COMPOUND MODIFICATION OF ASPHALT MIXTURES FOR LOW-NOISE, LOW-EMISSION AND DURABILITY PURPOSES

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CERTIFICATE OF ORIGINALITY

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ABSTRACT

Asphalt pavements are constructed widely all over the world because of various advantages, such as superior engineering performance, comfortable riding surface, the short maintenance time, to some extent, and alleviate the traffic noise. The utilization of different asphalt pavement has different strength, however, also has its limitations. High temperature needed when producing and constructing asphalt layers generates fumes and odors. Such emissions not only pollute the environment, but also pose health risks to the workers. In addition, the increasing volume of vehicular traffic on the roads also aggravates concerns of road pavement noise. Modifiers are introduced into the asphalt mixture to help make the asphalt a better performance in optimizing the air emissions, low-noise, and the durability properties.

This study aims to assess different modified asphalt mixtures with focus particularly on the mechanical properties, acoustical emissions, and air pollutant emissions. Within the constraints of available equipment in the laboratory and construction sites for different pavement surfaces, limited but well-designed laboratory tests and site monitoring works were conducted.

This study shows that the addition of modifiers, such as polymer and crumb rubber, can help improve the mechanical quality and low noise performances of the pavement but need higher working temperatures, which severely exaggerates the fume and odor issues as well as the concern of health. The warm mix additives, such as Sasobit®, mixed with the asphalt mixture can lower the working temperatures and thus reduce the air and odor emissions. The Gap-graded asphalt pavement with a smaller aggregate size has performed well in the mechanical and low-noise performances. With the modification by the Sasobit®, its particulate matters and volatile organic compound pollutants can be significantly reduced.

PUBLICATIONS ARISING FROM THIS THESIS

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CHAPTER 1

INTRODUCTION

1.1 PROBLEM STATEMENT

Asphalt pavements are constructed widely all over the world because of various advantages, such as superior engineering performance, comfortable riding surface, and the short maintenance time. More than 93% of the roads are paved with asphalt in the United States of America (NAPA, 2016); with more than 90 percent surfaced with asphalt in Europe (EAPA, 2011); and approximately 75% in Hong Kong (HyD, 2014).

Traffic noise is a major problem in cities (EPD, 2015) and the use of asphalt pavement could, to some extent, alleviate the traffic noise by reducing the tyre/pavement interaction noise, the latter is considered as the dominant source of traffic noise (Bernhard et al., 2005). Among various types of asphalt pavements, the low noise road surface (LNRS) has been considered an effective way to tackle this acoustical emission problem, because of its ability to reduce the tyre/pavement noise directly from where it is generated. Several factors could affect noise reduction in the above area, such as the porosity, nominal aggregate size, and elasticity (Bernhard et al., 2005). However, the optimization of such factors for low-noise performance might lead to an adverse effect on air emissions or structural performance.

Air emissions from asphalt pavement is another issue of great concern. High temperature is needed when producing and constructing asphalt layers, causing the generation of fumes and odors. Such emissions not only pollute the environment, but also pose health risks to the workers and the others within the nearby environment. It has been reported that employees in the asphalt industry have the greatest exposure to asphalt fumes (Amidon, 2013). In the U.S. and Europe, the asphalt paving industry employs about 400,000 workers (EAPA, 2011). Thus, the health of many people is potentially at risk, due to exposure to asphaltic fumes and odors. Symptoms which have been reported by workers include irritation of the upper respiratory tract, headaches, fatigue, shortness of breath, dizziness, and nausea (Amidon, 2013). The carcinogenic effect of bitumen fumes on human health, in particular lung function, has been indicated by epidemiological studies (Binet, Pfohl-Leszkowicz, Brandt, Lafontaine, & Castegnaro, 2002). The reduction of air emissions can lower the health risks to the asphalt pavement workers, and provide a better working environment for them.

It was indicated that noise reduction benefits are not, as yet, considered a major factor when selecting road surface material (Abbott et al., 2010). One basic requirement of pavements is the expectation of long service life without major maintenance (Schaffer et al., 2008). Durability is one of the primary factors that affects the pavement service level. Maximization of the asphalt pavements durability significantly reduces maintenance hence contributing to a responsible and feasible service life (Schaffer et al., 2008), with obvious social and economic benefits. Thus the principal aim of the relevant industries is to provide the most appropriate materials and methods to ensure a product of acceptable quality, with such characteristics as indicated above and strictly in accordance with the high standards set by relevant agencies (EAPA, 2011).

It is necessary to note that the durability properties also may vary with different pavement types. The utilization of different asphalt pavements has different advantages, however, also has its limitations. To strengthen the pavement weaknesses, to meet individual specifications, or to improve the mix performance for a better usage in local conditions, modifiers are thus being introduced into the asphalt individually or along with the others. Asphalt cement modification has been practiced for over 50 years and has received increasing attention over the past decade (Pavement Intertactive, 2010). Numerous modifiers with different functions are available on the market. For instance, it may be necessary to use filler if the voids are many and widely spread and in this way improve the bond between the aggregate and the asphalt, and subsequently the mixture stability (Pavment Intertactive, 2010). Antioxidants, such as carbon and calcium salts, are capable of enhancing the durability of hot mixed asphalt (HMA) by retarding their oxidation. Rubbers, including natural latex, block copolymer such as styrene-butadiene-styrene (SBS), and the reclaimed rubber like crumb rubber from old tyres, can be used to increase both the HMA stiffness at high service temperature and the fatigue cracking resistance. Warm mix additives, including zeolite, Evotherm ™, and Sasobit®, or foaming technology, can help lower down the production and laying temperatures of HMA (D'Angelo et al., 2008), which are developed for the environmental consideration.

The properly designed pavements are required to meet the demands for safety, durability, and qualify for the environmental loads are worth further exploration. Currently in Hong Kong, the dense-graded asphalt mixture (DG), referred as the wearing course (WC); the open-graded friction course (OGFC), known as the polymer modified friction course (PMFC); and the stone mastic asphalt (SMA), are the three most commonly used asphalt pavements. Based on current experience, the WC could provide a relatively quiet ride , but its durability is acceptable; with the use of SBS polymer, the PMFC has a low-noise performance, but needs higher temperatures during production and laying, and preforms not well structurally under heavy traffic loads; the properties of SMA vary greatly in accordance with the different design and materials used, but a quieter ride tends to result if smaller nominal aggregate size is used and the mechanical function is weaker.

Polymer modified SMA (PMSMA) with a small nominal aggregate size, i.e., 6mm, is under experiment in Hong Kong, but the performance has not yet been fully evaluated. Crumb rubber modified asphalt (CRMA), recycled rubber from the waste tyre, is currently considered a promising HMA modification material. Compared to the conventional asphalt production process, a higher temperature is needed for the production and laying of CRMA mixes. This exacerbates air pollutant emissions and the subsequently associated health concern. To lower the working temperatures and minimize the emissions, warm mix asphalt (WMA), which is capable of reducing the producing and compacting temperatures of the hot mix asphalt (HMA) without compromising its mechanical properties (Hurley & Prowell, 2005), is thus employed into the CRMA. In general, by applying the WMA additives, the temperatures could be reduced, by as much as 20 percent. Hence, warm mix additives are being considered in rubberized asphalt locally in Hong Kong.

1.2 OBJECTIVES OF THE RESEARCH

The Objectives of this thesis is to assess different asphalt mixtures. Focus is particularly on experience in terms of mechanical properties, acoustical emissions, and air pollutant emissions. Specifically, experiments include both laboratory experiments and the field tests, conducted on different types of pavements, including the conventional asphalt, polymer modified asphalt, and those using crumb rubber and warm-mix additives, based on Hong Kong experiences.

An associated aim is to develop a better understanding of air emissions during road pavement construction and to identify the degree of danger to the health asphalt workers from the toxicity of the air emissions. Furthermore, by fully examine the investigation results, to help build a better understanding of those properties leading to a possible application of a low-noise, low-emission and durable asphalt mixture for road surfaces in Hong Kong.

1.3 OUTLINE OF THE THESIS

The structure of this thesis is illustrated in Figure 1.1.

Chapter 1 provides an introduction to the research. It explains the background and the research problem and outlines the objectives.

Chapter 2 presents a comprehensive literature review on the related topics, including the air emissions and acoustic emissions assessment, compound modification of asphalt mixtures of

asphalt pavement in the field. This chapter provides an account of current knowledge and how it was obtained, relevant details of previous research findings and their suggestions for further work. Such knowledge provides a foundation upon which the further work in this thesis is based.

Chapter 3 introduces the experimental approach of this research study program to meet the research objectives. The mechanical properties, air emissions, and the acoustic performances of different types of asphalt pavement surfaces, which includes the conventional asphalt and the compound modified asphalt, will be evaluated by both the laboratory tests and the in-situ tests.

Chapter 4 presents the laboratory experiments results and findings. This chapter also compares and discusses the structure properties, and the air emissions among different kinds of asphalt mixtures analyzed based on the results.

Chapter 5 describes the in-situ tests results and findings. The air emissions and the acoustic performances of different pavement surfaces are analyzed and discussed.

This thesis is concluded in Chapter 6 with a summary of the major research findings, and the conclusions drawn from the previous chapters. The limitations and the suggestions for the future study are also stated in this chapter.

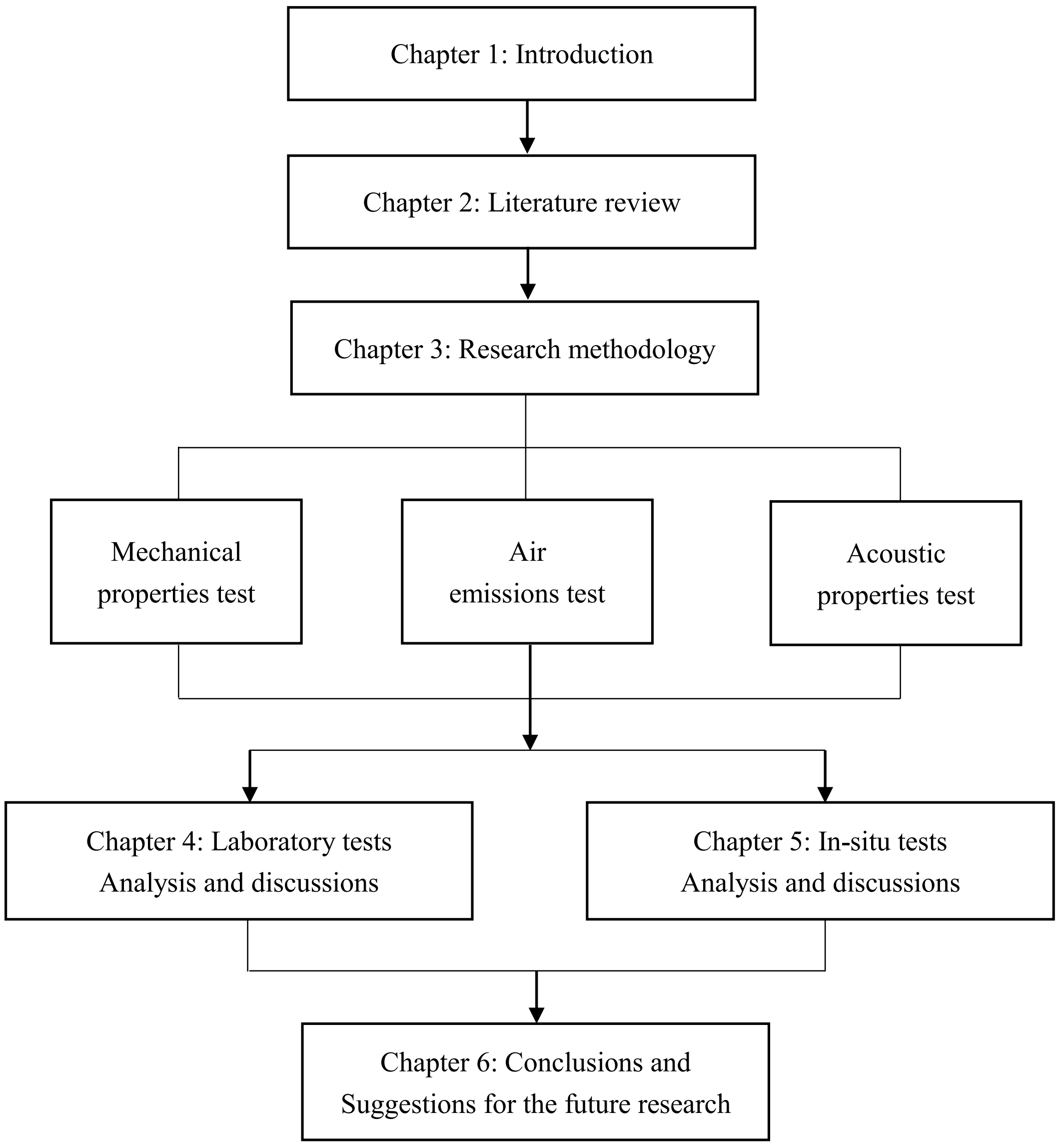


Figure 1.1. The structure of the thesis

CHAPTER 2

LITERATURE REVIEW

This chapter presents a review of research and literature on the air and acoustic emissions, and on the compound modification of asphalt mixtures. The purpose of this review is to provide relevant details of previous research findings in this area, an account of current knowledge, and their suggestions for further work. Such knowledge provides a foundation upon which the work in this thesis is based.

2.1 ACOUSTIC EMISSIONS

Traffic noise is a big concern that affects a large number of residents and pedestrians, especially in urban areas with heavy traffic such as Hong Kong (EPD, 2006). Road traffic noise increases with the economic development as there is more vehicular traffic on more roads. This environmental pollution does affect the public's comfort, health, and general standard of living (Kandhal, 2004). In addition to that, traffic noise may hinder communication, suppress real estate values, and cause stagnation of economic expansion due to the public resistance to the highways capacity expansion (Bernhard et al., 2005). Many communities and nationwide Departments of Transportation (DOT) are seeking to improve life quality by reducing environment noise (Bernhard et al., 2005).

The generation of traffic noise can be categorized into three general aspects: the power unit noise (engine, fan, exhaust and the transmission, etc.), the aerodynamic noise, which is related to the turbulent airflow around the vehicle, and the tyre/road noise (Hanson et al., 2002). For properly maintained vehicles, tyre/road interaction noise is the dominant highway traffic noise at speed above 50km/hr. (Bernhard et al., 2005). The proper selection of the pavement surface can be an appropriate noise abatement procedure (Hanson et al., 2002).

2.1.1 Tyre/road noise generation mechanism

For a better understanding of tyre/road noise reduction, the fundamentals relevant to tyre/road noise are first introduced in this section.

Noise

Noise is defined as unwanted sound and is a form of an acoustic energy or pressure. Humans can hear over a scale of pressure amplitude (Bernhard et al., 2005). The amplitude of noise is typically expressed by the sound pressure level represented by the unit decibel (dB). The term dB(A) is used when to the sound levels that have been A-weighted, in effect, corrected to account for human hearing (Hanson et al., 2002). Instead of a linear scale, dB(A) is a unit on a logarithmic scale, since the human auditory system is inherently non-linear (Haas, 2013). The formula used to represent, the logarithmic scale, a doubling or one-half of the sound is represented by a ten dB(A) change. For example, a dB(A) of 90 is twice as loud as a dB(A) of 87. Therefore, even a modest reduction of noise level requires considerable amounts of reduction in sound energy. The noise level alongside a freeway might be in the range of 70 to 80 dB(A), once the exterior continuous noise levels reach 65-70 dB(A), people inside a building have to close windows to hold a conversation (Kandhal, 2004).

Tyre/road noise generation

Tyre/road noise arises from a combination of physical processes, which could be classified into the following two groups (Graf et al., 2002; Haas, 2013; Mak, 2015; Sandberg & Ejsmont, 2002; Van Keulen & Duškov, 2005):

a. Source generation mechanisms

Mechanisms from sources that creates energy which is eventually radiated as sound are referred to as source generation mechanisms. As the tread blocks hit the pavement, the vibration is thus generated from the tyre, the energy is created, as is shown in Figure 2.1. In addition, the air pumping within the contact patch also generates the aerodynamic vibration that radiates as sound. Specifically, there will be the air entrained within the treads and grooves pattern from the tyre and the pavement, and these air will be compressed and pumped in and out when the vehicle is moving. Due to the compression and pumping effects, aerodynamically generated sound is created. The processes are shown in Figure 2.2.

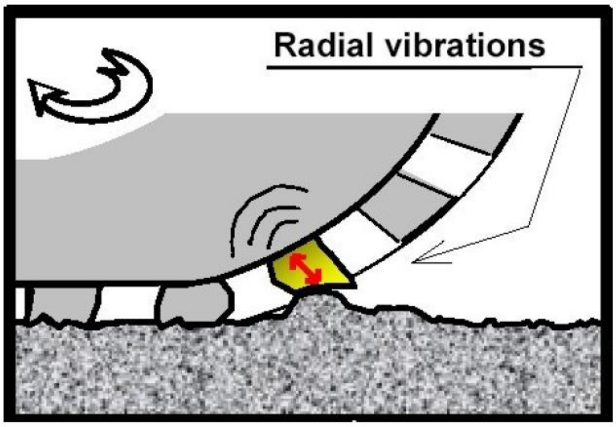


Figure 2.1. Vibration caused by tread block/pavement impact (Source from Sandberg & Ejsmont, 2002)

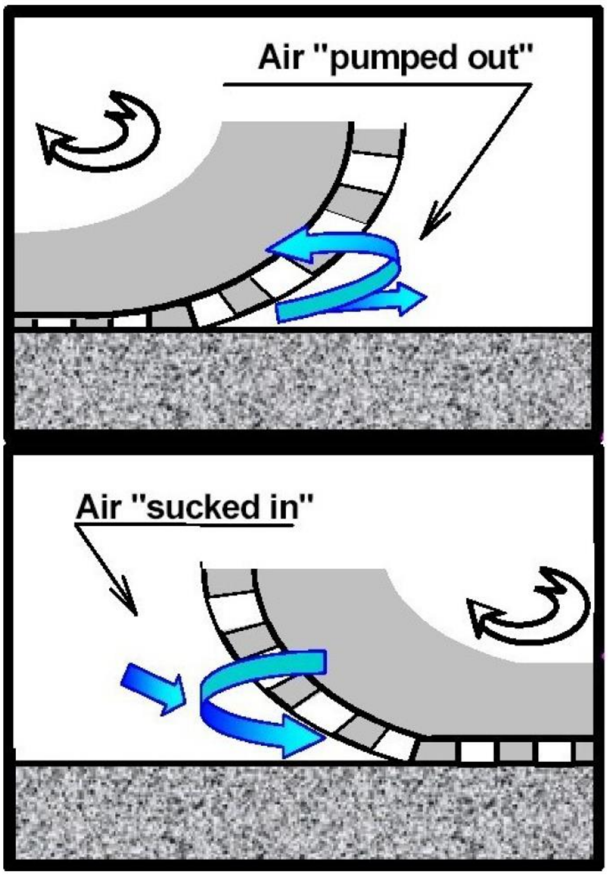


Figure 2.2. Air pumping at the entrance and exit of the contact patch (Source from Sandberg & Ejsmont, 2002)

Besides, the friction and the adhesion effect between contact between the tread blocks and the pavement texture also cause sound energy.

b. Sound enhancement mechanisms

The characteristics of the tyre/road interface that cause the sound energy to be radiated efficiently are referred to as sound enhancement mechanisms. One amplifier is called the horn effect. The horn effect is created by the horn-like geometry between the tyre belt and the pavement, which can provide a significant amplification for sound sources. Another amplifier is from the tread passages. The tyre tread passages can form the organ pipe resonances, which commonly happened in the musical instruments; and Helmholtz resonances, which are similar to the whistle produced when pulling the cork off the bottle. In addition, the vibration energy created at the tyre/pavement interface is enhanced by the response of the carcass.

These tyre/road noise generation mechanisms work collectively, which makes it difficult to make strategies to reduce the noise generated from different dominated cases. Moreover, the contribution from sound enhancement mechanisms is always difficult to distinguish from each other, and to identify which is the dominant amplifier under various surfaces and conditions. It is also worth emphasizing that many generation and enhancement mechanisms are associated with the safety, durability and cost issues (Bernhard et al., 2005). Despite the facts that the methods for tyre/pavement noise reduction is challenging and not straight forward, significant noise reduction has been demonstrated from the tyre/pavement interface.

The usage of pavements that produce less noise is named as low noise road surfaces (LNRS), which could be a strategic solution to tackle traffic noise on roads. LNRS, in particular, those constructed with asphaltic concretes, have been considered as an effective mitigation measure to alleviate the tyre/pavement noise directly from where it is generated (Abbott et al., 2010; Bernhard et al., 2005; EPD, 2006; Kandhal, 2004). The LNRS will be introduced in the next session.

2.1.2 Tyre/road noise of various pavement types

Among the abatement methods, such as the application of noise barrier, greenbelts, and traffic controls, the application of LNRS are considered to be the most effective means of reducing traffic noise without significant additional cost. Therefore, the silent road surfacing is under continuous study (Keulen & Duškov, 2005). Studies have indicated that mainly at vehicle speeds greater than 50 km/h, tyre/pavement interaction noise is the dominant noise pollutant source for the overall roadway traffic noise, (Bernhard et al., 2005; Donavan & Lodico, 2009). It is possible to achieve the noise reduction by a proper selection of pavement surface types, such as dense-graded hot mix asphalt (HMA), stone mastic asphalt (SMA), or open-graded friction course (OGFC) (Kandhal, 2004).

European countries have been very proactive in using LNRS as a mitigation strategy, numerous studies were conducted since the 1980s. They have found that the replacing HMA with an SMA surface would achieve an initial reduction of between 1 to 4 dB(A) depending on the mean traffic speed (10-60km/hr.) in Scottish noise management areas. The reduction is found to be independent of aggregate size in the range of 6 to 14mm (Abbott et al., 2010). The OGFC was quieter than HMA by 3 dB(A) according to the Italian experience (Kandhal, 2004). On the average comparative noise levels, using regular dense-graded HMA as a reference 0 dB(A), OGFC will be regarded as -4 dB(A), while SMA is -2 dB(A). And the cement concrete is +3 dB(A) (Kandhal, 2004).

It has been identified that an LNRS can be built with safety, durability, and cost-effectiveness by the following approaches (Hanson et al., 2002; Sandberg & Ejsmont, 2002):

a) A porous surface, such as an OGFC with a high air void content;
b) A surface with a smooth texture using small maximum size aggregate;
c) A pavement wearing surface with an inherent low stiffness at the tyre/pavement interface.

Research has been conducted on the low-noise performances of OGFC. The high air void content (over 18%) of its porous structure allows the air to vibrate internally, instead of being pumped strongly and noisily within the tyre/pavement interface, thereby reducing the traffic noise level. The larger air void contents allow this porous asphalt to absorb more noise. Thus, less noise will be reflected back to the environment. Previous studies have shown that OGFC may reduce traffic noise by 2 to 6 dB compared to regular dense-graded HMA (Sandberg & Ejsmont, 2002). Some other research found it is 3-5dB(A) quieter than conventional dense asphalt (Kandhal, 2004). Although OGFC has shown great performance in noise reduction, it still has some limitations. Due to its high porosity, not only air, but water and dust can easily penetrate into the structure and accelerate the water susceptibility of asphalt from the aggregates, which will result in a shorter service life. Sandberg reported that OGFC had the advantage of a significant noise reduction of up to 4dB(A) when newly laid. However, the accumulation of dust and debris generated mostly by vehicle tyres and road surface wear easily clogs the OGFC voids. Consequently, the noise reduction property is reduced. To maintain the low noise performance, extra road maintenance is essential, resulting in additional costs. Besides, the mechanical performance of OGFC is a major concern of the highway authority.

Meanwhile, new LNRSs are being explored for a more stable performance. Stone Mastic Asphalt (SMA) is a gap-graded asphalt mixture. Characteristically the smaller the aggregate size of the surface, the quieter the ride. SMA with smaller aggregate size is being considered as a potential LNRS. From SMA11 to SMA10, 0.25 dB(A) was lowered to the value measured on SMA11, which is a support that smaller sized SMA have more potential in low-noise performance (Sandberg, 2009).

In general, OGFC is quieter than SMA while both provide significantly better skid resistance surface than that of conventional wearing courses (WC) (Kowalski et al., 2009). SMA has a better mechanical performance than OGFC, and because of its smaller normal aggregate sizes has indicated a potential for providing a low-noise surface. A study conducted in Germany between 1991 and 1998 has shown an SMA surface to provide a 2-2.5dB(A) quieter ride than the HMA (Kandhal, 2004). Research in Italy has indicated that, by using SMA, as much as a 7.0 dB(A) reduction in noise levels at 110km/h can be achieved.

Moreover, SMA with a smaller aggregate size may perform better in noise level reduction. It was reported that SMA surface with a 9mm nominal aggregate size (SMA9) is 3 dB(A) quieter than SMA16 with the driving speed of 88km/h (Bernhard et al., 2005). However, the mechanical strength of the SMA mixtures weakens as the nominal aggregate size decreases. The properly optimized design between the low noise performance and structural capacity is of great significance. Hans et. al. (2013), have conducted CPX methods on PMSMA6, OGFC6, OGFC11 and HMA16 at the speed of 70km/h, CPX values are 92.5, 91.0 and 94.5 dB(A)and 94.0 respectively (Vaiskunaite et al., 2009). The mechanical strength of the SMA mixtures, however, weakens as the nominal aggregate size decreases. It is suggested that the application of polymer modified asphalt could improve the mechanical properties.

In Hong Kong, traditional hot mix asphalt (WC), OGFC (PMFC) and SMA are the three most commonly used pavement surfaces. Stone Mastic Asphalt (SMA) and Polymer Modified Friction Course (PMFC) are being explored to be potential Low Noise Road Surfaces (LNRS). Similar to the review from above, PMFC has its advantage of significant noise reduction of up to 4 dB(A) when it is newly laid (Sandberg, 2008), while SMA with small aggregates surface may reduce noise by 2-3 dB(A) (HyD, 1994), comparing to conventional bituminous surface (WC). SMA and PMFC surfaces provide a better skid resistance than WC on wet days. For better mechanical performances associated with low-noise performance, the SMA6 with SBS polymer modified (PMSMA6) has just been newly paved in a number of road sections in Hong Kong. Their comprehensive and long-term properties are to be evaluated.

Besides the studies on general LNRS, research has found that crumb rubber modified asphalt (CRMA) can help improve the low-noise performance (Vazquez et al., 2014). By adding crumb rubber (CR) into the asphalt, the binder becomes a material with a higher damping coefficient and reducing vibrations between the tyre and the pavement, thereby mitigating the noise generated in the tyre/pavement interface (Bernhard et al., 2005). The higher CR content, the better low-noise features. With crumb rubber (CR) modified asphalt, Texas DOT has implemented CR-OGFC as an overlay on the existing reinforced concrete pavement in San Antonio. This layer reduced the noise levels by an average of 8 decibels and improved the surface friction by more than 200% (Kandhal, 2004). Furthermore, CRMA also helps improve the anti-aging property, enhance its rutting and cracking resistance as well as durability (Akisetty et al., 2009; Vazquez et al., 2014). However, with the introducing of CR, the binder is becoming more viscous. The higher temperature is needed to make it workable with aggregates than the traditional HMA. This will produce more carbon footprint and cause serious odor and fume problems.

In order to evaluate the noise reduction effect, reliable noise measurement methods should be employed. Details are explained in the following section.

2.1.3 Tyre/road noise measurement methods

The general approach for the tyre/pavement noise measurement are briefly introduced as the following:

Statistical passby (SPB).

Statistical passby (SPB) methods utilize a random sample of typical vehicles. The maximum sound pressure level is captured for each passby using a sound measurement system located at a standard distance from the center line of the lane. The typical setup is shown in Figure 2.3. The measurements are taken from a great number of vehicles operating normally on the road. Results obtained are used to normalize to standard speeds for the type of road being evaluated (Trevino & Dossey, 2006). Specifically, Statistical Passby Index (SPBI), which can be used to compare various pavements, are computed according to the data. Details of the SPB international standard are specified in ISO 11819-1 (Bernhard et al., 2005). This method includes all factors of traffic noise at the sideline of the highways, such as the engine and the aerodynamic noise. However, the random vehicles measured at different sites could lead to a less accuracy. Additionally, this method requires the vehicle to be measured is the only one passing through the measurement site at a time. And the measurement site should be carefully selected to avoid background noise, reflections, or terrain that might affect the survey (Bernhard et al., 2005). The method is labor and time consuming but provides the best available data on the impact of traffic noise on the neighbors nearby the highways.

Figure 2.3. Typical measurement setup for SPB. (Source from Bernhard et al., 2005)

On-Board Sound Intensity System (OBSI)

On-Board Sound Intensity System (OBSI) system is developed by the California department of transportation (CalTrans). It uses the industry-standard sound intensity measurement technique adapted for a moving vehicle, using a jig that fastens the microphone assembly to the vehicle wheel (Figure 2.4). The measurements are made with microphones operating close to one and more test (reference) tyres, which are mounted on a test vehicle. The test vehicle is running along a road section over a specified distance. Results obtained are measured at standard speeds according to the category or type of road being considered. This technology allows quickly and accurately measure vehicle noise from a moving vehicle (Trevino & Dossey, 2006).

Figure 2.4. OBSI jig being attached to wheel hub on test vehicle (Source from Trevino and Dossey, 2006)

Close proximity methods (CPX)

Close proximity methods (CPX) has been actively pursued in Europe and is becoming the preferred method for conformity of production control of the acoustic quality of road surfaces (Mak et al., 2011). This method was developed to measure the tyre/pavement interaction noise independent of the OBSI. The details of the CPX procedure are described in ISO 11819-2 (Bernhard et al., 2005). The measurement system is in a trailer, as is shown in Figure 2.5. Microphones are equipped inside the trailer pointing at the interface between the tyre and the pavement and could obtain the sound level from the source. This method reduces most of the interference from the others, such as the wind noise and the noise from the other traffic, and thus allows it to measure in the traffic stream. This method could monitor and measure the different pavement conditions, however, with limited vehicle variation.

Figure 2.5. Typical CPX trailer measurement (Source from Bernhard et al., 2005)

2.2 AIR EMISSIONS

Production and laying of asphalt pavement at high temperatures produce fume and odor emissions. When the modifiers, such as the crumb rubber, or the polymer are added, even higher production and laying temperatures are needed. The concern on the air emissions is even greater. The fume and odors not only pollute the environment but also pose health risks to the workers and the others in the nearby micro-environment.

2.2.1 Air emissions from asphalt mixtures

The primary air emissions from the hot mix asphalt (HMA) production most noticeably include particulate matter (PM), volatile organic compounds (VOCs), and polycyclic aromatic hydrocarbons (PAHs) (Kitto et al., 1997).

PM2.5 is considered more damaging to human health than PM10 due to its fine size that could penetrate the lung (Amidon, 2013). Most of the PM produced from HMA are within a fine and respirable size range, hence leading to damages to the respiratory system and thus adversely affecting human health. Local authorities have controlled threshold values of PM2.5. Hong Kong Environmental Protection Department (EPD) implements a limitation of 75μg/m^3 (IAQMG, 2003). Canadian Ambient Air Quality Standards (CAAQS) specify 28μg/m^3 (EACC, 2013). A quantified evaluation of the PM emissions from HMA using laboratory asphalt fractionation analyses found that more than 75% by weight of the particles were in the respirable size range of 0.9~3.5μm; some of which are capable of deep penetration into the respiratory system, causing health risks (Kitto et al., 1997).

VOCs have been shown to have toxicological effects on the central nervous system, liver, kidneys, and blood of the human body (Kitto et al., 1997). Exposure to VOCs compounds, such as benzene, at high levels over long periods, which may increase the risk of cancer (Nikolaou et al., 1984). Over 50 species of VOCs have been detected in asphalt, some of these species are recognized as toxic and have been regulated by the environmental protection organizations (Nikolaou et al., 1984). The predominant VOC emissions were reported to be mainly composed of benzene, toluene, and ethylbenzene. When temperatures increased from 150ºC to 200ºC, the toluene and ethylbenzene emissions increased correspondingly and substantially (Kitto et al., 1997). The gaseous emissions of the mixtures with regular bitumen and polymer modified asphalt at the paver were studied and polymer modified asphalt was found to emit less total VOCs (Kitto et al., 1997). Others found that porous asphalt mixtures generated more VOCs than nonporous asphalt mixtures (Chong et al., 2013).

In addition to PM and VOCs, PAHs have been proved to be the carcinogenic compounds, which are present in the atmosphere in a particulate form. Animal studies have reported respiratory tract tumors due to exposure to PAHs (EPA, 2016). However, the exposure threshold of PAHs has yet to be determined, such exposure is considered harmful to health (WHO, 2010). Researchers from the National Institute for Occupational Safety and Health (NIOSH) believe that PAHs in a 4-7 ring may be more carcinogenic, while ones in the 2-3 ring may be more likely to be irritative (Burr et al., 2001). PAHs were found to undergo decomposition at high temperatures and react in the atmosphere simultaneously producing a number of derivatives, which could be more toxic (Burr et al., 2001). PAH concentrations significantly escalated when the asphalt temperature increased from 150ºC to 200ºC (Kitto et al., 1997). The Occupational Safety and Health Administration (OSHA) has mandated a permissible exposure limit in the workplace of 0.2 mg/m^3 (8-hour time-weighted average), or 200,000 ng/m^3 (Gehle, 2009). The PAH carcinogen of the conventional asphalt producer was detected in a very low concentration (Watts et al., 1997).

2.2.2 Factors affecting air emissions from asphalt mixtures

Studies on asphalt air emissions have been carried out in the laboratory (Porot et al., 2010; Zanetti et al., 2014), and also on construction site (Chong et al., 2013; Zanetti et al., 2014).

They found that compositions of the fume were affected by several materials specific such as mix designs, binder types, air temperatures, ambient environment. For instance, on a construction site, emission measurements on a construction site might be affected by some other pollution sources, such as vehicle emissions and construction dust. NIOSH in cooperation with the Federal Highway Administration (FHA) found that, in real construction conditions, the places suffering the highest exposure were near the paver or asphalt delivery trucks (Burr et al., 2001). They also found that the screed operators and roller operators were exposed to more PM during the asphalt paving process (Burr et al., 2001). Nevertheless, the bitumen type, content and composition were shown to be the most relevant (Zanetti et al., 2014).

2.3 ASPHALT PAVEMENT DURABILITY

It is clear that the environmental issues, including the air emissions and the low-noise, are still not the determinants. But the safety, cost and the durability are. Durability is one of the most basic requirements for the use of any pavement. Durable asphalt can result in a longer service life and reduce the efforts and the cost of repair and maintenance.

The durability of asphalt pavement is the ability for a long-term performance. With the repeated load from the vehicles and the complicated environment, asphalt pavements should provide the ability to maintain a satisfactory performance and structure in long-term service under increasingly demanding conditions (Hihara, Adler, & Latanision, 2013). The engineers are responsible for assuring an optimum performance of the pavement.

For flexible pavement, the primary forms of distress are fatigue cracking, rutting, and thermal cracking (Vivar & Haddock, 2006; Woo et al., 2007).

Rutting develops in the early life of a flexible pavement. At high temperatures, the asphalt mixtures are less stiff. The combination of consolidation and shear deformation lead to the material flow. To prevent from rutting, the stiffness of the asphalt pavement layers at high temperatures should be improved (Woo et al., 2007). Polymer modification to improve the asphalt mixture stiffness has worked well. However, the high stiffness leads to the more brittle material, and therefore susceptible to cracking under the repeated loading. At low temperatures, the stiffness increases and cracks can be more easily developed because of the restrained shrinkage and its brittle property. This kind of distress is called the thermal cracking. Consequently, even the rutting in the pavement is under control, the fatigue cracking is still a big problem (Woo et al., 2007).

The fatigue cracking occurs over the long term under repetitive traffic load, and will propagate rapidly to a structural collapse of the pavement (Woo et al., 2007). The fatigue characteristics of asphalt mixtures are usually expressed as relationships between the initial stress or strain and the number of load repetitions to failure-determined by using repeated flexure, direct tension, or diametric tests performed at stress or strain levels (Xiao et al., 2009). Several methods could be used in predicting the fatigue resistance. For example, the early empirical models developed by the Asphalt Institute model and the Shell nomograph as well as the beam flexural fatigue test (Woo et al., 2007; Xiao et al., 2009).

In designing a durable pavement, Marshall stability and flow are also important assessment criteria used for the mix design and evaluation of asphalt mixtures (ASTM, 2015). Typically, Marshall stability measures the maximum resistance load during a constant rate of deformation loading sequence (ASTM, 2015). The test load is increased until it reaches a maximum. The Marshall flow is the measure of deformation of the asphalt mixture determined during the stability test at a certain temperature. The value refers to the vertical deformation when the maximum load is reached. As bituminous pavement is subjected to severe traffic loads from time to time, it is necessary to adopt bituminous material with good stability and flow to provide a satisfactory durability.

2.4 COMPOUND MODIFICATIONS OF ASPHALT MIXTURES

As discussed above, the tyre/road noise, the air emissions, and the durability are the important issues, which should be taken good care of in the pavement design. The introducing of different compound modification on pavement asphalt mixtures can be a prospective way to improve and optimize the pavement surfaces behavior. It is possible that low-noise, low-emissions, and durable pavements can be achieved with certain modification practices. Indeed, modifiers are thus being introduced into the asphalt to strengthen the weaknesses or improve the mix performance to suit the local conditions. Numerous modifiers with different functions are available on the market. For instance, it may be necessary to use filler if the voids are many and widely spread and in this way improve the bond between the aggregate and the asphalt, and subsequently the mixture stability (Intertactive, 2010). An antioxidant such as carbon, calcium salts is capable of enhancing the durability of HMA by retarding their oxidation. Rubbers, including natural latex, block copolymer such as styrene-butadiene-styrene (SBS), and the reclaimed rubber like crumb rubber from old tyres, can be used to improve both the HMA stiffness at high service temperature as well as the fatigue cracking resistance. Warm mix additives, including zeolite, Evotherm ™, and Sasobit®; or foaming technology, can help lower the production and laying temperatures of HMA (D'Angelo et al., 2008), and thus reduce air emissions.

2.4.1 Polymer modification

Polymer modification of bitumen is the incorporation of polymers in bitumen by mechanical mixing or chemical reaction (Lu, 1997). During the last 40 years, more and more researchers began to concentrate on polymer modification of bitumen (Zhu et al., 2014). These various investigated polymers included plastomers (e.g. polyethylene (PE), polypropylene (PP), ethylene–vinyl acetate (EVA), ethylene–butyl acrylate (EBA)) and thermoplastic elastomers (e.g. styrene–butadiene–styrene (SBS), styrene–isoprene–styrene (SIS), and styrene–ethylene/butylene–styrene (SEBS)) (Zhu et al., 2014). These polymers were reported to improve some properties of bitumen, such as higher stiffness at high temperatures, higher cracking resistance at low temperatures, better moisture resistance or longer fatigue life (Alataş & Yilmaz, 2013; Gorkem & Sengoz, 2009; Isacsson & Zeng, 1998; Tayfur et al., 2007; Von et al., 2007). The characteristics of the bitumen and the polymer, the content of polymer and the manufacturing processes, all contribute to the overall properties of polymer modified bitumen (Larsen et al, 2009; Lu, 1997).

2.4.2 Crumb rubber modification

Blending of crumb rubber into asphalt cement has been practiced for years. For the asphalt concrete mixture, the viscoelastic property has been found to be one of the main factors influencing tyre/pavement noise (Biligiri et al., 2010). CR has been identified to work as a modifier because its presence affects the property of the asphalt mixtures. The principle source of the crumb rubber is from the waste tyre (Papagiannakis & Lougheed, 1995). The reuse of this material not only improve the elastic properties and the thermal stability property of the compound but also helps recycle waste.

There are basically two methods to produce crumb rubber modified asphalt (CRA) – the wet and dry processes (Papagiannakis & Lougheed, 1995). In this wet process, crumb rubber is blended well before mixing with aggregates. The dry process refers to the method that adds CRM directly into the asphalt mixture to replace part of aggregates or fillers. It has been demonstrated that CRMA mixtures produced by the wet process has superior engineering performance than those produced by the dry process. The modification effect can be influenced by a number of factors including the base bitumen composition, blending time and temperature, percentage and gradation of crumb rubber, and the grinding method ((Chesner et al., 1998; West et al., 1998). The implementation of rubberised asphalt can result in various advantages such as improved durability, improved fatigue cracking resistance, improved aging and oxidation resistance (Presti, 2013).

2.4.3 Warm mix technology

Warm mix asphalt technology is a concept that originated from Europe with the German Bitumen Forum in 1997 in response to a variety of concerns. At that time, Kyoto agreement on greenhouse gas reduction was in the process of being adopted by the European Union. Since then, a number of products and processes for Hot Mix Asphalt (HMA) temperature reduction have been developed in both Europe and the United States. The technologies that are used to make asphalt to be mixed and placed at a lower temperature are called Warm Mix Asphalt (WMA). WMA technology promotes the workability by reducing the viscosity or interfacial friction of the asphalt binder, so that binders can be coated on the aggregate in lower temperatures than conventional HMA.

The application of WMA has several benefits. First of all, by reducing the production temperatures, less energy is needed, thereby reducing the consumption of the fossil fuels. According to Federal Highway Administration (FHWA), the reduction of fuel consumption typically ranges from 20-50% (John D'Angelo et al., 2008). Temperature reduction about 60^{o}F (15^{o}C) compared to HMA can save fuel by around 0.5-1 gallons (1.9-3.8L) of fuel per ton of mix. For the 42 million tons of WMA produced in 2010 in the U.S., this equates to over 35 million gallons (132 million L) of fuel that is saved, from which indicates that WMA saves energy and is cost-effective. Second, based on lower production temperatures, fewer fossil fuel is needed to heat the materials and operate the burners, and reduce the carbon footprint to the environment. Meanwhile, the lower compacting temperature makes it possible for asphalt to be hauled to a more distance place as well as extended the paving season. In addition, less fumes and odors are emitted with the lower production temperature. This helps improve the working condition and thus provide a safer health for the onsite workers. Moreover, although they do not consider it as a prime advantage, but some contractors in the Europe acknowledged that improvement in field compaction was realized when using WMA (John D'Angelo et al., 2008).

Currently, numerous WMA technologies are available in the U.S., which can be classified into three main groups, i.e., organic additives, foaming technologies, and chemical additives.

The use of organic additives is accomplished by adding an organic wax to bitumen or asphalt mixtures, which reduces the viscosity of the binders (Capitão et al., 2012). When the mixture temperature goes down, the additive inside crystallizes, and forms a crystal structure of microscopic particles, which increases the mixture stiffness and the resistance to deformation (Capitão et al., 2012). Sasobit® is one of the most common commercial products available of this additives type. Studies have shown that the use of Sasobit® generally decreases the rutting potential of the asphalt mixtures, lowers the indirect tensile strength, but may increase to potential for moisture damage (Hurley & Prowell, 2005b).

Foaming processes refers to the small amount of water injected into the hot binder, and steam is thus generated and entrapped in the binder. This phenomenon produces a large volume of foam, and temporarily reduce the viscosity (Capitão et al., 2012; Rubi et al., 2012). This effect remarkably improves the workability of the bitumen, but the period of time is very limited, and special precaution should be taken while adding water. Moreover, the quantity of water added should not be too much to cause the stripping problems (Rubio et al., 2012). Water could be injected into the binder directly, also could be introduced into the binder by using some water-containing materials, such as zeolite. The very commonly commercial product of synthetic zeolite is called Aspha-min®. Studies have shown the adding of Aspha-min® does not comprise the resilient modulus; and the field test with no traffic shows that the moisture susceptibility does not increase after one year (Hurley & Prowell, 2005a).

2.5 DURABILITY, AIR AND NOISE EMISSIONS OF MODIFIED ASPHALT MIXTURES

The use of the crumb rubber asphalt improves the durability of the asphalt mixture. Besides, CR helps make asphalt a more damping material. A study conducted by Biligiri et. al. (2010) concluded that open-graded asphalt rubber friction course (CR-OGFC) mixes reduce tyre/pavement noise in comparison with the other bituminous surfaces because they act as acoustic absorbers owing to the increased viscoelastic nature of the CR-OGFC mix (Biligiri et al., 2010). Biligiri (2013) has quantified the acoustical damping properties of dense-graded HMA and CR-OGFC, damping ratios and dynamic magnification factors were estimated from the mixtures. This research has indicated that, CR-OGFC provides higher noise-damping response then HMA, which means a better low-noise effect (Biligiri, 2013). Continuously, Biligiri (2014) has conducted field noise evaluation experiments in 2007 and 2011, CR-OGFC performed well in low-noise (Biligiri & Way, 2014). Combining asphalt rubber and a gap-graded aggregate structure- CRSMA is a promising product to achieve better noise absorption capacity and improved durability.

However, to achieve the workability of the high-viscosity rubberized asphalt, CRA had to be constructed at higher temperatures which in turn caused fumes and odors. The polymer modified asphalt faces the similar situation. Therefore, although CRSMA is a promising material in noise reduction and durability, the public’s criticisms on its high construction emissions have limited its application.

WMA is expected to perform as good as or even better than HMA. Up until now, research findings have confirmed that WMA performs as well as HMA (D'Angelo et al., 2008; Zaumanis, 2010).

The review above reveals the necessity of further examining the impacts of asphalt modifiers on air and acoustical emissions collectively in addition to the durability assessment of the modified asphalt. The current study is to perform a laboratory and field study to look into these impacts, under the constraints of available laboratory equipment and road construction sites. The detailed comprehensive methodology will be presented in the next chapter.

CHAPTER 3

RESEARCH METHODOLOGY

The methods to assess the durability, air emissions and the acoustic performances used by other researchers are reviewed in this chapter. It also presents the rationale and the research methodology employed in this study to answer the research questions given in Chapter 1.

3.1 RESEARCH FRAMEWORK

The research framework is shown in Figure 3.1. The basic asphalt pavement mechanical properties, the odor and fume emissions from the production and laying processes, as well as the tyre/road noise produced from various types of pavements will be evaluated.

Both laboratory and the field tests will be carried out because (i) it is important to check whether the performance of pavement surfaces are consistent in both the laboratory and the field and (ii) the field data of mechanical tests is not available (note that we have no access to the field test results by contractors) and can only be obtained in the laboratory and the noise measurement can only be performed in field study.

The description of each test to be performed is given below. Some tests, for example, the tyre/road noise measurement, cannot be performed in the laboratory because there is no equipment available. And, some pavement types, for example, the rubberized asphalt, are not monitored on site because this material has not been laid on the roads in Hong Kong. All the pavement surface types to be examined in this study are either commonly adopted or being considered by the road authority – Highways Department- in Hong Kong.

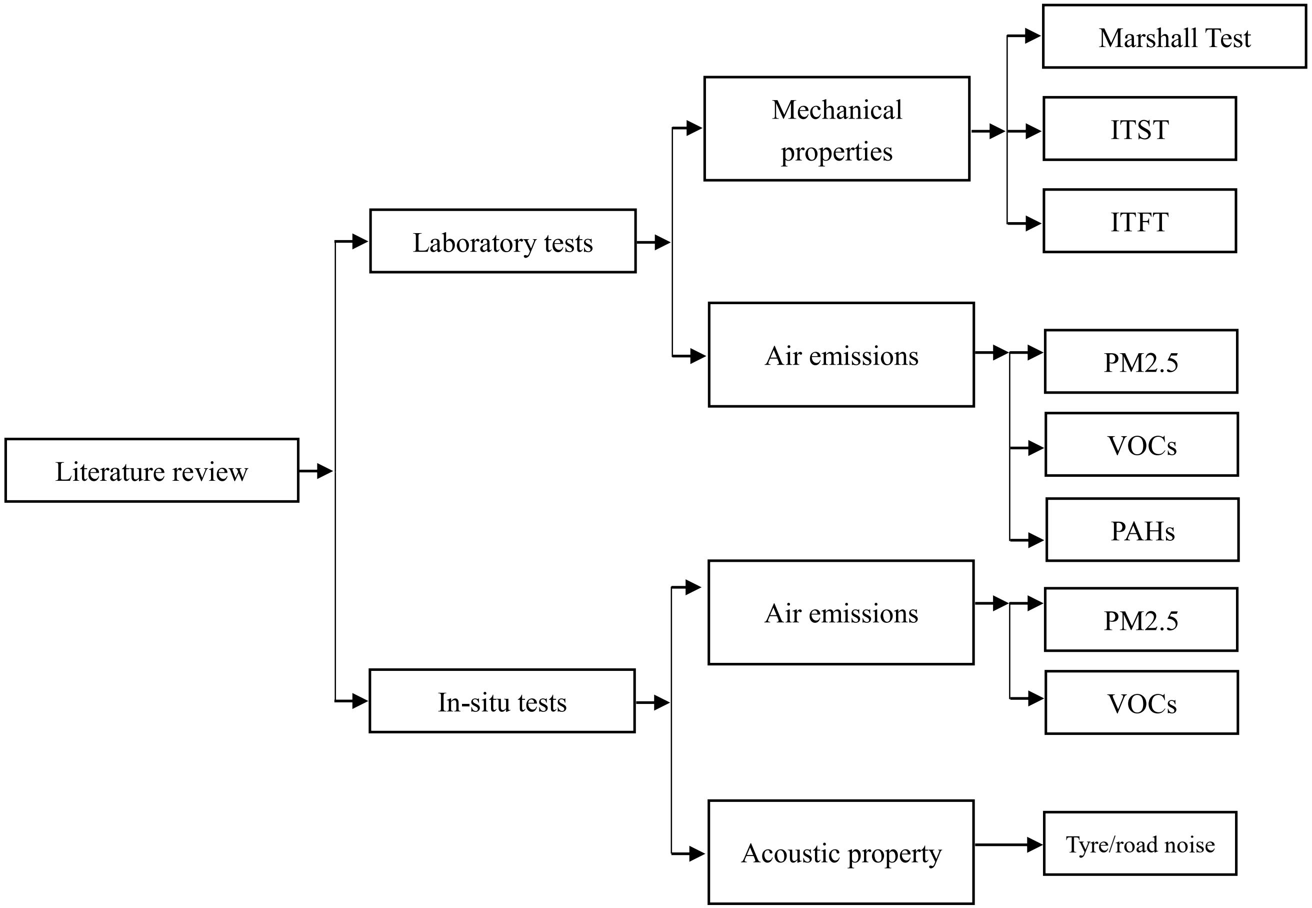


Figure 3.1. Research framework of this study

3.2 LABORATORY ASSESSMENT OF MECHANICAL PROPERTIES AND AIR EMISSIONS OF ASPHALT MIXTURES

3.2.1 Laboratory Marshall sample preparation

Marshall samples of different pavement types were produced in the laboratory for evaluation. Included were mixtures using a conventional asphalt binder, such as the dense-graded asphalt mixture (DG) and the Stone Mastic Asphalt (SMA); those using SBS polymer modified asphalt (PG76), including the OGFC and PMSMA, and the SMA using both the crumb rubber and warm mix additives (RWSMA).

Marshall sample grading

In Hong Kong, of the above asphalt mixtures, the DG is known as the Wearing Course (WC), and the OGFC, the Polymer Modified Friction Course (PMFC). The mix designs are based on recipes approved by the Highways Department (HyD). Hereinafter, the number followed by the type of pavement surface refers to the nominal aggregate size of this type of pavement, for instance, WC10 means that the mixture has a WC grading with a nominal aggregate size of 10mm. In this study, eight different types of asphalt mixtures, i.e., WC10, WC20, SMA6, SMA10, PMSMA10, PMFC10, PMSMA6, and RWSMA6 were prepared. The specific mix aggregate gradations of these mix designs are shown in Figure 3.2. The binder content and the additional additives such as lime and cellulose fiber content are shown in Table 3.1. SMA6, PMSMA6, and RWSMA6 are of the same SMA6 aggregate grading but have different bitumen use. As mentioned in the paragraph above, Pen 60/70 conventional grade bitumen was used for SMA6, SMA10, WC10 with a mixing temperature of above 155°C; PG76 as used in the PMFC10 and PMSMA6 with a mixing temperature of above 175°C; and the Pen 60/70 modified with both crumb rubber and Sasobit® was used in the RWSMA6 mix, at 145°C.

Marshall samples of these mixtures were first fabricated in the laboratory. The Marshall Test, Indirect Tensile Stiffness Test, and Indirect Tensile Fatigue Test were then carried out for the mechanical and durability properties evaluation.

Table 3.1 Binder contents and extra additives for SMA10, PMSMA10, PMFC10, SMA6, PMSMA6, RWSMA6, WC10 and WC20

Bituminous Materials	**SMA10**	**PMSMA10**	**PMFC10**	**SMA6 PMSMA6 RWSMA6**	**WC10**	**WC20**
Binder content (%)	6	6.5	5.5	6	6	5
	(including 2% hydrated lime and 0.3% Cellulose Fibre)	(including 2% hydrated lime and 0.3% Cellulose Fibre)	(including 1.5% hydrated lime)	(including 2% hydrated lime and 0.3% Cellulose Fibre)	-	-
Mixing temperature (^{o}C)	155	175	175	SMA6-155 PMSMA6-175 RWSMA6-145	155	155
Compaction temperature (^{o}C)	135	155	135	SMA6-135 PMSMA6-155 RWSMA6-125	135	135

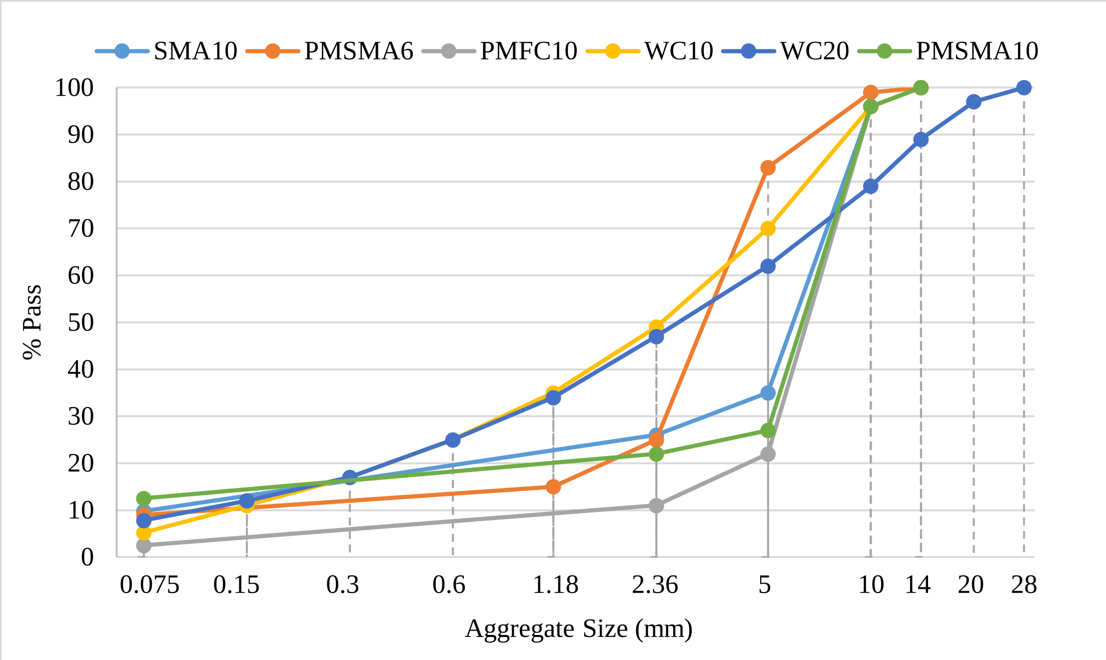
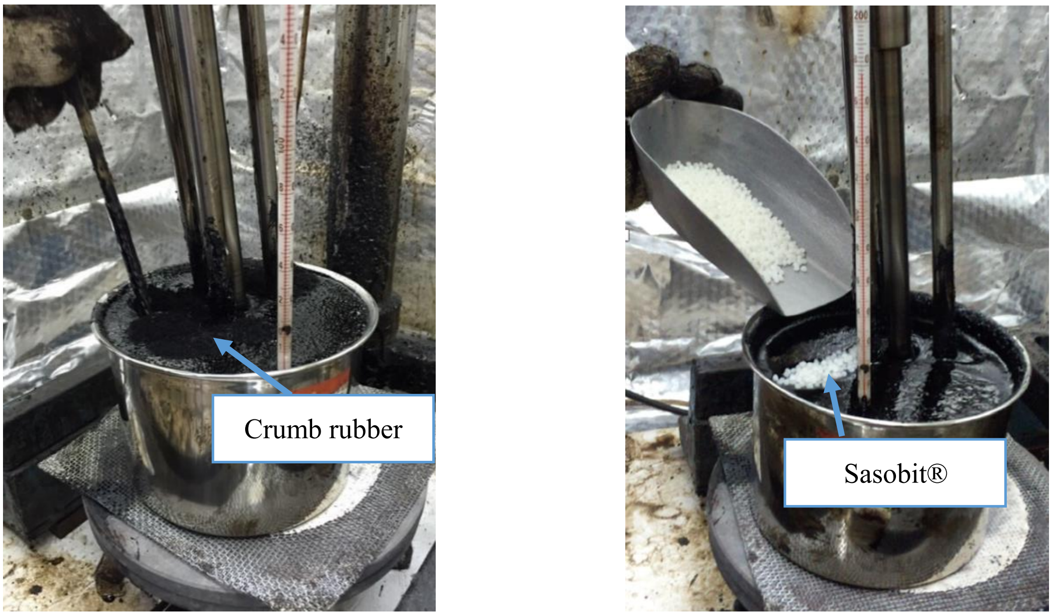


Figure 3.2. Aggregate gradations of SMA10, PMSMA10, PMSMA6, PMFC10, WC10 and WC20

Materials preparation

The two types of bitumen, Pen60/70 (regular binder) and the PG76 (modified binder) are commercial products from the Shell Corporation. The crumb rubber modified asphalt with the Sasobit® has to be prepared before mixing. The crumb rubber should be gradually introduced into the regular binder, using a high-shear emulsifying machine. They were mixed with a rotating speed of 3000r/min for about 45 minutes to make a homogeneous binder mixture. During this process, the temperature is kept at around 180ºC. A thermometer is immerged into the middle of the binder detect and hence to control the inside binder temperature. Sasobit® is introduced after. The temperature should be controlled around 150ºC with a rotating speed of 600r/min. Bubbles may appear when mixing with Sasobit®, we will wait till the bubble go away with rotation, and then transfer this mix to the oven. The production process, when adding the modifiers is shown in Figure 3.3.



(a) Adding crumb rubber (b) Adding Sasobit®

Figure 3.3. Production of modified asphalt

Granite from the local quarry was used as the aggregate for all the mixtures. The raw aggregates were dried at 105ºC in an oven for 24 hours and then sieved to enable separation into the desired fraction sizes. The aggregates were sieved and dried in an oven for 24 hours, at 105ºC. The required amount of each fraction size was weighed in individual fraction containers. All the aggregate blends and heat mould cylinders, bases, extension collars were placed in an oven and heated to a temperature of approximately 28ºC above the mixing temperature. The bitumen was placed in an oven at a temperature not higher than the mixing temperatures.

Mixing and compacting procedure

The mixing procedure in the laboratory complied with the Guidance Notes Mix Design of Bituminous Materials (RD/GN/022G) (Department, 1996). Preheated aggregates were firstly placed in a mixing bowl, and the required binder mass was then poured into the bowl. They were rapidly and thoroughly mixed by a trowel to achieve a uniform distribution. The mixing temperature was detected by pointing an infrared thermometer at a center point during the mixing process. The heating plate was controlled manually to better ensure an acceptable mixing temperature. During the mixing process of each sample, three temperature points were recorded.

A mould was taken from the oven, a filter paper disk placed over the bottom of the mould. The mixed materials were then transferred into the mould, the mixture spaded with a heated spatula 15 times around the mould perimeter and 10 times over the interior of the mould. The top of the mixture was formed into a dome (Department, 1996). It is considered compacted when the temperature lies at the compaction temperature ±2^{o}C. When the specimen has cooled to room temperature, 25^{o}C, the specimen was extruded and the height/thickness measured in accordance with ASTM D3549. A caliper was used to measure the space between the upper and lower surfaces, to ensure well-defined construction demarcation lines. Four measurements at approximate quarter points on the periphery of the cores or the approximate midpoint of each of the four sides of a rectangular were then recorded. The average of these measurements, were taken as the thickness of the specimen, At least three samples of each type were replicated (ASTM, 2011).

3.2.2 Laboratory physical and mechanical property tests

To identify the physical properties of the samples described above were according to ASTM standards to identify the sample qualities tested. Focus was on such as air voids, bulk density, Marshall flow and stability. The Indirect Tensile Stiffness Modulus Test (ITST) and Indirect Tensile Fatigue test (ITFT) were conducted to specifically identify the mechanical and durability property of the different types of asphalt mixtures.

Marshall Test

Marshall samples were first prepared. The Marshall machine is shown in Figure 3.4. Marshall Tests in accordance with the ASTM D 6927-Standard test method for Marshall Stability and Flow of asphalt mixtures (ASTM, 2015) were conducted to evaluate the Marshall Stability and Flow. Four replicas for each mixture were prepared. After a 35-minute immersion period in a 60^{o}C water bath, samples were tested by a Marshall Test machine as is shown in Figure 3.5. Marshall Stability and Flow were recorded by a recorder in conjunction with a load cell and a linear variable differential transducer (LVDT).

Figure 3.4. The Marshall machine

Figure 3.5. Marshall Test

Indirect Tensile Stiffness Modulus Test

An Indirect Tensile Stiffness Modulus Test (ITST), in accordance with BS EN 12697-26: Bituminous mixtures - Test methods for hot mix asphalt -Part 26: Stiffness (BSI, 2012) was carried out to find the stiffness modulus of a selection of different mixture samples. Four replicas of each mixture were prepared for this test. As shown in Figure 3.6., load pulses were applied on the specimen, through the vertical shaft to achieve a target peak transient horizontal deformation of 5 microns at a constant temperature of 20°C. The applied load was measured by a load cell while the horizontal deformation was measured by two LVDTS. The rise-time was controlled within 124±4ms. For each sample, 5 repeated load pulses were conducted (BSI, 2012).

The specimen stiffness modulus was determined using the following equation:

$$E = \frac{F \times (v + 0.27)}{(z \times h)} \quad (1)$$

where

E is the measured stiffness modulus (MPa);

F is the peak value of the applied vertical load (N);

z is the amplitude of the horizontal deformation obtained during the load cycle (mm);

h is the mean thickness of the specimen (mm);

v is the Poisson's ratio, which is 0.35 for this experiment.

The measured stiffness modulus was adjusted by using the following equation.

$$E' = E \times (1 - 0.322 \times (\log(E) - 1.82) \times (0.60 - k)) \qquad (2)$$

where

E' is the adjusted stiffness modulus (MPa), based on a load area factor of 0.60;

k is the measured load area factor;

E is the measured stiffness modulus(MPa).

The stiffness modulus for one type of mixture was taken as the average value from the mixtures.

Figure 3.6. Indirect Tensile Stiffness Modulus Test

Indirect Tensile Fatigue Test

The Indirect Tensile Fatigue Test (ITFT) was conducted to measure the durability of the asphalt mixtures based on BS EN 12697-26: Bituminous mixtures -Test methods for hot mix asphalt -Part 26: Stiffness to evaluate the durability of all mixtures (BSI, 2012). The temperature were controlled at a constant 20°C. The vertical cyclic sinusoidal stress of 250MPa was applied to the samples. The ITFT used the displacement transducer built into the actuator to determine the vertical deformation. The failure criterion was 10mm, but the samples were always permanently destructed before reaching 5mm. Therefore, based on the sample's failure the test was terminated, and the fatigue resistance was characterized as the recorded load pulse number at failure. The test is shown in Figure 3.7.

Figure 3.7. Indirect Tensile Fatigue test

3.3 LABORATORY ASSESSMENT OF AIR EMISSIONS

PM2.5, VOCs and PAHs were monitored in the laboratory controlled environment while the Marshall samples were being manufactured at their corresponding mixing temperatures. PM2.5 was monitored in real time using a PM monitor, DustTrack 8530 (Figure 3.8.). VOCs emissions were sampled by using vacuum canisters with a flow rate of approximately 200ml/min. This flow rate enables the sampling process to approximately fit the mixing period. Samples were analyzed by the HP6980 gas chromatograph (GC) coupled with HP5973 mass selective (MS) detector, shown in Figure 3.9., in accordance with the International Organization for Standardization (ISO) TO14 Method. The Photoelectric Aerosol Sensor (PAS) 2000 was used to measure the PAHs concentrations. The machine is shown in Figure 3.10. During the five-minute mixing of the asphalt mixture, the PM monitor, canister, and the PAHs sensor were placed on a fixed platform at the height of the worker's breathing zone. The detected levels of VOCs were the average concentrations in the sampling period while the detected level of PM2.5 was the real-time records with an interval of one minute. The real-time concentrations of PAH are recorded by every 10 seconds. The mixing temperature was around 155°C for the SMA6, SMA10, WC10 and WC20, around 175°C for the PMSMA6, PMSMA10 and PMFC10, and about 145°C for RWSMA6. The equipment setup is shown in Figure 3.11.

Figure 3.8. PM monitor: DustTrack 8530

Figure 3.9. GCMS machine

Figure 3.10. EcoChem PAS2000 machine

The three monitoring machines were set at the breathing zone of the operator, which was about 1 m above the mixing bowl to catch the emissions from mixing. The air emission monitor setup is shown in as the following:

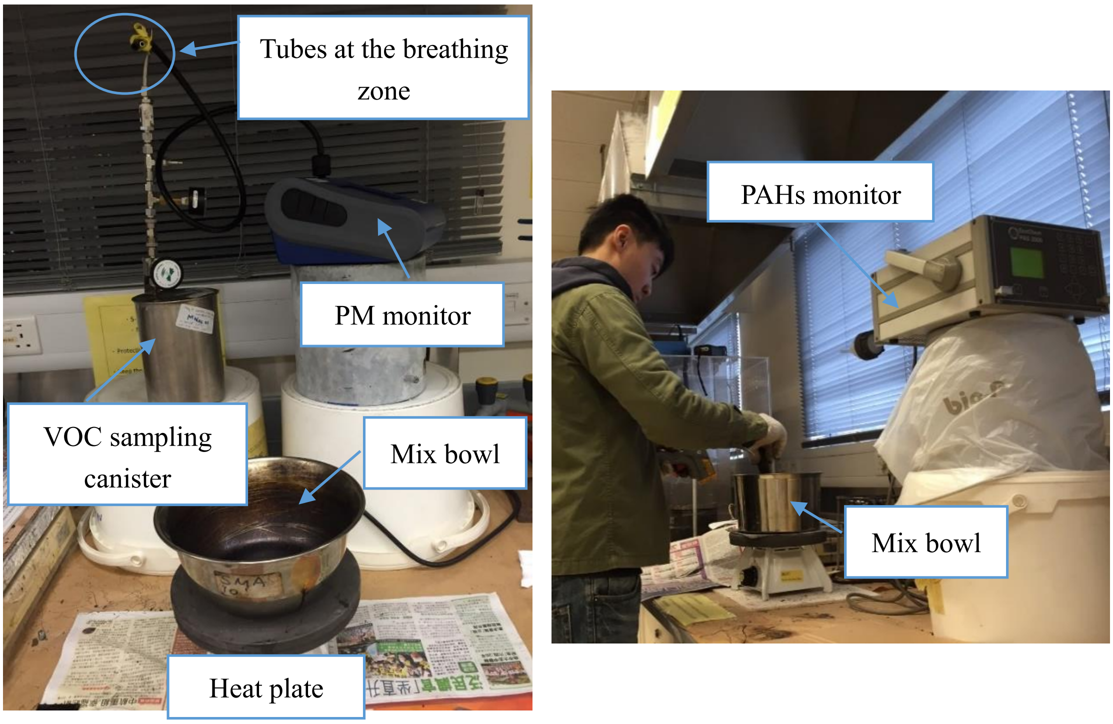


Figure 3.11. Air emissions monitoring setup

The number of samples tested for each asphalt mixture was recorded and is shown in Table 3.2. The sample size of each HMA for laboratory tests are shown as below.

Table 3.2. Sample size of each HMA for laboratory tests

	SMA10	PMSMA10	PMFC10	SMA6	PMSMA6	RWSMA6	WC10	WC20
Marshall test	6	3	3	3	4	4	4	3
ITST	3	-	10	3	4	3	4	-
ITFT	3	-	10	3	4	3	4	-
PM2.5	4	3	3	3	5	4	3	3
VOCs	3	3	3	3	4	4	3	3
PAHs	-	3	-	-	3	4	3	3

3.4 IN-SITU ASSESSMENT OF AIR EMISSIONS AND ACOUSTICAL PROPERTIES OF ASPHALT MIXTURES

3.4.1 In-situ assessment of air emissions

For the field experiments, air pollutant emissions, including PM2.5 and VOCs during the laying and compacting processes were monitored at pavement construction sites. The air samples were each monitored for PMFC10, PMSMA6, PMSMA10 and WC20. As shown in Table 3.3., the PMFC10, PMSMA6, PMSMA10 and WC20 air samples were each monitored at 12 pavement construction sites in Hong Kong. For each type of surface, three data samples, from each type of pavement construction sites were collected. The details of the site locations, air temperatures are presented in the Appendix.

Table 3.3. In-situ Sampling information

Types of surfaces	PMFC10	PMSMA6	PMSMA10	WC20
Sampling number of Construction site	3	3	3	3

The process of PM2.5 and VOCs sampling on site is similar to that in the laboratory, for instance, a VOC canister was placed together with a PM monitor. The VOC samples were first collected through a pre-vacuumed canister with a flow rate of around 200ml/min, and then objected to a GCMS analysis in the laboratory. Four canisters in total were used for each construction site sampling. Of these four, one canister was used for the background ambient emissions before construction while the other three were used during the paving process. Meanwhile, PM2.5 was measured in real time by the PM monitor and recorded every minute. The background emission level before construction was also measured. When the paver began to operate, the monitoring equipment started simultaneously. For each survey, the air monitors were set at a spot 15 meters from the paver start point and 40 cm from the curb as shown in Figure 3.12.

Figure 3.12. In-situ air assessment

3.4.2 In-situ assessment of acoustic performance

Among several noise measurement methods, the Close Proximity (CPX) method is the most commonly used method internationally, which allows valid comparisons between sites over time (Ho et al., 2013; Sandberg, 2008). In this study, the acoustic property of the pavements was evaluated by measuring the tyre/road noise level using the CPX trailer fabricated by the PolyU, as shown in Figure 3.13. The trailer was designed in accordance with the ISO11819-2 Acoustics–Method for Measuring the Influence of Road Surfaces on Traffic Noise–Part 2: The Close Proximity Method (Ho et al., 2013; Hung, Lam, & Kam, 2012; Hung, Wong, & Ng, 2008). The specific illustration of the microphones in the trailer is illustrated in Figure 3.14. A twin-wheeled CPX trailer was equipped with two mandatory microphones at each wheel, positioned 200mm from the tyre side walls and

100mm above the surface and pointing at ±45° to the tyre and the road contact interface (Hung et al., 2012; Mak, et al., 2012). The CPX surveys were carried out on the PMSMA6, PMFC10, SMA10, and WC10 at a reference driving speed of 50km/h. The Standard Road Testing Tyre (SRTT) was fitted for performing the tyre/road noise measurements.

Figure 3.13. The CPX vehicle with trailer

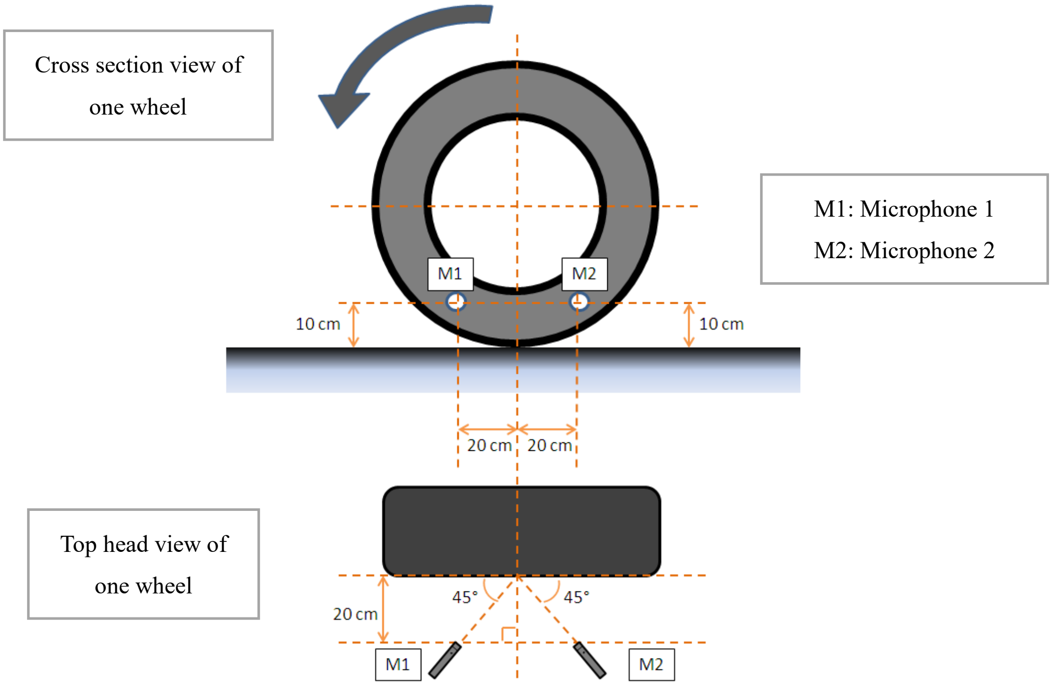


Figure 3.14. Microphone positions of one-side wheel in the CPX trailer

In addition to the results of the previous study conducted by PolyU, the sample numbers of the four pavement types are summarized in the following table. To ensure data reliability, each tested section underwent at least three runs (Hung et al., 2012).

Table 3.4. Sample numbers in the CPX survey for the four pavement surfaces

	PMFC10	PMSMA6	SMA10	WC10
Sample numbers (section)	63	8	4	4

CHAPTER 4

LABORATORY MECHANICAL PROPERTIES AND AIR EMISSIONS BEHAVIOR OF ASPHALT MIXTURES

This chapter presents the data obtained in the laboratory experiments conducted as mentioned in the Chapter 3. The physical properties, and the air emissions monitoring results are analyzed and discussed in this chapter.

4.1. LABORATORY MECHANICAL PROPERTIES OF ASPHALT MIXTURES

4.1.1 Mechanical Properties of asphalt mixtures

Different asphalt mixtures were fabricated in the laboratory. The physical properties of these samples, including air voids, bulk density were measured, and the Marshall Flow and Stability were evaluated by the Marshall test. By comparing the test results to the standards set by the Highways Department (HyD), the samples were of acceptable quality. Specific results are given in Table 4.1.

Table 4.1. Physical properties of laboratory samples

	Air voids (%)	Bulk density (Specific gravity)	Marshall flow (mm)	Marshall stability (KN)
SMA10	3.61 (3.5-4.5)	2.31	2.39 (≤4)	10.49 (≥6)
PMSMA10	3.53 (3.5-4.5)	2.28	3.77	14.83 (≥6)
PMFC10	18.81 (18-25)	1.97	2.34	7.74
SMA6	8.35	2.17	1.34	8.23
PMSMA6	8.69 (7-10)	2.18	2.82	12.49 (≥6)
RWSMA6	9.82	2.11	2.75	10.36
WC10	3.31 (3.0-5.0)	2.32	2.02 (≤4)	14.18 (≥10)
WC20	3.07 (3.0-5.0)	2.36	2.38 (≤4)	17.6 (≥10)

SMA-stone mastic asphalt
PMSMA-polymer modified stone mastic asphalt
PMFC-polymer modified friction course
RWSMA-crumb rubber modified asphalt with warm mix stone mastic asphalt
WC-wearing course

The mix design was based on the available technical specifications from the Highways Department (HyD) of the Hong Kong government. The specifications are cited in the blankets in Table 4.1. These specifications are in line with the American standards; for example, the air void of dense graded and the typical SMA are designed in a range of 3 to 5% (NCHRP, 2011); while the open-graded mixture is targeted in the range of 18 to 22% in US. By comparing the test results to the specification, the samples were of acceptable quality.

As shown in Table 4.1., the dense-graded mixtures (WC10 and WC20) have the densest structure among the others, and have high Marshall stability values. WC20 shows a higher density than WC10. The porous asphalt (PMFC10) has the highest air void content of over 18%, leading to a low Stability value. For the SMA10, PMSMA10, the air void contents vary little around 3.5%. However, when the nominal aggregate size of SMA change from 10 to 6mm, SMA6 has a much higher air void of 8.35%, while PMSMA6 of 8.69 and RWSMA6 of 9.82. This is because with the same mixture volume and similar bitumen content, the one with more crushed aggregates has a greater surface area, and the interlock skeleton of these aggregates has formed more interspace.

For the SMA6, PMSMA6 and RWSMA6, which are in the same grading but with different binders, their bulk densities and the air voids value are quite similar with each other. By introducing different modifiers into the SMA6, both the PMSMA6 and the RWSMA6 mixture samples performed better in the Marshall test. The Marshall Flow values were both considerably increased. This indicated that the elastic property of SMA6 was improved by adding these modifiers. With the modification of SBS Polymer (PMSMA6), the Stability result was greatly improved, the value was closer to that of the well-graded mixture, i.e., WC10. For the SMA6 modified by the crumb and the Sasobit (RWSMA6), the Stability value is slightly increased, and was close to that of the SMA10.

With the SBS polymer modification, the Stability of PMSMA10 was greatly improved compared to SMA10 and PMSMA6 was also improved to have a higher Stability value than SMA6. The Marshall Stability of polymer modified mixes was similar to that of the well-graded mix, WC10. As for SMA10, WC10 and PMFC10 with the same nominal aggregate size, the larger the air voids, the smaller is the Marshall Stability value.

It can be seen from Table 4.1., the mixtures have the same nominal aggregate size, including SMA10, WC10 and PMFC10, showed that the larger the air voids, the smaller is the Marshall Stability value.

4.1.2 Indirect tensile stiffness modulus

The stiffness modulus of various types of asphalt mixtures were evaluated by the ITSM test. The testing results are shown in Figure 4.1. RWSMA6 has the highest stiffness while the PMFC10 has the lowest. After the polymer was added in the SMA6 (PMSMA6), PMSMA6 and SMA6 actually have similar stiffness modulus. The stiffness value hardly changed. However, by using the crumb rubber asphalt mixed with Sasobit®, the stiffness is greatly improved. In general, SMA is a stiffer material than OGFC (PMFC). With the modification of crumb rubber, the stiffness increases (Mashaan, et al., 2014). With the mix of SMA and Sasobit®, the stiffness increases, too (Al-Qadi, et al., 2012).

Meanwhile, it shows that among SMA10, PMFC10 and WC10, with the same normal aggregate size in 10 mm, SMA10 is the one with the highest stiffness value. This results illustrate that this gap-graded structure is stronger than others.

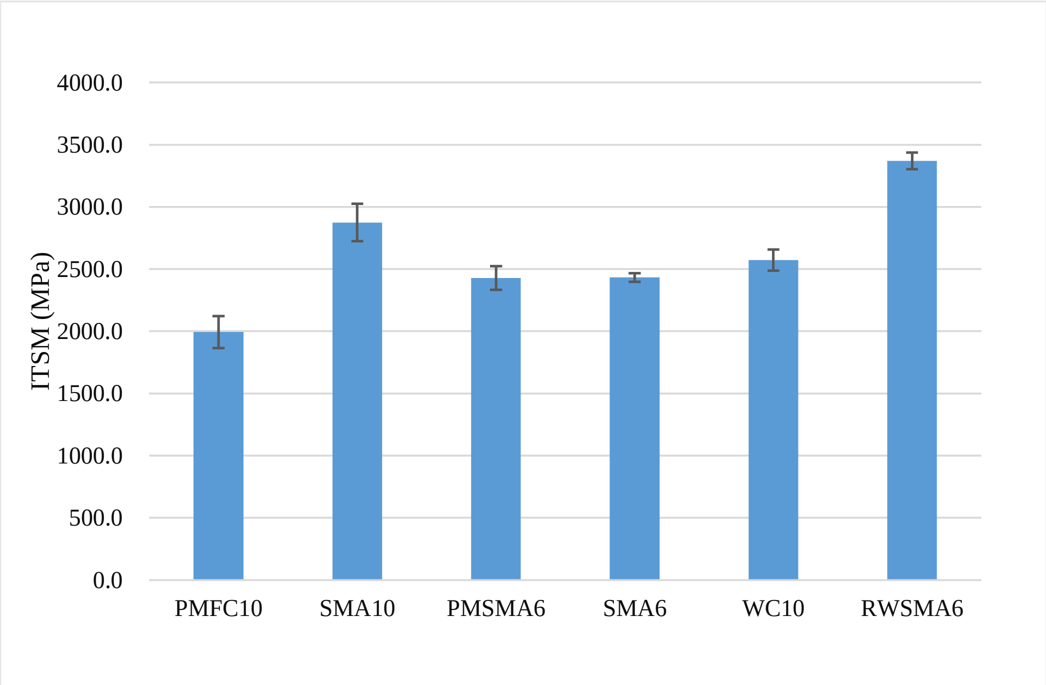


Figure 4.1. Indirect tensile stiffness modulus of different asphalt mixtures

4.1.3 Indirect tensile fatigue resistance

Indirect tensile fatigue test results are shown in Figure 4.2. Compared to the other asphalt mixtures, PMSMA6 has shown its great fatigue resistance, which has the average pulse number up to 30,000. Without the improvement by SBS modified asphalt PG76, SMA6 has the worst durability under cyclic loading. The highest value of pulse number indicates that the PMSMA6 was the most durable mix among the different mixes tested. It is probably PMSMA6 has the smallest grain size leading to largest surface area which is coated with the polymer modifier bitumen (a binder with better viscosity).

PMFC10 also has a good performance in durability with a pulse number of 6632. In this test, the fatigue performance of different pavement surfaces can be ranked from high to low as PMSMA6, PMFC10, SMA10, and WC10.

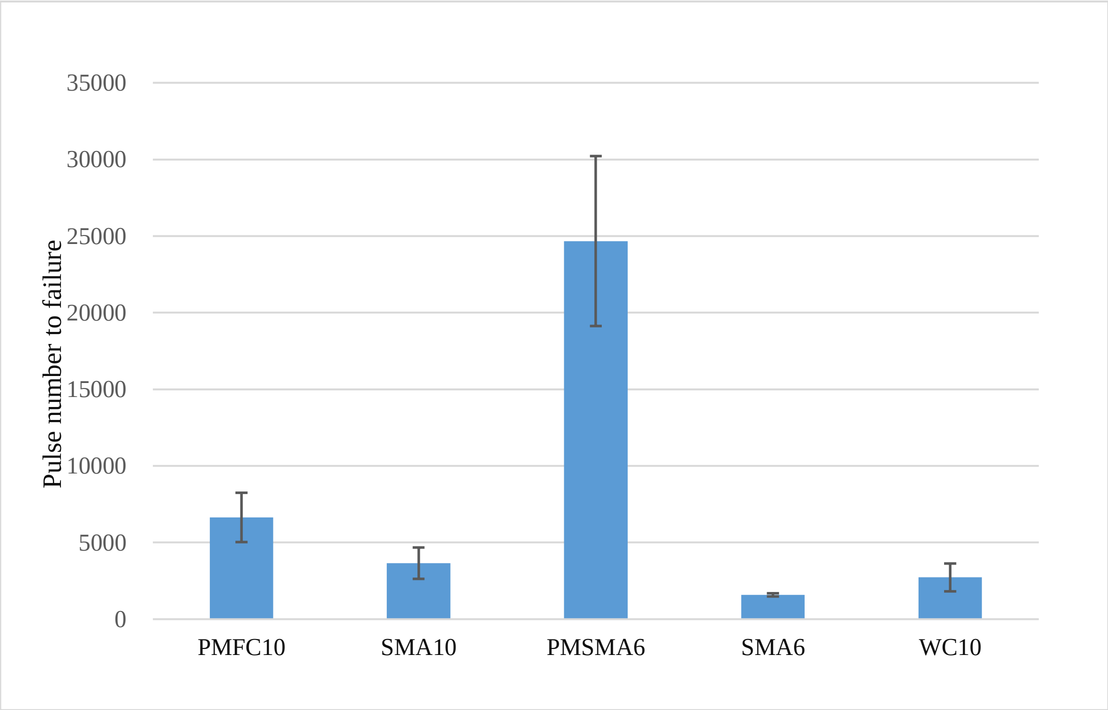


Figure 4.2. Pulse number to sample failure for ITFT

Correlation analysis has been conducted. It was found that, the indirect tensile fatigue test results have a quite significant positive linear relationship with the Marshall flow. In the meanwhile, the indirect tensile stiffness modulus results completely have no linear relationship with the Marshall flow.

4.2 LABORATORY AIR EMISSION OF ASPHALT MIXTURES

4.2.1 PM2.5 results from laboratory

The PM2.5 concentrations of the different mixtures are presented in Figure 4.3. and Figure 4.4. Since laboratory experiments were conducted in two different laboratories, the results of different mixtures were presented by laboratory (Lab1 and Lab 2) in two figures. PM2.5 concentrations of SMA10, SMA6, PMFC10, WC10 and PMSMA6 measured in Lab 1 are illustrated in Figure 4.3.; and the concentration of RWSMA6 measured in Lab 2 is shown in Figure 4.4. For comparison purpose, the SMA6 modified by the crumb rubber (RASMA6) only was also produced in the Lab 2.

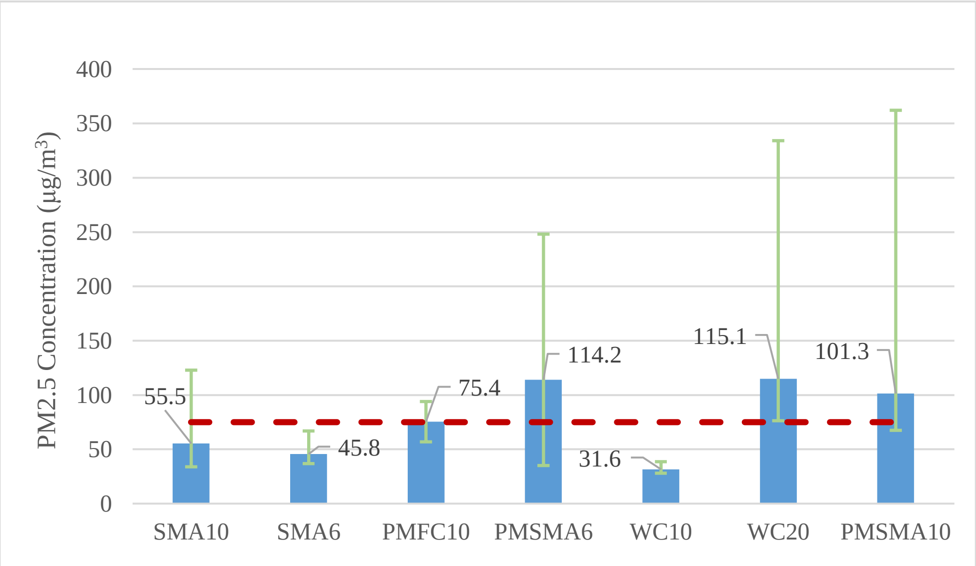


Figure 4.3. PM2.5 results from Lab 1 (temperature=155 – 175°C)

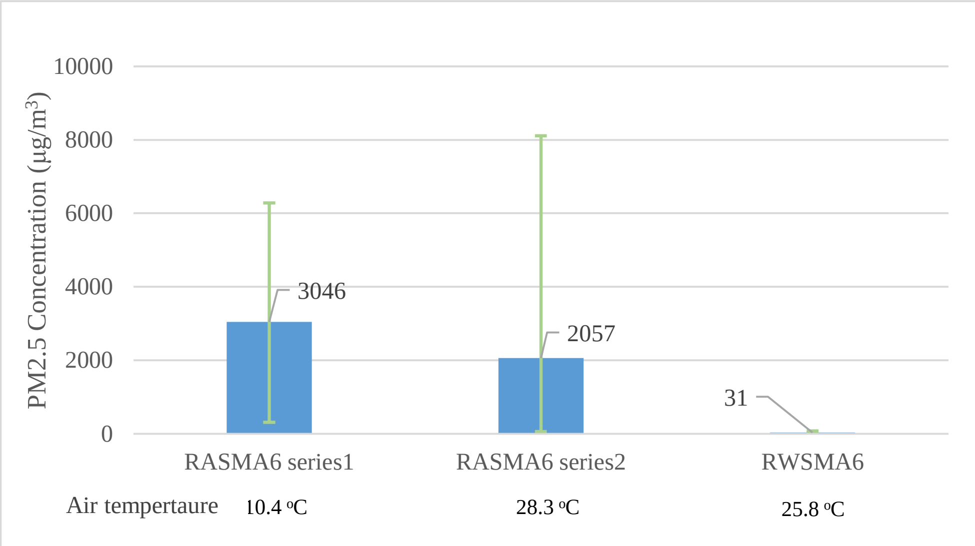


Figure 4.4. PM2.5 results from Lab 2 (temperature=145 – 165ºC)

It can be seen from Figure 4.3. that more PM2.5 was emitted by the PMSMA6, PMSMA10 and WC20 than the SMA10, and WC10 during the laboratory mixing process. Their detected concentrations exceeded the EPD specified standard of 75μg/m^3 (IAQMG, 2003). This was probably caused by multi-factors especially the higher mixing temperature needed for the polymer modified asphalt. Additionally, the relatively high portion of the fillers in PMSMA and WC20 also contributed to the amount of particulate matters detected.

It is worth noticing that the two batches of RASMA6 and one batch of RWSMA6 were tested under different air temperature. The air temperatures were recorded accordingly. The RASMA6 batch 1 was mixed and tested at 10.4ºC, while RASMA6 batch 2 was at 28.3ºC. These two batches of RASMA were produced with the same material design and laboratory equipment, but different air temperature. It can be seen that the RASMA6 batch 1 was produced at a lower air temperature, and lower PM2.5, of about 1000μg/m^3 in average, was emitted. This results obtained suggest that the air temperature significantly affect the PM2.5 emissions. It also suggests that the lower air temperature could result in the higher PM2.5 emissions. In addition, under the similar air temperature, the RASMA6 emitted considerable higher PM2.5 concentrations than that of the RWSMA6. It indicates that the adding of warm mix additives into the crumb rubber asphalt resulted in a great reduction in the PM2.5 emissions.

4.2.2 VOCs results from laboratory samples

VOC samples were collected and analyzed by GCMS according to the Compendium Method TO-14. In total, 41 VOCs compounds were detected and quantified. Since 30 out of the 41 compounds were below the limit of detection, 11 were thus listed and analyzed. The concentrations of these 11 compounds and the total VOCs of these 11 species from the seven tested mixtures are tabulated in the following two tables. While SMA10, SMA6, PMFC10, PMSMA6 and WC10 were tested in Lab 1, RASMA6 and RWSMA6 were tested in Lab 2. Results are shown in the Table 4.2 and Table 4.3., respectively. The Indoor Air Quality Objectives from Hong Kong for good class are also tabulated for reference.

Table 4.2. VOC concentrations of different asphalt mixtures from the Lab1 (ppb)

Compound Name	Lab 1 Background	SMA10	PMSMA10	SMA6	PMFC10	PMSMA6	WC10	WC20	IAQ objectives for good class
Chloroform	0.02	0.00	0.04	0.03	0.01	0.01	0.03	0.04	5
Benzene	0.05	0.10	0.27	0.04	0.09	0.14	0.16	0.16	5
Carbon Tetrachloride	0.03	0.01	0.05	0.02	0.02	0.05	0.05	0.05	16
Trichloroethylene	0.05	0.07	0.41	0.00	0.00	0.02	0.02	0.39	143
Toluene	0.15	0.59	0.29	0.47	0.22	0.37	0.55	0.24	290
Tetrachloroethylene	0.01	0.01	0.02	0.04	0.00	0.01	0.02	0.02	37
Ethylbenzene	0.03	0.29	0.07	0.09	0.04	0.10	0.05	0.07	333
p-Xylene	0.01	0.07	0.09	0.02	0.02	0.07	0.08	0.09	333
o-Xylene	0.00	0.04	0.11	0.02	0.02	0.03	0.03	0.10	
1,2-Dichlorobenzene	0.00	0.01	0.00	0.01	0.01	0.00	0.02	0.00	83
1,4-Dichlorobenzene	0.00	0.01	0.02	0.00	0.00	0.00	0.01	0.02	33
Total 11 VOCs	0.35	1.19	1.36	0.73	0.44	0.81	1.02	1.17	-

SMA-stone mastic asphalt
PMSMA-polymer modified stone mastic asphalt
PMFC-polymer modified friction course
RWSMA-crumb rubber modified asphalt with warm mix stone mastic asphalt
WC-wearing course

According to Table 4.2., the concentrations that were detected in the Lab 1 are, in general, extremely low comparing to the IAQ Objective. Actually, all of the components are within in the suggested good class standard. Although the PMFC10 and PMSMA6 have a higher mixing temperature, in most of the compounds, they have a lower emission category than the SMA10 and WC10. As the total VOC (11 listed) in Table 4.2. shows that SMA10, WC10 and WC20 have the relatively high VOC emissions. The PMFC10 also has the lowest total VOCs emissions. This phenomenon is probably caused by the bitumen polymeric phase dispersed on the bitumen surface at a higher temperature. This could act as a protective layer and suppress the emissions from the bitumen.

Table 4.3. VOC concentrations of different asphalt mixtures in Lab 2 (ppb)

Compound Name	Lab 2 RASMA6 background	RASMA6	Lab 2 RWSMA6 background	RWSMA6	IAQ objectives for good class
Chloroform	0.00	0.00	0.00	0.00	5
Benzene	0.35	0.28	0.45	0.19	5
Carbon Tetrachloride	0.01	0.01	0.00	0.00	16
Trichloroethylene	10.02	10.37	1.46	1.49	143
Toluene	1.54	4.62	4.59	4.56	290
Tetrachloroethylene	0.00	0.05	0.51	0.43	37
Ethylbenzene	0.14	0.35	1.06	1.11	333
p-Xylene	0.44	0.54	0.86	0.95	333
o-Xylene	0.17	0.13	0.76	0.74	
1,2-Dichlorobenzene	0.05	0.00	0.00	0.00	83
1,4-Dichlorobenzene	0.02	0.00	1.23	1.26	33
Total 11 VOCs	12.74	16.35	10.93	10.74	-

SMA-stone mastic asphalt
PMSMA-polymer modified stone mastic asphalt
PMFC-polymer modified friction course
RWSMA-crumb rubber modified asphalt with warm mix stone mastic asphalt
WC-wearing course

The VOC compounds concentration of RASMA6 and the RWSMA6 made in the Lab 2, are listed in Table 4.3. Since the variations were large, the background VOCs before mixing RASMA6 and the RWSMA6 were recorded respectively. Despite the higher background VOCs, the RASMA6 produced the highest VOC emissions. With the mixing of warm mix additive: Sasobit®, the total VOCs decreased, and was even lower than the background level.

The results presented in graphic form is shown in Figure 4.5.

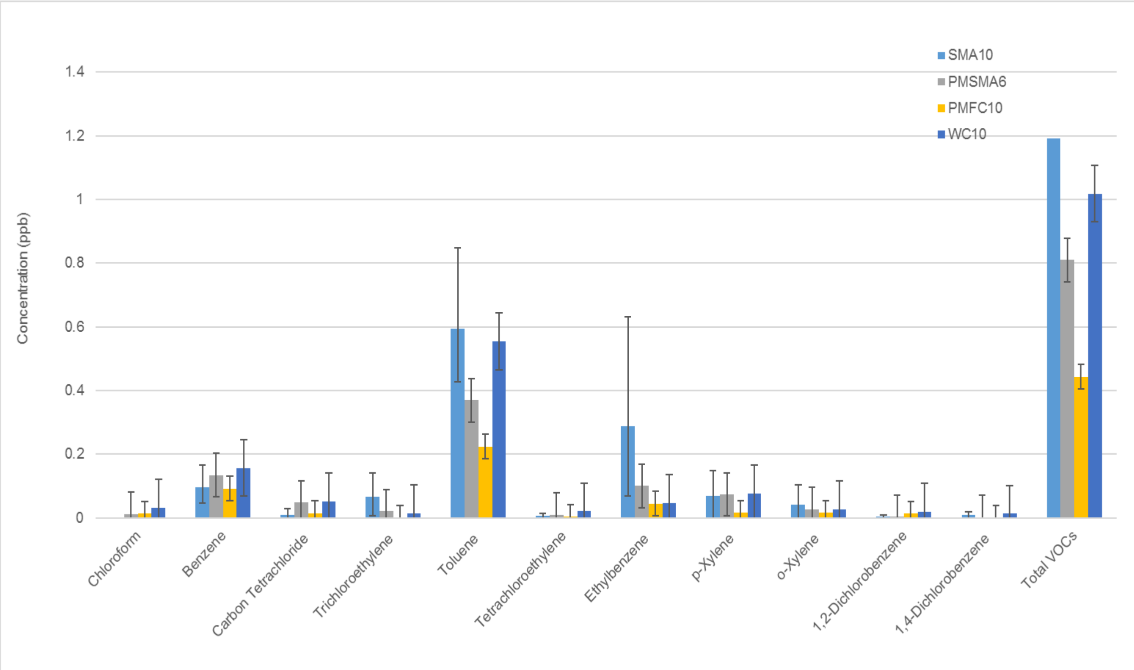


Figure 4.5. VOCs from asphalt mixtures at mixing (temperature=145 – 175°C)

As shown in Figure 4.5., benzene, toluene, trichloroethylene, and ethylbenzene, are the four dominant VOC species in all the mixtures. This finding is consistent with that of the previous study (Kitto et al., 1997). The SMA10 has the highest toluene and ethylbenzene emissions. The SMA10 has the highest toluene and ethylbenzene emissions. In general, mixes using binder 60/70 emits more VOC compounds than using PG76. PMFC10 has the lowest total VOC emissions. This phenomenon is probably caused by the polymeric phase dispersed on the bitumen surface at a higher temperature. This could act as a protective layer and suppress the emissions from the bitumen. However, PMSMA10 has the highest total VOC emissions with a large variation. This indicates an uncontrollable VOC plume may have interfered one of the experiments. For the four dominated species, i.e., benzene, toluene, trichloroethylene and ethylbenzene, EPD specified levels for good air quality class are at 5, 290, 143 and 333 ppb respectively (IAQMG, 2003). As illustrated in Figure 4.5., the measured concentrations of these four emittants are respectively all below 0.2, 0.6, 0.5 and 0.3ppb, indicating that the VOCs concentrations measured in the laboratory are extremely low.

4.2.3 PAHs results from the laboratory samples

Total PAH values of PMSMA6 and WC10 were measured in the laboratory; the results are shown in Table 4.4.

Table 4.4. Total PAHs from asphalt mixtures at laboratory mixing

	PMSMA6	PMSMA10	WC10	WC20
Mixing temperature	175 - 190ºC	175 - 185ºC	165 - 180ºC	155 - 170ºC
Mean value (ng/m^3)	26.3	18.8	54.7	20.9
Standard derivation	35.1	6.4	65.9	51.9
Maximum value	330.6	54.5	484.7	57.9

SMA-stone mastic asphalt
PMSMA-polymer modified stone mastic asphalt
PMFC-polymer modified friction course
RWSMA-crumb rubber modified asphalt with warm mix stone mastic asphalt
WC-wearing course

During the 10 minutes of mixing, great variations of total PAHs were observed for all asphalt mixtures. It is very likely caused by the temperatures. PAH concentrations were observed significantly increased when the temperature increased from 150 to 200ºC (Kitto et al., 1997). It could possibly be explained by the fact that the PAHs with high vapor pressures volatilized at a lower temperature, whereas the ones with relatively low vapor pressures also volatized when temperature increased (Kitto et al., 1997). The PMSMA6 was mixed at a higher temperature range of 175 - 190ºC than that of the PMSMA10 of 175 - 185ºC, and the maximum PAHs detected is considerably higher with a big standard derivation. The similar trend is found between the WC10 and the WC20. It could be concluded from Table 4.4. that with the same binder, the higher the temperature, the more PAHs were emitted; and the greater was the variation. Total PAHs emitted from PMSMA6 has the mean value of 26.3ng/m^3, peaking at about 330ng/m^3. For WC10, the total PAHs values fluctuated around 55ng/m^3, and peaking at approximately 484ng/m^3. Even with a lower mixing temperature, the use of conventional binders resulted in a higher emission of PAH. The difference may be caused by (i) different binders, i.e., PG76 and conventional binder; (ii) different mixing temperature; and the (iii) different design mix. Nevertheless, these measured levels are far below the limiting value of 200,000ng/m^3 specified by the Occupational Safety and Health Administration (OSHA) (Watts et al., 1997).

CHAPTER 5

IN-SITU AIR EMISSIONS AND ACOUSTICAL BEHAVIOR OF ASPHALT MIXTURES

This chapter presents and discussed the data obtained at the road construction sites. The sites were identified through local road contractors who happened to have projects during the period of this study. The road surfaces constructed are either commonly adopted or being trailed in Hong Kong. The air emissions, including PM2.5, VOC concentration monitored the sites are presented. The results of tyre/pavement noise level measured in some of these sites and other previous sites are also presented and discussed.

5.1 IN-SITU AIR EMISSIONS OF ASPHALT MIXTURES

These monitors were placed at the spot 15 meters away from the paver at start, 40 cm away from the curb. The monitoring process could be explained as follows. Before pavement construction, background air quality of PM2.5 and VOC were measured for around 10 minutes. At each site, the freshly manufactured hot mixed asphalt was transported in a truck to site and poured from the truck into the paver. When the paver started moving, the PM2.5 monitor was switched on and the VOC sampling was started as well. It took a few minutes for the paver to pass the monitoring/ sampling point. A steel wheel compactor then started to compact the paved asphalt mixture after the paver. It moved back and forth frequently by the side of monitoring point; and then moved away with the paving machine but moved back for only a few times. The PM2.5 monitor was then switched off and the VOC sampling was completed.

5.1.1 In-situ PM2.5 results

The onsite PM2.5 results of WC20, PMSMA10, PMSMA6, and PMFC10 were measured.

The results show that the onsite PM2.5 concentrations are significantly higher than those in the laboratory, even within the same type of bituminous mixtures. Actually, most of the surveys have far higher concentrations than the EPD standard of 75μg/m^3 (IAQMG, 2003). This is because the real environment is affected by multiple factors, such as the different laying processes, the daily air temperature, the traffic situation and wind speed and direction.

The PM2.5 concentrations of different mixture types showed a similar trend as illustrated in the Figure 5.1. The results show that PM2.5 concentrations vary in accordance with the construction phase. Despite the high background levels, the construction still contributed a lot to the PM2.5 concentrations. The peak PM2.5 concentrations generally appear as soon as the paver was passing the monitoring point. When the paver passes by, the emissions from the paver diesel engine also can have contributed, and have showing some episodes. The pavement temperature was still at a high level and more volatile compounds and vapors evaporated. When the paver passed by, the emissions from the paver diesel engine also contributed to the PM2.5, as demonstrated by the episodes shown in the Figure 5.1. The PM2.5 increased upon commencement of compaction process because of the fume emissions caused by the compactor and the paver diesel engine. When the temperature dropped over time, the PM2.5 concentrations decreased. PM2.5 was considerably higher when the temperature difference between the heated asphalt mixtures and the air temperature was bigger (owing to lower air temperature).

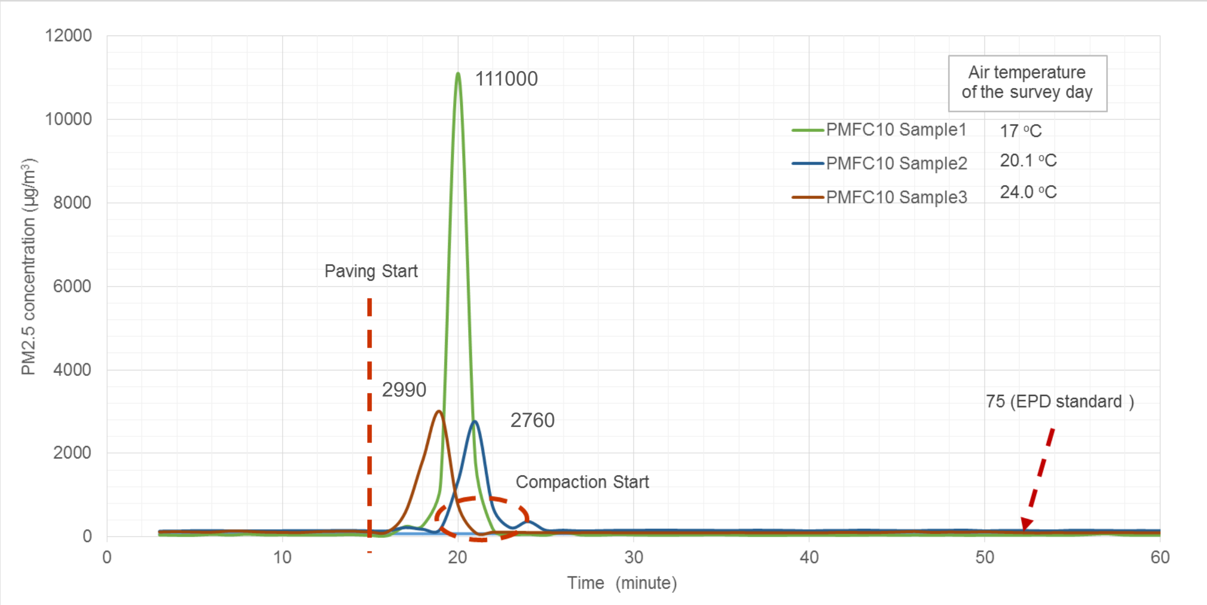


Figure 5.1. Measured PM2.5 onsite for PMFC10

5.1.2 VOCs emission from the construction site

The measured VOC compounds onsite for WC20, PMSMA10, PMSMA6, and PMFC10 are shown in Figure 5.2. to 5.4. Figure 5.2. shows the concentrations VOC species for the first 15 minutes. During this period, the paver was passing the stationary monitor, with a temperature of approximately 135~200ºC. Figure 5.3 shows the VOC concentrations in the following 15 minutes, during which the roller was working back and forth by the side of the VOC monitor. Another 15-minute sample was collected when the roller was in general working at a distance from the monitoring spot, and occasionally returning for compaction. The results are shown in the Figure 5.4.

Different from the laboratory sample tests, toluene, benzene and p-xylene are the dominant compounds for the onsite VOCs. This maybe owing to the paver engine exhaust, the cigarette smoke from the workers, as well as the gasoline vapored from the vehicles nearby; xylene however was mainly found in the workplace (Forxall, 2010). The laboratory experiment was under a controllable environment, while the in-situ assessments were exposed under the real emissions environment, which was uncontrollable. In the previous study, benzene concentration was 1.1ppb for the polymer modified asphalt measured in the laying process at a temperature of 165°C (Zanetti, Fiore, Ruffino, Santagata, & Lanotte, 2014). In this study as presented in Figure 5.2., benzene concentration from PG76 is around 0.5ppb. Both results indicate the low level of benzene emitted from the asphaltic concrete pavement laying process. The highest VOC concentrations are observed during the paving process. The VOCs content decreased in line with the lowering of temperatures.

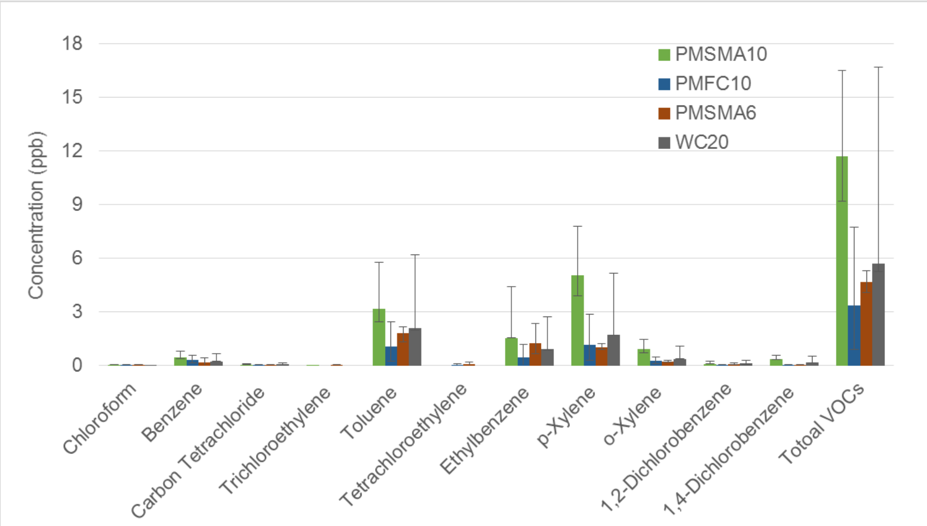


Figure 5.2. VOCs from asphalt mixtures at paving (temperature=135 – 200°C)

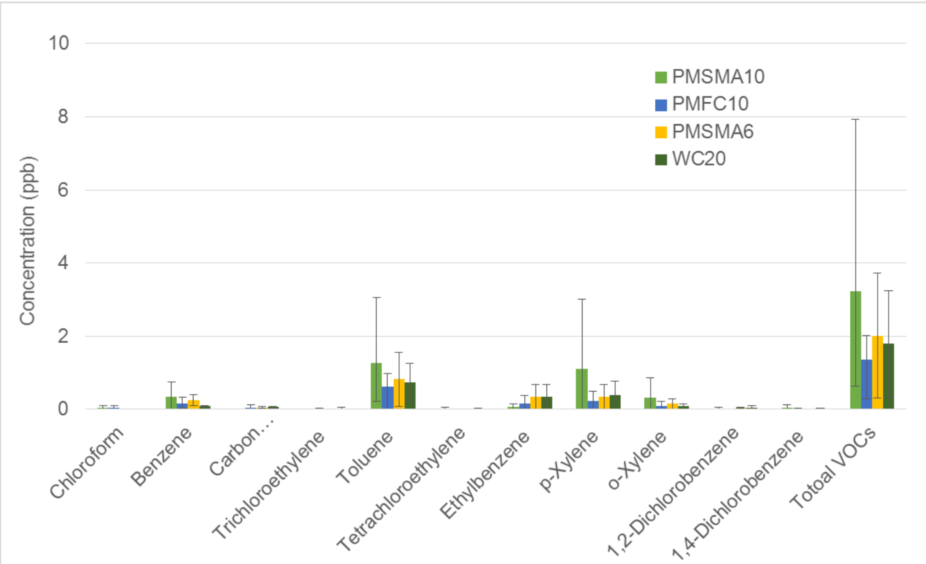


Figure 5.3. VOCs from asphalt mixtures at compaction 1(temperature=70 – 140°C)

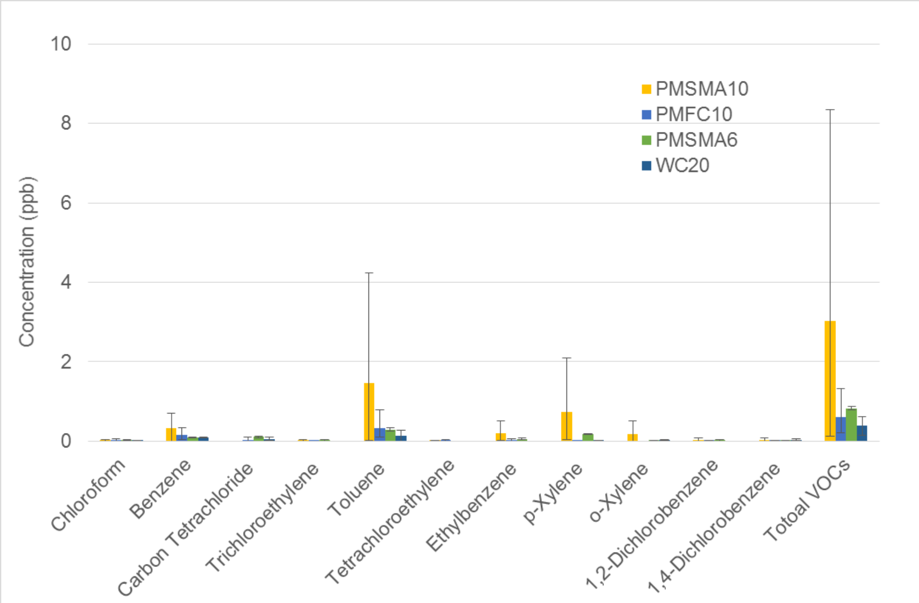


Figure 5.4. VOCs from asphalt mixtures at compaction 2 (temperature=60 – 80°C)

The onsite total VOC (TVOC) concentrations of PMSMA10, PMFC10, PMSMA6 and WC20 in average in different time periods are shown in Figure 5.5. It indicates that the TVOC concentrations decreased with time. For all kinds of surfaces, concentrations in the paving stage (at the first 15 minutes) are higher than those after. When the paving crew moved away, and the temperatures decreased with time, the VOC concentrations decreased in the meantime.

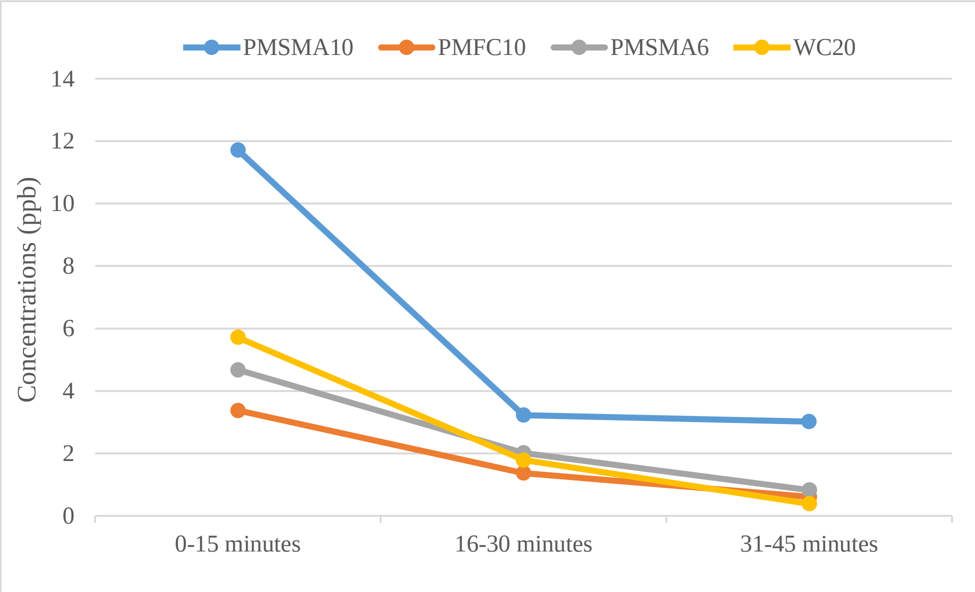


Figure 5.5. Trends of total VOC concentrations of asphalt mixtures with time

The VOC concentrations of PMSMA10, PMFC10, PMSMA6 and WC20 in different paving stages were analyzed by Pearson Correlation two-tailed test. The test results are attached in the Appendix. The analysis indicated that most of the VOC concentrations are positively correlated. It suggests that the linear correlation is present in the VOCs over time, the TVOC concentrations during the compaction process would get higher if the initial concentration when paving is higher.

5.1.3 Relationship between laboratory and in-situ air samples

To further explore the relationships between the laboratory and in-situ air samples, the Pearson correlation analysis was employed. By running the Pearson correlation, hardly any significant correlation was found between the PM2.5 samples from the laboratory and the construction sites for various types of road surfaces. It shows that uncontrollable factors might have great impacts on the PM levels.

The VOCs from both the construction sites and the laboratory were analyzed by surface type.

In particular, there appears to be a very strong, positive correlation for PMSMA6 (r=0.884, p=0.000) and PMFC10 (r=0.815, p=0.002) between the laboratory and in-situ concentrations, while no significant correlation was observed for PMSMA10 (r=0.223, p=0.510) and WC20 (r=0.236, p=0.485). It suggests that the uncontrollable factors could have great impact on the VOC emissions of asphalt mixtures.

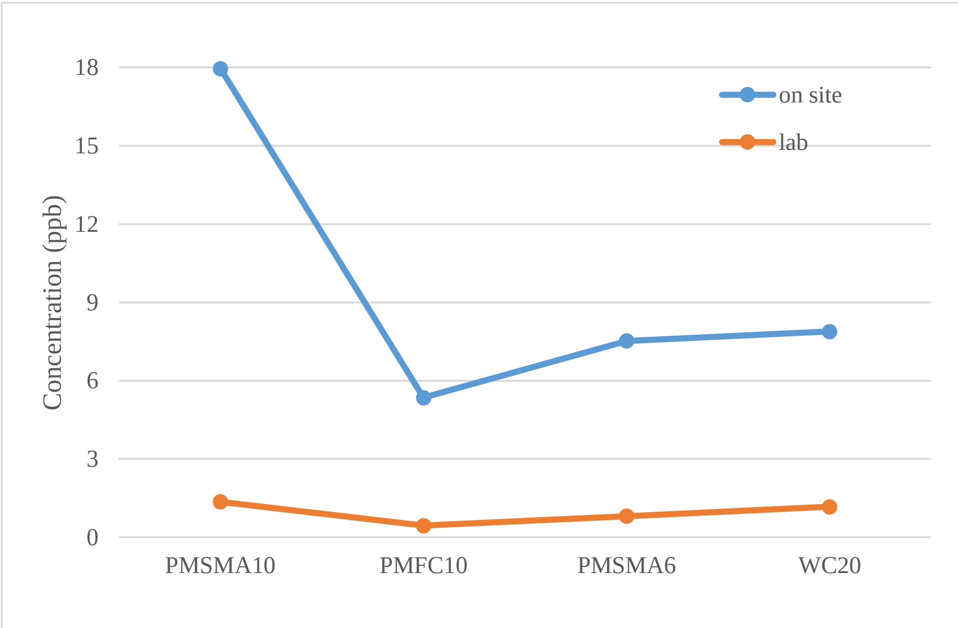


Figure 5.6. Total VOC concentrations of asphalt mixtures in the laboratory and on site

The Figure 5.6 shows that the average TVOC concentrations in the field and in the laboratory have a similar trend for different road surface types. In particular, PMSMA10 was detected to have highest TVOC levels, while PMFC10 has the lowest.

5.2 CPX SURVEY RESULTS

The tyre/road noises results measured with the SRTT tyre at 50km/h are illustrated in the Figure 5.7. As illustrated, SMA10 is the nosiest pavement surface, while a smaller aggregate size, such as PMSMA6, is responsible for less noise. The noise performance with PMFC10 varies greatly, as there are new and old surfaces. Although in general a good performance is shown when it is newly laid, but deteriorates as the surface ages especially when the air pores are clogged. It is worth noting that there are about 60 PMFC10 surfaces while less than 10 of the other types of surfaces were surveyed. Overall, for the low noise performance, different pavement surfaces can be ranked from high to low as PMSMA6, PMFC10, WC10, and SMA10.

These findings are consistent with other research. One research conducted by the University of California pavement research center (Ongel et al., 2008). It evaluated the noise performance trends for Dense-graded asphalt (DG), Open-graded asphalt (OGFC), gap-graded asphalt, and rubberized asphalt concrete by using the On-board Sound Intensity (OBSI) method. It has shown that, with the reference speed of 60mp/h (96km/h), the pavements that were currently in use for no more than two years, the DG mixes have the highest sound intensity level, while the OGFC has a quieter sound intensity level, but with a big variation. This indicated a good low-noise performance of OGFC, but this low-noise characterize varied with time significantly. However, no less than 9.5 mm the nominal aggregate size was tested in this research.

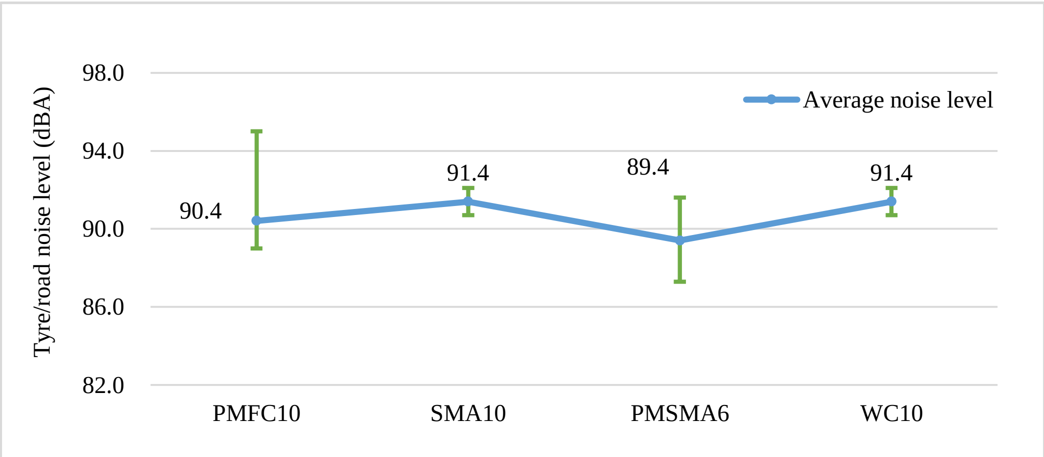


Figure 5.7. The CPX tyre/road noise of PMFC10, WC10, SMA10 and PMSMA6 measured with SRTT at 50km/h

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

6.1 SUMMARY OF THE STUDY

This study sets out to assess different modified asphalt mixtures with focus particularly on the mechanical properties, acoustical emissions, and air pollutant emissions. Within the constraints of available equipment in the laboratory and construction sites for different pavement surfaces, limited but well-designed laboratory tests and site monitoring works were conducted.

This study shows that the addition of modifiers, such as polymer and crumb rubber, can help improve the mechanical quality and low noise performances of the pavement but need higher working temperatures, which severely exaggerates the fume and odor issues as well as the concern of health. The high temperatures needed when producing and laying asphalt pavements bring about the fume and odor problems, which pose health risk to the workers and affect other nearby environment. The warm mix additives, such as Sasobit®, mixed with the asphalt mixture can lower the working temperatures and thus reduce the air and odor emissions.

6.2 MAJOR FINDINGS

The major findings are summarized below:

6.2.1 The laboratory experiments reveal that the mixing temperature of asphalts has a great effect on gaseous and particulate emissions. Comparing WC and SMA with a mixing temperature of 155°C, to PMFC and PMSMA with a mixing temperature above 175°C, the average PM2.5 concentrations emitted from PMFC and PMSMA was 75.4 and 114.2μg/m^3 respectively while the average PM2.5 concentrations emitted from WC and SMA had a respective concentration of only 55.5 and 31.6μg/m^3.

6.2.2 An elevated concentration of 484 ng/m^3 of total PAHs was observed at mixing of asphalts, which was still far below that of the Occupational Safety and Health Administration (OSHA) standard of 200,000ng/m^3.

6.2.3 As observed from the construction site study, PM2.5 concentrations of different types of mixtures were higher than the regulated level. Furthermore, PM2.5 concentrations significantly increased owing to the greater temperature difference between the heated bitumen and the air temperature. This observation however, has to be carefully interpreted because of field study limitations in; the wind speed, wind direction as well as nearby activities were uncontrollable. The PM variation level can be significant.

6.2.4 VOC contents were, in general, extremely low, when measured in both the laboratory and on the construction sites. The total VOC and the 11 detected VOC species by the GCMS barely exceeded 3ppbv, and hence compared with the specified excellent class IAQ air objectives of 87ppbv for public places (8-hour average). VOC concentration was shown to vary in accordance with the type of mixtures used and the temperatures. The mixing temperature of the PMFC and PMSMA was 175^{o}C, while that of the SMA and WC was 155^{o}C; the VOCs from the PMFC and PMSMA were less than the SMA and WC.

6.2.5 The SMA6 modified by crumb rubber and Sasobit® showed a great decrease in PM2.5 emissions and the VOC concentrations. The RWSMA6 has the PM2.5 aerosol concentration of 31μg/m^3, while the RASMA6 has the concentration over 2000μg/m^3. And the RWSMA6 even had the effect that the Total VOC concentrations were lower than the background.

6.2.6 The use of crumb rubber and Sasobit® into asphalt mixtures resulted in a significant improvement in stiffness modulus.

6.2.7 The PMSMA6 showed a better low noise performance with an average tyre/road noise of 89.4dB(A), compared to 90.4dB(A) for PMFC10, 91.4dB(A) for SMA10 and 91.4dB(A) for WC10.

6.3 CONCLUSIONS

Based on the research, the following conclusions can be drawn:

- The modification by polymer could result in an improvement in fatigue resistance of the asphalt mixtures.
- The modification of polymers could increase the particulate emissions of asphalt mixtures.
- The VOC concentrations of the asphalt pavements are all in a very low level, in both the laboratory and the construction sites. The adding of the warm mix additive, Sasobit®, into the crumb rubber modified SMA6, help reduce the emissions of PM as well as the VOC compounds.
- The PM concentration observed in the construction sites is generally high and exceeds the regulated level in Hong Kong.
- PMSMA6 is a durable pavement surface with, by far, the lowest noise and low-emissions properties.

6.4 RECOMMENDATIONS FOR THE FURTHER WORK

This study has investigated and compared several asphalt pavements in terms of the mechanical properties, the air emissions, and the acoustic properties. So far, the PMSMA6 has been identified as the best pavement type balancing these three aspects. However, there are some limitations in this research. As a continuation of the study, the following recommendations are proposed:

- In this study, the samples numbers were made according to the standards, to ensure at least three replicates for one experiment. Actually, a larger sample size is recommended in the future work to reduce the errors.
- In the field air emission sampling and measurement, static sampling was adopted in this study. This method detects the emissions at a certain one point during construction. In future work, a dynamic sampling, with the monitors in the breathing zone and moving along with the paver, is recommended to supplement the static method. This can detect instantaneous emissions at the site working process and their influence on the workers.

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APPENDIX

Summary of Pearson Correlation between different asphalt mixture samples at different time period A

		PS10_1	PS10_2	PS10_3	PMFC_1	PMFC_2	PMFC_3
PS10_1	Pearson's Correlation	1	.900**	.789**	.968**	.685*	.324
	Sig. 2-tailed		.000	.004	.000	.020	.331
PS10_2	Pearson Correlation	.900**	1	.950**	.950**	.867**	.644*
	Sig. 2-tailed	.000		.000	.000	.001	.032
PS10_3	Pearson Correlation	.789**	.950**	1	.899**	.973**	.816**
	Sig. 2-tailed	.004	.000		.000	.000	.002
PMFC_1	Pearson Correlation	.968**	.950**	.899**	1	.832**	.536
	Sig. 2-tailed	.000	.000	.000		.001	.089
PMFC_2	Pearson Correlation	.685*	.867**	.973**	.832**	1	.887**
	Sig. 2-tailed	.020	.001	.000	.001		.000
PMFC_3	Pearson Correlation	.324	.644*	.816**	.536	.887**	1
	Sig. 2-tailed	.331	.032	.002	.089	.000	
PS6_1	Pearson Correlation	.794**	.785**	.867**	.881**	.889**	.626*
	Sig. 2-tailed	.004	.004	.001	.000	.000	.039
PS6_2	Pearson Correlation	.731*	.855**	.951**	.869**	.982**	.828**
	Sig. 2-tailed	.011	.001	.000	.001	.000	.002
PS6_3	Pearson Correlation	.755**	.889**	.932**	.850**	.920**	.783**
	Sig. 2-tailed	.007	.000	.000	.001	.000	.004
WC20_1	Pearson Correlation	.927**	.926**	.930**	.972**	.889**	.592
	Sig. 2-tailed	.000	.000	.000	.000	.000	.055
WC20_2	Pearson Correlation	.801**	.857**	.939**	.900**	.950**	.722*
	Sig. 2-tailed	.003	.001	.000	.000	.000	.012
WC20_3	Pearson Correlation	.228	.564	.687*	.414	.759**	.918**
	Sig. 2-tailed	.500	.071	.020	.206	.007	.000

Summary of Pearson Correlation between different asphalt mixture samples at different time period B

		PS6_1	PS6_2	PS6_3	WC20_1	WC20_2	WC20_3
PS10_1	Pearson Correlation	.794**	.731*	.755**	.927**	.801**	.228
	Sig. 2-tailed	.004	.011	.007	.000	.003	.500
PS10_2	Pearson Correlation	.785**	.855**	.889**	.926**	.857**	.564
	Sig. 2-tailed	.004	.001	.000	.000	.001	.071
PS10_3	Pearson Correlation	.867**	.951**	.932**	.930**	.939**	.687*
	Sig. 2-tailed	.001	.000	.000	.000	.000	.020
PMFC_1	Pearson Correlation	.881**	.869**	.850**	.972**	.900**	.414
	Sig. 2-tailed	.000	.001	.001	.000	.000	.206
PMFC_2	Pearson Correlation	.889**	.982**	.920**	.889**	.950**	.759**
	Sig. 2-tailed	.000	.000	.000	.000	.000	.007
PMFC_3	Pearson Correlation	.626*	.828**	.783**	.592	.722*	.918**
	Sig. 2-tailed	.039	.002	.004	.055	.012	.000
PS6_1	Pearson Correlation	1	.940**	.802**	.946**	.980**	.417
	Sig. 2-tailed		.000	.003	.000	.000	.202
PS6_2	Pearson Correlation	.940**	1	.887**	.917**	.971**	.678*
	Sig. 2-tailed	.000		.000	.000	.000	.022
PS6_3	Pearson Correlation	.802**	.887**	1	.876**	.894**	.728*
	Sig. 2-tailed	.003	.000		.000	.000	.011
WC20_1	Pearson Correlation	.946**	.917**	.876**	1	.964**	.443
	Sig. 2-tailed	.000	.000	.000		.000	.172
WC20_2	Pearson Correlation	.980**	.971**	.894**	.964**	1	.541
	Sig. 2-tailed	.000	.000	.000	.000		.086
WC20_3	Pearson Correlation	.417	.678*	.728*	.443	.541	1
	Sig. 2-tailed	.202	.022	.011	.172	.086	

**. Correlation is significant at the 0.01 level (2-tailed)

*. Correlation is significant at the 0.05 level (2-tailed)

PS10 - PMSMA10

PMFC - PMFC10

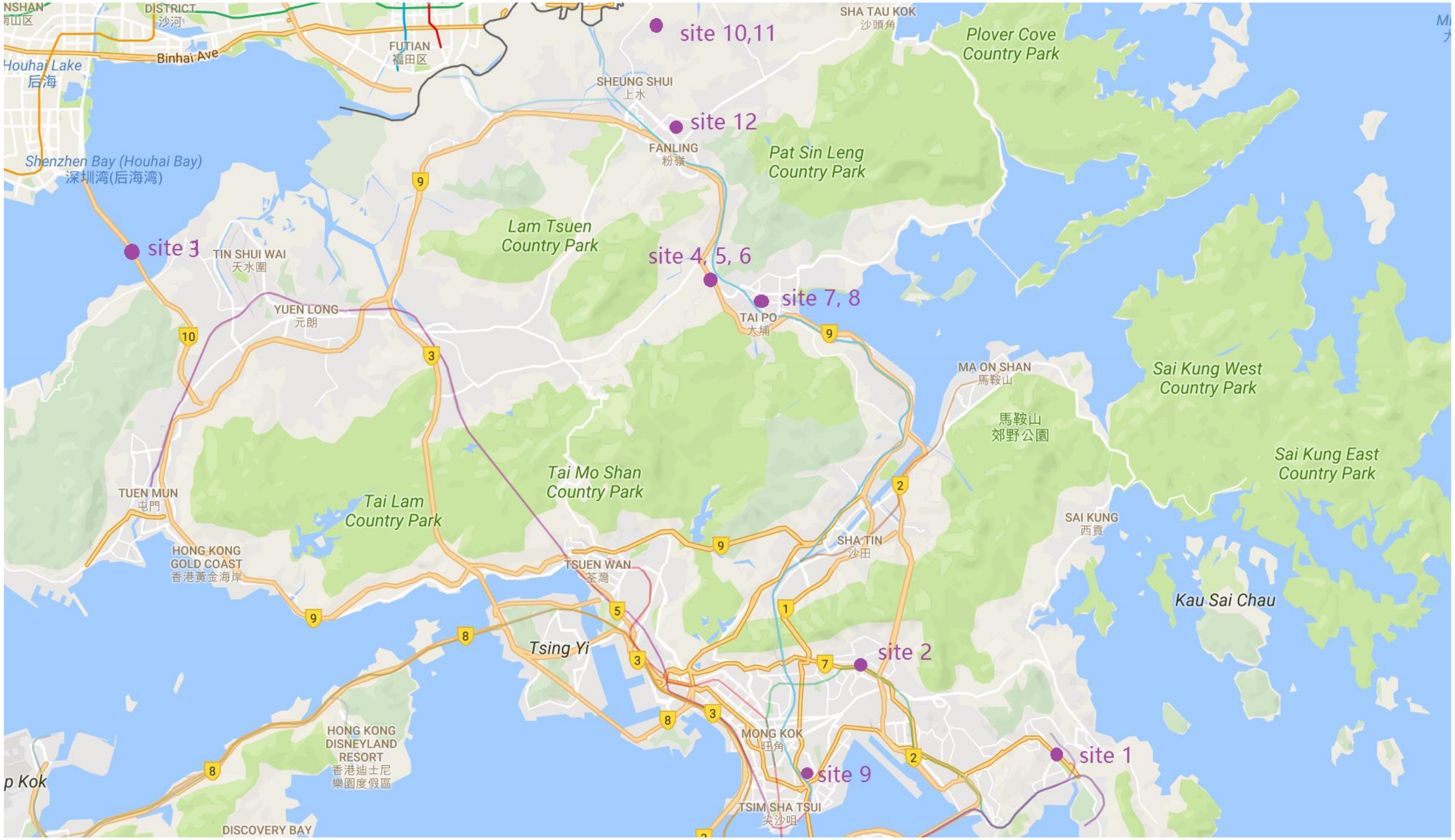
PS6 - PMSMA6

_1. Paving process

_2. Compaction 1

_3. Compaction 2

The 12 survey sites location details are shown as below:



Site No.	Surface type	Survey date	Air temperature (ºC)	Road name
1	PMFC10	2015. Dec. 5	17.0	Tseung Kwan O Tunnel Expressway
2	PMFC10	2015. Dec. 12	20.1	Lung Cheung Avenue
3	PMFC10	2015. Dec. 13	24.0	Shenzhen Bay Bridge
4	PMSMA10	2015. Nov. 25	16.1	Fan Ling Express Sideway
5	PMSMA10	2015. Nov. 26	12.9	Fan Ling Express Sideway
6	PMSMA10	2015. Nov. 27	19.5	Fan Ling Express Sideway
7	PMSMA6	2015. Aug. 28	28.3	Ting Kok Road
8	PMSMA6	2015. Sep. 1	27.4	Ting Kok Road
9	PMSMA6	2015. Sep. 12	27.9	Chung Hau Street
10	WC20	2015. Sep. 10	28.1	Ma Tso Lung Road
11	WC20	2015. Sep. 11	28.1	Ma Tso Lung Road
12	WC20	2015. Nov. 8	26.5	San Wan Road