-flexible pavements against heavy vehicles and static loadings are considerably better than that of asphalt pavements. Different tests such as low temperature bending test, indirect tensile stiffness modulus, indirect tensile test (ITS), saturated Marshall test, and rut test freeze–thaw test were typically used to assess the SFP's performance to failures further to low temperature, moisture damage, fatigue, and permanent deformation.(Hassani et al., 2020).

The moisture susceptibility of SFP has been studied, and it has been discovered that it is less than that of asphalt mixtures. As a result, SFP has a higher Tensile Strength Ratio (TSR) than asphalt mixtures (Hou et al., 2016, An et al., 2018, Luo et al., 2020). This means that the grout phase content has a positive impact in SFP and the sufficient coating in the asphalt mixture mastic (asphalt binder, fine aggregates, and filler). Furthermore, hardened cement mortar (hardened cement paste) with sufficient coating wraps the asphalt mixture (wraps on the asphalt binder film) strengthen the adhesion between asphalt binder and aggregates, improving the moisture and freeze–thaw resistance of SFP. (figure 2-1) (Hou et al., 2016).



Figure(2-1): Test results of (a) Marshal stability and (b) ITS of controlled and conditioned grouted macadam composite materials(GMCM) and conventional asphalt (AC-16) specimens (Hou et al., 2016).

2.4.1.2 Fire exposure resistance

Fire in highway tunnels paved by asphalt concrete creates a severe crisis and dangerous situation for road users which can have irreparable financial and compensatory damages (Qiu et al., 2019). The flammable component of asphalt concrete increases the severity and effects of fire in the tunnel, and smoke produced during fire exposure causes extreme poisoning and oxygen deficiency, as well as reducing vision which greatly hampers the escape of people and vehicles (see Plate2-4).

Plate (2- 4): (A highway tunnel fire that causes a perilous situation: (a) fire spread; (b) increased gases concentration; (c) impaired vision; (d) chaos and danger for road users) (Qiu et al., 2019)).

According to recent studies, in the event of a tunnel fire, the heat produced by the asphalt pavement will raise the tunnel temperature to 800 ^{0}C (Qiu et al., 2019). If a truck fuel tank catches fire, the tunnel temperature could rise to 1000 ^{0}C or higher, releasing a large amount of poisonous and dangerous fumes (Liu et al., 2015, Shu et al., 2014).

As a result, the probability of fire initiation and propagation, as well as the chaotic and dangerous situation caused by asphalt pavement in tunnels, is significantly higher than that of concrete pavement, according to the above paragraph. Furthermore, the time needed for SFP building, repair, and recovery is less than that required for PCC. As a result, it can be concluded that SFPs are a superior choice in similar constructions.

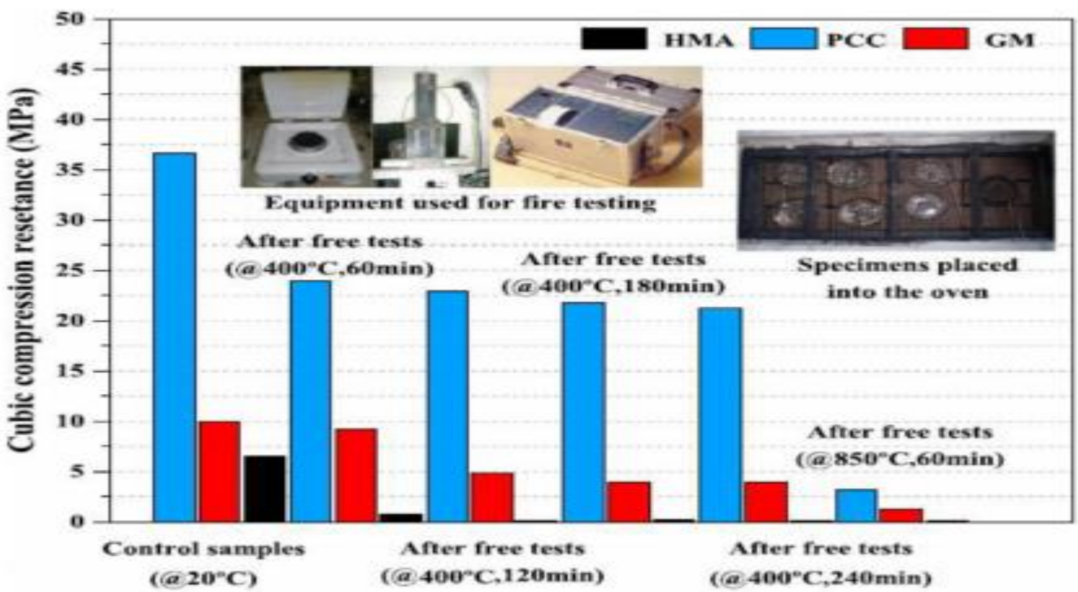


Figure (2-2): The findings of a fire and explosion study procedure (Toraldo, 2013)

2.4.1.3 SFP's skid resistance and fuel corrosion

Cihackova et al. (2015) investigated the anti-skid properties of SFPs. The macro-texture and micro-texture parameters were calculated to determine the skid resistance of a pavement surface. According to the data, SFPs have a stronger surface roughness and higher skid resistance than asphalt mixtures. Bharath et al. (2020) used a British Pendulum Tester (BPN instrument) to assess the skid resistance of a cement grouted bituminous mix(CGBM) surface (ASTM, 2013e). The measured value of skid resistance, expressed in terms, The BPN for the wet state was 60, and the BPN for the dry situation was 70 .The maximum allowed skid value in wet conditions is 55as suggested(Hosking, 1992.). The SFP surface's anti-skid output has been found to be satisfactory in both dry and wet environments.

2.4.2 Durability of SFPs

According to continuous studies, SFPs perform better under heavy and repeated loading than conventional asphalt pavements (Corradini et al., 2017, An et al., 2018, Afonso et al., 2016a, Yang et al., 2015a, Cihackova et al., 2015, Hong et al., 2020) , implying that SFPs should be prioritized for use as bridge deck pavement and bus rapid transit (BRT)stops (An et al., 2018, Al-Qadi et al., 1994a). The durability of SFPs is affected by a variety of factors, such as the quality and type of the compounds (i.e., aggregates, asphalt binder, cement, additives), initial air void content of OGA mixtures, performance of grouting materials, remaining air void content of SFPs, and the construction quality of pavements.. the durability of SFPs was compared with conventional asphalt mixtures, using Cantabro test (Bharath et al., 2020). The results indicated that the durability of SFPs, resistance to abrasion and weight loss, is at least 10 times greater than that of conventional asphalt mixtures. Another study was conducted with the purpose of investigating the durability of SFPs through rut test using Hamburg wheel-tracking tester (Cai et al., 2017). The results shown that SFPs had substantially less rutting depth than traditional asphalt mixtures. Hou et al. (2015) Showed that the rut depth of the grouted macadam composite materials (GMCM) which equals to a value (0.040) is less than (AC-16) conventional asphalt mix (0.553).As a result, the durability of SFPs against heavy loading and their high-temperature stability is more than that of conventional asphalt mixture.

2.5 Constitutions of Semi-Flexible Pavement

SFP is a porous asphalt layer that has been injected with cementitious grout material and is used as a surface layer to resist both heavy and light traffic loads (Hassani et al., 2020). SFP is made up of an open-graded asphalt mixture with cementitious grout material injected into a porous asphalt skeleton with 25-35 percent air voids. Plates 2–5 demonstrate how semi-flexible pavements are built.

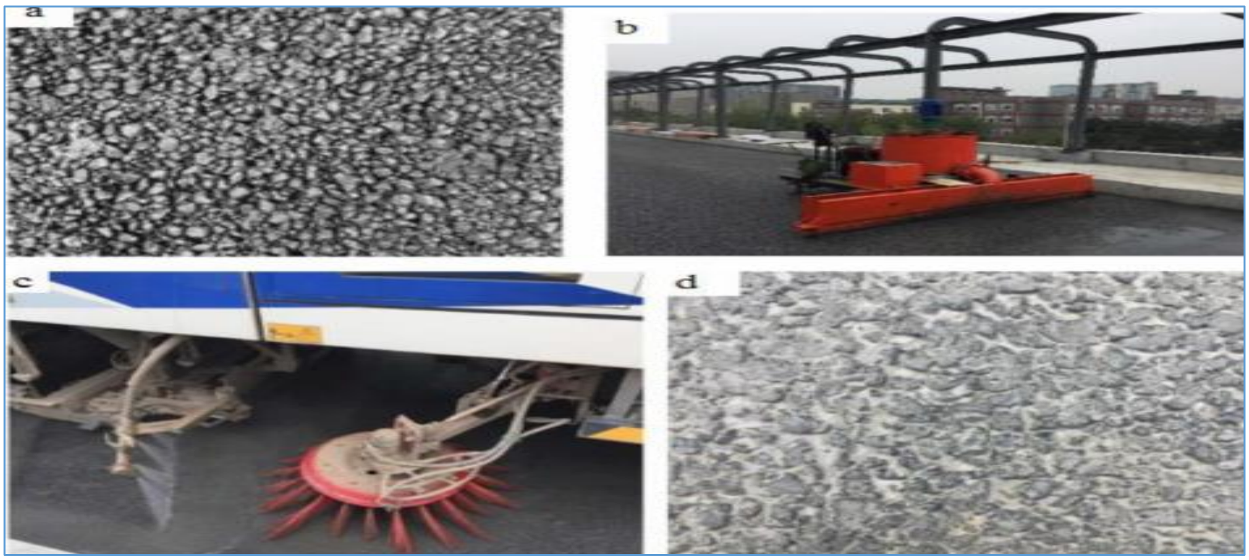


Plate (2-5):Construction of semi-flexible pavements in situ: (a) porous asphalt mixtures; (b) cement grout preparation; (c) cleaning of the pavement surface; (d) curing of the pavement surface (An et al., 2018)) .

The final product gathers the best characteristics of rigid and flexible pavements, such as asphalt's durability and lack of joints, high bearing capacity and wear resistance (Huang et al., 2012, Yang et al., 2015b, Wang et al., 2018a). When compared to rigid pavement , the speed with which SFP is installed and the time it takes to open to traffic is a significant improvement (Setyawan, 2006). These sort of surface layer is often used with a thickness of 30 to 60 mm(DENSIT, 2000), while some research has been done with thicknesses as high as 80 mm (Van de Ven et al., 2004), and some grout producers say that thicknesses as high as 200 mm are conceivable (Contec, 2005). It's worth noting that the building of a grouted macadam is a two-stage process that requires allowing the asphalt layer to cool before putting the grout into its spaces. As a result, most building projects take two days to complete.

To avoid the formation of cracks or tracks in the porous asphalt structure, the porous asphalt layer is built using natural paving and then lightly compacted with a steel roller without vibration. After the porous asphalt layer has cooled, it is injected with a cementitious grout material with a high fluidity (Zoorob et al., 2002). Rubber scrapers (squeegees) are used to spread grout on the surface layer. A light steel roller in the vibration mode can be used to ensure that the air voids are thoroughly filled with grout. The surface layer can be cured after filling the voids to improve its properties, such as skid resistance, durability, and aesthetics.

2.6 Application Fields of Semi-Flexible Pavement

SFPs have been used as the pavement of highways, freeways, bridge deck pavement, tunnels, harbors, warehouses, distribution centers, road crossing, bus terminals, parking areas with heavy traffic, cargo centers, airports pavements, holding bays, hangar pavements and other fields undergo heavy and light loads (Corradini et al., 2017, An et al., 2018, Afonso et al., 2016a, Hassan et al., 2002, Saboo et al., 2019b, Saboo et al., 2019a). Some investigations have stated that the use of SFP at airports is a result of the high cost that rigid pavement needs during maintenance and the need for a more flexible airport pavement to prevent deformations without cracking (Setyawan, 2006). Between 1988 and 2000, 165,000 m^2 of grouted macadam's were constructed in Copenhagen Airport, which is a practical example of the application of these pavements. Since then, several studies have been conducted to investigate the performance characteristics of this pavement surfaces type (Afonso et al., 2016b).

2.7 The influence of material Properties on SFP Characteristics

2.7.1 Porous Asphalt Mixtures

The OGFC mixture is a thin overlay layer that is built over existing traditional dense graded asphalt pavement with a thickness of 19 to 50 mm (Lyons et al., 2013) as demonstrated in Plate (2-6). It is a form of asphalt mixture with a porous aggregate skeleton in which fines and fillers are screened or reduced while coarse aggregate amounts are increased. As a result, this provide stone-on-stone contact and high air voids content reached to 20% (Alvarez et al., 2010, Wu et al., 2020).

Plate(2- 6):Photograph of open graded friction course (NCAT, 2015)

Depending on the appropriate functional properties, agencies around the world gave Porous Asphalt (PA) mixtures different names: open grade asphalt (OGA), porous friction course (PFC), porous asphalt concrete (PAC), porous asphalt (PA), and open graded friction course (OGFC)(Wu et al., 2020). PA mixtures have many advantages, including reducing spray and splash, reducing hydroplaning phenomena, improve surface frictional resistance, improve night visibility during wet weather, in addition to reduce tire-noise problems (Suresha et al., 2009, Alvarez et al., 2011). The first design of these mixtures was published by the Federal Highway Administration (FHWA) in 1974, and it was updated again in 1980 and 1990(Watson et al., 2003, Putman et al., 2012). This type of asphalt mixture varies from conventional impervious pavements in that it has a high asphalt content and a gap aggregate gradation with little fines and fillers, The pavement skeleton has a number of interconnected pores that allow water to flow through the system, as well as supporting urban drainage and supplementing the natural water cycle (Lyons et al., 2013, Lu et al., 2019).

In SFP, the porous asphalt design differs in terms of air voids, higher range is required to ensure grout injection (Zarei et al., 2020, Hlail et al., 2021). The porous asphalt for SFP application is designed according to the required air voids content. This depends on the type and gradation of the aggregate, the asphalt used, and the number of blows, (Hlail et al., 2020b). Extensive research efforts have been conducted to optimize the volumetric properties suitable for high performance SFP, as shown in Table (2-1) and Figures (2-3, 4)

Table (2-1): Different components of porous asphalt from the literature

Researchers	Aggregate type	Filler type	Bitumen type	Bitumen content	No. of blows	Air voids (%)
Al-Qadi (1994b)	Dolomitic limestone	limestone	Virgin Asphalt	4.05	10 x 2	25 – 30
Koting (2007a)	Granite	Limestone	Asphalt 80/100	3.7	50 x 2	27.2
Hu (2008)	Basalt	Limestone	SBS modified	3.2	50 x 2	26.0
Ling (2009a)	Limestone	Limestone	Asphalt rubber	3.6	50 x 2	20 – 28
M. G. Al-Taher (2015)	Limestone	Limestone	Asphalt 60/70	4.4	50 x 2	27.7
Hou (2015)	Limestone	Hydrated Lime	Virgin Asphalt	3.8	50 x 2	29.0
Tran (2017)*	Limestone	Limestone	Asphalt 60/70 Fiber	3.0 0.3	25 x 1	28.5 – 30
Jatoi (2018)	Limestone	Limestone	Asphalt 60/70	4.35	25 x 1	25 – 35
Wang and Hong (2018b)	Limestone	Mineral powder	Polymer Modified	2.9	50 x 2	24.8
Luo (2018b)	Basalt	Limestone	SBS modified	3.4	50 x 2	26.43

* In his study, the aggregate gradient based on the aggregate gradient of (Anderton, 2000) study.

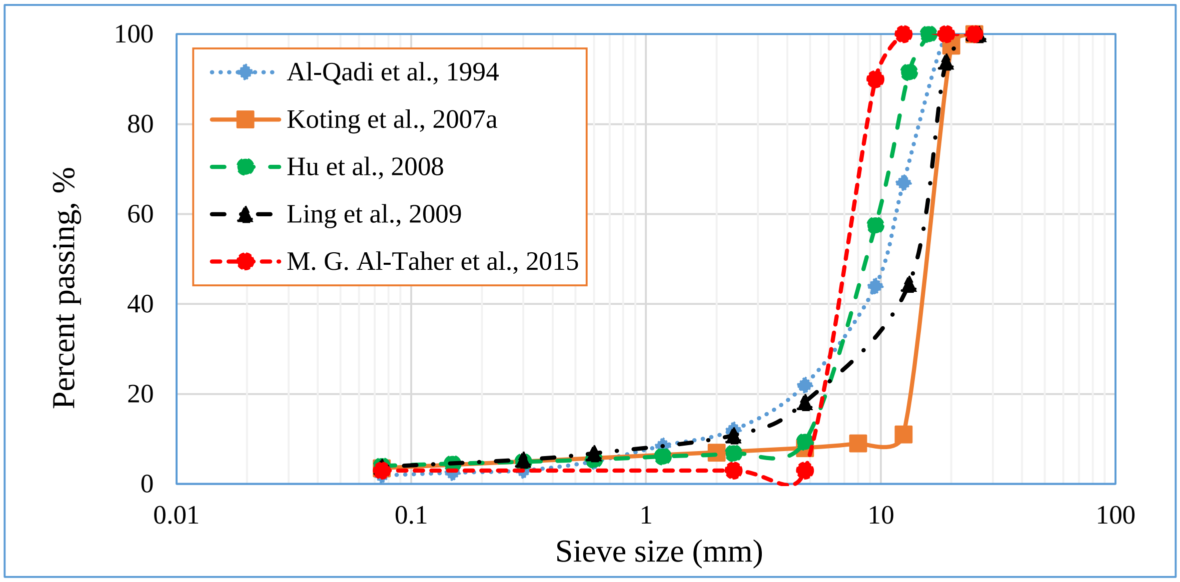


Figure (2-3): Various aggregate gradations acquired from literature

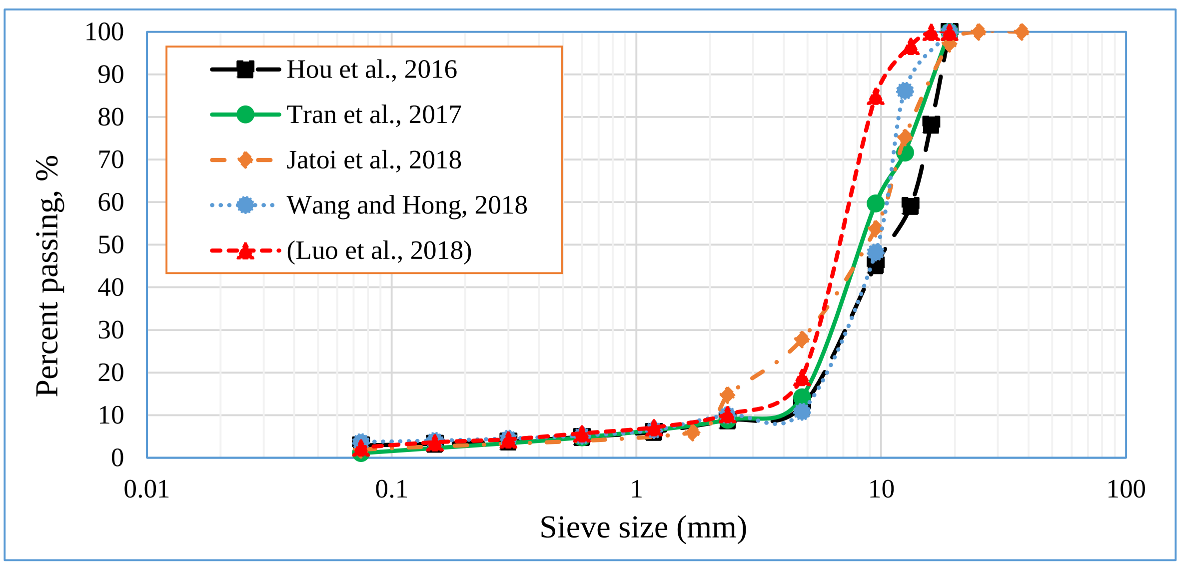


Figure (2-4): Another aggregate gradations used in SFP from literature

In summary, the form and gradation of the aggregate, the type and content of the asphalt, as well as the number of blows, all affect the porous asphalt structure, and therefore there are no accepted standard requirements for designing porous asphalt with air voids within the specified range. The main goal is to achieve a high air void of 25-35 percent to ensure grout penetration, so various compaction efforts have been recommended.

2.7.2 Cementitious Grout Materials

Grout is characterized as a mixture of cementitious materials, water, and sometimes a superplasticizer admixture (SP), with or without aggregates, in its most basic form (Celik et al., 2015, Sha et al., 2018). Cement grouts have been used in precast construction, structural reconstruction, and soil stabilization, among other applications in civil engineering. Cement grouts are used in a variety of applications, including soil grouting and rock grouting(Müller et al., 2016), coating pre-stressed cables in precast constructions, post tensioned cable duct grouting, and stabilize ground near tunnels are all applications for crack injection and filling holes in concrete structures (Lacerda et al., 2018, Tullini et al., 2016). The strength of grout is very crucial in its application in precast constructions. One factor which affects the grout strength substantially is its water to cement ratio (W/C), Grouts with low W/C necessitates the use of superplasticizer to acquire the desired rheology to flow through joints or crack (Vasumithran et al., 2020b).

In 1802, Charles found that the soil was being erosion by water as a result of the tidal process in the harbor of Dieppe, which had a negative impact on the built structure. The injection technology was used at the time to protect the soil from erosion (Glossop, 1960). Grout forms include bonded prestressed tendon grout, auger cast pile grout, masonry grout, and pre-placed aggregate grout, depending on where they are applied (O’Malley et al., 2010, Vasumithran et al., 2020a, AbdelRahman et al., 2020). Grout can also improve fire resistance, security, acoustic efficiency, termite resistance, blast resistance, thermal storage capacity, and anchorage capabilities (NRMCA, 2004, Teymen, 2017). Grout can also be used in semi-flexible pavement to improve its performance by penetrating the voids in the pavement. (Zhang et al., 2016b, Pei et al., 2016a).

Fluidity, impermeability, strength, corrosion safety, sulfate resistance, and, in certain instances, frost toughness are all performance requirements for a high-performance cementitious grout intended for structural repair (Shannag, 2002, Ryan, 2007). Cement grouts are made up of cement and water, with or without sand and other additives. Admixtures are used to boost the flowability, permeability, and strength of grout. The most popular admixture in grout mixes is super plasticizers (SP). If sand is used, more water and super-plasticizer will be needed to achieve the desired workability (Glossop, 1960). Silica fume was among the most effective mineral admixtures because of its remarkable ability to boost the strength of grout, mortar, or concrete. (Habib et al., 2021, Kanamarlapudi et al., 2020, Ma et al., 2021) (Vasumithran et al., 2020b). Table (2-2) Influence of silica fume replacement on the compressive strength performance (Koting et al., 2014a).

Table (2-2) :Influence of silica fume replacement on the compressive strength performance (Koting et al., 2014a)

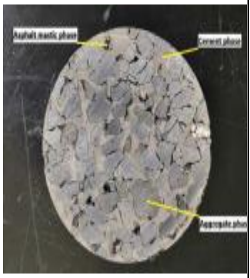
m70 Grout mixture description			Compressive strength (N/mm^2)	
Grout content	w/c ratio	% of SP	1 day	28 days
100% OPC	0.30	1.5	57.6	85.5
		2.0	59.3	87.2
	0.35	1.5	40.2	68.1
		2.0	38.3	66.2
95% OPC + 5% SF	0.30	1.5	55.4	91.7
		2.0	57.5	92.5
	0.35	1.5	54.4	86.1
		2.0	57.3	87.0
90% OPC + 10% SF	0.30	1.5	57.5	90.2
		2.0	59.7	92.8
	0.35	1.5	55.4	88.6
		2.0	57.1	89.7

2.8 Properties of Semi-Flexible Pavement

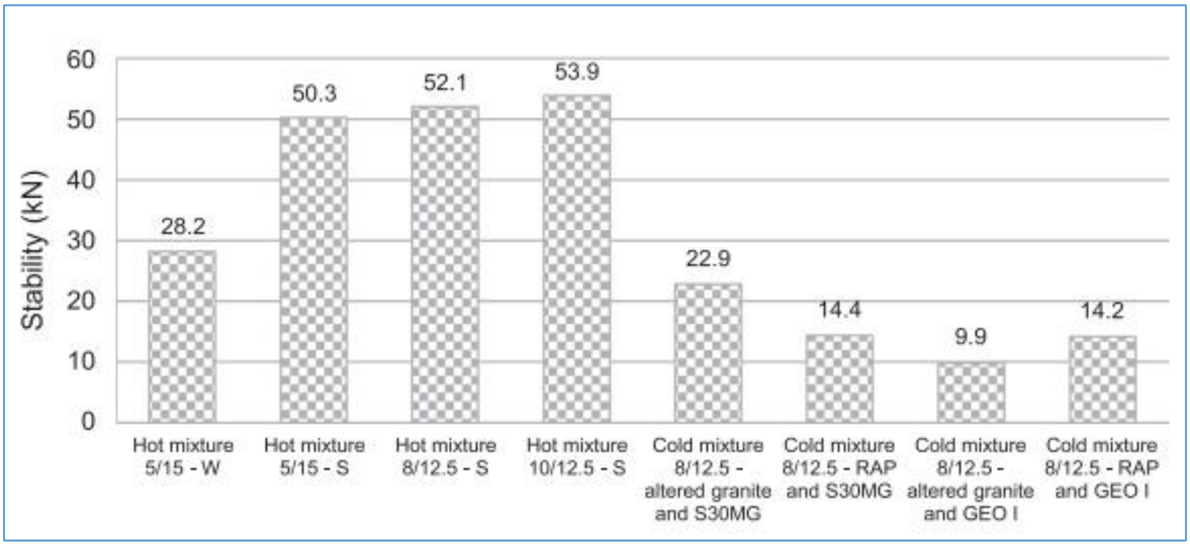
Tables (2–3) show the test technique, sample geometry details, and test results from several investigations undertaken by the authors.

Authors	***Test method***	***resulting A test sample***
(Afonso et al., 2016a)	Compressive strength tests, rutting tests, Marshall Strength and indirect tensile stiffness module	SFPs with better grout (lower fluidity and greater compressive strength) have a higher indirect tensil e stiffness modulus, Marshall Stability, and resista nce to permanent deformation than SFPs with poo rer cementitious grout.
(Cai et al., 2017)	Marshall Stability tests, Wheel tracking tests, moisture sensitivity tests	Marshall Stability rutting resistance and tensile strength ratio (TSR) would improve by raising the initial air space of asphalt mix and raising the grouting materials amount, which will also fill a greater portion of asphalt mix in SFP. 
(Luo et al., 2018a)	Moisture susceptibility tests, Hamburg wheel tracking tests, and low temperature cracking tests	SFPs have a poorer low-temperature fracture and fatigue life than asphalt mixtures, although its resilience to permanent deformation is substantially higher. The moist susceptibility and low-temperature performance of the latex modified SFPs, on the other hand, were both satisfactory. 

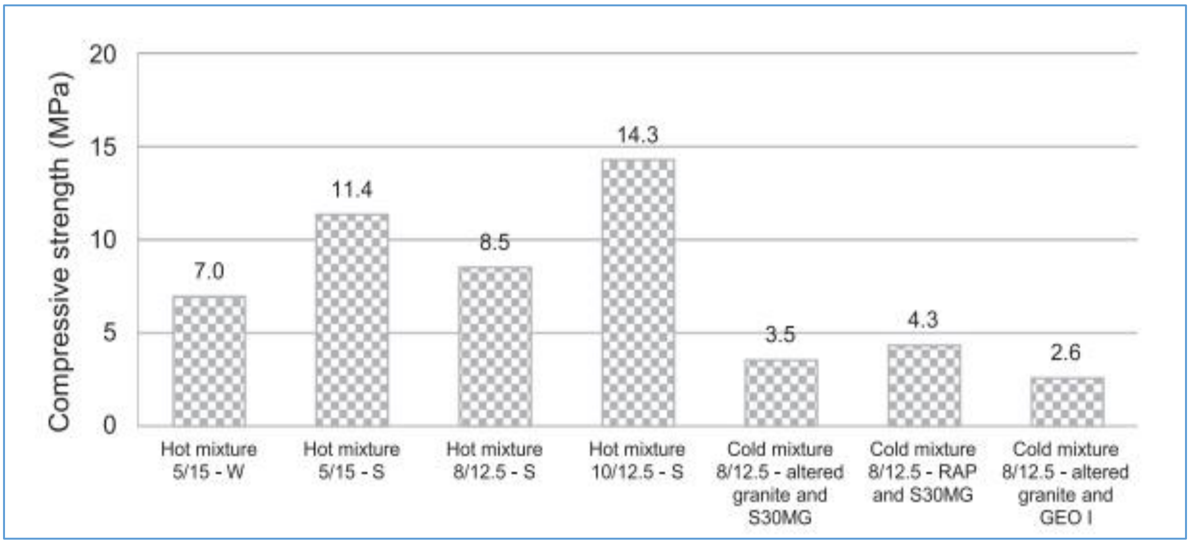
(Zarei et al., 2020)	Low-temperature bending test, Moisture susceptibility test, and Wheel tracking test	SFP presented higher resistance against rutting. As well, the study carried out that the utilization of 20% of asphalt emulsion to cement ratio (AE/C) during the design of SFP mixtures improve the sensitivity of mixture to water damage. The use of the latter SFP is more required to implement in the wet regions at both hot summer and cold winter in contrast with pure cement paste.	
(Bharath et al., 2019b)	Marshall stability tests, compressive strength, Wheel tracking tests and indirect tensile strength (ITS) tests	SFPs have higher compressive strength, tensile strength, and Marshall strength than ordinary asphalt mixtures. Furthermore, this form of pavement has a lower rutting depth than typical asphalt mixtures.	
(Setyawan, 2013)	Compressive strength tests	SFPs' compressive strength is affected by the compressive strength of the cement grouts.	
(Zhong et al., 2020)	High temperature stability, Low temperature crack resistance, Moisture susceptibility, and Fatigue life	Moreover, the Grouted Open Graded Asphalt Concrete (GOAC) offered better results in terms of Marshall stability, tensile strength ratio and DS by about 4.8%, 5.6% and 2.5 times, respectively compared with dense graded asphalt mixtures. Under lower stress levels, the resistance of GOAC and dense asphalt mixtures show comparable fatigue life. On the other hand, the increment of stress ratio widens the fatigue life difference between GOAC and dense asphalt mixture. Furthermore The dynamic stability of a dense asphalt mixture is really only 40% that of a GOAC mix.	

(Cihackova et al., 2015)	Wheel tracking test, Stiffness modules test, Skid resistance and low temperature cracking tests.	The rutting resistance of SFPs is substantially higher than that of asphalt mixes.) SFPs also have excellent micro and macro-texture as well as superior skid resistance when compared to asphalt mixtures. SFP, on the other hand, has a worse resilience to low-temperature cracking than asphalt mixes..) 
Bang et al., 2017 [69].	Rut tests, Marshall stability, bending, and compressive strength	When compared to a standard asphalt mixture, SFP has higher compressive strength, flexural strength, and Marshall stability, while its flexural strain is lower. The results of the tests revealed that the fluidity time of grouting materials is the most important factor in determining the mechanical properties of SFPs under constant porous asphalt mixture skeletal conditions. 
(An et al., 2018)	Rut tests, Marshall stability, moisture sensitivity, and three-point flexural tests.	SFPs outperform asphalt mixes in terms of performance at extreme temperatures and resilience to moisture damage. However, the bending failure strain suffered by these mixes is lower than that of asphalt mixes at relatively low temperature. According to the findings of a moisture susceptibility test, the tensile strength of SFPs is 20% more than that of asphalt mixes. 
(Hou et al., 2015)	fatigue test, wheel tracking test and moisture susceptibility test	SFPs outperform standard HMA mixes in terms of moisture stability, high-temperature stability, and fatigue resistance, with an acceptable compromise in low-temperature fracture resistance because of brittleness of hardening grouting observed at lower temperatures.

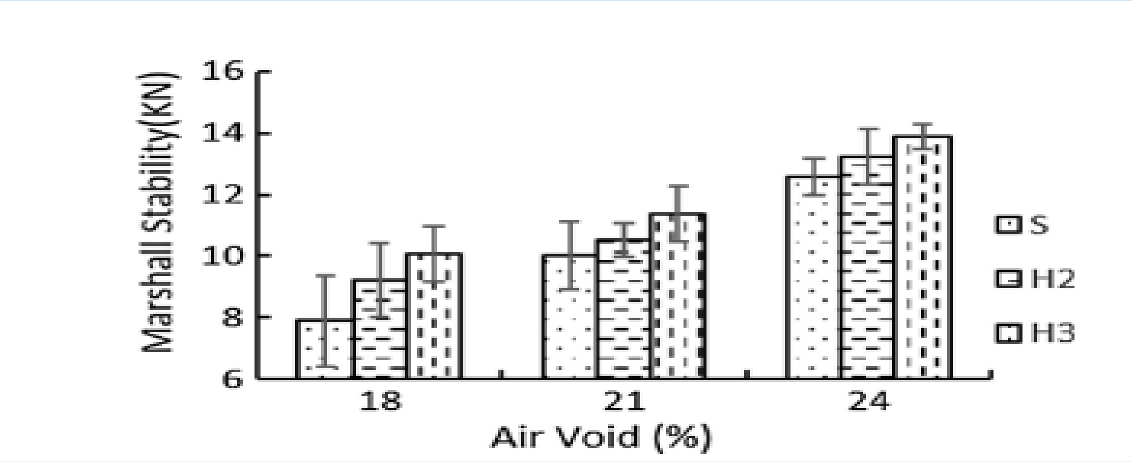
Figures (2.5-2.12) are examples of the tests in the Table (2-3).



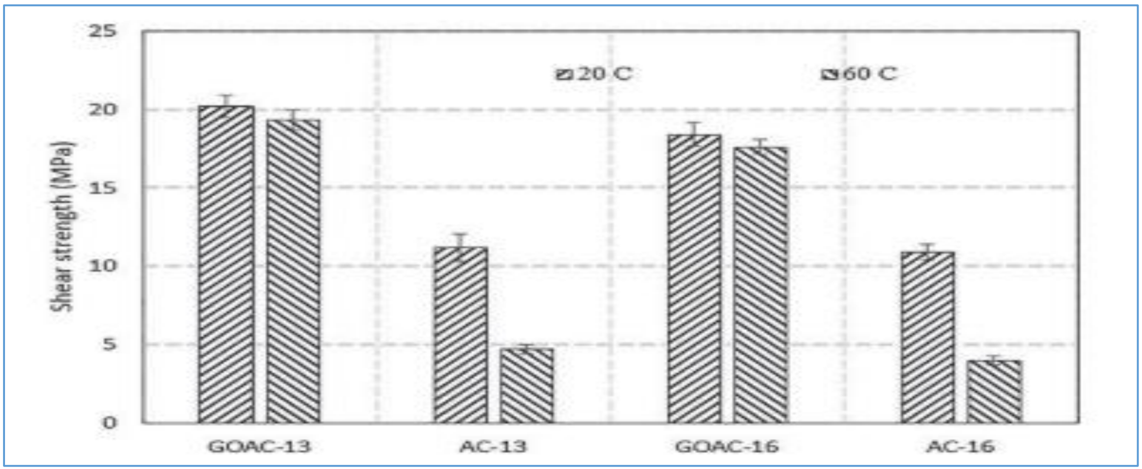
figure(2-5):Marshall test results for grouted macadam (Afonso et al., 2016a)



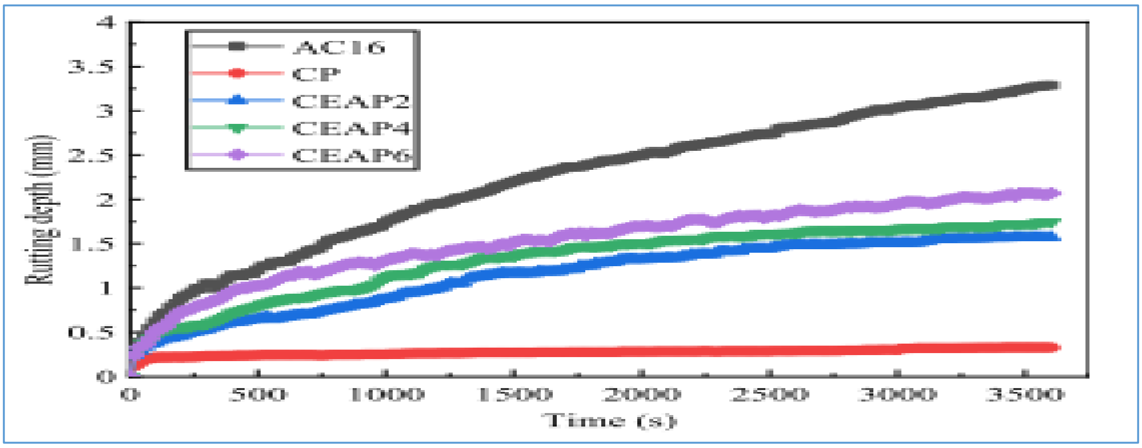
figure(2-6):Compressive strength results for grouted macadam (Afonso et al., 2016a)



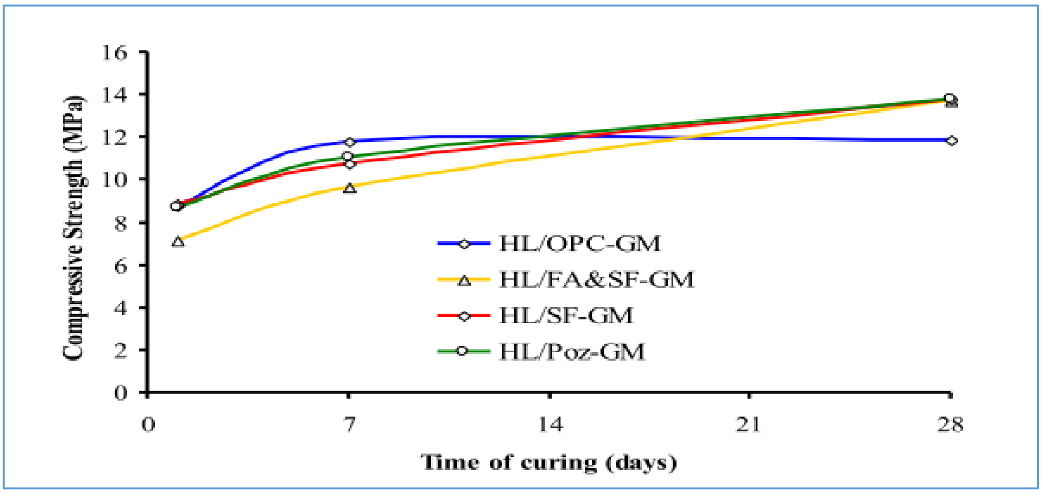
figure(2-7):Marshall stability of H2, H3 and S with different air voids of matrix asphalt mixture (Cai et al., 2017)



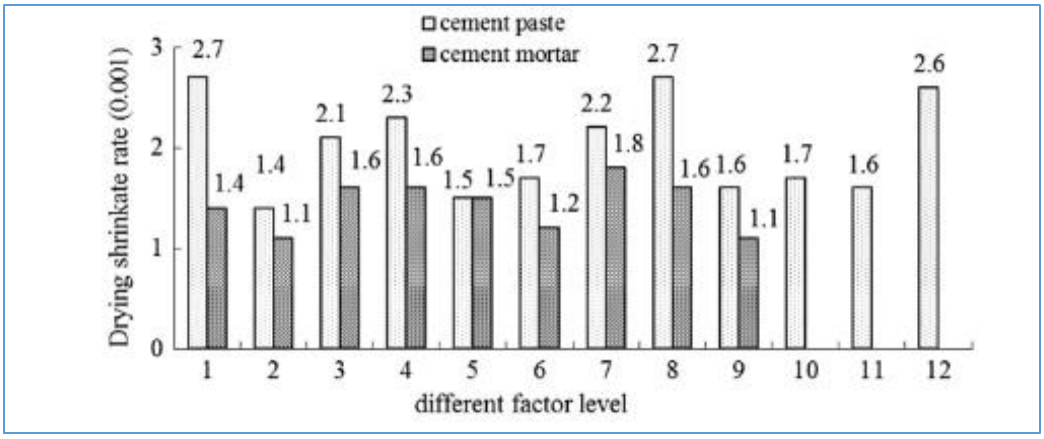
figure(2-8):The shear test result (Luo et al., 2018a).



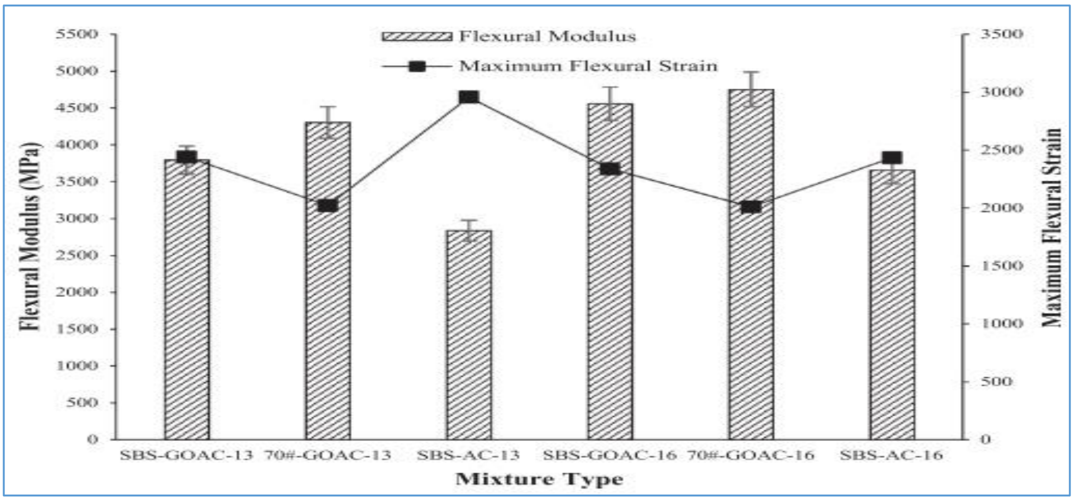
figure(2-9):Rutting test results of AC16 and SFP.(Zarei et al., 2020)



figure(2-10):Compressive strengths of grouted macadam with different grout types (Setyawan, 2013)



figure(2-11):The comparison of cement paste and cement mortar in drying shrinking rate.(Zhang et al., 2016b)



figure(2-12):Low temperature crack resistance of GOAC and dense asphalt mixture (Zhong et al., 2020)

2.9 Summary

A semi flexible mixture is a composite material made up of porous asphalt mixtures with (25-35%) air voids filled with a specific cement grout. Among the benefits of these mixtures high resistance to loads and waterproof layer, resistant to oils, fuels, and chemical materials as a result of the closure of the air voids for porous asphalt with grout, Resistant to heat, free of joints, that are necessary for rigid pavements, and many other benefits. According to research, semi-flexible pavements outperform asphalt pavements in terms of performance, stability, and longevity when subjected to heavy vehicles and static loads. the main characteristics of some of these mixtures and a group of SFP mixtures was presented were discussed In this chapter.

Chapter Three
Material, Testing and Methodology

3.1 Introduction

This chapter contains the materials used during this research study, the aggregate type and gradation, the methods of examination, and the method of developing semi-flexible mixtures through the use of PA mixtures that include high air voids and injected with grout to obtain the required mixture. The chapter also includes the methodology that has been followed during this scientific research.

3.2 Materials used in Design of SFP

The materials that were used in the process of designing the cementitious grout and PA mixture were two types: local and non-local materials. Local materials are fine and coarse aggregates, asphalt binders and cement. Non-local materials are silica fume, super-plasticizer and asphalt emulsion since the (emulsion that is produced locally is not of good quality).

3.2.1 Aggregates

Crushed Limestone aggregates, which were supplied from Karbala quarries, were used in the design of PA mixture. The middle gradation with 12.5 mm NMAS was used, gradation limits were suggested by (Anderton, 2000), to achieve the air voids content within the permissible range from (25-35) % and ensure penetration of grout into the porous mixture. It is worth mentioning that the proposed aggregate gradation suggested according to the ASTM D7064/D7064(ASTM, 2013d)was used firstly, however, the required air voids content was not achieved within the permitted range. Therefore, it was discarded and Anderton gradation was adopted. The physical properties of this type of aggregate are summarized in Table (3-1).The middle gradation with 12.5mm NMAS was used as demonstrated in Table (3-2) and

Figure (3-1). Moreover, two types of filler were used in the same time with equal quantities to complete the design of the mixtures.

Table (3- 1): Properties of coarse and fine aggregate

Aggregates properties testing	***ASTM Specifications***	***Results ****	
		coarse	***Fine***
Bulk specific gravity of coarse aggregate(gm/cm³)	C127 (ASTM, 2015)	2.59	
Bulk specific gravity of fine aggregate (gm/cm³)	C128 (ASTM, 2015)		2.641
Water absorption of coarse aggregate (%)	C127 (ASTM, 2015)	2.24	
Water absorption of fine aggregate (%)	C128 (ASTM, 2015)		2.41
Los Angeles abrasion value (%)	C131 (ASTM, 2003a)	25.5	
percentage of fractured particles in one side, %	D5821 (ASTM, 2013b)	96	
percentage of fractured particles in two sides, %	D5821 (ASTM, 2013b)	95	

* Physical properties of aggregate were conducted in the Highway Lab. / Engineering department/University of Kerbala.

Table (3- 2): Gradation of OGFC mixture as recommended by (Anderton, 2000)

Sieve (mm)	***Size (in)***	***Passing by weight %***	***Passing %***
19.0 mm	[3⁄4 in.]	100	100
12.5 mm	[1⁄2 in.]	54-76	71.7
9.5 mm	[3⁄8 in.]	38-60	59.7
4.75 mm	[No. 4]	10-26	14.2
2.36 mm	[No. 8]	8-16	8.9
0.075 mm	[No. 200]	1-3	1.1

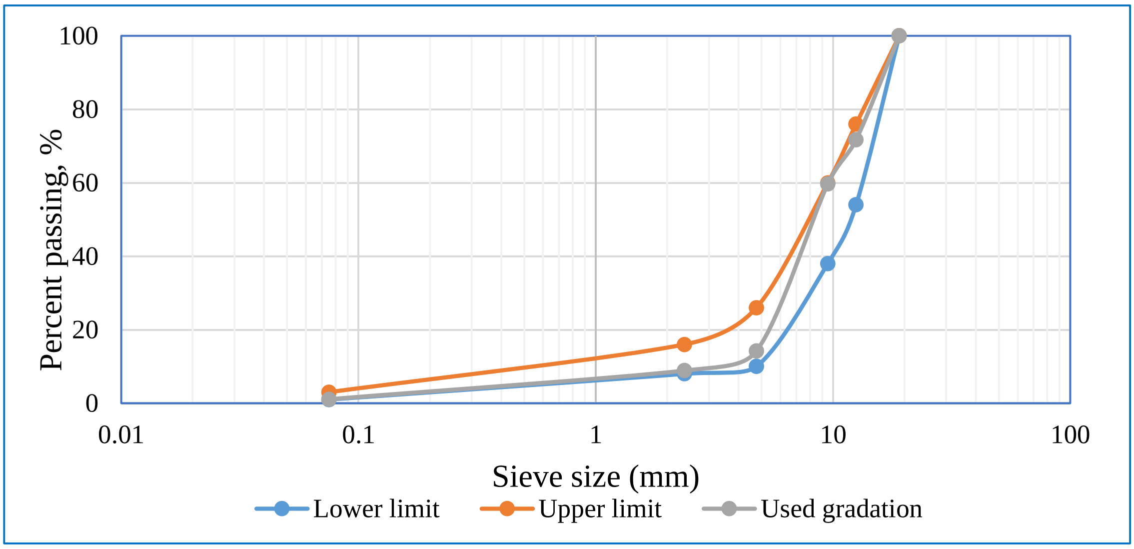


Figure (3-1): Particle size distribution of used aggregate gradation

Filler in the construction of asphalt mixtures has many advantages including increasing the pavement resistance to water damage, increasing the bearing strength, increasing the bitumen viscosity, and decreasing the mixture brittleness. The shape, physical and chemical combination, and gradation of fillers, on the other hand, have a major impact on the asphalt mixture efficiency. As a result, selecting the right filler is critical (Modarres et al., 2015). Material that pass- through sieve No. 200 is commonly referred to as filler in practical applications (Institute, 2014). This study combined the use of two forms of fillers: conventional mineral filler (CMF) and hydrated lime (HL). The CMF reflects the materials that pass- through sieve No. 200. This material is derived from the crushing the Limestone aggregated gradation's screening method. The other kind of filler is HL, which was obtained from the Furat Lime Plant. In the dry state, about 1.5 percent of the total aggregate weight is filled with HL filler. Tables (3-3) shows the chemical and physical properties of the fillers.

Table (3- 3): Physical and chemical properties of fillers used.

Chemical properties		
Oxide/property	**Concentration/amount**	
	CMF	**HL**
SiO_2	81.891	0.881
Al_2O_3	3.780	-----
Fe_2O_3	1.922	2.240
CaO	7.371	90.591
MgO	3.450	3.611
K_2O	0.732	0.570
Na_2O	0.193	1.011
Physical properties		
Density (g/cm^3)	2.651	2.302
Surface area (m^2/Kg)	224	1241

3.2.2 Ordinary Portland Cement (OPC)

Cement used in this study is OPC (CEM I 42.5R) that confirm to Iraqi standard No: 5/1984 type I. OPC was produced at Karbala Cement Plant. Table (3-4) shows the physical and chemical properties of this type of cement.

Table (3-4): Physical and chemical properties of OPC

Physical properties	
Specific Surface Area(m^2\kg)	410
Density (g\cm^3)	2.987
Chemical properties	
SiO_2	18.1
Al_2O_3	3.05
Fe_2O_3	5.45
CaO	62
MgO	1.38
K_2O	0.760
Na_2O	1.714

3.2.3 Super-plasticizer (SP)

Superplasticizer (SP) was supplied by LYKSOR Company (under the trade name Nano Flow 5500). Nano Flow 5500 is a polycarboxylate based, high-range water reducer/superplasticizer.It is a type of chemical admixture designed for the production of very flowable concretes or self-compacting concrete. Nano Flow 5500 provides very high flowability and slump retention performance. Table (3-5) shows the properties of Superplasticizer.

Table (3-5): Properties of superplasticizer

Property	**value**	**specification**
Colour and form	Yellowish-liquid	-
Chemical base	Polycarboxylate	-
Density (kg/lt)	1.06	1.05-1.09 (at+20^0 C)
Chloride ion content	0.05	Max 0.1% - Chloride free acc.to EN 934-2)
Alkali content	3%	Max.5%
Ph	4	3-7
Conformity	-	ASTMC494 Table 1

3.2.4 Silica Fume (SF)

The silica fume was provided by CONMIX Company. Silica fume, also known as condensed silica fume or micro silica, is a fine powder with a high concentration of amorphous silicon dioxide(Hlail et al., 2020a). This substance is a by-product of the smelting of silicon and ferrosilicon (Lewis, 2018). SF's physical and chemical properties can be shown in Table (3-6).

Table (3-6): physical and chemical properties of SF

Physical properties			**Specification, ASTM C1240**
Surface area (m^2/kg)		18100	15000
Density		700 (kg/m^3)	-
Chemical properties			**Specification, ASTM C1240**
NaO		1.534	-
MgO		0.432	-
Al_2O_3		0.091	-
SiO_2		92.05	>85%
Cl_2O		0.001	-
K_2O		1.886	-
CaO		3.035	-
TiO_2		0.002	-
MnO		0.149	-
Fe_2O_3		0.448	-
Co_2		0.006	-
CuO		0.017	-
ZnO		0.179	-
SrO		0.016	-
Y_2O_3		0.005	-
BaO		0.057	-
LOI		0.01	<6%
moisture		0.05	<3%

3.2.5 Water

The water used in the mixture and during the curing time was tap water.

3.2.6 Asphalt Emulsion

The Fosroc Company supplied the asphalt emulsion (under the trade name Nitoproof 10).Table (3-7) summarizes the Nitoproof 10 properties given by the manufacture(Hlail et al., 2021).

Table (3-7): Properties of asphalt emulsion

Property	Standard ASTM	Limits	Results
Emulsion type	D2397(ASTM, 2013a)	Rapid, medium and slow-setting	Medium-setting (CMS)
Color appearance			Dark brown liquid
Residue by evaporation, %	D6934(ASTM, 2008)	Min. 57	60
Specific gravity	D70(ASTM, 2009a)	-------	1.03
Penetration, mm	D5(ASTM, 2013b)	100-250	235
Ductility, cm	D113(ASTM, 2007b)	Min. 40	44
Viscosity, rotational paddle viscometer 50 °C, mPa.s	D7226(ASTM, 2013c)	110-990	225
Freezing	D6929(ASTM, 2010d)	Homogenous, broken	Homogenous
Solubility in trichloroethylene, %	D2042(ASTM, 2015e)	Min. 97.5	97.8
Emulsified asphalt/job aggregate coating practice	D244(ASTM, 2009b)	Good, fair, poor	Good
Miscibility	D6999(ASTM, 2012a)	-------	Non miscible
Aggregate coating	D6998(ASTM, 2011a)	-------	Uniformly-thoroughly coated

3.2.7 Neat and modified bitumen

For the purpose of completing the requirements of the PA mixture design, the neat bitumen with a penetration degree of 40-50 was supplied from the Nasiriyah refinery .The physical properties of neat bitumen (NB) are summarized in Table (3-8).

Table (3- 8): Physical properties of neat bitumen

Property	***Specification***	***Amount***
Penetration, 25℃, 0.1mm	ASTM D5-D5M (ASTM, 2013a)	42.8
Softening point, ℃	ASTM D36-95 (ASTM, 2009b)	44
Ductility, 25℃, cm	ASTM D113-07 (ASTM, 2007a)	143
Flash point, ℃	ASTM D92-05 (ASTM, 2005)	335
Specific gravity	ASTM D70-09 (ASTM, 2009a)	1.04
Loss on heat		
Penetration aging index (PAI)	ASTM D1754/D1754M (ASTM, 2014b)	-2.603
Softening point index (SPI)	(Cong et al., 2012),(Zhang et al., 2018)	4.6

In order to improve the penetration grade of the bitumen and in turn the performance of PA mixture, additive material were added, as demonstrated below:

3.2.7.1 waste-Low-Density Polyethylene (w-LDPE)

Waste-Low-Density Polyethylene (w-LDPE) is a type of polyethylene material that is recommended for use in asphalt binder modification processes due to its availability and low cost. After being a solid waste, w-LDPE is typically obtained from recycled carry bags of household goods. The use of w-LDPE has been found to aid in the reduction of problems associated with deformations due to its unstable crystallization property, which leads to an improvement in asphalt rigidity (Mahdy et al., 2020). Generally, the use of such materials helps in the reduction of cracking at high and low temperatures, the improvement of mixture hardness, the improvement of mixture fatigue, and the improvement of water damage problems (Al-Hadidy et al., 2009, Yan et al., 2015).Polyethylene (PE) is derived from the polymerization of ethylene and it formalize a long chain of one monomer(Othman, 2010, Akinci et al., 2012). The w-LDPE used in this research was recycled material supplied from a small factory located in Karbala City. Table (3-9) shows the physical properties of w-LDPE modifier that are obtained from the aforementioned factory, Plate (3-1) shows the shape of w-LDPE.

Table (3-9): physical Properties of Waste Low-Density Polyethylene (w-LDPE).

Properties	***Amount***
Density (g/cm^3)	0.91
Tensile strength (MPa)	8.5
Tensile elongation (%)	>350
Melting temperature (◦C)	110
Flexural modulus (MPa)	7.2
Hardness shore D	45

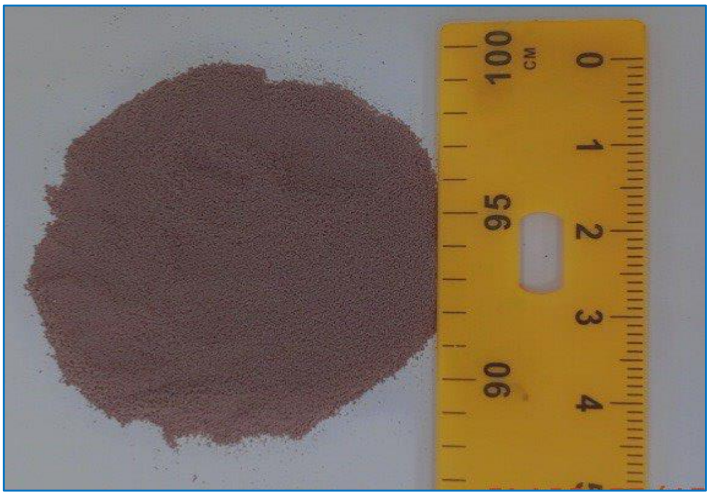


Plate (3-1). Waste-Low-Density-Polyethylene shape.

3.2.7.2 Preparation of modified bitumen

Waste- Low Density Polyethylene (w-LDPE) was used to modify the neat bitumen, by adding (3%) by weight of bitumen and mixing at a temperature of 170 °C, as recommended by a previous study conducted in the University of Kerbala (Al-Busaltan et al., 2021) . As shown in Plate (3-2), a high-speed shear mixer is used to make the modified binder. The preparation began with the neat bitumen being heated until it became fluid, while the mixer container was also heated to the correct temperature depending on the additive form, as shown in Table (3-7). After that, the heated mixer container was filled with the fluid bitumen, and the mixing process began until the temperature reached the appropriate level; the additive content of bitumen by weight is usually applied to the heated bitumen while the mixer is rotating, and the heating process continues during mixing to achieve a homogeneous blend. The mixing process lasted 30 minutes and was done at a pace of about 3000 rpm. When the mixing is over, to prepare samples for processing, the modified bitumen was extracted from the mixer container and divided in appropriate amounts to prepare samples for testing purposes suitable quantities.

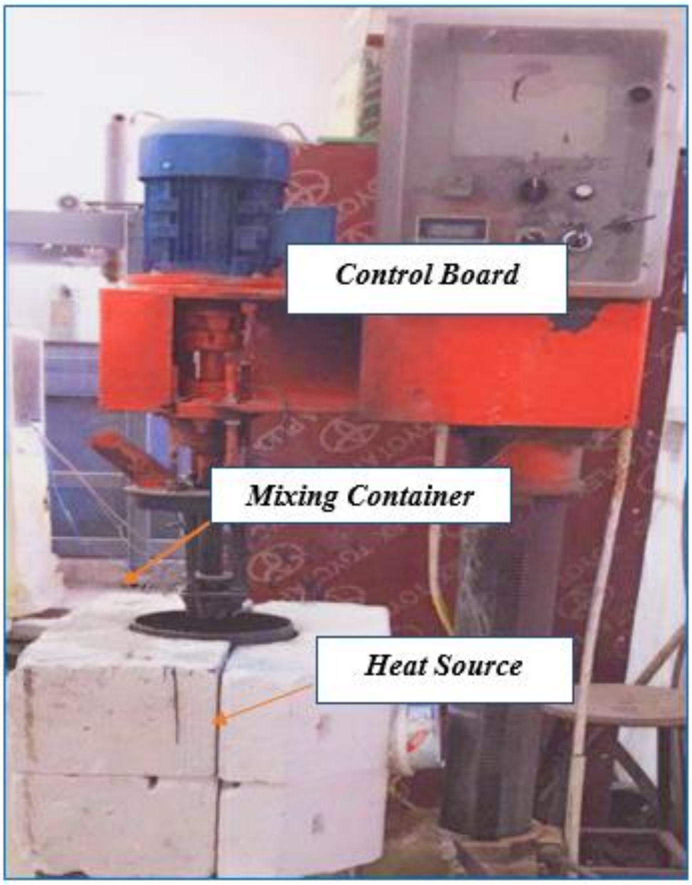


Plate (3- 2): shear mixer device

3.3 Preparation of PA mixture

To characterize the performance of PA mixtures were prepared including the control mixture (CM) and modified mixture (MM). In addition, to meet the research criteria, these mixtures were designed using two different types of specimens. The first set was to prepare the CM, which included the addition of 4 percent penetration grade bitumen to meet the PA- CM design specifications as documented in ASTM D6932/D6932M (ASTM, 2008). Marshall Specimens with a height of 63.5± 2.5 mm

(2.5 ±0.2 in) and a diameter of 100 mm (4 in) were made with 20 blows of the Marshall hammer on each face, as a trial and error process to satisfy 25-35 % air void content. Other researchers have used this method to achieve the necessary limit of air voids, for example (Punith et al., 2011b, Wu et al., 2019, Punith et al., 2011a). Then, according to ASTM D7064/D7064M (ASTM, 2013d), PA asphalt mixtures with 4% asphalt content were characterized in terms of air voids, voids in coarse aggregate, draindown, and Cantabro tests to determine the mixture with the best performance. The second step involves modifying the CM by making PA MM with additive contents (see section 3.2.7.1) and then repeating the same process. The specimens were then used to determine the volumetric, mechanical, functional and durability properties of the mixture. Other types of samples prepared in this study included slab samples with dimensions of 300 x 165 x 40 mm, with compacted the method described in BS EN 12697-32:2003 (BSI, 2003), for More information, (see section 3.6.2.5). Plate (3-3) shows Marshall Specimen

Plate (3-3): Marshall PA Specimens

3.4 Designing of Cementitious Grout Mixes

The advanced grout was designed have a replacement of OPC with other materials and different proportions of water in the first stage, different percentages of water were used, ranging from (0.3 to 0.45)%, as well as a super-plasticizer amount of 2% of the binder's weight. The SF replacement ratios determined from earlier research efforts were used to confirm dependability (Koting et al., 2014a). In the second stage, OPC was replaced with emulsion ratios of (20, 40 and 60)% according to the range used in previous study (Zarei et al., 2020), with the W/B ratio constant 40%. Table (3-10) shows the matrix of cementitious grout.

Table (3-10): Matrix of cementitious grout

Mix	stage	OPC%	S.F%	EM%	W\B	S.P%
M0	one	95	5	0	0.3	2
M1		95	5	0	0.35	2
M2		95	5	0	0.4	2
M3		95	5	0	0.45	2
M4	two	75	5	20	0.4	2
M5		55	5	40	0.4	2
M6		35	5	60	0.4	2

3.4.1 Preparation of Cementitious Grout Materials

Grout mixtures were made at a controlled temperature in a laboratory setting. The steps for preparing each mixture are as follows:

1. Mixing water with superplasticizer until it is well homogenous.

2. Depending on the various proportions of each mixture, thoroughly and homogeneously mixing the dry materials.

3. Adding the dry materials gradually to the water. The mixing machine remains in operation while the dry materials are adding to the water.

4. Filling a flow cone test with 1750 mL of the mix and measure the grout flow over time.

5. Lastly, the mixture was then poured into molds for cubes (50 x 50 mm) and beams (160 x 40 mm). as shown in Plate (3-4).

6. Following the pouring of the grout into the mold, the samples are left in the mold for one day before being demolded and cured in water until test day.

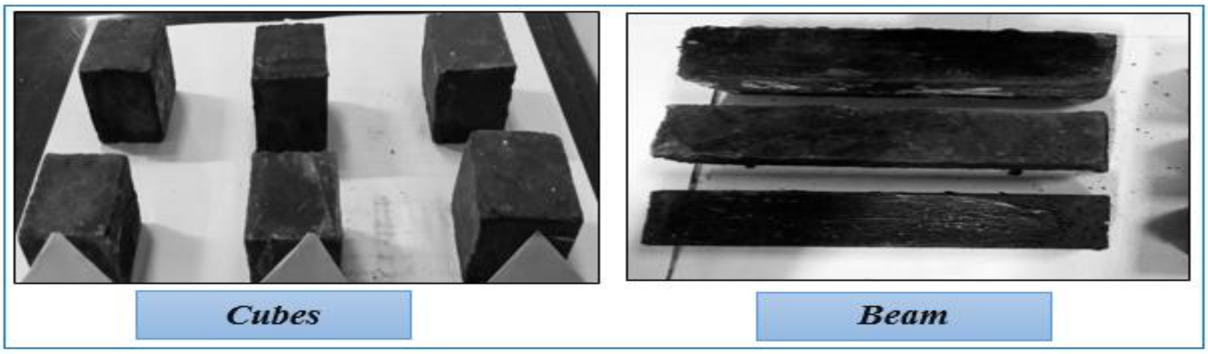


Plate (3-4): Specimen of compressive and flexural strength

3.4.2 Test of Cementitious Grout Materials

The following are the two types of grout testing that were carried out:

1.Fresh test (Fluidity test): The flow time is used to determine the fluidity of grouting materials conform to the conducted according to the procedure recommended by ASTM C939-10 (ASTM, 2010a). The implementation of this test is summarized by, the flow cone was filled with 1750 mL of grouting materials while the outlet was closed, and the efflux time was registered when the grouting material was fully discharged from the flow cone.

2-hard test (Compressive and flexural strength tests): The compressive strength test for the grout cubes was performed according to ASTM C 942-10(ASTM, 2010b) for ages of 3,7,14.28,56, and 96 days. In addition, standard-dimensional moldings that comply with adhere to ASTM C 348-14 (ASTM, 2014a) were used to measure the grout's flexural strength at 3, 7 and28 days. This test is conducted on hardened grout. Plates (3-5, 6) show the device of compressive strength, the device of flexure strength for the grout and the mold of the flow cone test.

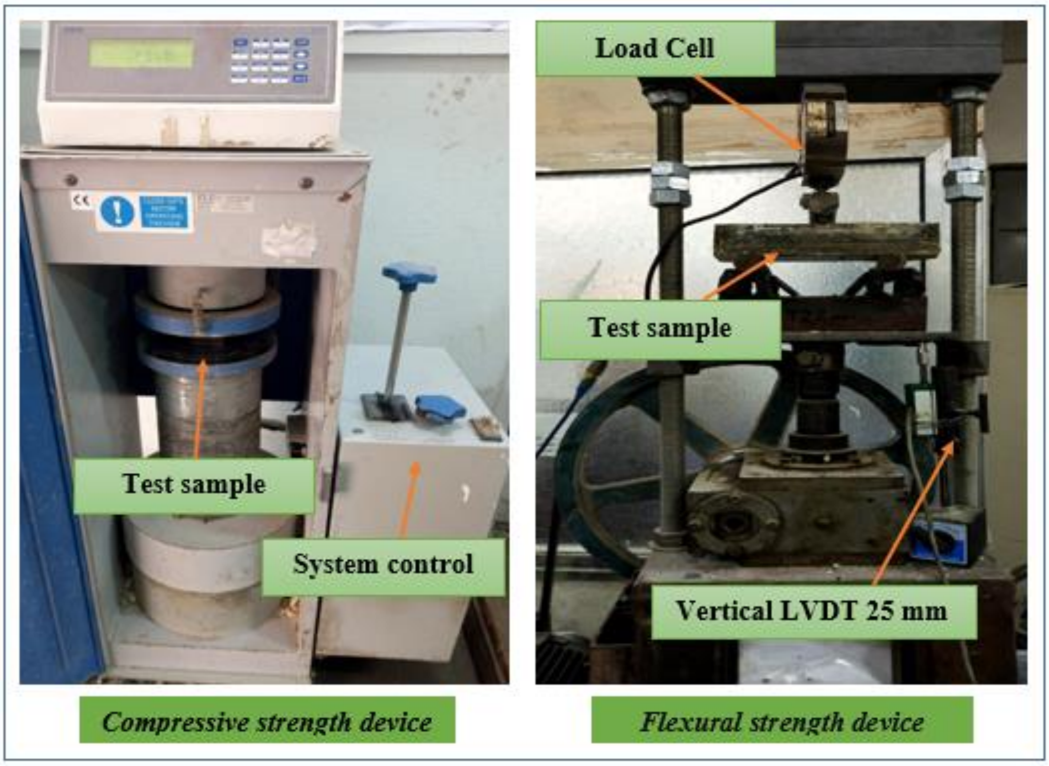


Plate (3-5): The devices used to test the grout

Plate (3-6): The mold of the flow cone test

3.5 Design of Semi-Flexible Mixtures

In this study, the optimization of the high performance SFP mixture was conducted in three stages: the first stage, is optimizing the cementitious grout material composition represented by (95% OPC+5% SF), (75% OPC+5% SF+20% EM), (55% OPC+5% SF+40% EM), (35% OPC+5% SF+60% EM). The second stage is designing a porous asphalt mixtures using modified asphalt (R-LDPE). The final stage is characterizing the SFP after injecting the cementitious grout materials into the PA specimens.

3.5.1 Preparation of Semi-Flexible Mixtures

After finishing the first and second stages of the semi-flexible mixtures design, the following is conducted:

1. The samples were wrapped in plastic food wrap membrane, then placed on a vibrator, and the cementitious grout materials are injected into the samples to ensure that they are thoroughly entered and injected well. The technique of injecting cementitious grout materials into the PA specimen is shown in Plate (3-7).
2. The samples were placed inside plastic containers that have been prepared in advance by placing aggregate inside it with a height of 10 cm and the water immersed the aggregate to make sure of the curing process. The specimen was stored in the humid container to the date of testing. Plate (3-8) shows the specimen of SFP prior to test.

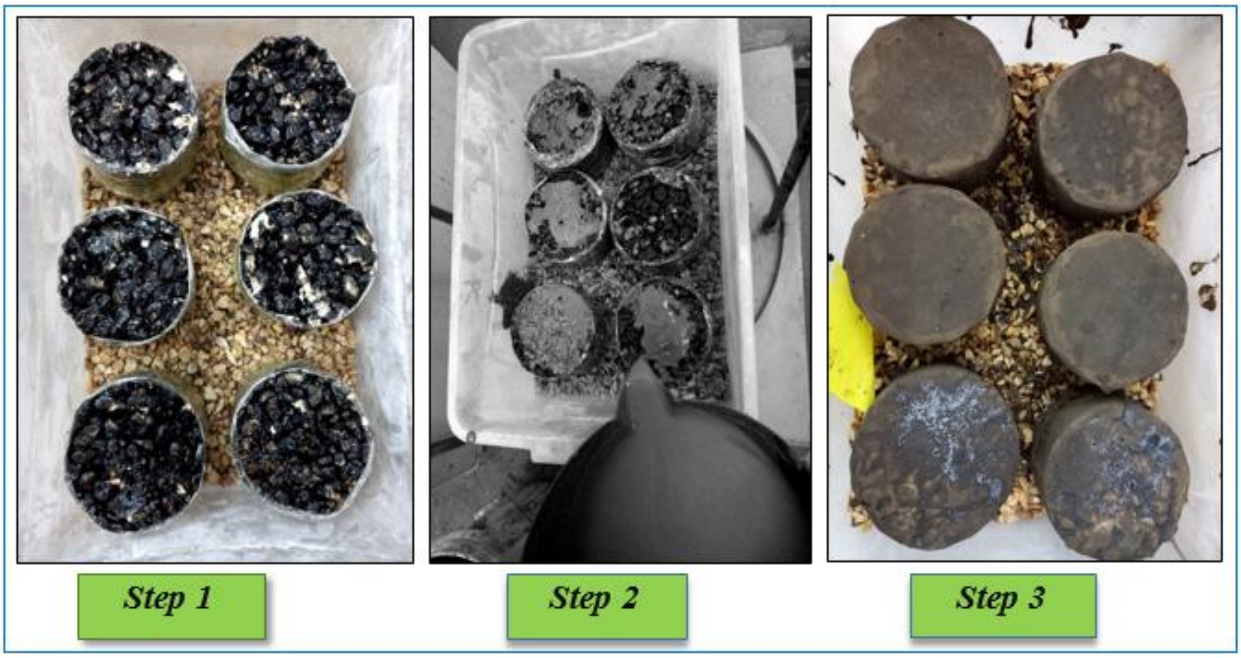


Plate (3-7): Preparation of semi-flexible mixture

Plate (3-8): Specimens of semi-flexible mixture

3.6 SFP Mixture Testing Methods

3.6.1 Volumetric Properties Tests

3.6.1.1 Air voids (AV) and effective porosity (EP)

The accessible and inaccessible pores in the compacted mixture are represented by air voids. Complete air voids in compacted PA mixtures should not be less than 18 %, according to ASTM D7064/D7064M(ASTM, 2013d), which can be measured using Equation (3-1). It is worth mentioning, that 18% and even 22% of the upper limit of OGFC were found unsuitable to ingress of grout through PA mixture, therefore, the recommended limit of 25-35 % has been followed (Zhang et al., 2016a). ASTM D3203/D3203M (ASTM, 2011) and ASTM D2041(ASTM, 2003b) were followed to determine bulk specific gravity (*Gmb*) and maximum theoretical specific gravity (*Gmm*) specific gravities respectively, These value are required to calculate percent of air voids in the total mixture. Effective porosity, on the other hand, is a form of pore that makes up a portion of total pores in PA mixtures. These pores refer to the part of the PA mixture that allows water to move through the porous skeleton to obtain its permeability property. The procedure followed to get the amount of these pores as used by Lyons et al. (2013) was employed. The dry weight of compacted Marshall Samples was measured after the dimensions of the samples were determined in terms of height and diameter. The compacted samples were then immersed for about 30 minutes in a water path with a temperature of 25°C. After that, each sample was rotated 180° and tapped five times on the bottom of the bath carefully to release the air voids, then rotated again 180°, then the submerged weight of the sample was recorded. Equation (3-3) is used to determine the effective porosity of the compacted PA mixture.

$$V_a = \left(1 - \frac{G_{mb}}{G_{mm}}\right) \times 100$$ Equation 3- 1

$$G_{mb} = \frac{W}{V * \gamma_W}$$ Equation 3- 2

$$Porosity = \left(1 - \left(\frac{W_{dry} - W_{sub}}{\rho_w V_T}\right)\right) \times 100$$ Equation 3- 3

where,

V_{A}: percent of air voids in total mixture,

G_{mb}: bulk specific gravity of compacted mixture,

G_{mm}: maximum theoretical specific gravity of a loose mixture,

W_{dry}: dry weight of the compacted sample,

W_{sub}: wet weight of the compacted sample in water,

ρ_w: density of water, and

V_T: total volume of the compacted sample.

3.6.1.2 Draindown test (DRT)

Draindown test measures the amount of bitumen removed from the mixture with a little amount of filler materials during mixture production, hauling and placing. The minimum acceptable level of draindown is 0.3% recommend by ASTM D7064/D7064M(ASTM, 2013d). This research was conducted using four samples, each of which was measured at two different temperatures: anticipated plant production temperature and anticipated plant production +15 as recommended by AASHTO T305 (AASHTO, 2001). The test was carried out on a loose mixture placed in a standard basket with 6.3 mm mesh and placed over a known weight pan as shown in Plate (3-9). The draindown sample then be conditioned for 1 hour and

5 minutes in a force draft oven, as shown in Plate(3-10), as recommended by AASHTO T305 (AASHTO, 2001). Following the completion of the conditioning process, the basket containing the sample and the pan were removed from the oven and allowed to cool down to room temperature. The weight of the asphalt and filler in the pan were then calculated. The draindown calculated using Equation (3-4).

$$Draindown\ (percent) = \frac{(D-C)}{(B-A)} \times 100 \qquad \text{Equation 3-4}$$

where:

A: mass of the empty wire basket,

B: mass of the wire basket and sample,

C: mass of the empty catch plate or container, and

D: mass of the catch plate or container plus drained material

Plate (3- 9); Draindown test basket and sample

Plate (3- 10): Force draft oven used.

3.6.2 Functional and Mechanical Properties Tests

3.6.2.1 Permeability test (K)

In the Permeability test, permeable aggregate allows the water to flow through it. The minimum level of permeability for OGFC according to the ASTM D7064/D7064M (ASTM, 2013d) is 100 m/day depending on the falling head principle. The procedure followed to conduct this test was implemented as suggested by ASTM D5084 (ASTM, 2003a). To perform this test a set of four Marshall compacted specimens with dimensions of 63.5 mm height and 100 mm diameter was used. The device shown in Plate (3-11) was used. To allow the water to flow in one direction, each specimen was only wrapped on one side with plastic film. The specimen was then secured in the stand pipe, which was then filled with water from the outlet to approximately 370 mm above the top surface of the specimen, and the specimen was left to be saturated for a while. The water is then allowed to flow through the specimen by opening the valve at the bottom of the stand-pipe, and the period of water flowing from 365 mm (h1) to 140 mm (h2) above the top surface of the specimen is measured using the stop-watch. For each specimen, the process was repeated three times for each specimen and the average time was calculated using Darcy's law in Equation (3-5)(Lyons et al., 2013). Although permeability is not required for SFP mixture, but it can be a vital tool to expect sufficient grout injection.

$$K = \frac{aL}{At} \ln\left(\frac{h_1}{h_2}\right) \qquad \text{Equation 3- 5}$$

where:

K: is permeability of the sample,

A: is the cross-sectional area of the specimen (80.91cm^2),

a: is the cross-sectional area of the stand pipe (81.71 cm^2),

L: is the height of the specimen,

t: time required for water to flow through the sample,

h_1: the head above the sample surface equal to 365 mm, and

h_2: the head above the sample surface equal to 140 mm.

Plate (3- 11): Laboratory permeability device used for permeability test

3.6.2.2 Indirect tensile strength test (ITS)

The indirect tensile strength (ITS) is one of the best test methods for determining the cracking resistance strength of asphalt mixtures under stress. The test procedure was performed on SFP mixtures at ages of 3, 7, and 28 days based on the AASHTO T283 (AASHTO, 2003a), using set of three samples to assess the specimen's resistance to cracking. The Marshall specimen was subjected to a constant rate of compressive load, and the load's effect on the specimen was measured in two directions using two different LVDT sizes (vertical LVDT with 25 mm displacement and two horizontal LVDT with 10 mm displacement). Equation (3-6) was used to calculate the tensile strength of the specimens, and Table (3-11) summarizes the limitation of this test. Plate (3-12) shows the device used in the laboratory.

$$ITS = \frac{2000\,P}{\pi\, t\, D}$$ Equation (3- 6)

where:

ITS: tensile strength, Kpa,
P: maximum load, N
t: specimen thickness, mm, and
D: specimen diameter, mm

Table(3- 11): Indirect tensile strength test limitations according to AASHTO T283 (AASHTO, 2003a)

Parameters	***Standard limits***	***Test condition***
No. of specimens	3	3
Rate of loading, mm/min	50 ± 5	50
Measuring device accuracy, N	Min. 0.01	0.01
Test temperature, ºC	25 ± 2	25
Specimen diameters, mm	150 ± 9	100
Thickness specimen, mm	38 - 50	63.5 ± 2.5
Compaction (Marshall Hammer)	50 blow each face	20 blow each face
Specimen conditioning before the test	2 hr. in oven-dry @ 25 ºC	2 hr. in oven-dry @ 25 ºC
Curing	24 hr. in the mold at lab temperature	24 hr. in the mold at lab temperature, then tested at either 3,7, or 28 days

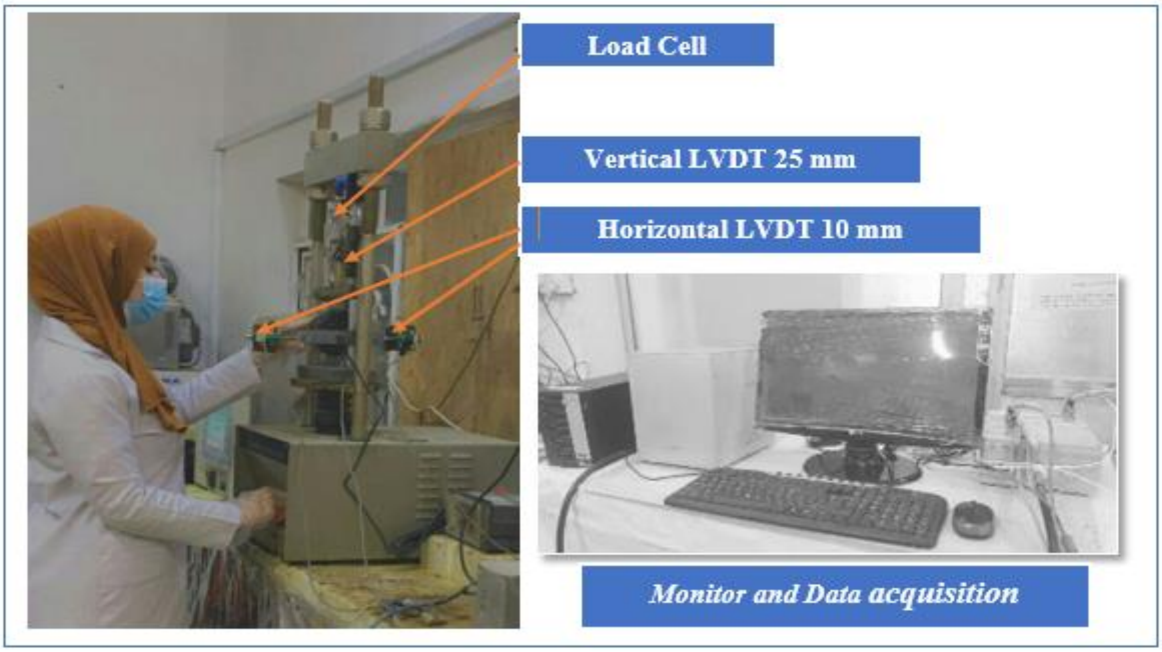


Plate (3- 12): indirect tensile strength device used.

3.6.2.3 Creep compliance test (CCT)

Creep Compliance is characterized as strain per unit stress and it is time-dependent. The test procedure was performed on SFP mixtures at ages of 3, 7, and 28 days based on the AASHTO T322 (AASHTO, 2003b). This test is widely used to determine the rate of the accumulative damage in asphalt mixtures, where the creep compliance curve represents the time-dependent behavior of asphalt mixture (Sheikhmotevali et al., 2014) . For a given time, a static load is applied along a diametric axis of a temperature-controlled specimen (1000 seconds). During the loading period, vertical and horizontal deformations are measured by using LVDTs as shown in Plate (3-13). Equations (3-7, 8 and 9) are used to calculate creep compliance parameter, and the test limitations are summarized in Table (3-12).

$$CC_{(t)} = \frac{\Delta X \times D_{avg} \times b_{avg}}{GL \times P_{avg}} \times C_{cmpl}$$ Equation 3- 7

where:

$CC_{(t)}$: creep compliance at time t, 1/Kpa

ΔX: trimmed mean of the horizontal deformations, mm

D_{avg}: average specimen diameter, mm

b_{avg}: average specimen thickness, mm

P_{avg}: average force during the test KN,

GL: gage length, mm, and

C_{cmpl}: creep compliance parameter at any given time, computed as:

$$C_{Cmpl} = 0.6345 \times \left(\frac{X}{Y}\right)^{-1} - 0.332$$ Equation 3- 8

where:

X/Y is the ratio of horizontal to vertical deformation, taken at mid testing time.

The limitations of the Ccmpl value as shown in the following equations:

$$\left[0.704 - 0.213\left(\frac{b_{avg}}{D_{avg}}\right)\right] \le C_{Cmpl} \le \left[1.566 - 0.195\left(\frac{b_{avg}}{D_{avg}}\right)\right]$$ Equation 3- 9

Table (3- 12): Creep compliance test limitations according to AASHTO T322 (AASHTO, 2003b)

Parameter	***Standard limits***	***Test condition***
Ram movement (vertical), mm/min	12.5	12.5
Device accuracy	0.001N	0.001N
Strain rate, mm	0.00125-0.019	Within rang
Testing time, sec	100 ± 2 or 1000 ± 20.5	1000 ± 20.5
Testing temperature, ℃	0, -10, -20, +10	0
No. of specimens	3	3
Specimens diameter, mm	150 ± 9	100
Specimens height, mm	38 - 50	63.5 ± 2.5
Compaction (using Marshall hammer)	Compacted to 7 ± 0.5% air voids	Compacted using 20 blow each face

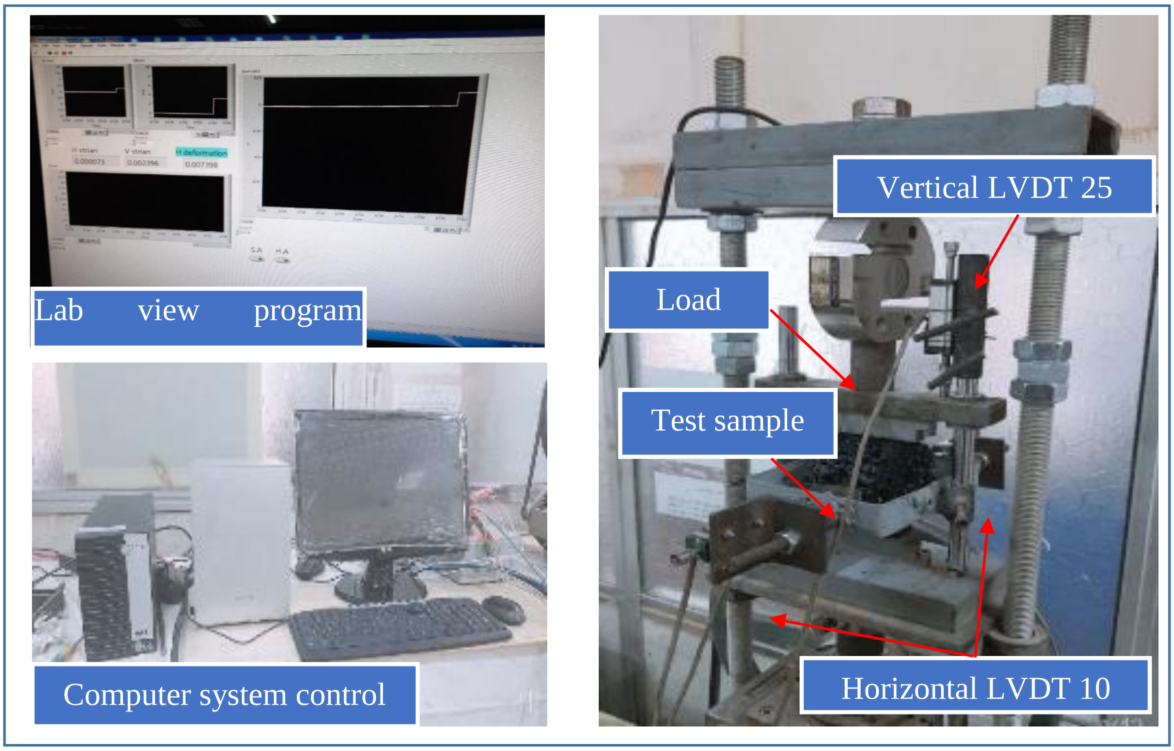
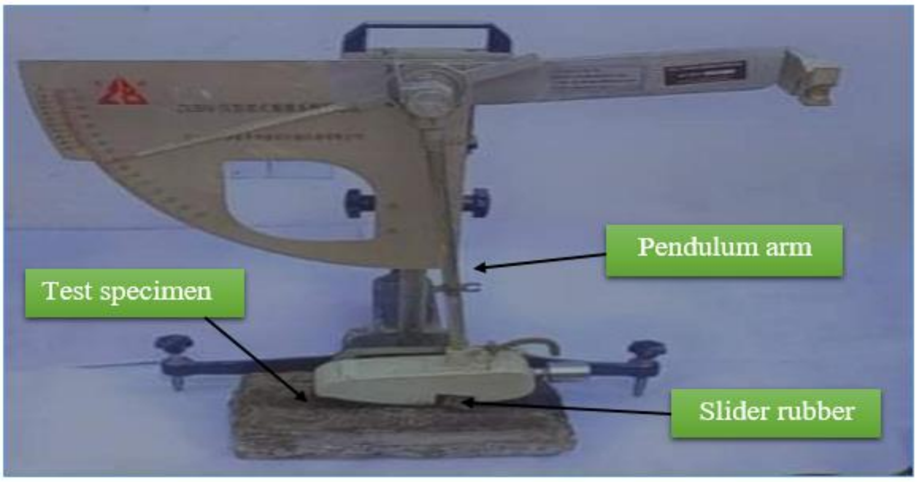


Plate (3- 13): Laboratory Creep compliance device used.

3.6.2.4 Skid resistance test (SRT)

The resistance of the asphalt pavement surface to slipping vehicle tires is measured by means of skid resistance. When a tire slides on a road surface, it creates a relationship between horizontal and vertical forces. Skid resistance was measured using British Pendulum skid resistance according to ASTM-E303(ASTM, 2013e). For each specimen in the dry condition, four readings were taken, and then the sample was moistened by spraying it with water, and readings were taken for the wet surface as well. The same samples were used in this test as in the wheel track test (as will be explained later). Plate (3-14) shows British Pendulum skid resistance tester



Plate(3-14): British Pendulum Device in Highway Lab at the University of Kerbala.

3.6.2.5 Wheel track test (WTT)

The wheel track test (WTT) simulates the action of asphalt mixtures under repeated wheel loads in operation. The test procedure was carried out according to the BS EN 12697-22:2003 code (BSI, 2003). The rut depth of SFP mixtures was determined using an average of two small slab samples. The used slabs having dimensions of 300×165×40 mm, with a minimum air voids content of about 30 %, that resulting by using vibratory compaction procedure according to the procedure recommended by BS EN 12697-32:2003code (BSI, 2003) and by following a number of trials as it can be seen in Figure (3-2), which indicate that 1 min of vibratory compaction is sufficient to reach the required air void level. Plate (3-15) shows the specimen in the mold and specimen of slab after grouting. Small size device shown in Plates (3-16, 17) was used to perform this test.

To understand the ability of SFP mixture to resist repeated load permanent deformation at high service temperature, each sample was first conditioned at 60 °C before performing the test to simulate the critical performance requirements. To simulate the effect of repeated load, a number of 52 pass/min and a total of 10,000 passes were used; the test criteria were mentioned in Table (3-13). The rut depth and rate of rut were determined by a wheel track test, which also provided information for calculating the dynamic stability of asphalt mixtures. The number of wheel passes within a specified time that causes a unit rut depth in asphalt mixtures is called Dynamic stability (DS)(Read et al., 2003). Equation (3-10) was used to compute the DS.

$$DS = \frac{N_{15}}{D_{60} - D_{45}}$$ Equation 3- 10

where:

DS: dynamic stability, (passes/mm)

N_{15}: no. of wheel passes after 15 min of testing, passes, and

D_{60} - D_{45}: the change in rut depth at the last 15 min of testing, mm

Table (3- 13): Limitations of wheel-track test according to BS EN 12697-22:2003 code (BSI, 2003)

Parameter	***Standard limits***	***Test condition***
No. of required specimens	2	2
Diameter of wheel	200 - 205	200
Wheel width, mm	50 ± 5	50
No. of wheel passes per min.	50 ± 5	52
Speed of wheel, cycle/min	26.5 ± 1	26
Load on the wheel, N	700 ±10	700
Specimen thickness, mm	25 - 80	40
Air voids content specimens, %	4 or 7	18-22
Test temperature, ºC	40± 2 to 60 ± 2	60
Specimens type	Slab/beam or Cylinder	slab
Specimen dimensions, mm	300 × 260	300 × 165
Compaction	Depended on the required air voids 25-35%	1 min, Figure (3-4)

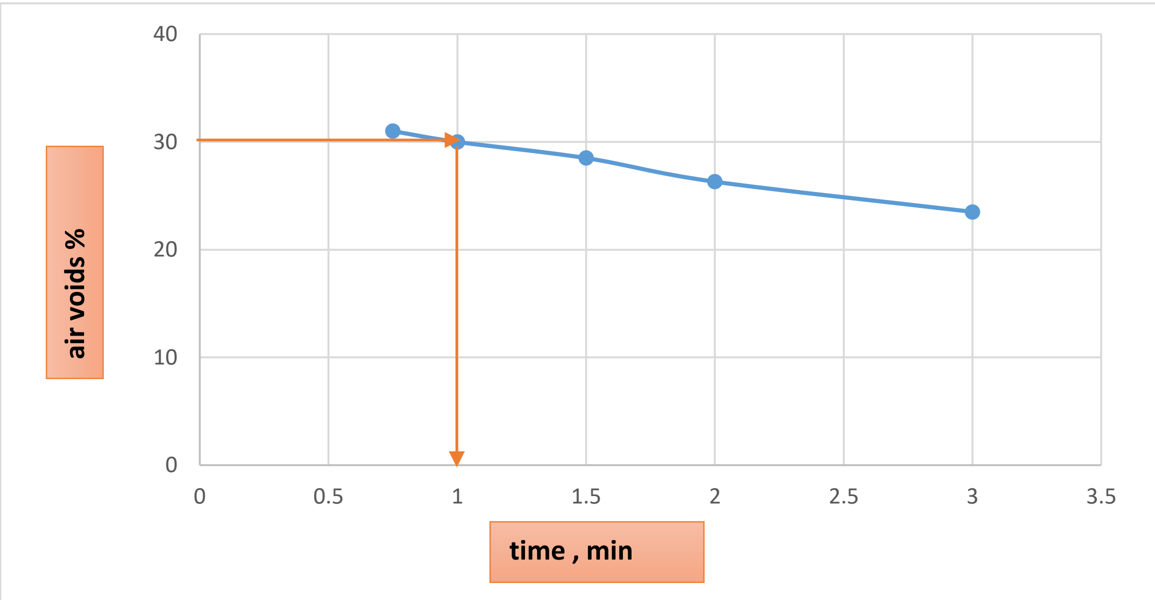


Figure (3-2) Compaction time trials of wheel track slabs

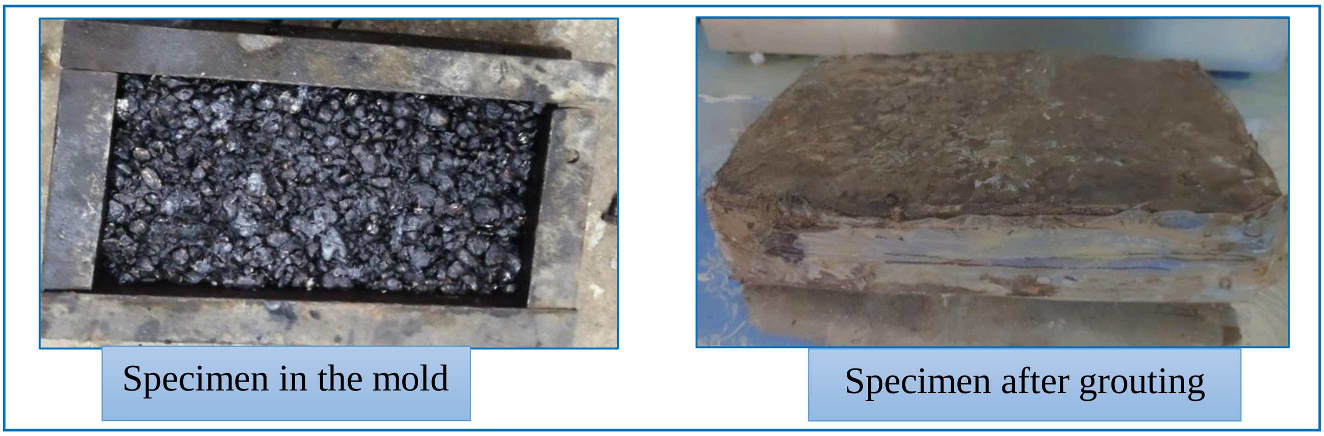


Plate (3-15): shown specimen in the molded and after grouting

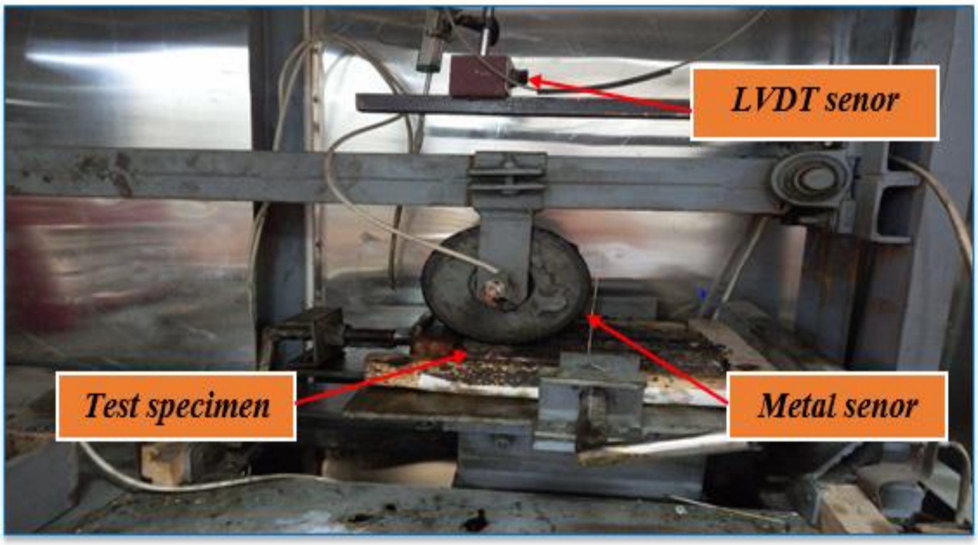


Plate (3- 16): Apparatuses for Wheel Track Device

Plate (3- 17): Computer System for Wheel Track Device

3.6.3 Durability Properties Tests

3.6.3.1 Cantabro loss test (CLT)

Cantabro test gives an indication about the resistance of asphalt mixtures to degradation (resistance to raveling). The test was performed on SFP mixtures at ages of 7days according to ASTM D7064/D7064M(ASTM, 2013d) and as have been used by other researchers, for example,(Alvarez et al., 2012, Al-Jawad et al., 2019, Chen et al., 2013, Mansour et al., 2013). To complete the test criteria for the unaged Cantabro loss (UCL) condition, three specimens were used. The cylindrical specimens were fabricated using Marshall Hammer with 20 blows effort on each face. Using an abrasion machine and the samples in Plates as an example (3-18, 19). Before performing the test, the specimens should be put in an oven for four hours at a temperature of (25 ± 5) °C. After that, samples were placed into abrasion machine without steel balls, and then it was operated for 300 revolutions at 10 min period and at speed ranged between (30-33) revolution/min. Subsequently, the loss percentage of the specimen's weight was calculated using Equation (3-11), the percentage represents the resistance of asphalt mixture to raveling. ASTM D7064/D7064M (ASTM, 2013d) recommend that the percent of loss of specimen’s weight should be not more than 20% for UCL and 30% for aged samples, Table (3-14) summarizes the characteristics of this test.

Table (3- 14):Cantabro test characteristics according to ASTM D7064/D7064M (ASTM, 2013d)

Parameter	***Standard limits***	***Test condition***
No. of samples required	6	6
Specimens diameter, mm	101.5-101.7	100
Specimens thickness, mm	63.5 ± 2.5	63.5
Compaction effort, Marshall hammer	50×2	20×2
Time of preparing specimen prior to conducting the test	4 hours	4 hours
Test temperature	(25 ± 5) °C (77 ± 10) °F	(25 ± 5) °C
No. of revolutions	300	300
Operating speed, revolution/min	30-33	30-33

$$P = \left(\frac{P_1 - P_2}{P_1}\right) \times 100 \qquad \text{Equation 3- 21}$$

where:

P: abrasion loss percentage,
P_1: specimen weight before abrasion test
P_2: specimen weight after abrasion test

Plate (3-18): specimen for testing

Plate (3- 19): Los Angeles Abrasion Machine.

3.6.3.2 Tensile Strength Ratio (TSR)

Damage caused by moisture is one of the most disturbing problems of asphalt pavements. TSR can be obtained by following the procedure mentioned in AASHTO-T283(AASHTO, 2007a). The conditioned specimen were immersed in a water bath at 60°C for 24 hrs. Finally, the specimens were placed in a water bath at 25°C for 2hr prior testing In this test, measuring the tensile strength ratio (TSR) by

ITS at age 28 days of conditioned samples to ITS at age 28 days of unconditioned samples is used as a criterion for water damage resistance assessment shown below as mentioned in AASHTO-T283(AASHTO, 2007b) , as can be clarified in Table (3-15). Nevertheless, the value of conditional over an unconditional strength ratio of not less than 70% depending on to Iraqi specification GSRB/R9 was adopted (GSRB, 2003). TSR is obtained according to the Equation (3-12).

Table (3-15): Water damage testing condition

Item	Range
No. of required specimens	6
Rate of loading, mm/min	50 ± 5
Measuring device accuracy, N	Min. 0.01
Test temperature, ºC	25 ± 1
Specimen diameters, mm	101.6
Thickness specimen, mm	72.2
Compaction (Marshall Hammer)	20 blow each face
Unconditioned specimen protocol	2 hr. in oven-dry @ 25 ºC after 28 days
Conditioned specimen protocol	24 hr. in water bath at 60 ± 1 ºC + 1 hr. in water bath at 25 ± 1 ºC

$$TSR = \frac{S2}{S1} \qquad Equation\ 3\text{-}12$$

Where:

TSR= Tensile Strength Ratio.
S1=Average tensile strength of the dry subset KPa.
S2=Average tensile strength of the conditioned subset KPa.
The accepted values ranged between (0.7 - 0.9).

3.8 Methodology

To achieve the main aim of this research, the methodology involves developing SFP mixtures through four stages. The flowchart in Figure (3-3) illustrates the research methodology, which involves the following stages

1. Identifying development opportunities about semi flexible mixtures through reviewing current practice and global research attempts.
2. Designing of cementitious grout materials conventional and modified with EM.

3. Designing of porous asphalt mixtures using 4% asphalt and modified the mixtures using 3% of w-LDPE.

4. Investigating the volumetric, mechanical and durability properties of developed SFP mixtures.

5. The final step displays the observed conclusions and recommendations for future work.

Table (3- 16): Tests matrix of different SFP mixtures.

Tests		Traditional mixtures	Reference mixtures	SFP mixture types			
		OAC, %	w-LDPE %				
		4%	3%	M2	M4	M5	M6
Volumetric Properties	VCA	✓	✓	✓	✓	✓	✓
	AV	✓	✓	✓	✓	✓	✓
	VMA	✓	✓	✓	✓	✓	✓
	VFA	✓	✓	✓	✓	✓	✓
	EP	✓	✓				
	DRT	✓	✓				
Functional and mechanical properties	K	✓	✓				
	ITS	✓	✓	✓	✓	✓	✓
	CCT	✓	✓	✓	✓	✓	✓
	SRT	✓	✓	✓	✓	✓	✓
	WTT	✓	✓	✓	✓	✓	✓
Durability properties	TSR	✓	✓	✓	✓	✓	✓
	CLT	✓	✓	✓	✓	✓	✓

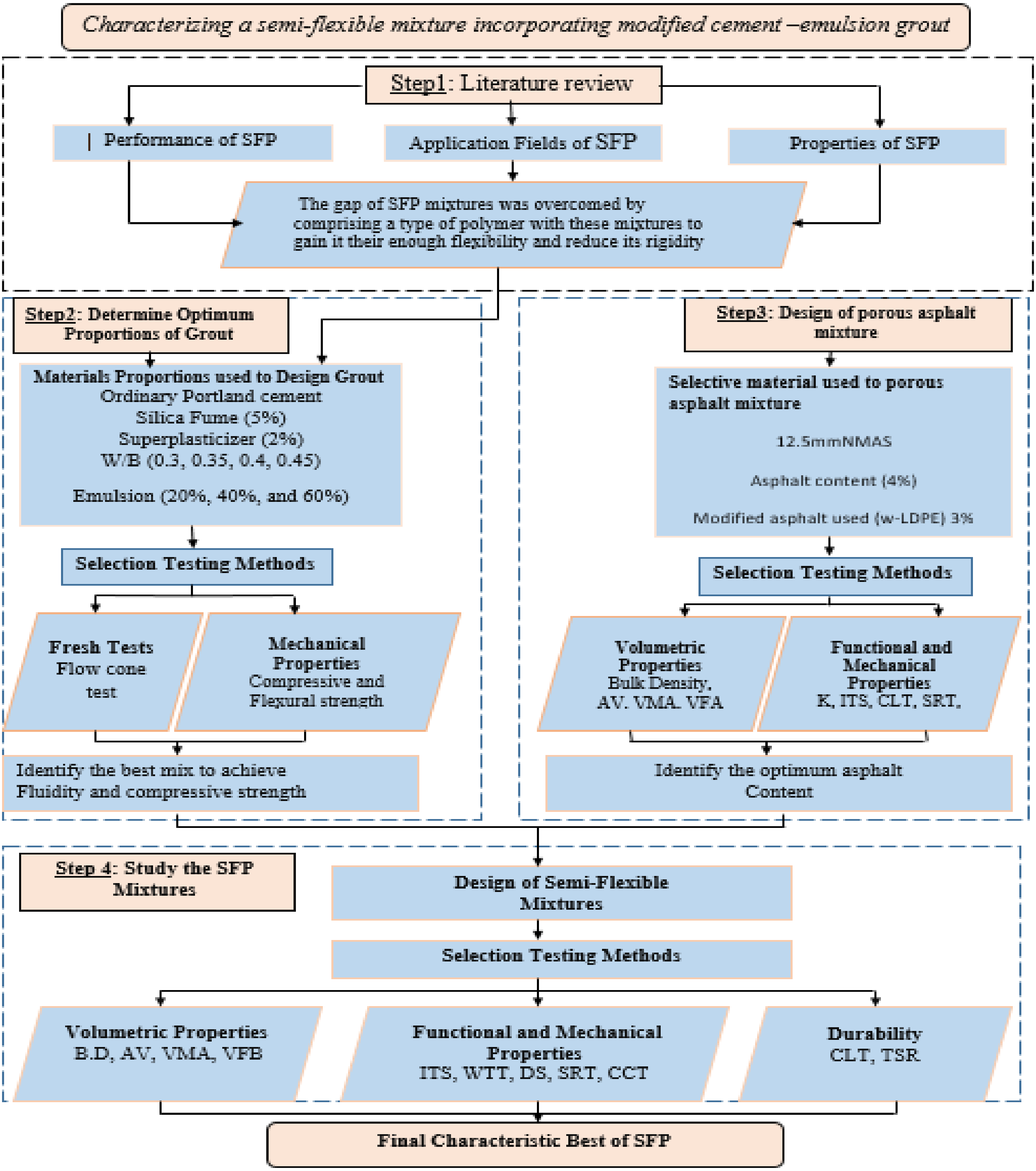


Figure 3- 3: Flowchart of the followed methodology

3.9 Summary

This chapter gives an overview about the materials used in this research to design the SFP mixtures including: aggregate gradation, fillers, neat bitumen, ordinary Portland cement, and super-plasticizer, Silicafume, water, asphalt emulsion, and additives materials. The SFP mixed was developed on cementitious grout material design and porous asphalt mixture design. In addition, information related to the preparation of modified bitumen was provided and design of cementitious grout. All available laboratory tests were demonstrated, including volumetric, functional, mechanical and durability tests, all of which are important in characterizing SFP mixtures in order to understand their performance. In addition, a perspective on the tests matrix and the methodology used in this study to achieve the research aim was illustrated.

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Chapter four

Results and discussion

4.1 Introduction

The findings of the laboratory tests are given and discussed in this chapter. These studies are carried out to determine the impact of cementitious grout materials on the properties of SFP mixtures.

4.2 Cementitious Grout Materials

This section includes a discussion on the results of examining the cementitious grout which include the examination of fluidity, compressive strength, and flexural strength.

4.2.1 Fluidity of Cementitious Grout Materials

Table (4-1) and Figure(4-1) show the result of the fluidity for all mixture. The results reveal that the fluidity of mixes M0 to M3 (stage one: identifying optimum W/B ratio for conventional grout), which contain variable percentages of W/B, show the increase the percentage of W/B due to increases the flow time; the maximum flow value is 19 s, created by 30% of W/B, and the lowest flow value is 9 s, created by 45 % of W/B. It is worth mentioning that previous studies (e.g., Koting et al Koting et al. (2014a), Husain et al (2014a)) recomended flow time of 11 s to 16 s as an acceptable limit to ensure suffecient grout penteration. Obiviousley, mixtures M1and M2 within this range, whereas mixtures M0 and M3 are not. The increase in W/B ratio stimulates the grout mixtures to become more liquid and flow easier, as shown in the analysis. This factor will allow more grout slurries to exit the flow cone tester's discharge tube more quickly, which agree to (Koting et al., 2014b). Therefore, including SP in the grout is required to improve the workability of the cement slurries and to minimize the high W/B ratio, as recommended by previous study (Hassan et al., 2017). Accordingly grout slurries with a W/B ratio of 0.40 to 0.45 have a higher workability. The SP allows for improved cement particle dispersion, resulting in a more fluid paste. The water concentration of the mix was found to be a factor affecting workability in a study, because merely adding water increases the interparticle lubricant. Because the flow time is inversely related to the water content, the larger the W/B ratio, the lower the viscosity.

The result of mixtures from M4 to M6 showed that the flow time increased with the increase of emulsion but the fluidity decrease, the results is agree with previous research (Zarei et al., 2020). This result suggests that lower emulsion ratios can be used to achieve high fluidity or decrease flow time. Because emulsion develops during the coalescence process, which reduces the workability, increasing the fraction of emulsification lengthens the flow time. According to the range of flow time from 11 s to 16 s suggested from previous researchers of Koting et al (2014a), Husain et al (2014a), the mixture M4, M5 and M6 are within the range. The W/B ratio of 40% is selected with those mixes with grouts having emulsion because it took less time and was within the range required, and it did not show less than 11 seconds because the material became filled with water and air, preventing cement penetration. Emulsion is suggested in the mix to make ductile grout, to minimize the brittleness, and to reduce the ability of quickly breaks of the traditional cement grout. Moreover, the asphalt has a long-life expectancy.

Table (4-1): Fluidity of cementitious grout

Mix	stage	OPC (%)	EM (%)	SF (%)	W/B (%)	SP (%)	Flow Time (Control/developed mix), %
M0 (control)	one	95	0	5	0.3	2	100
M1		95	0	5	0.35	2	126.6
M2		95	0	5	0.4	2	172.7
M3		95	0	5	0.45	2	211.1
M2(control)	two	95	0	5	0.4	2	100
M4		75	20	5	0.4	2	100
M5		55	40	5	0.4	2	91.6
M6		35	60	5	0.4	2	84.6

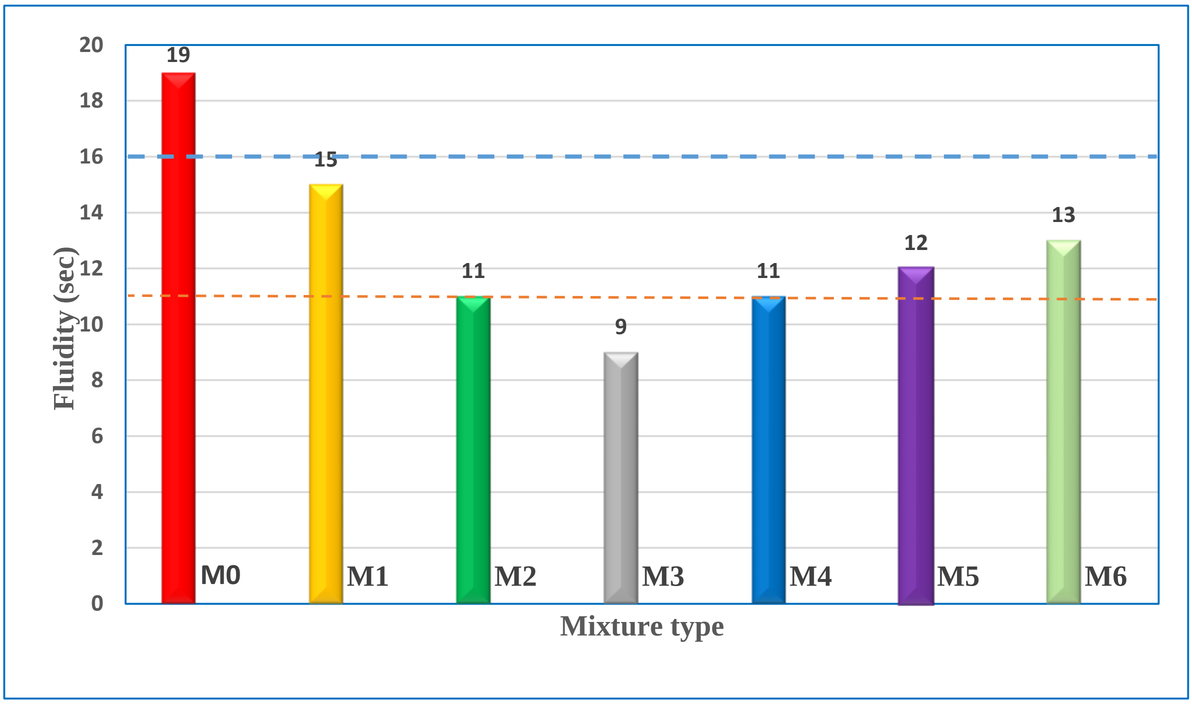

Figure (4-1): Fluidity of cementitious grout

4.2.2 Compressive Strength of Cementitious Grout Materials

The compressive strength for grouts at different W/B ratios are shown in stage one of Table (4-2), Figure (4-2), at 3, 7, 14, 28, 56, and 96 days and Figure (4-4) shows the compressive strength of all grouts at age of 28 days. The compressive strength for all mixes increased with age from M0 to M3, indicating that cement requires time to complete its hydration process and acquire substantially mature strength (Hlail et al., 2020a). This is intriguing because SF is known to boost the compressive strength of concrete mixtures. All mixes obtained the majority of their compressive strength at an early age (14 days); after 28 days, the gains in strength are less visible. The highest compressive strength can be achieved when using 40% W/B, which is considered the best, after that, the compressive strength decreases due to the silica fume, and the cement added requires enough water to complete the hydration process. To some extent, the increase in water causes a decrease in the compressive strength because the water will occupy a space if it does not dry out, and these voids will be weak points. On the other hand, as the W/B ratio increases and the flow time decreases, the compressive strength of the M3 mix decreases. As a result, the ratio of added water and resistance must be balanced.

Table (4-2): Compressive strength for different ages

Mix	stage	Control/developed mix (%)					
		3 days	7 days	14 days	28 days	56 days	96 days
M0 (control)	one	100	100	100	100	100	100
M1		44.9	77.9	82.5	81.6	81.3	84.3
M2		39.6	74.1	74.5	74.4	70.0	73.4
M3		48.1	95.0	91.3	83.7	81.4	84.7
M2 (control)	two	100	100	100	100	100	100
M4		407.5	329.3	255.1	235.9	214.2	182.5
M5		580.8	481.7	340.0	331.4	268.5	227.6
M6		749.8	700.9	404.0	391.5	335.6	278.0

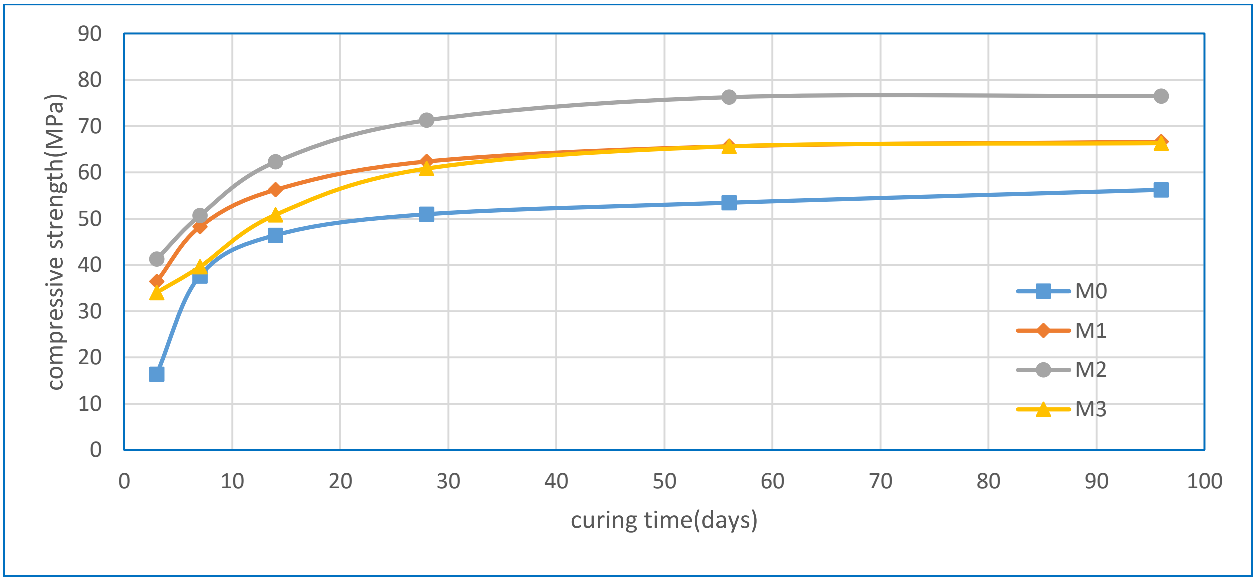

Figure (4-2): Compressive strength of grouts comprising different W/B ratios

Figure (4-3) and stage two of Table (4-2) show the compressive strength of grout comprising emulsion. With increasing emulsion, the compressive strength of the pastes (M4, M5, and M6) reduces. Because asphalt is softer than cement hydrates, the compressive strength of grouting pastes reduces with increasing asphalt emulsion percentage, as evidenced by earlier research (Ouyang et al., 2018), This is because the emulsifier in asphalt emulsion has a big influence on cement hydration at an early age. Furthermore, the development of an asphalt emulsion film, which is determined by curing time, is linked to the compressive strength of mixtures. As a result, adding asphalt emulsion to a standard mixture reduces both the compressive strength and the rate of hardening. As the coalescence process happens, which is emulsions droplets are naturally unstable and insoluble in water; over time, the addition of water from the emulsion impacts the resistance to compression (it could be hours or years). The bitumen phase will eventually separate from the water and degrade causing the droplets to clump together. The production of bitumen emulsion droplets is triggered by small charges from two sources: the emulsifier and the ionic components in the bitumen itself. As a result of these tiny charges, an electrostatic barrier forms on the surface of the droplets, preventing bitumen droplets from approaching each other. As a result, flocculation occurs when the energy of bitumen droplets exceeds the electrostatic barrier causing droplets to approach and adhere. This flocculation can be avoided in a variety of methods including the inclusion of additives, agitation and dilution.

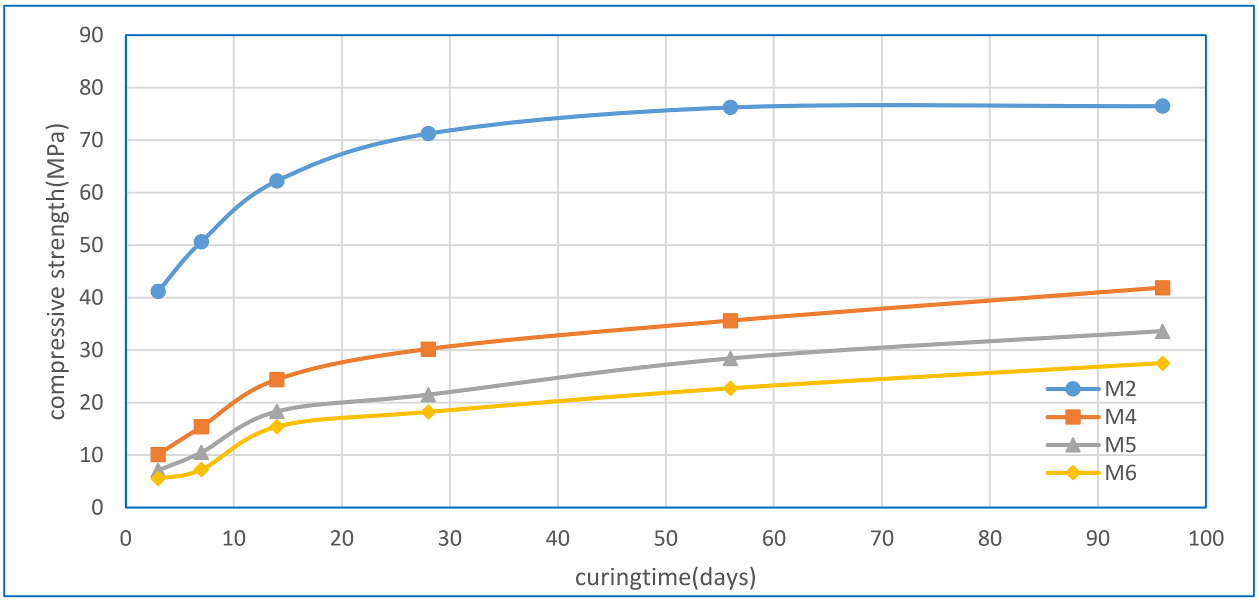

Figure (4-3): Compressive strength of grouts comprising emulsion.

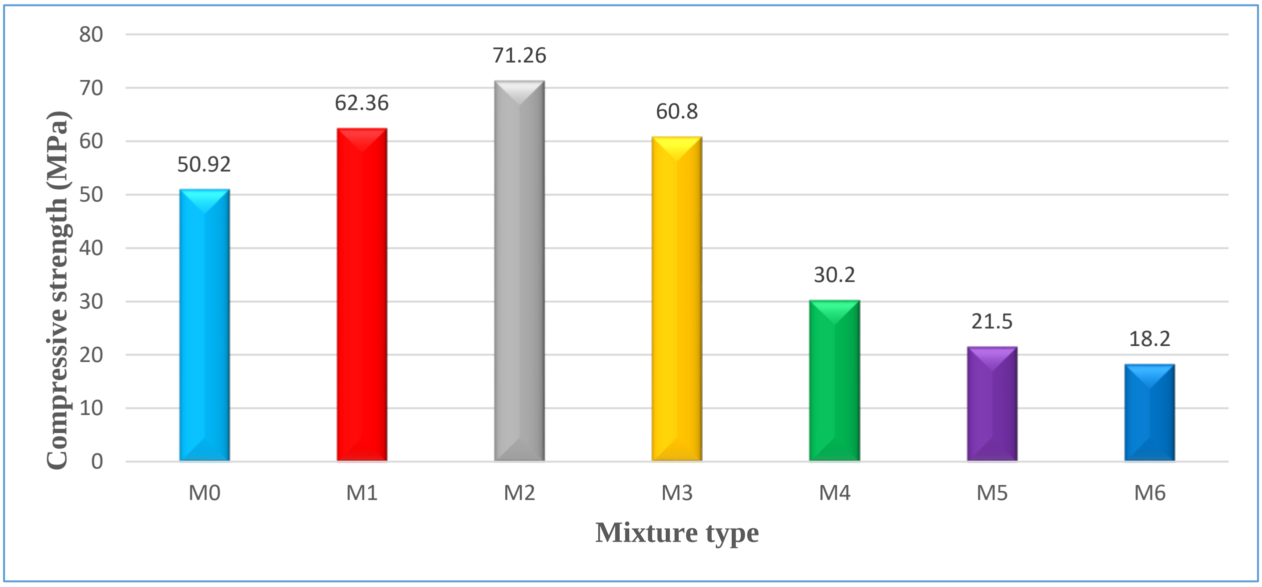

Figure (4-4): Compressive strength for all pastes at age of 28 days.

4.2.3 Flexural Strength of Cementitious Grout Materials

The flexural strength of cementitious grout is shown in Table (4-3) stage one, and Figures (4-6,7). The results show that the flexural strength for the mixture of (M0-M3) increases with the increase in the age, whereas the mixture containing 40% W/B have the highest flexural strength, compared by Koting et al. (2014b) that showed the using of 30% W/B supplied the highest flexural strength. However, mix ingredients' properties control such ratio. Adding a suitable dose of SP to grout mixtures will improve their ability to permeate into unfilled compacted skeletons under gravity. The addition of SP improves cement dispersion, resulting in higher fluidity.

The results of the mixtures (M4-M6) show that the flexural strength decreases with the increase in the emulsion percentage, and using 20% of emulsion indicate the highest flexural strength. Conversely,Zarei et al. (2020) showed that the highest flexural is gained when 60 % emulsion is used, and that the adding asphalt emulsion does not have a harmful effect on paste flexural strength. In this research, the emulsion had a significant negative impact on flexural strength which is normal as the hydration process is affected due to the presence of emulsifier that is coating the cement particles.

Table (4-3): Flexural strength of cementitious grout at 28 days

Mix	Stage	OPC%	W/B (%)	SF%	EM%	SP (%)	28 days (control/ Developed mix), %
M0 (control)	one	95	0.3	5	0	2	100
M1		95	0.35	5	0	2	91.9
M2		95	0.4	5	0	2	69.9
M3		95	0.45	5	0	2	81.8
M2 (control)	two	95	0.4	5	0	2	100
M4		75	0.4	5	0.2	2	144.5
M5		55	0.4	5	0.4	2	241.5
M6		35	0.4	5	0.6	2	261.0

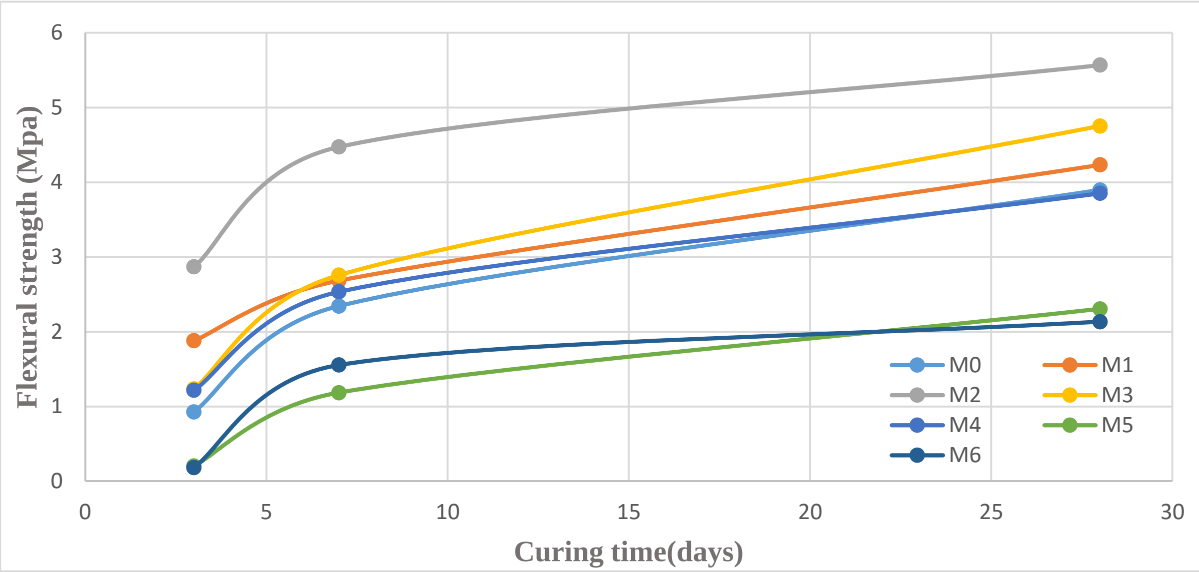

Figure (4-5): Flexural strength of all mixtures of cementitious grout.

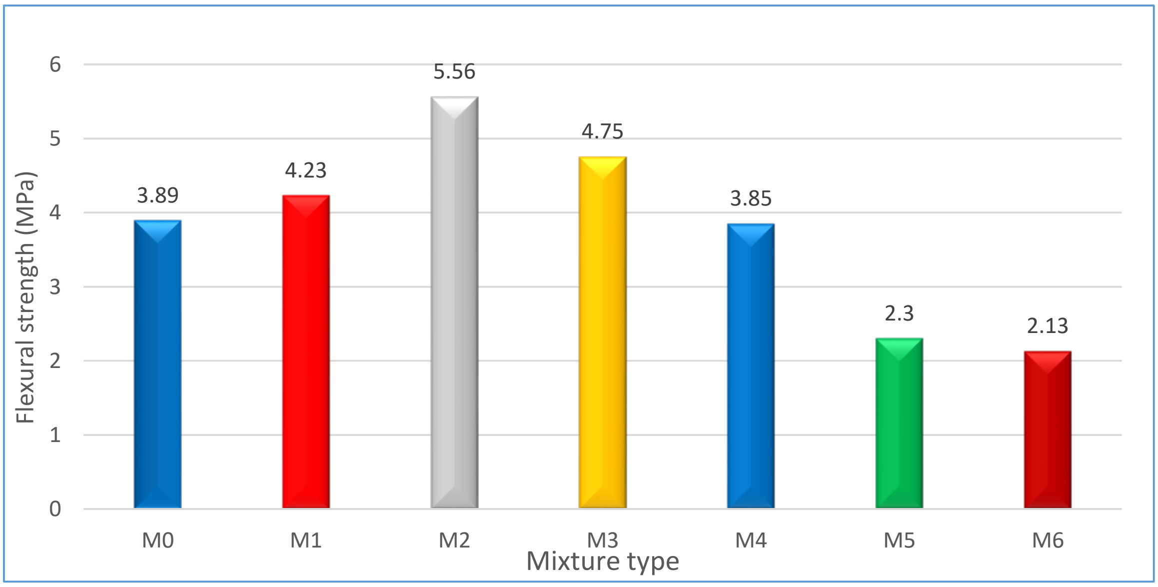

Figure (4-6): Flexural strength of cementitious grout at 28 days.

4.3 Characterization of Porous Asphalt Mixtures

4.3.1 Volumetric Properties

Figure (4-7) shows the result of bulk density of control mixture (CM) and modified mixture (MM). The results show that using w-LDPE as an asphalt stabilizer material reduced slightly the bulk density (BD) of PA combinations below the CM. This could be due to a change in asphalt viscosity characteristics. Because modified binder (MB) has a higher viscosity than neat binder (NB). Figure (4-8) shows the result of air void and effective porosity of CM and MM. The result indicates that the used of w-LDPE leads significantly to increase the air void and the porosity. This finding sustains the trend of obtaining acceptable volumetric properties that ensure penetration of grout easily, especially the result of porosity where the improvement more significant.

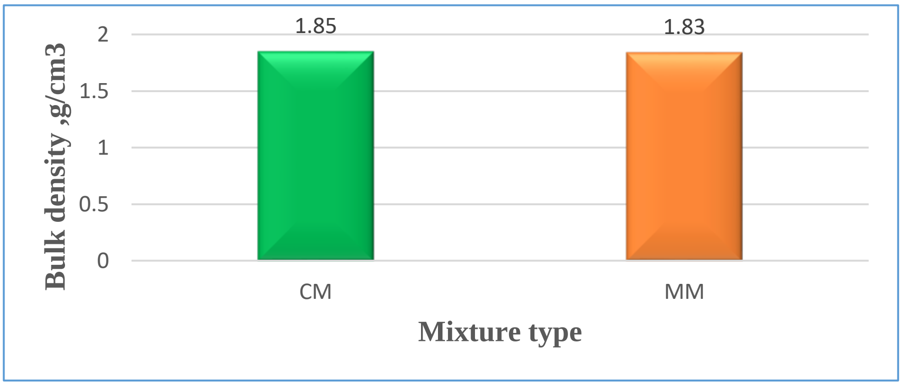

Figure (4-7): Bulk density of modified and unmodified PA asphalt mixtures

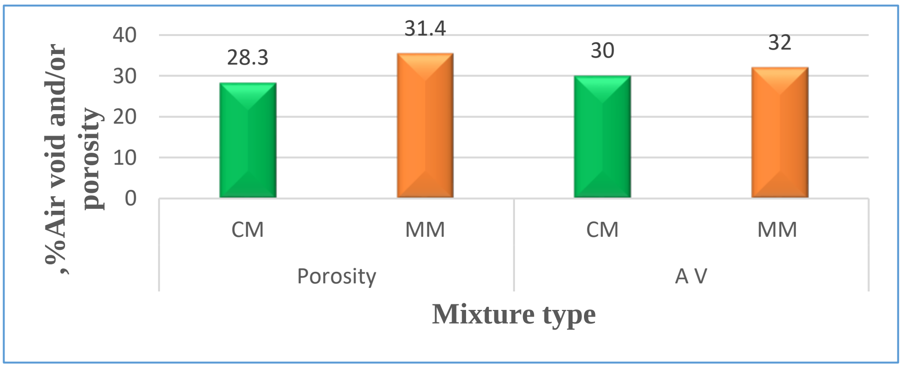

Figure (4-8): Air voids effective porosity of modified and unmodified PA mixture

Figure (4-9) shows the results of voids in mineral aggregates (VMA) and voids filled with asphalt (VFA) for CM and MM. The usage of recycled additives materials such as w-LDPE has an effect on the amount of VMA and VFA, according to the findings this also sustain the requirements. For example, it can be seen that the methods of modification tend to raise VMA, and the amount of increment appears to be closer between them, resulting in an increase in VMA according to CM. The VFA of MM increased compared to CM. In summary, the role of stabilization playing by w-LDPE is effective.

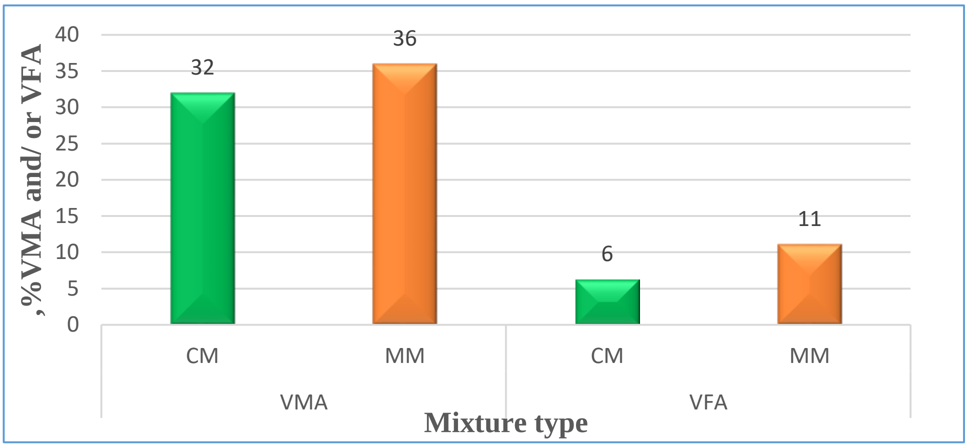

Figure (4-9): VMA and VFA of modified and unmodified PA mixture

Figure (4-10) shows the result of drain dawn of CM and MM following a one-hour conditioning period in a forced-draft oven, while Plate (4-1) shown the result of draindown of CM and MM of PA mixture at 165℃ and 180℃ . The test determines whether modification materials are successful in preventing binder runoff. ASTM D7064/D7064M (ASTM, 2013c) recommend that the amount of draindown of PA asphalt mixtures should be not more than 0.3%. The results show that using additives lowered the amount of draindown as compared to the CM at various levels.

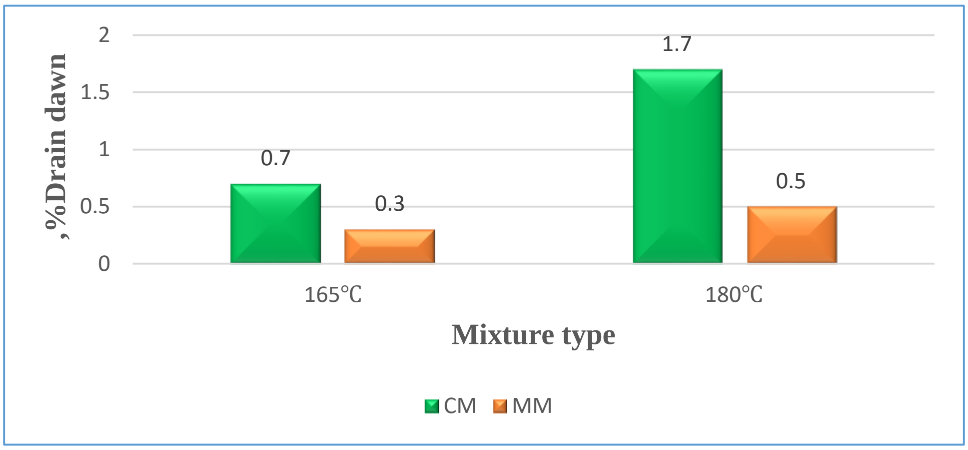

Figure (4-10): Draindown amounts of CM and MM of PA at 165℃ and 180℃.

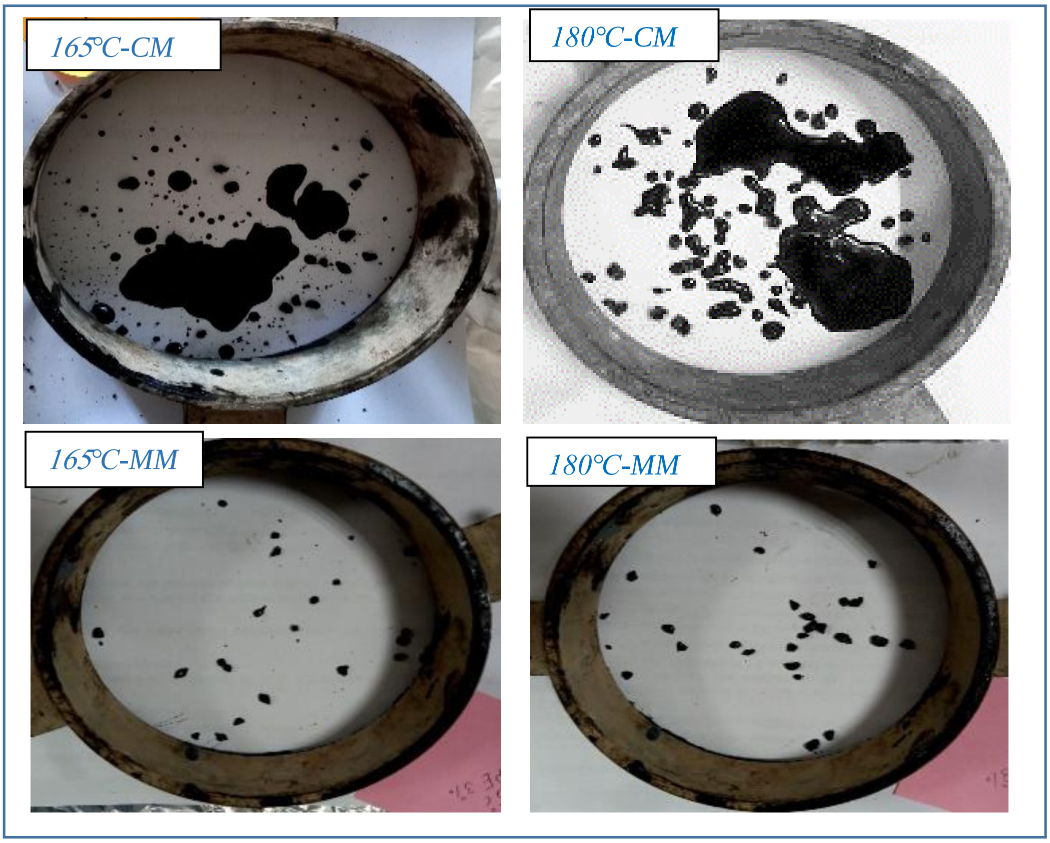

Plate (4- 1): Draindown of CM and MM of PA mixture at 165℃ and 180℃.

4.3.2 Functional and Mechanical Properties

4.3.2.1 Permeability

The permeability of the PA mixture is evaluated using a falling head conductivity test, the results of which are shown in Figure (4-11). The ASTM D7064/D7064M (ASTM, 2013c) specification specifies a minimum permeability of 100 m/day. Using w-LDPE in the PA mixture as a modifier results in higher permeability values than the control mixture (CM). This is due to an increase in viscosity values as a result of increased additive content, which makes the asphalt more stable. As a result, the interconnected pore and pore size that allows water to flow are increased.

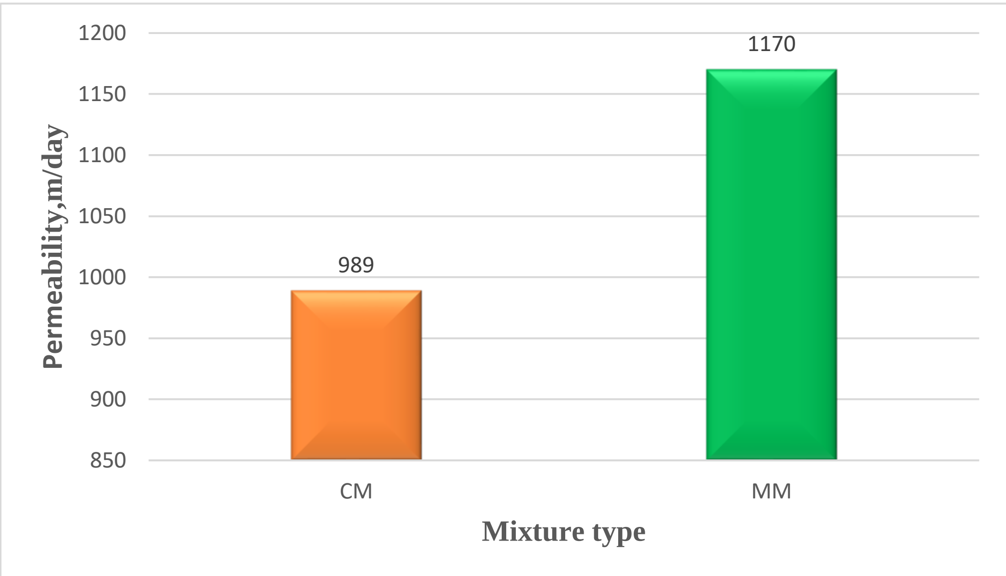

Figure (4-11): permeability of modified and unmodified PA mixture

4.3.2.2 Indirect tensile strength (ITS)

Figure (4-12) shows the result of ITS of CM and MM of PA mixtures. Results show that the ITS of MM increases compared to unmodified mixture. The presence of hydrated lime, in general, is linked to the first cause for the rise, which leads to enhanced bitumen polarity, subsequently leads to higher bitumen-aggregate bonding. In addition, the inclusion of additives affects the resistance of the PA combination to strain

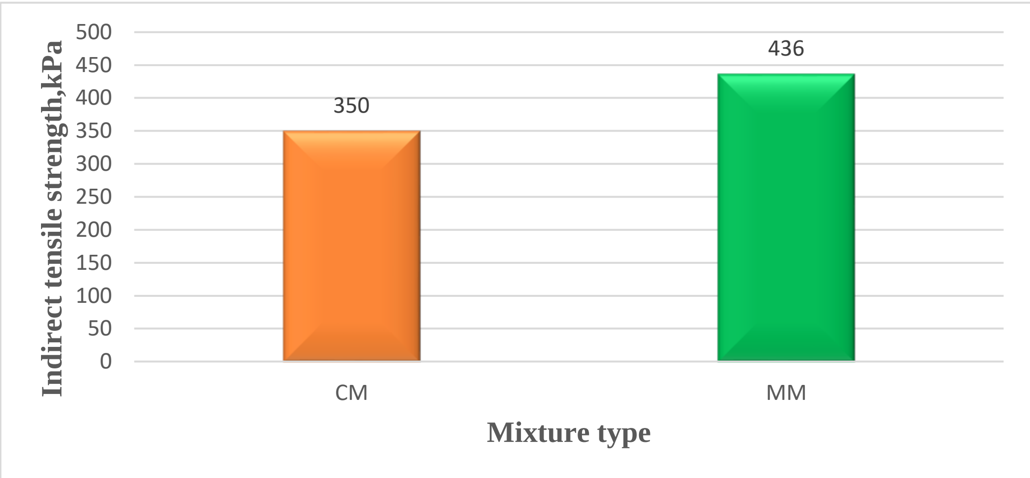

Figure (4-12): ITS of modified and unmodified PA mixture

4.4 Characterization of Semi-Flexible Mixtures

In this section, the volumetric, mechanical and durability characteristics of the developed SFP mixtures depending on the optimum of cementitious grout ratio and the improved asphalt ratio are presented.

4.4.1 Volumetric Properties

Figure (4-13) shows the density of semi-flexible mixture. The density of all mixture decreases as curing time increased because cementitious grout materials contain a large amount of water in addition to the superplasticizer, as the curing age increases, the amount of water evaporates, leaving air voids, resulting in a decrease in density. In addition, shrinkage occurs in the grout due to OPC shrinkage, as confirm by previous study (Pei et al., 2016a). Moreover, the density decreases with the increase emulsion. This is mostly due to the fact that the water in asphalt emulsion facilitates the backing at first, but as its content increases, the mixture after curing becomes more void-filled, lowering the density.

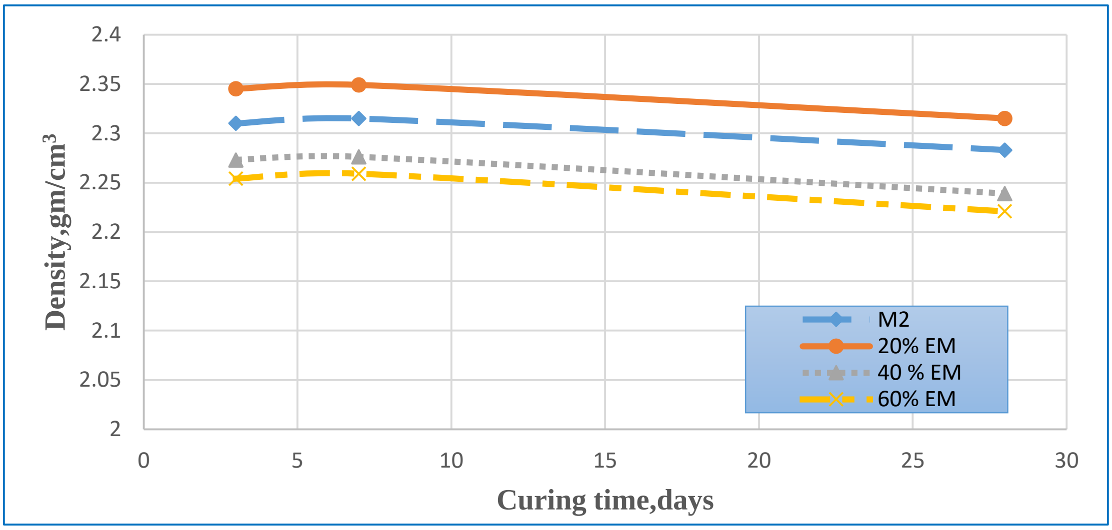

Figure (4-13): Density vs. curing time of SFP

Figure (4-14) shows that the air void of SFP mixtures. The increase of the curing age leads to increase air voids content. There is an inverse relationship between air voids and density air voids, as the increase in air voids leads to decrease in density with increasing curing age, and for the same reason referred to in the decrease in density. Compared to previous studies, the air voids obtained is somehow higher than by 5.1 % in (An et al., 2018), 4.8% in (Hou et al., 2015) and between 3.1-3.5% in (Husain et al., 2014b) studies.

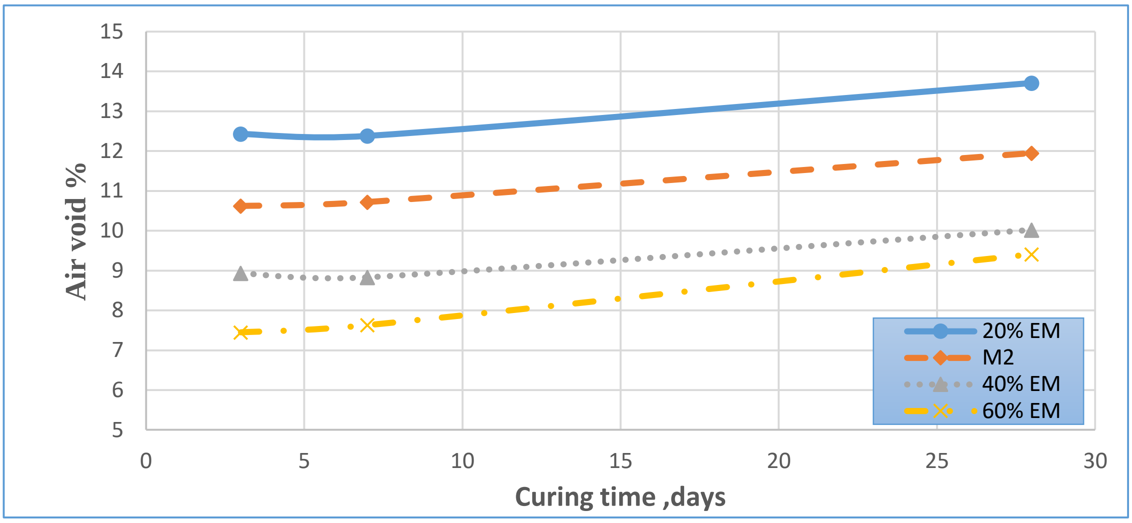

Figure (4-14): Air voids vs. curing time of SFP

The result of the VMA is showed in the Figure (4-15), the figure shows that the VMA of all mixture increases with the curing age increase, There is a direct relationship between the air voids and the VMA, as the increase in the air voids leads to an increase in the VMA and for the same reason mentioned in the density.

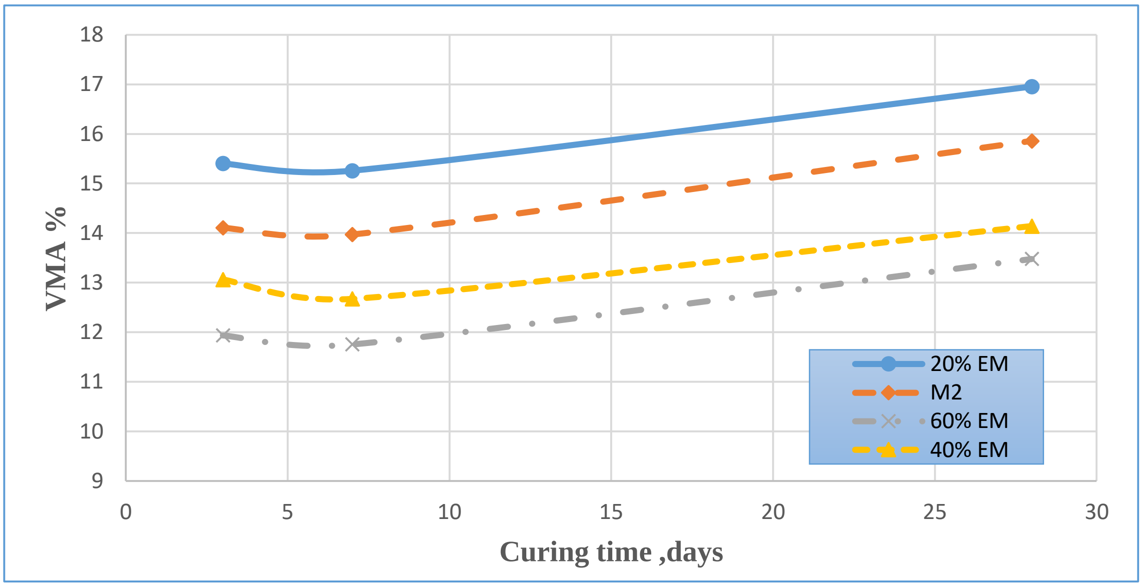

Figure (4-15): VMA vs. curing time of SFP

Figure (4-16) shows the results of the VFA of all SFP mixtures, the VFA decreases with the increase curing age and the same reason referred to in the density can be adopted. VFA is calculated as a percentage of the VMA that contains a binder.

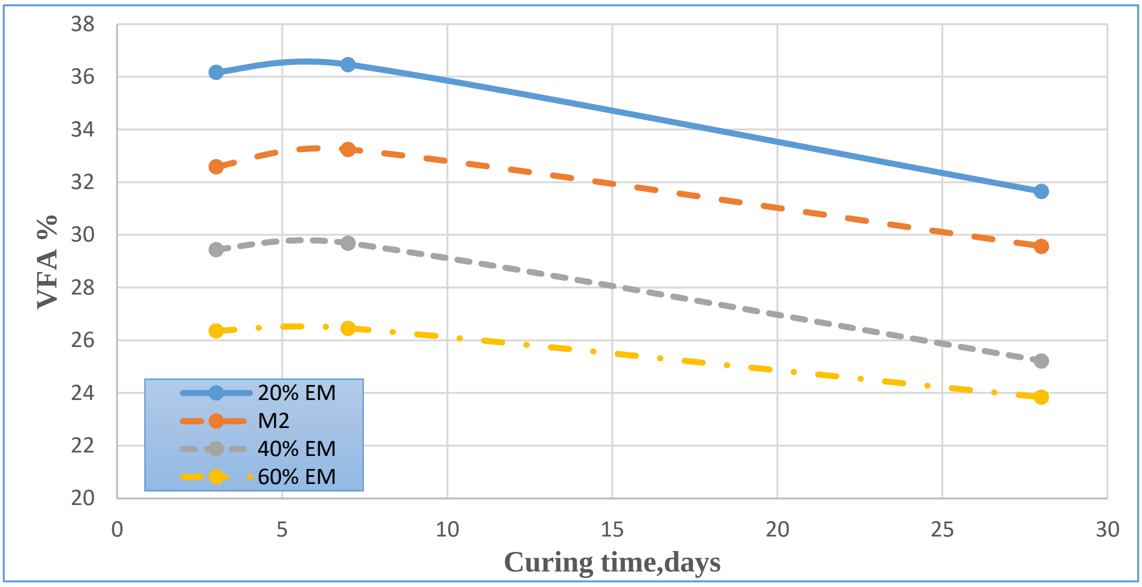

Figure (4-16): VFA vs. curing time of SFP

4.4.2 Mechanical and Functional Properties

The mechanical and functional characteristics of SFP mixtures were assessed in terms of ITS, CCT, SRT and wheel track test.

4.4.2.1 Indirect Tensile Strength (ITS)

Figure (4-17) shows the result of ITS for four types of mixtures and ages of 3, 7, and 28 days also Figure (4-18) shows the result of indirect tensile strength at 28 days. Through the results, it was found that the ITS of all mixtures, develops with an increase in curing time and this is because the cement hydration process needs time to complete the reaction and thus increase the strength, this is agreed with (Al-Qadi et al., 1994b, Bonicelli et al., 2019). For comparison between the four mixtures, the highest values for ITS are for the M2, while the lowest values for ITS are for mixtures containing 60% EM. The ITS for mixture contains 20% is ahigher than the mixture contains 60% because increase emulsion decrease ITS. The emulsion contains a percentage of water, and this reduces the Indirect Tensile Strength, as well as due to the hydration process ,as agree with(Zarei et al., 2020).Plate (4-2) shows some sample after testing, where the fauilare trasfer through aggregate and mastic as well .

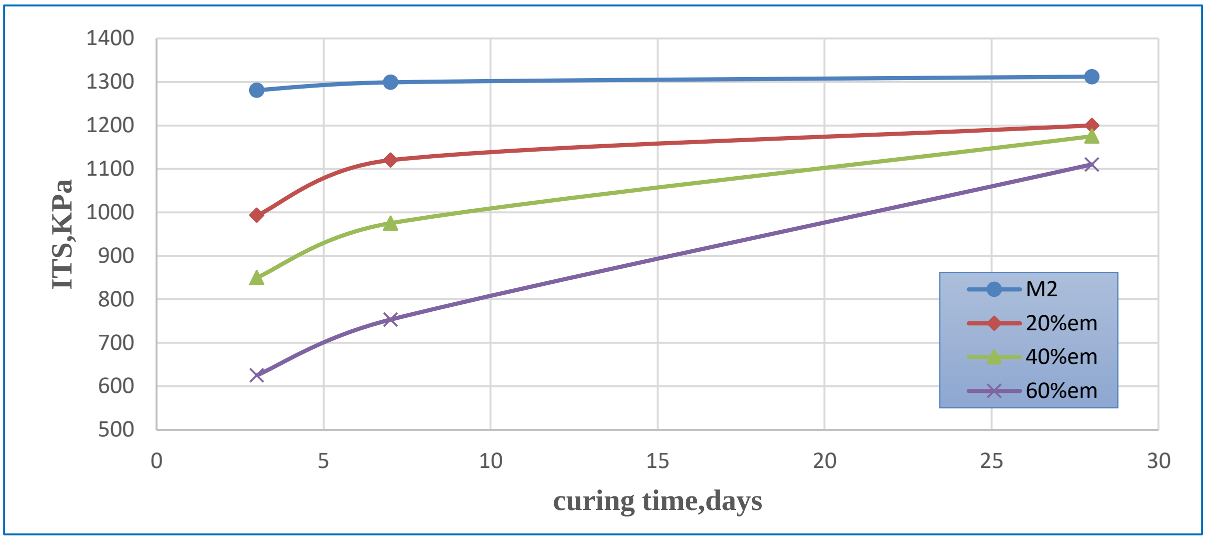

Figure (4-17): ITS test of SFP for different ages

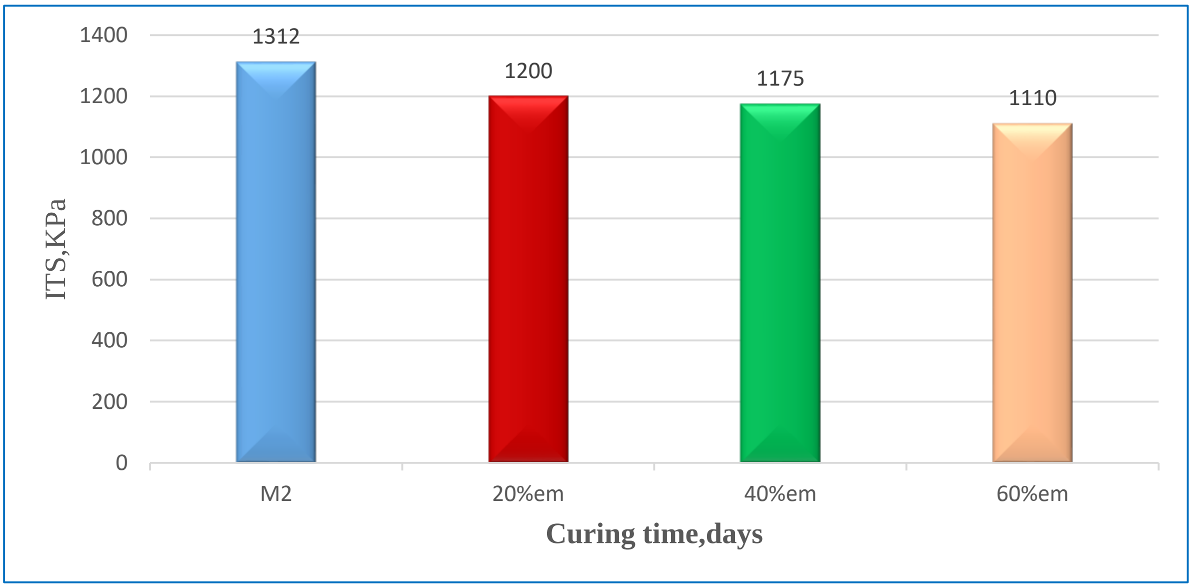

Figure (4-18): ITS test of SFP at 28 days

Plate (4-2): ITS specimens after testing

4.4.2.2 Creep compliance test (CCT)

Figures (4-19, 20 and 21) show a comparison of creep compliance result for all mixtures at ages 3, 7 and 28 days that were carried out at 0 °C. The creep values increase with time for all mixture. The results show highest value for M2 and lowest value for mixture containing 60% EM, to complete cementitious hydration process. The lower creep compliance indicates a stiffer composition that is more resistant to fatigue cracking or crack propagation. An increase in the proportion of emulsion leads to an increase in the value of the creep, and that using the lowest value for emulsion shows the lowest value for creep value.

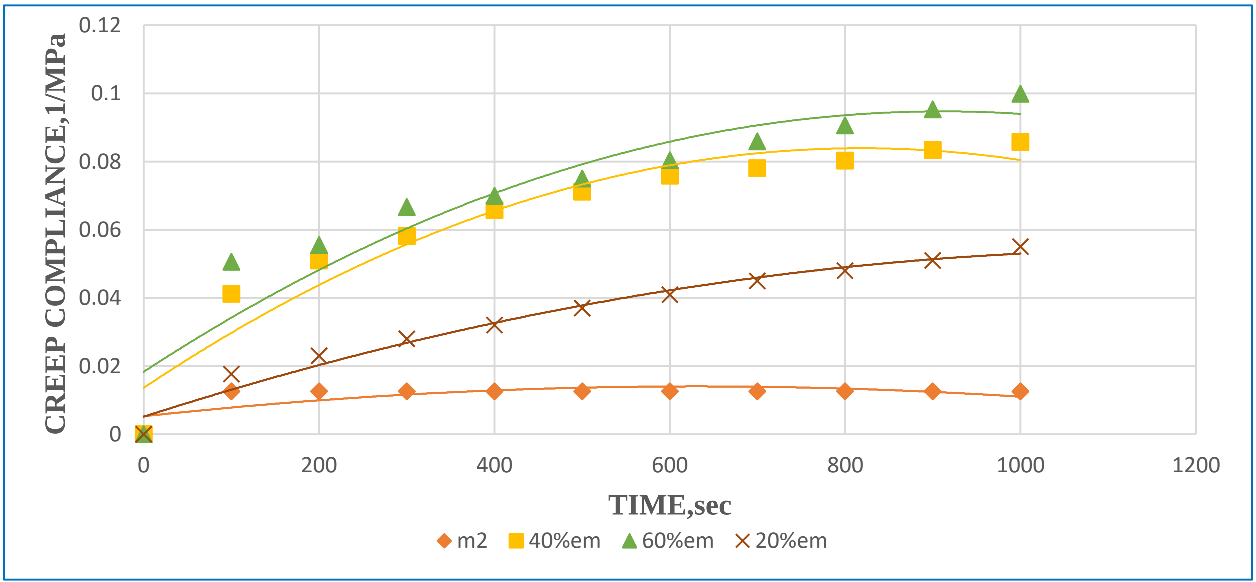

Figure (4-19): Creep Compliance vs. Time for SFP at 3 days

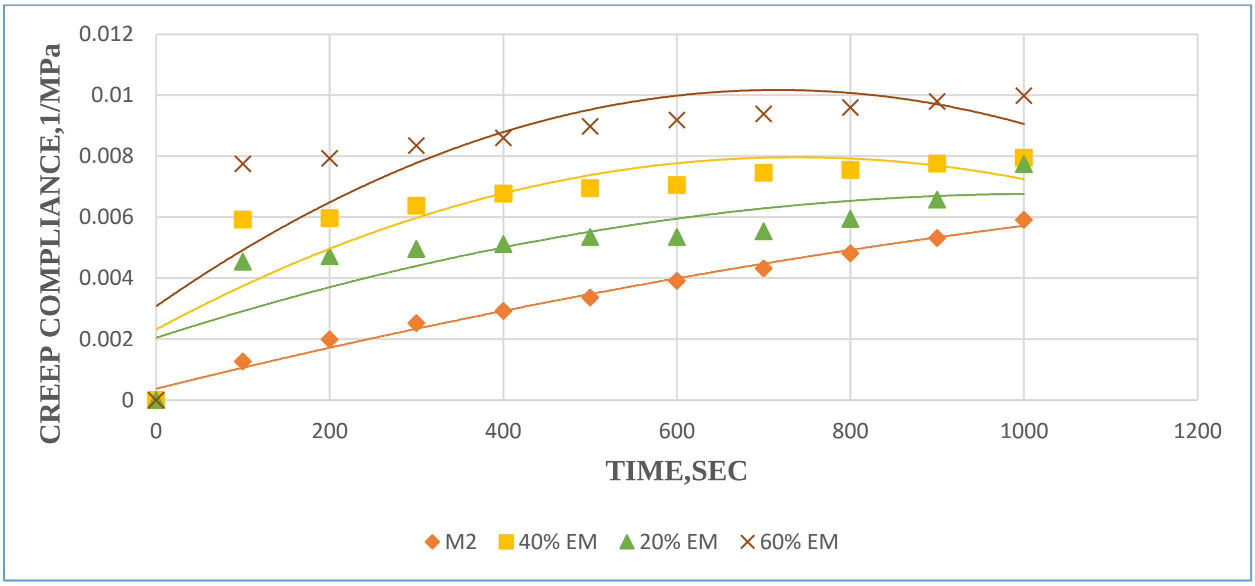

Figure (4-20): Creep Compliance vs. Time for SFP at 7 days

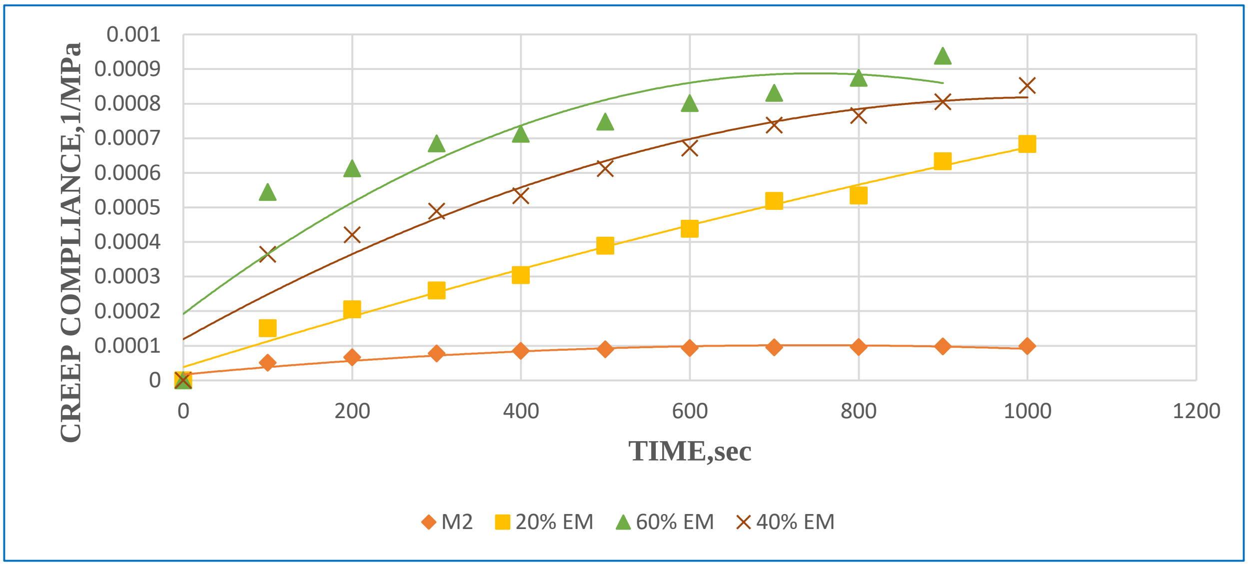

Figure (4-21): Creep Compliance vs. Time for SFP at 28 days

4.4.2.3 Skid Resistance Test

The degree of roughness of the pavement surface is indicated by skid-resistance. The results of skid resistance for all mixture show in the Figure (4-22). Because water is one among the components that affects skid resistance, the results demonstrate that the SFP combinations provide superior skid resistance in dry conditions than in wet conditions, this agree with (Pei et al., 2016b). The results revealed that SFPs possess a better surface texture and higher skid resistance (Hassani et al., 2020). The reason for this is that after injecting the cementitious grout materials into the OGFC mixture. Scrape the surface of the sample using a scraper so that the gravel covered with a little grout appears, which is the reason for giving the required roughness to the road. However, this increases the SFP layer's capacity to withstand daily road demands under hard braking. When comparing the results, mixes containing 20% EM, 40% EM, and 60% EM provide better skid resistance than the M2 mixture and modified mixture MM. In dry conditions, the improved skid resistance is attributed to the change in material composition, however in wet condition, the same results appear greater than the M2 mixture due to the ability of these emulsion to absorb water.

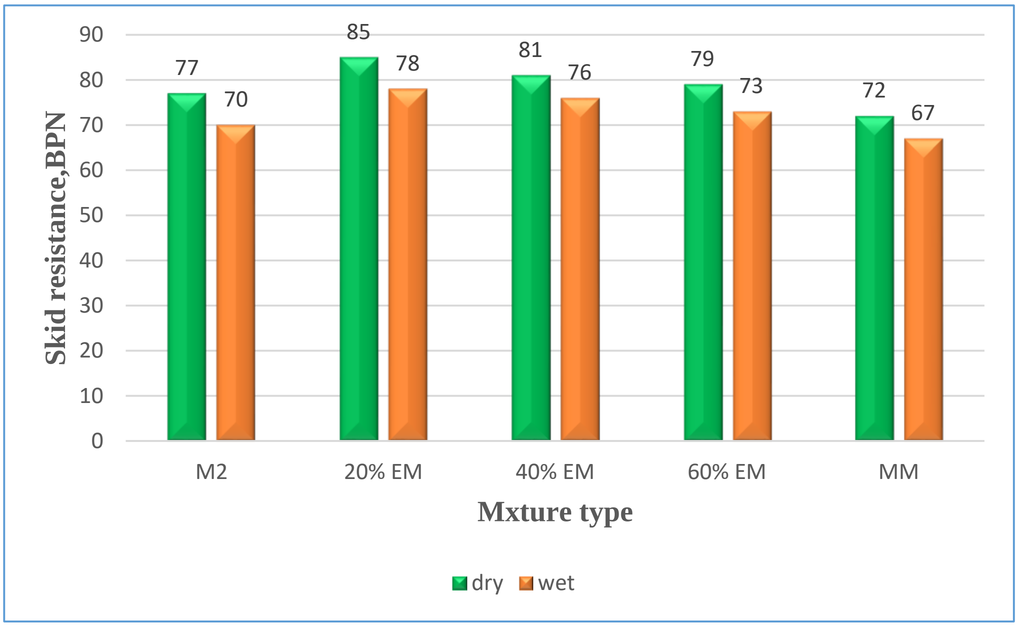

Figure (4-22): Skid resistance for SFP

4.4.2.4 Wheel Track Test (WTT)

Wheel Track Test was used to assess the resilience of all SFP mixes to permanent deformation. The results of 10,000 pass at 60 °C temperature are shown in Figure (4-23), the variation in rut depth for each of SFP mixture type are shown in Plate (4-3). The effect of cementitious grout materials on rutting resistance is seen in these figures. The inclusion of cementitious grout components to the PA improves the rutting resistance, significantly. Because the PA is full of cementitious grout materials, this causes the structure of porous asphalt to be restricted under the impact of stresses and temperature, and so leads to the rutting resistances improvement, and the rutting resistance of grouting materials is better than that of the modified asphalt mixture, which leads to the rutting depths decrease, This is agreed with (Hou et al., 2015, Luo et al., 2018a, Cai et al., 2017).

Figure (4-24) shows the results of the dynamic stability. It can be seen from Figure (4-23) and Figure (4-24) that SFP without emulsion has an extremely low permanent deformation resistance and low dynamic stability. Accordingly, mixture M2 is a no-rutting pavement material. Compare to SFP emulsion has a large permanent deformation because mixture becomes a typical viscoelastic and temperature-dependent material (Zarei et al., 2020).Plate (4-3) shows some tested specimen.

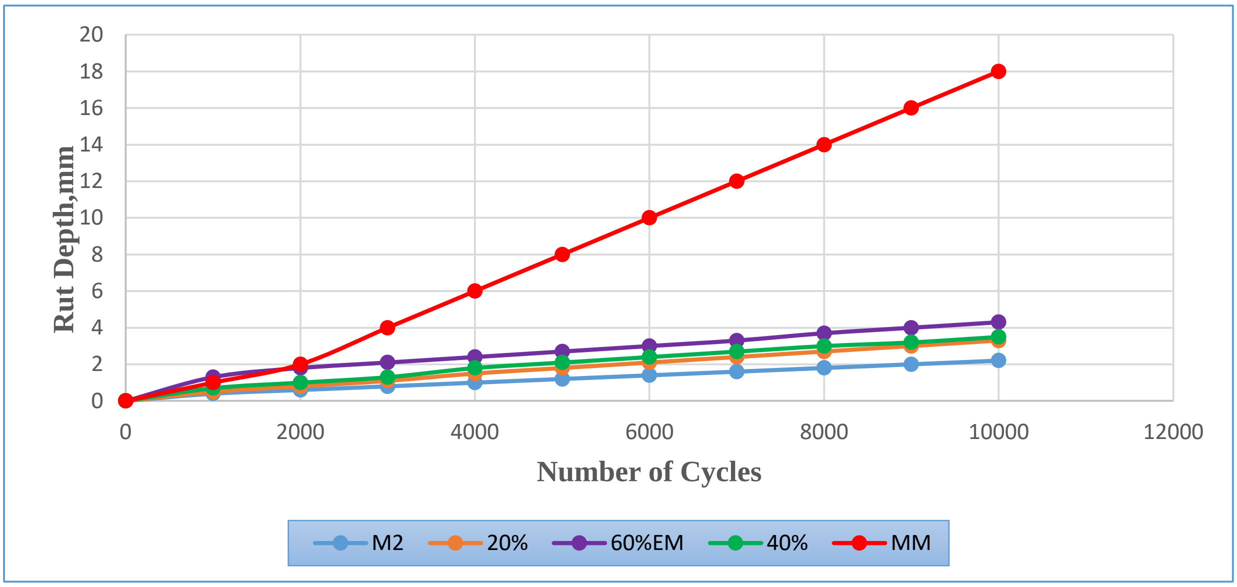

Figure (4-23): Rut Depth vs. Number of Cycles for SFP Mixture

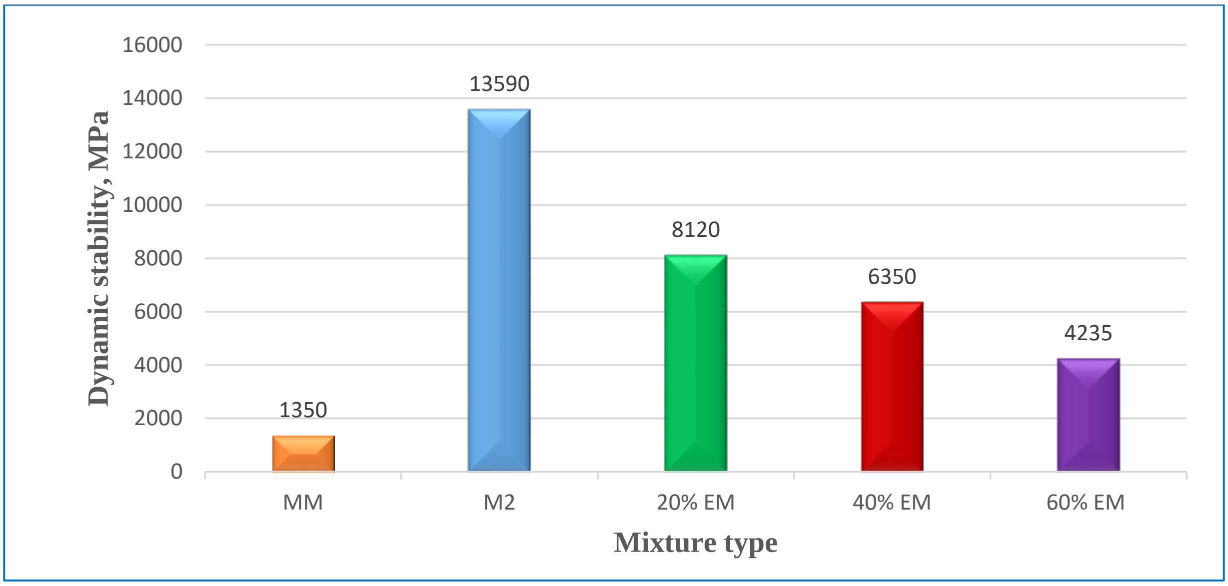

Figure (4-24): Dynamic stability for SFP mixtures

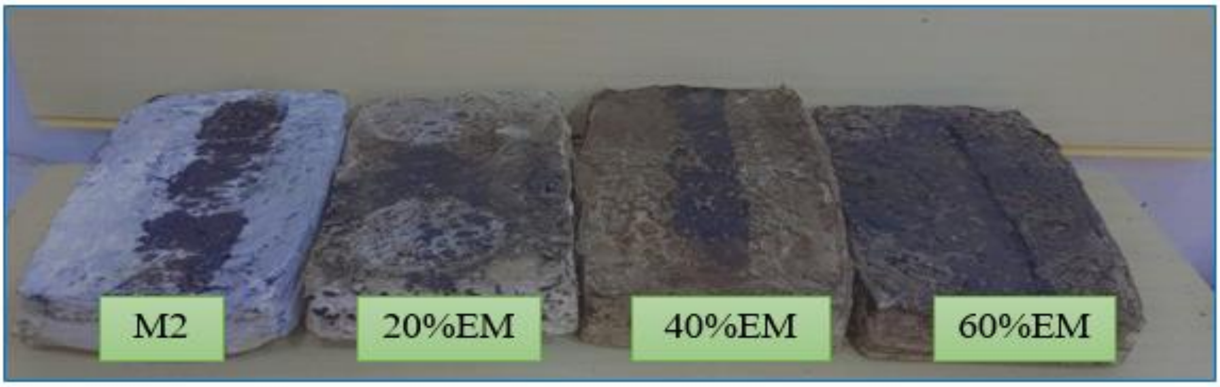

Plate (4-3): Specimen after testing

4.3 Durability Properties

4.3.1 Cantabro abrasion Test

Cantabro durability is recommended for OGFC asphalt mixtures, and there is little interest in using it in dense-graded mixtures. ASTM D7064/D7064M (ASTM, 2013c) recommended that the abrasion loss from this test should not exceed 20% for unaged specimens and 30% for aged specimens .Figure (4-25) shows the results of Cantabro test for all mixture after 7 days, while Plate (4-4) shows the samples before and after abrasion. The result of all mixtures prepared in the contents of various cementitious grout materials were positive. The results indicate that aged specimens have higher abrasion loss than unaged samples, which is due to an increase in brittleness. This is true after curing in the oven-dry. Results obtained in this research agree with the results of (Koting et al., 2011), where it was found that the Cantabro loss is 12.9, 10.1, 8.9% and also agree with the results of (Bharath et al., 2019a), where were the Cantabro loss by 16.1% and also do not agree with the results (Hlail et al., 2021) where it was found that the Cantabro loss is 85.38%,93.78%,59.52% and the reason for this is to use WMA in designing of porous mixtures, while in our study HWA was used.

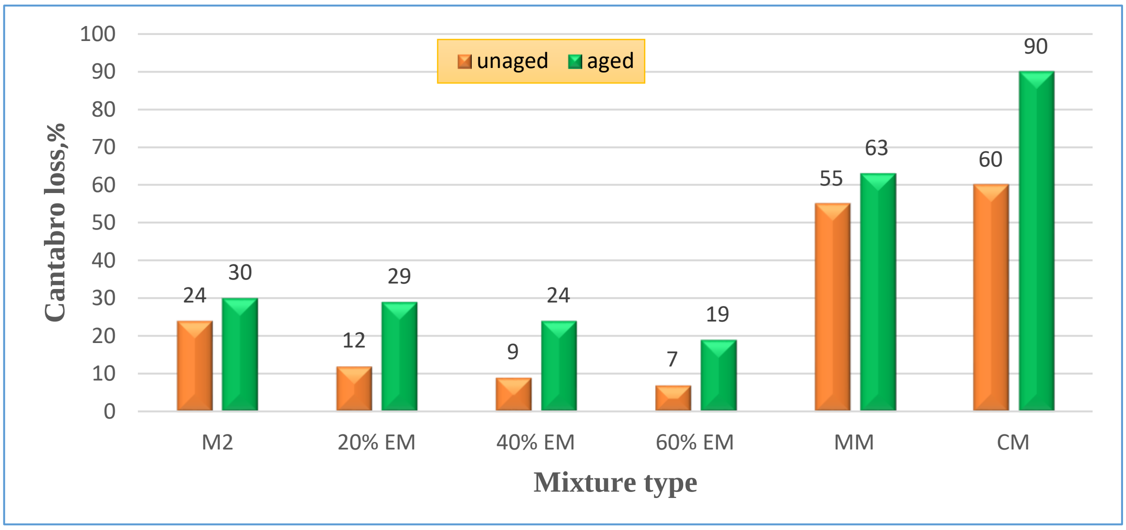

Figure (4-25): Cantabro Loss for aged and unaged specimens at 7 days

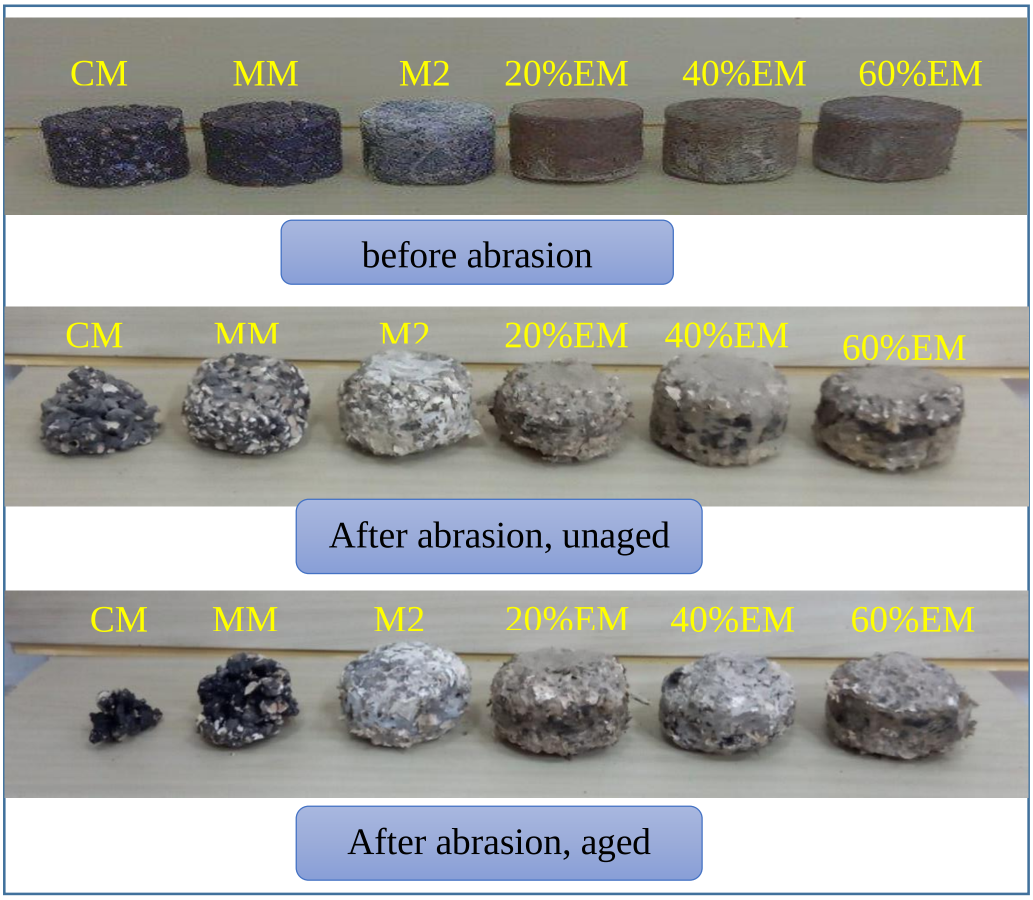

Plate (4-4): specimen after testing

4.3.2 Tensile Strength Ratio (TSR)

The results of ITS and TSR for both conditional and unconditional specimens at the age of 28 days are shown in the Figure (4-26). The results show that ITS for unconditional specimens is greater than ITS for conditional specimens. The highest indirect tensile strength for unconditioned mixtures M2. However, the highest indirect tensile strength value for conditional mixtures that containing 40% EM. As indicated the results indicate that ITS for conditional specimens is lower than ITS for unconditional specimens. That is, the deterioration in the mixtures was caused by the specimens' adaptation to moisture, and as a result, the indirect tensile strength of the mixtures was significantly reduced. The TSR value of SFP increases with the increasing asphalt emulsion content. Compare to, SFP without emulsion (mixture M2) has a very low TSR value which can just meet the minimum requirement for asphalt mixture. TSR values are greater in all SFPs with emulsion. The TSR value is a measure of a mixture's resistance to moisture damage. As a result, SFP with emulsion has a higher resistance to TSR values. The TSR value is an indicator of the resistance of mixture to moisture damage. As a result, SFP with emulsion has a higher moisture resistance than SFP without emulsion. There are two possible explanations for this phenomenon: (1) Due to the viscoelastic nature of asphalt, the mixture including emulsion can absorb more stripping energy than the mixture without emulsion (Xie et al., 2014); (2) Due to the hydrophobicity of asphalt, the water absorptivity of the mixture with emulsion is lower than that of the mixture without emulsion (Song et al., 2006). The highest value of TSR for all mixtures is 88.7%, which is agreed with the results obtained by (Zarei et al., 2020).

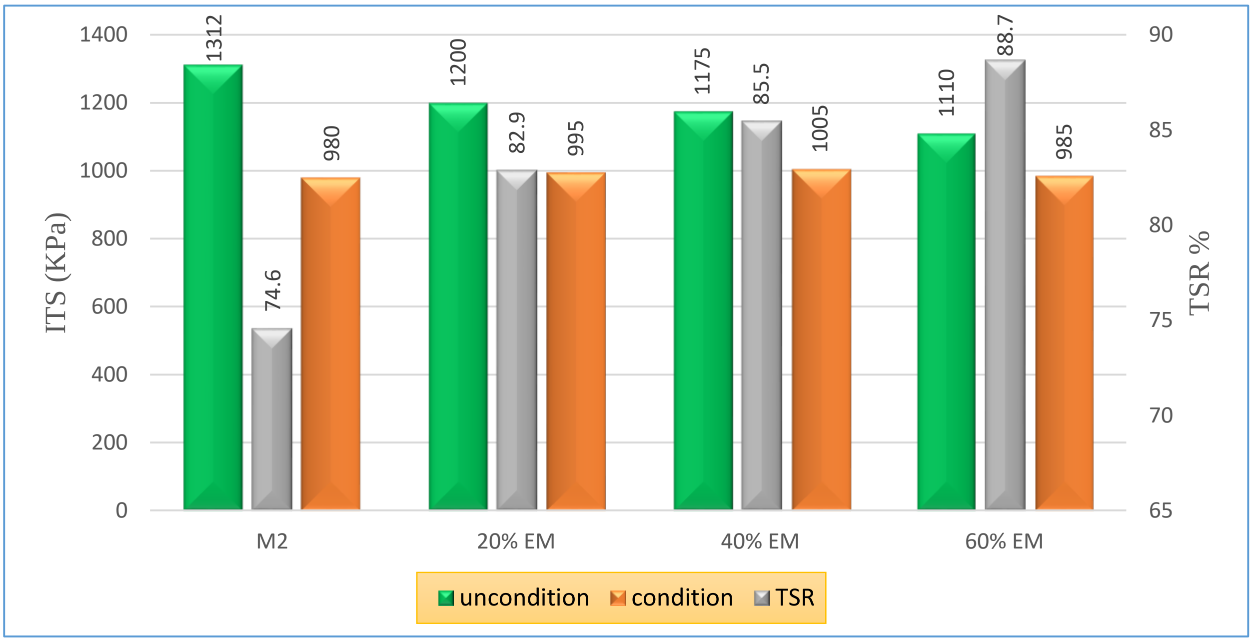

Figure (4-26): Tensile Strength Ratio for different mixtures

4.4 Summary

This chapter displays all information related to the tests cementitious grout and properties for the PA mixtures and properties for SFP. These characteristics can be summarized as follows:

1. The first section of this chapter introduces the results of tests cementitious grout materials in terms of fluidity, compressive strength, and flexural strength by using emulsion in various proportions to replacement of cement.
2. The second section check the volumetric and mechanical and durability properties for the PA mixture.
3. The third section summarizes all results related the volumetric, mechanical, functional, and durability properties for SFP. As well as, the result of durability improve meet the purpose compared to previous studies.

Chapter five

Conclusions and recommendations

5.1 Introduction

This research project is an effort to look at the possibilities of using SFP techniques to develop and preserve local infrastructure for highways, so a study was performed to determine the characteristics of this form of mix.

5.2 Conclusions

In this research work, as a first stage, cementitious grout materials were designed then porous asphalt (PA) in the second stage was characterized, After that ,at the third stage included evaluation of cementitious grout materials were injected into PA specimens and finally the volumetric, mechanical and durability properties of SFP mixtures was thoroughly characterized. The following can be drawn from the experimental program:

5.2.1 Cementitious Grout Materials

1. Flow time decreases with increasing water percentage, while it increases with increasing emulsion percentage.
2. The use of 40% W/B has the highest compressive strength, and with increasing age, the compressive strength increases.
3. The use of 40% W/B has the highest flexural strength, and with increasing age, the flexural strength increases.
4. 20% EM replacement of OPC in grout production is the optimum value when mechanical properties is governed the required properties

5. Increasing the emulsion percentage decreases the compressive strength and flexural strength while the flow time increases.

5.2.2 PA mixtures

1. The use of 4% of unmodified asphalt in the design of the PA mixture exhibited an acceptable volumetric and mechanical properties, as the amount of draindown exceeded 3% and the amount of abrasion loss reached to 60% and 90% for unaged and aged Cantabro abrasion loss, respectively.
2. comprising of w-LDPE with bitumen helps in enhance the physical properties of bitumen. Also, it improve the performance of mixture in terms of volumetric properties (i.e. air voids and effective porosity, VMA, VFA and draindown). In addition to the enhancement of the functional and mechanical properties of PA mixture in terms of, permeability, indirect tensile strength and Cantabro abrasion loss for aged and unaged all improve noticeably.

5.2.3 Semi-Flexible Mixtures

1. The cementitious grout materials is extremely fluid and capable of penetrating 63.5 mm thick of PA specimen.
2. Conventional SFP mixtures without emulsion exhibit the highest ITS values in all ages, while increasing the emulsion ratio inversely affects the ITS.
3. Skid resistance in dry and wet conditions for all SFP mixtures shows an improvement in contrast to the control mixture.
4. The SFP mixture gives a very high rutting resistance and for all mixtures than the control SFP mixture.
5. Water damage sensitivity for mixtures containing emulsion is better than that of mixtures without emulsion, they are satisfy the Iraqi specification GSRB, R/9), which needs moisture sensitivity to be at least 70%.
6. Cantabro abrasion loss results for all SFP mixtures are within the required value for highway specification.

5.3 Recommendations and Further works

Depending on the result of the laboratory experiments, a collection of recommendations for future work can be made, including the following:

1. Inducement the government directorates to begin working on a detailed specification for such a semi flexible mixtures.

2. It is critical to conduct research and work with local cement factories to develop a form of cementitious grout material that is made from waste in order to be more sustainable, and this type is now available for use in a variety of applications.

3. Several tests can be performed using emulsion in lower proportions to obtain better properties of the semi-flexible mixture.

4. Some characteristics of cementitious grout material, such as drying shrinkage, sulfate or chloride attack resistance, and so on, may need to be studied.

5. Testing the SFP asphalt mixture in the field to see how it performs in actual situations and comparing the findings to those achieved in lab tests.

References

AASHTO 2001. AASHTO T305 - 97 (2001) ' Determination of draindown characteristics in uncompacted asphalt mixtures'.

AASHTO 2003a. AASHTO T 283-03 'Standard method of test for resistance of compacted asphalt mixtures to moisture-induced damage'.

AASHTO 2003b. AASHTO T 322-03 'Standard of test method for determining The creep compliance and strength of hot-mix asphalt (HMA) using the indirect test device'.

AASHTO 2007a. Standard Method of Test for: Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage. .

AASHTO 2007b. Standard Method of Test for: Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage. Washington: American Association of State Highway Transportation Officials

ABDELRAHMAN, B. & GALAL, K. 2020. Influence of pre-wetting, non-shrink grout, and scaling on the compressive strength of grouted concrete masonry prisms. *Construction and Building Materials,* 241**,** 117985.

AFONSO, M. L., DINIS-ALMEIDA, M., PEREIRA-DE-OLIVEIRA, L. A., CASTRO-GOMES, J. & ZOOROB, S. E. 2016a. Development of a semi-flexible heavy duty pavement surfacing incorporating recycled and waste aggregates–Preliminary study. *Construction and Building Materials,* 102**,** 155-161.

AFONSO, M. L., DINIS-ALMEIDA, M., PEREIRA-DE-OLIVEIRA, L. A., CASTRO-GOMES, J. & ZOOROB, S. E. 2016b. Development of a semi-flexible heavy duty pavement surfacing incorporating recycled and waste aggregates – Preliminary study. *Construction and Building Materials,* 102**,** 155-161.

AKHTER, M. 2018. Construction of Flexible pavements-An Overview. *International Journal of Recent Trends in Engineering and Research, 4, 352-355.*

AKINCI, A., YILMAZ, S. & SEN, U. 2012. Wear behavior of basalt filled low density polyethylene composites. *Applied composite materials,* 19**,** 499-511.

AL-BUSALTAN, S., AL-YASARI, R., AL-JAWAD, O. & SAGHAFI, B. 2021. Durability assessment of open-graded friction course using a sustainable polymer. *International Journal of Pavement Research and Technology,* 13**,** 645-653.

AL-HADIDY, A. I. & YI-QIU, T. 2009. Effect of polyethylene on life of flexible pavements. *Construction and Building Materials,* 23**,** 1456-1464.

AL-JAWAD, O. A. & AL-BUSALTAN, S. 2019. Statistical Modeling for the Characteristics of Open Graded Friction Course Asphalt. *Journal of University of Babylon for Engineering Sciences,* 27**,** 366-381.

AL-QADI, I., GOURU, H. & WEYERS, R. 1994a. Asphalt Portland cement concrete composite: laboratory evaluation. *Journal of transportation engineering,* 120**,** 94-108.

ALVAREZ, A. E., FERNANDEZ, E. M., EPPS MARTIN, A., REYES, O. J., SIMATE, G. S. & WALUBITA, L. F. 2012. Comparison of permeable friction course mixtures fabricated using asphalt rubber and performance-grade asphalt binders. *Construction and Building Materials,* 28**,** 427-436.

ALVAREZ, A. E., MARTIN, A. E. & ESTAKHRI, C. 2010. Internal structure of compacted permeable friction course mixtures. *Construction and Building Materials,* 24**,** 1027-1035.

ALVAREZ, A. E., MARTIN, A. E. & ESTAKHRI, C. 2011. A review of mix design and evaluation research for permeable friction course mixtures. *Construction and Building Materials,* 25**,** 1159-1166.

AN, S., AI, C., REN, D., RAHMAN, A. & QIU, Y. 2018. Laboratory and Field Evaluation of a Novel Cement Grout Asphalt Composite. *Journal of Materials in Civil Engineering,* 30**,** 04018179.

ANDERTON, G. L. 2000. Engineering properties of resin modified pavement (RMP) for mechanistic design. Engineer Research and Development Center Vicksburg Ms Geotechnical Lab.

ASTM 2003a. ASTM D5084-03 'Standard test methods for measurement of hydraulic conductivity of saturated porous materials using a flexible wall permeameter'.

ASTM 2003b. ASTM D 2041 – 03a 'Standard Test Method for Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures''.

ASTM 2003a. ASTM C131-03 'Standard test method for resistance to degradation of small-size coarse aggregate by abrasion and impact in the Los Angeles Machine'.

ASTM 2005. ASTM D92-05 'Standard Test Method for Flash and Fire Points by Cleveland Open Cup Tester'.

ASTM 2007a. ASTM D 113 - 07 'Standard test method for ductility of bituminous materials'.

ASTM 2007b. Standard Test Method for Ductility of Bituminous Materials. *D113, American Society for Testing Material.* West Conshohocken, PA, United States.

ASTM 2008. Standard Test Method for Residue by Evaporation of Emulsified Asphalt. *D6934, American Society for Testing Material.* Conshohocken, PA, United States.

ASTM 2009a. ASTM D70 - 09'Standard Test Method for Density of Semi-Solid Bituminous Materials (Pycnometer Method)'.

ASTM 2009b. ASTM D 36 – 95 (Reapproved 2000) 'Standard test method for softening point of bitumen (ring-and-ball apparatus)'.

ASTM 2009a. Standard Test Method for Density of Semi-Solid Bituminous Materials (Pycnometer Method). *D70, American Society for Testing Material.* Conshohocken, PA, United States.
ASTM 2009b. Standard Test Methods and Practices for Emulsified Asphalts. *D244, American Society for Testing Material.* West Conshohocken, PA, United States.
ASTM 2010a. ASTM C939-10 "Standard test method for flow of grout for preplaced-aggregate concrete (flow cone method)".
ASTM 2010b. ASTM C942-10 "Standard Test Method Compressive Strength of Grouts for Preplaced -Aggregate Concrete in the Laboratory".
ASTM 2010d. Standard Practice for Freezing of Emulsified Asphalts. *D6929, American Society for Testing Material.* West Conshohocken, PA, United States.
ASTM 2011. ASTM D3203/D3203M − 11 'Standard test method for percent air voids in compacted dense and open bituminous paving mixtures'.
ASTM 2011a. Standard Practice for Evaluating Aggregate Coating using Emulsified Asphalts. *D6998, American Society for Testing Material.* West Conshohocken, PA, United States.
ASTM 2012a. Standard Practice for Miscibility of Emulsified Asphalts. *D6999, American Society for Testing Material.* West Conshohocken, PA, United States.
ASTM 2013a. ASTM D5-D5M - 13 'Standard test method for penetration of bituminous materials'.
ASTM 2013b. ASTM D5821-13 'Standard test method for determining the percentage of fractured particles in coarse aggregate'.
ASTM 2013c. ASTM D7064/D7064M− 08 (Reapproved 2013) 'Standard practice for open-graded friction course (OGFC) mix design'.
ASTM 2013a. Standard Specification for Cationic Emulsified Asphalt. *D2397, American Society for Testing Material.* West Conshohocken, PA, United States.
ASTM 2013b. Standard Test Method for Penetration of Bituminous Materials. *D5, American Society for Testing Material.* West Conshohocken, PA, United States.
ASTM 2013c. Standard Test Method for Determining the Viscosity of Emulsified Asphalts Using a Rotational Paddle Viscometer. *D7226, American Society for Testing Material.* West Conshohocken, PA, United States.
ASTM 2014a. ASTM C348-14 "Standard Test Method for Flexural Strength of Hyraulic-Cement Mortars".
ASTM 2014b. ASTM D1754/D1754M − 09 (Reapproved 2014) 'Standard test method for effects of heat and air on asphaltic materials (Thin-Film Oven Test)'.
ASTM 2015. ASTM C127 − 15 'Standard test method for relative density (specific gravity) and absorption of coarse aggregate'

ASTM 2015e. Standard Test Method for Solubility of Asphalt Materials in Trichloroethylene. *D2042, American Society for Testing Material.* West Conshohocken, PA, United States.

ASTM, A. 2013d. ASTM, D7064/D7064M-08 (Reapproved 2013)"Standard practice for open-graded friction course (OGFC) mix desugn".

ASTM, A. 2013e. Standard test method for measuring surface frictional properties using the British pendulum tester.

AZIZ, M. M. A., RAHMAN, M. T., HAININ, M. R. & BAKAR, W. A. W. A. 2015. An overview on alternative binders for flexible pavement. *Construction and Building Materials,* 84**,** 315-319.

BANG, J. W., LEE, B. J. & KIM, Y. Y. 2017. Development of a Semirigid Pavement Incorporating Ultrarapid Hardening Cement and Chemical Admixtures for Cement Grouts. *Advances in Materials Science and Engineering,* 2017**,** 1-9.

BHARATH, G., SHUKLA, M., NAGABUSHANA, M., CHANDRA, S. & SHAW, A. 2020. Laboratory and field evaluation of cement grouted bituminous mixes. *Road Materials and Pavement Design,* 21**,** 1694-1712.

BHARATH, G., SHUKLA, M., NAGABUSHANA, M., CHANDRA, S., SHAW, A. J. R. M. & DESIGN, P. 2019a. Laboratory and field evaluation of cement grouted bituminous mixes. 1-19.

BONICELLI, A., PRECIADO, J., RUEDA, A. & DUARTE, A. 2019. Semi-Flexible Material: A Solution for High-Performance Pavement Infrastructures. *IOP Conference Series: Materials Science and Engineering,* 471**,** 032062.

BSI 2003. BS EN 12697-22 2003 'Bituminous mixtures test methods for hot mix asphalt'.

BSI 2003 BS EN 12697-32-2003 'Bituminous mixtures —Test methods for hot mix asphalt'.

CAI, J., PEI, J., LUO, Q., ZHANG, J., LI, R. & CHEN, X. 2017. Comprehensive service properties evaluation of composite grouting materials with high-performance cement paste for semi-flexible pavement. *Construction and Building Materials,* 153**,** 544-556.

CELIK, F. & CANAKCI, H. 2015. An investigation of rheological properties of cement-based grout mixed with rice husk ash (RHA). *Construction and Building Materials,* 91**,** 187-194.

CHEN, J.-S., SUN, Y.-C., LIAO, M.-C., HUANG, C.-C. & TSOU, K.-W. 2013. Evaluation of permeable friction course mixes with various binders and additives. *Journal of materials in civil engineering,* 25**,** 573-579.

CIHACKOVA, P., HYZL, P., STEHLIK, D., DASEK, O., ŠERNAS, O. & VAITKUS, A. 2015. Performance characteristics of the open-graded asphalt concrete filled with a special cement grout. *The Baltic Journal of Road and Bridge Engineering,* 10**,** 316-324.

CONG, P., WANG, J., LI, K. & CHEN, S. 2012. Physical and rheological properties of asphalt binders containing various antiaging agents. *Fuel,* 97**,** 678-684.

CONTEC 2005. The new generation semi-flexible wearing course. Available: http://www.confalt.com.

CORRADINI, A., CERNI, G., D'ALESSANDRO, A. & UBERTINI, F. 2017. Improved understanding of grouted mixture fatigue behavior under indirect tensile test configuration. *Construction and Building Materials,* 155**,** 910-918.

CRONEY, D. & CRONEY, P. 1991. *The design and performance of road pavements*.

DENSIT, A. S. 2000. Densiphalt® Handbook. Aalborg.

DIAS, T., PEREIRA, P. A. & PAIS, J. C. 2005. Recycling of porous bituminous mixtures.

GLOSSOP, R. 1960. The Invention and Development of Injection Processes Part I: 1902–1850. *Geotechnique,* 10**,** 91-100.

GSRB 2003. General Specifications for Roads and Bridges, SECTION R9. Iraq.

HABIB, A., AIAD, I., EL-HOSINY, F. & MOHSEN, A. 2021. Studying the impact of admixtures chemical structure on the rheological properties of silica-fume blended cement pastes using various rheological models. *Ain Shams Engineering Journal*.

HASSAN, K. & SETYAWAN, A. Cold mix, cold laid semi-flexible grouted macadams, mix design and properties. Performance of Bituminous and Hydraulic Materials in Pavements: Proceedings of the Fourth European Symposium, Bitmat4, Nottingham, UK, 11-12 April 2002, 2017. Routledge, 105.

HASSAN, K., SETYAWAN, A. & ZOOROB, S. Effect of cementitious grouts on the properties of semi-flexible bituminous pavement. Proceedings of the Fourth European Symposium on Performance of Bituminous and Hydraulic Materials in Pavement, 2002. 113-120.

HASSANI, A., TAGHIPOOR, M. & KARIMI, M. M. 2020. A state of the art of semi-flexible pavements: Introduction, design, and performance. *Construction and Building Materials,* 253**,** 119196.

HIRATO, T., MURAYAMA, M. & SASAKI, H. 2014. Development of high stability hot mix asphalt concrete with hybrid binder. *Journal of Traffic and Transportation Engineering (English Edition),* 1**,** 424-431.

HLAIL, S. H., AL-BUSALTAN, S. & SHABAN, A. M. Sustainable Development of Highly Flowable Cementitious Grouts for Semi-flexible Pavement Mixture. IOP Conference Series: Materials Science and Engineering, 2020a. IOP Publishing, 022068.

HLAIL, S. H., AL-BUSALTAN, S. & SHABAN, A. M. 2020b. Toward Semi Flexible Pavement Application for Iraqi Highway and Airport Pavements: Review its feasibility. *Kerbala Journal for Engineering Science,* 1**,** 1-15.

HLAIL, S. H., AL-BUSALTAN, S. & SHABAN, A. M. Durability Evaluation: Sustainable Semi-flexible Pavement Mixtures. IOP Conference Series: Materials Science and Engineering, 2021. IOP Publishing, 012076.

HONG, J., WANG, K., XIONG, Z., GONG, M., DENG, C., PENG, G. & ZHU, H. 2020. Investigation into the freeze–thaw durability of semi-flexible pavement mixtures. *Road Materials and Pavement Design*, 21**,** 2198-2214.

HOSKING, J. R. 1992. *Road aggregates and skidding.*

HOU, S., XU, T. & HUANG, K. 2015. Investigation into engineering properties and strength mechanism of grouted macadam composite materials. *International Journal of Pavement Engineering,* 17**,** 878-886.

HOU, S., XU, T. & HUANG, K. 2016. Investigation into engineering properties and strength mechanism of grouted macadam composite materials. *International Journal of Pavement Engineering,* 17**,** 878-886.

HU, S., HUANG, S., DING, Q. & ZHANG, R. Study on the cementitious mortar for semi-flexible pavement. International Conference on Microstructure Related Durability of Cementitious Composites, 2008. RILEM Publications, 1237-1246.

HUANG, C., LIU, J. P., HONG, J. X. & LIU, Z. F. Improvement on the crack resistance property of semi-flexible pavement by cement-emulsified asphalt mortar. Key Engineering Materials, 2012. Trans Tech Publ, 26-32.

HUSAIN, N. M., KARIM, M. R., MAHMUD, H. B. & KOTING, S. 2014a. Effects of Aggregate Gradation on the Physical Properties of Semiflexible Pavement. *Advances in Materials Science and Engineering,* 2014**,** 1-8.

INSTITUTE, A. 2014. MS-2 asphalt mix design methods. Lexington Kentucky, USA.

JATOI, G. H., MEMON, N. A., SHAIKH, P., MALANO, A. Q. & MEMON, A. H. 2018. Design and Evaluation of Open Graded Hot Mix Asphalt Using Cement as A Grouting Material. *International Journal of Modern Research in Engineering & Management (IJMREM),* 1**,** 75-83.

KANAMARLAPUDI, L., JONALAGADDA, K. B., JAGARAPU, D. C. K. & ELURU, A. 2020. Different mineral admixtures in concrete: a review. *SN Applied Sciences,* 2**,** 1-10.

KOTING, S., KARIM, M. R. & MAHMUD, H. The Properties of bituminous mixtures for semi-flexible pavement. Proceedings of the Eastern Asia Society for Transportation Studies Vol. 6 (The 7th International Conference of Eastern Asia Society for Transportation Studies, 2007), 2007a. Eastern Asia Society for Transportation Studies, 281-281.

KOTING, S., KARIM, M. R., MAHMUD, H. & ABDUL HAMID, N. 2011. Development of cement-bitumen composites for semi-flexible pavement surfacing.

KOTING, S., KARIM, M. R., MAHMUD, H., MASHAAN, N. S., IBRAHIM, M. R., KATMAN, H. & HUSAIN, N. M. 2014a. Effects of using silica fume and polycarboxylate-type superplasticizer on physical properties of cementitious grout mixtures for semiflexible pavement surfacing. *ScientificWorldJournal,* 2014**,** 596364.

LACERDA, M. M. S., DA SILVA, T. J., ALVA, G. M. S. & DE LIMA, M. C. V. 2018. Influence of the vertical grouting in the interface between corbel and beam in beam-to-column connections of precast concrete structures–An experimental analysis. *Engineering Structures,* 172**,** 201-213.

LEWIS, R. C. 2018. Silica Fume. 25**,** 99-121.

LING, T.-Q., ZHAOZ, Z.-J., XIONG, C.-H., DONG, Y.-Y., LIU, Y.-Y. & DONG, Q. 2009a. The Application of Semi-Flexible Pavement on Heavy Traffic Roads. *International Journal of Pavement Research and Technology,* 2.

LING, T.-Q., ZHENG, X.-W., LING, M., XIONG, C.-H. & DONG, Q. 2010. Research on performance of water-retention and temperature-fall semi-flexible pavement material. *China Journal of Highway and Transport,* 2.

LING, T., ZHOU, J., ZHAO, Z., LI, C. & DONG, Y. 2009b. Study on Optimization of Polymer Modified Cement Slurry for Poured Semi-flexible Pavement [J]. *Journal of Highway and Transportation Research and Development,* 6.

LIU, Y.-J. & LI, Z.-F. 2015. Structural characterisation of asphaltenes during residue hydrotreatment with light cycle oil as an additive. *Journal of Chemistry,* 2015.

LU, G., RENKEN, L., LI, T., WANG, D., LI, H. & OESER, M. 2019. Experimental study on the polyurethane-bound pervious mixtures in the application of permeable pavements. *Construction and Building Materials,* 202**,** 838-850.

LUO, S., YANG, X., ZHONG, K. & YIN, J. 2018a. Open-graded asphalt concrete grouted by latex modified cement mortar. *Road Materials and Pavement Design,* 21**,** 61-77.

LUO, S., YANG, X., ZHONG, K. & YIN, J. 2020. Open-graded asphalt concrete grouted by latex modified cement mortar. *Road Materials and Pavement Design,* 21**,** 61-77.

LYONS, K. R. & PUTMAN, B. J. 2013. Laboratory evaluation of stabilizing methods for porous asphalt mixtures. *Construction and Building Materials,* 49**,** 772-780.

M. G. AL-TAHER, A. MOHAMADY, M. I. ATTIA & SHALABY, M. A. 2015. Technical Evaluation of Using Grouting For Producing Semi-Flexible Asphalt Concrete Mixtures. *Mansoura Engineering Journal, (MEJ), Vol. 40, Issue 4, December 2015.*

M. GKOVEDAROU, I. B. 2019. ROAD ASSET CLASSIFICATION SYSTEM. *European Conference on Computing in Construction*.

MA, C., LIU, Y., ZHOU, H., JIANG, Z., REN, W. & HE, F. 2021. Influencing mechanism of mineral admixtures on rheological properties of fresh magnesium phosphate cement. *Construction and Building Materials,* 288**,** 123130.

MAHDY, R., AL-BUSALTAN, S. & AL-JAWAD, O. Functionality properties of Open Grade Friction Course asphalt mixtures using sustainable materials: Comparison Study. 19th Annual International Conference on Highways and Airport Pavement Engineering, Asphalt Technology, and Infrastructure International Conference, Liverpool, UK, 2020.

MANNA, D., SANTHOSHKUMAR, G. & GHOSH, P. 2021. Upper-bound limit load of rigid pavements resting on reinforced soil embankments-kinematic approach. *Transportation Geotechnics*, 100611.

MANSOUR, T. N. & PUTMAN, B. J. 2013. Influence of aggregate gradation on the performance properties of porous asphalt mixtures. *Journal of Materials in Civil Engineering,* 25**,** 281-288.

MAYER, J. & THAU, M. 2001. Jointless pavements for heavy-duty airport application: the semi-flexible approach. *Advancing Airfield Pavements.*

MODARRES, A., RAHMANZADEH, M. & AYAR, P. 2015. Effect of coal waste powder in hot mix asphalt compared to conventional fillers: mix mechanical properties and environmental impacts. *Journal of Cleaner Production,* 91**,** 262-268.

MUDIYONO, R., NOR, H. M., HAININ, M. R. & LING, T.-C. 2006. *Performance of concrete block pavement on sloped road section.* Universiti Teknologi Malaysia.

MÜLLER, U., MICCOLI, L. & FONTANA, P. 2016. Development of a lime based grout for cracks repair in earthen constructions. *Construction and Building Materials,* 110**,** 323-332.

NCAT, A. U. 2015. Porous asphalt.

NRMCA 2004. Concrete in Practice (CIP 22-grout). National ready mixed concrete association. *What, Why & How.*

O'MALLEY, J. & ABDELGADER, H. S. 2010. Investigation into viability of using two-stage (pre-placed aggregate) concrete in Irish setting. *Frontiers of Architecture and Civil Engineering in China,* 4**,** 127-132.

OTHMAN, A. M. 2010. Effect of low-density polyethylene on fracture toughness of asphalt concrete mixtures. *Journal of Materials in Civil Engineering,* 22**,** 1019-1024.

OUYANG, J., ZHAO, J. & TAN, Y. 2018. Modeling Mechanical Properties of Cement Asphalt Emulsion Mortar with Different Asphalt to Cement Ratios and Temperatures. *Journal of Materials in Civil Engineering,* 30**,** 04018263.

PANDA, B. C. & GHOSH, A. K. 2002. Structural behavior of concrete block paving. II: Concrete blocks. *Journal of transportation Engineering,* 128**,** 130-135.

PAVEEN, K., SACHIN, D. & ANKIT, S. 2013. Guidelines on Composite Pavement-Design and Evaluation of Composite pavements.

PEI, J., CAI, J., ZOU, D., ZHANG, J., LI, R., CHEN, X. & JIN, L. 2016a. Design and performance validation of high-performance cement paste as a grouting material for semi-flexible pavement. *Construction and Building Materials,* 126**,** 206-217.

PUNITH, V., SURESHA, S., RAJU, S., BOSE, S. & VEERARAGAVAN, A. J. J. O. T. E. 2011a. Laboratory investigation of open-graded friction-course mixtures containing polymers and cellulose fibers. 138**,** 67-74.

PUNITH, V. S. & VEERARAGAVAN, A. 2011b. Characterization of OGFC Mixtures Containing Reclaimed Polyethylene Fibers. *Journal of Materials in Civil Engineering,* 23**,** 335-341.

PUTMAN, B. J. & KLINE, L. C. 2012. Comparison of Mix Design Methods for Porous Asphalt Mixtures. *Journal of Materials in Civil Engineering,* 24**,** 1359-1367.

QIU, J., YANG, T., WANG, X., WANG, L. & ZHANG, G. 2019. Review of the flame retardancy on highway tunnel asphalt pavement. *Construction and Building Materials,* 195**,** 468-482.

READ, J. & WHITEOAK, D. 2003. *The shell bitumen handbook*, Thomas Telford.

RYAN, T. P. 2007. *Modern engineering statistics*, John Wiley & Sons.

SABOO, N., KHALPADA, V., SAHU, P. K., RADHAKRISHNAN, R. & GUPTA, A. 2019a. Optimal proportioning of grout constituents using mathematical programming for semi flexible pavement. *International Journal of Pavement Research and Technology,* 12**,** 297-306.

SABOO, N., RANJEESH, R., GUPTA, A. & SURESH, M. 2019b. Development of hierarchical ranking strategy for the asphalt skeleton in semi-flexible pavement. *Construction and Building Materials,* 201**,** 149-158.

SETYAWAN, A. 2006. *Development of semi-flexible heavy-duty pavements.* University of Leeds.

SETYAWAN, A. 2013. Asessing the Compressive Strength Properties of Semi-Flexible Pavements. *Procedia Engineering,* 54**,** 863-874.

SHA, F., LI, S., LIU, R., LI, Z. & ZHANG, Q. 2018. Experimental study on performance of cement-based grouts admixed with fly ash, bentonite, superplasticizer and water glass. *Construction and Building Materials,* 161**,** 282-291.

SHANNAG, M. J. 2002. High-performance cementitious grouts for structural repair. *Cement and Concrete Research,* 32**,** 803-808.

SHEIKHMOTEVALI, A. H. & AMERI, M. 2014. Application of bitumen rheological parameters to predict thermal cracking behavior of polymer modified asphalt mixture. *Construction and Building Materials,* 66**,** 259-267.

SHU, X. & HUANG, B. 2014. Recycling of waste tire rubber in asphalt and portland cement concrete: An overview. *Construction and Building Materials,* 67**,** 217-224.

SONG, H., DO, J. & SOH, Y. 2006. Feasibility study of asphalt-modified mortars using asphalt emulsion. *Construction and building materials,* 20**,** 332-337.

SUN, Y., CHENG, Y., DING, M., YUAN, X. & WANG, J. 2018a. Research on Properties of High-Performance Cement Mortar for Semiflexible Pavement. *Advances in Materials Science and Engineering,* 2018**,** 1-10.

SURESHA, S. N., VARGHESE, G. & SHANKAR, A. U. R. 2009. Characterization of porous friction course mixes for different Marshall compaction efforts. *Construction and Building Materials,* 23**,** 2887-2893.

TEYMEN, A. 2017. Effect of mineral admixture types on the grout strength of fully-grouted rockbolts. *Construction and Building Materials*, 145**,** 376-382.
TORALDO, E. 2013. Comparative laboratory investigation into pavement materials for road tunnels. *Road materials and pavement design,* 14**,** 310-324.
TRAN, T. N., NGUYEN, H. T., NGUYEN, K. S. & NGUYEN, N. H. Semi-flexible material: The sustainable alternative for the use of conventional road materials in heavy-duty pavement. Congrès International de Géotechnique–Ouvrages–Structures, 2017. Springer, 552-559.
TULLINI, N. & MINGHINI, F. 2016. Grouted sleeve connections used in precast reinforced concrete construction–Experimental investigation of a column-to-column joint. *Engineering Structures,* 127**,** 784-803.
VAN DE VEN, M. & MOLENAAR, A. 2004. MECHANICAL CHARACTERIZATION OF COMBI-LAYER (WITH DISCUSSION). *Journal of the Association of Asphalt Paving Technologists,* 73.
VASUMITHRAN, M., ANAND, K. & SATHYAN, D. 2020a. Effects of fillers on the properties of cement grouts. *Construction and Building Materials,* 246**,** 118346.
WANG, D., LIANG, X., LI, D., LIANG, H., YU, H. J. A. I. M. S. & ENGINEERING 2018a. Study on Mechanics-Based Cracking Resistance of Semiflexible Pavement Materials. 2018.
WANG, K. & HONG, J. 2018b. Hybrid Concrete for Advancing Pavement Performance.
WATSON, D. E., ANN MOORE, K., WILLIAMS, K. & ALLEN COOLEY JR, L. 2003. Refinement of new-generation open-graded friction course mix design. *Transportation Research Record,* 1832**,** 78-85.
WEI, W., HUIMING, H., RUXI, W., MEIDAN, L. & WEI, W. 2017. Optimization design principle of poured cement slurry ratio for semi-flexible pavement. *Journal of Highway and Transportation Research and Development, China,* 34**,** 35-41.
WU, D. Q. & ZHANG, Y. 2011. The semi-rigid pavement with higher performances for roads and parking aprons. *CAFEO 29, Sustainable Urbanization-Engineering Challenges and Opportunities***,** 27-30.
WU, H., YU, J., SONG, W., ZOU, J., SONG, Q. & ZHOU, L. 2020. A critical state-of-the-art review of durability and functionality of open-graded friction course mixtures. *Construction and Building Materials,* 237.
WU, Y., CHEN, H., XU, Q., ZHANG, Z. & JIAO, F. 2019. Evaluation of experimental testing methods for the design of permeable friction course mixtures. *Construction and Building Materials,* 206**,** 385-396.
XIE, Y.-J., FU, Q., ZHENG, K.-R., YUAN, Q. & SONG, H. 2014. Dynamic mechanical properties of cement and asphalt mortar based on SHPB test. *Construction and Building Materials*, 70**,** 217-225.

YAN, K., XU, H. & YOU, L. 2015. Rheological properties of asphalts modified by waste tire rubber and reclaimed low density polyethylene. *Construction and Building Materials,* 83**,** 143-149.

YANG, B. & WENG, X. 2015a. The influence on the durability of semi-flexible airport pavement materials to cyclic wheel load test. *Construction and Building Materials,* 98**,** 171-175.

YASUHISA, K., ANDO, Y., OMOTO, S., YAGINUMA, K. & TORIIMINAMI, K. Study on block shifting of interlocking block pavement. Proceedings of the 8th International Conference on Concrete Block Paving (CBP'06), 2006. 447-456.

YOON, S., KANG, K., YOON, Y., HASTAK, M. & JI, R. 2018. Systematic decision-making process for composite pavement maintenance. *Journal of Construction Engineering and Management,* 144**,** 04018044.

ZAREI, S., OUYANG, J., YANG, W. & ZHAO, Y. 2020. Experimental analysis of semi-flexible pavement by using an appropriate cement asphalt emulsion paste. *Construction and Building Materials,* 230**,** 116994.

ZHANG, H., CHEN, Z., XU, G. & SHI, C. 2018. Physical, rheological and chemical characterization of aging behaviors of thermochromic asphalt binder. *Fuel,* 211**,** 850-858.

ZHANG, H., LIANG, S., MA, Y. & FU, X. 2016a. Study on the mechanical performance and application of the composite cement–asphalt mixture. *International Journal of Pavement Engineering,* 20**,** 44-52.

ZHANG, J., CAI, J., PEI, J., LI, R. & CHEN, X. 2016b. Formulation and performance comparison of grouting materials for semi-flexible pavement. *Construction and Building Materials,* 115**,** 582-592.

ZHONG, K., SUN, M., ZHANG, M., QIN, Y. & LI, Y. 2020. Interfacial and mechanical performance of grouted open-graded asphalt concrete with latex modified cement mortar. *Construction and Building Materials,* 234**,** 117394.

ZOOROB, S. E., COLLOP, A. C. & BROWN, S. F. 2002. *Performance of bituminous and hydraulic materials in pavements: Proceedings of the Fourth European Symposium, Bitmat4, Nottingham, UK, 11-12 April 2002*, CRC Press.

الخلاصة

ان الزيادة المستمرة في الحركة المرورية بالإضافة الى زيادة الاحمال المسلطة على الطريق سوف تسبب في ظهور العديد من أنواع الفشل على سبيل المثل التشقق والتخدد والكلل الخ.. لذلك، تم إجراء جهود بحثية مكثفة لتقديم بدائل لخلطات الرصف التي تُظهر أداءً أفضل من الخلطات الاسفلتية التقليدية. تم اقتراح الرصيف شبه المرن (SFP) بخليط الأسفلت ذي التدرج المفتوح والذي تم تصميمه من (25-35) ٪ فراغات هوائية مملوءة بمواد الجص الإسمنتية الخاصة، كأحد أفضل البدائل، في حين أن أداء الرصيف تحت هذه الخلطات يظهر امتدادًا لعمر الطريق. يستخدم SPF على نطاق واسع في العديد من البلدان بسبب خصائصه الميكانيكية الفائقة، وزيادة مقاومته لدرجات الحرارة العالية والتدهور، ويتميز بمرونة رصف الأسفلت الخرساني وصلابة الرصيف الخرساني الإسمنتي، مما يقلل من المشاكل المبكرة الناتجة عن زيادة تدفق حركة المرور وأحمال المرور.

الهدف الأساسي من هذا البحث هو تطوير أداء SFP من خلال موازنة صلابة ومرونة الخلطات المطورة. تم تصميم SFPsالمطورة من المواد المحلية، بما في ذلك تقييم مساهمة مكونات الجص الإسمنتية وتأثيرها على أداء SFP. تم استخدام السمنت البورتلاندي العادي (OPC)، ودخان السليكا (SF)، والمستحلب (EM)، والملدن الفائق (SP)، والماء لصنع مخاليط الجص.

أظهرت النتائج أن "وقت التدفق" يتناقص مع زيادة نسبة الماء بينما يزداد بزيادة نسبة المستحلب الاسفلتي . تزداد قوة الانضغاط مع زيادة العمر وترتبط أعلى مقاومة للضغط بـ 40٪ ماء / مادة رابطة (W / B)، كما تقل قوة الانضغاط مع زيادة نسبة EM. .

علاوة على ذلك، يتم استخدام 3٪ من البولي إيثلين منخفض الكثافة (W-LDPE) لإعداد عينات أسطوانية وألواح ذات محتوى فراغ هوائي بنسبة 32٪ ضمن نطاق القيم المسموح بها. تم تصنيع خلائط الملاط الإسمنتية وتطبيقها على عينات خليط الأسفلت المسامي، مع مواد ملاط اسمنتية تخترقها بالكامل. ومع ذلك، فإن قوة الشد غير المباشرة (ITS)، واختبار الامتثال للزحف (CCP)، واختبار التخدد (WTT)، والاستقرار الديناميكي (DS)، واختبار فقدان Cantabro (CLT)، ومقاومة الانزلاق، واختبارات المتانة من حيث حساسية الماء (TSR) والشيخوخة لتقييم أداء مخاليط SFP. تظهر النتائج أن (ITS)، على سبيل المثال، يزداد مع زيادة العمر، حيث يمكن لمكونات المزيج الأمثل تحقيق هذه الزيادة بدون EM. تم التعرف على نتائج مماثلة تقريبًا لفحص الشد لاختبار الامتثال للزحف، والاستقرار الديناميكي، وفقدان Cantabro ٪ واختبار التخدد. عكسيا، ترتبط خاصية مقاومة الانزلاق بالخليط الذي يحتوي على 20٪ EM، بينما ترتبط أعلى قيمة لـ TSR بـ 60٪ EM، وتصل إلى 88.7٪.

أخيرًا، كخلاصة رئيسية، فإن استخدام كمية صغيرة من المستحلب الاسفلتي تصل إلى 20٪ مع مكونات SFP الأخرى المثلى تلعب دورًا حيويًا في تحسين خليط SFP وتقترح مواد عالية الأداء في بناء الطرق.

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جمهورية العراق
وزارة التعليم العالي والبحث العلمي
جامعة كربلاء
كلية الهندسة
قسم الهندسة المدني

تحديد خواص المزيج الاسفلتي شبة المرن المحسن بحقين اسمنتي مع مستحلب اسفلتي

رسالة مقدمة الى قسم الهندسة المدنية، جامعة كربلاء وهي جزء من متطلبات الحصول على درجة الماجستير في الهندسة المدنية

من قبل:
فاطمة علي جواد
بكلوريوس في علوم الهندسة المدنية لسنة (2017-2018)

بأشراف:
أ. د شاكر فالح شاكر

محرم 1443 ‏ ‏ ‏ ‏ اب 2021