Università Politecnica delle Marche
Corso di Dottorato di Ricerca in Ingegneria Civile, Ambientale, Edile e Architettura
Curriculum in Ingegneria Civile, Ambientale, Edile e Architettura
XXXIV edition - new series

Dynamic characterization of interlayer shear performance in asphalt pavement

PhD Dissertation of:

Xiaotian Jiang

Advisor: **Prof. Francesco Canestrari**

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To my parents

Acknowledgments

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Abstract

Asphalt pavement consists of several structural layers bonded together to form a monolithic structure. The contact area between every two layers is defined as the interlayer. Since the 1970s, many research results have revealed that interlayer bonding conditions significantly affect only pavement performance. Poor bonding conditions could cause premature damage, such as rutting, slippage, top-down cracking, premature fatigue cracking, and delamination. They may result in a loss of two-fifths to five-sixths of the pavement service life. Therefore, bonding conditions between pavement layers play a critical role in the performance of the asphalt pavement structure.

Many devices have been developed to investigate interlayer bonding conditions. Generally, laboratory testing methods can be divided into two categories: static tests and dynamic tests. Due to the advantage of convenience, the evaluation of interlayer bonding of asphalt pavements is usually performed by measuring the interfacial shear stiffness (ISS) of double-layer specimens using static laboratory tests. Dynamic testing devices simulate traffic loads on pavements more realistically than static tests. Moreover, the test results can reveal the decrease of shear stiffness and the accumulation of permanent deformation at the interface.

This study performed dynamic interlayer shear tests were by a new test equipment Cyclic-ASTRA developed at the Marche Polytechnic University to investigate interlayer shear behavior. The ISS and shear fatigue life of specimens were evaluated in this research. For ISS, the effects of testing parameters such as temperature, load frequency, and load amplitude were studied. ISS and shear fatigue life are two main indicators for evaluating interlayer bonding property. In terms of the time consuming, fatigue life takes much longer than interlayer shear stiffness. Another advantage of ISS measurement is that it does not break the specimen. However, for shear stiffness, in terms of the deformation resistance the curve of lower stiffness (low stress but high strain) may behave better than higher stiffness (high stress but low strain). Thus, it is not reliable to evaluate the fatigue life directly by the value of ISS. Therefore, the relationship between ISS and shear fatigue life was investigated in this study.

Sommario

La pavimentazione in conglomerato bituminoso è composta da diversi strati strutturali incollati insieme per formare una struttura monolitica. L'area di contatto tra ogni due strati definita strato intermedio. Dagli anni '70, i risultati di molte ricerche hanno rivelato che le condizioni di incollaggio tra gli strati hanno un impatto sostanziale sulle prestazioni della pavimentazione. Le cattive condizioni di incollaggio possono causare danni prematuri, come l'ormaiamento, lo slittamento, la fessurazione dall'alto verso il basso, la fessurazione prematura per fatica e la delaminazione. Potrebbero ridurre la vita utile della pavimentazione da due quinti a cinque sesti. Pertanto, le condizioni di legame tra gli strati della pavimentazione giocano un ruolo critico nelle prestazioni della struttura della pavimentazione in conglomerato bituminoso.

Sono stati sviluppati diversi dispositivi per studiare le condizioni di incollaggio tra gli strati. In generale, i metodi di prova in laboratorio possono essere divisi in due categorie: prove statiche e prove dinamiche. La valutazione dell'incollaggio interstrato delle pavimentazioni in conglomerato bituminoso viene solitamente eseguita misurando la rigidità al taglio interfacciale (ISS) di campioni a doppio strato utilizzando prove statiche di laboratorio. I dispositivi di prova dinamici simulano i carichi di traffico sulle pavimentazioni in modo più realistico rispetto alle prove statiche. Inoltre, i risultati delle prove possono rivelare la diminuzione della rigidità al taglio e l'accumulo di deformazione permanente all'interfaccia.

Per valutare il comportamento a taglio dell'interstrato, questo lavoro ha utilizzato una nuova apparecchiatura di prova chiamata Cyclic-ASTRA, che è stata sviluppata presso l'Università Politecnica delle Marche. In questo studio, sono stati valutati l'ISS e la vita a fatica a taglio dei campioni. La temperatura, la frequenza di carico e l'ampiezza del carico sono stati studiati come parametri di prova per l'ISS. La proprietà di legame tra gli strati è stata valutata da due indicatori chiave: ISS e vita a fatica al taglio. La vita a fatica richiede molto più tempo rispetto alla rigidità a taglio dell'interstrato in termini di tempo. Un altro vantaggio della misurazione ISS è che il provino non viene rotto. Comunque, per la rigidità al taglio, in termini di resistenza alla deformazione la curva di rigidità inferiore (bassa sollecitazione ma alta deformazione) può dare risultati migliori della curva di rigidità superiore (alta sollecitazione ma bassa deformazione). Quindi, valutare la vita a fatica direttamente dal valore di ISS non è un metodo affidabile. Di conseguenza, questo studio ha indagato la relazione tra ISS e la vita a fatica al taglio.

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Chapter 1

Introduction

1.1 Background

A pavement is a set of several layers of imported materials (selected, processed unbound, and bound materials) placed on the natural soil to construct a road. Asphalt pavement is a multi-layered structure consisting of the following elements: wearing course, binder course, base course, subbase course, and subgrade. Each layer has its own design characteristics such as stiffness, modulus, resistance, friction, and smoothness. The pavement structure bears traffic loads and environmental stresses, and each layer has different functions. Figure 1.1 presents a typical structure illustration of an asphalt pavement.

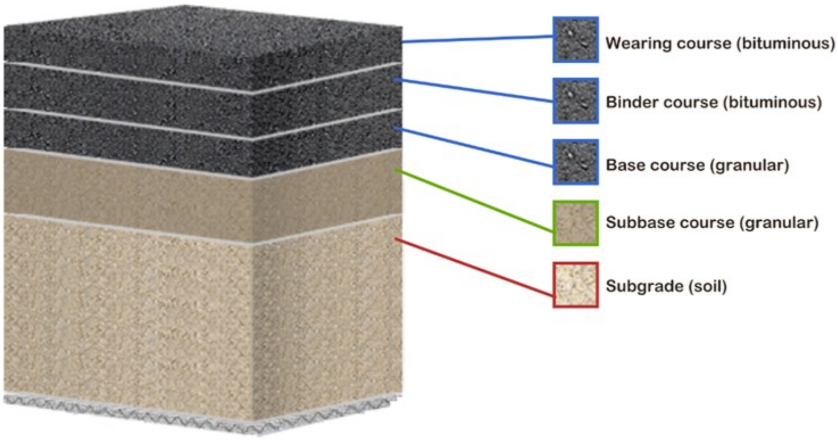


Figure 1.1. Asphalt pavement structure.

The whole pavement structure must provide enough bearing capacity under repeated traffic loads to have a long service life, which means it should have enough strength and resistance to deformation. For the surface layer that contacts directly with traffic loads, its characteristics should meet requirements including smoothness, skid resistance, noise deduction, rutting and cracking resistance, and drainage. Because of its high asphalt content, it is the most expensive layer to construct. The target is to provide a comfortable and safe driving experience.

The binder course is between the base course and the surface layer. The asphalt used should have the same properties as the asphalt base. But the binder content is higher, and the thickness is larger than the wearing course. Its purpose is to provide an even platform for constructing the surface layer.

The base course is constructed over the unbound or hydraulically bound base. It distributes the traffic load from up layers to the under layers and improves the strength of the pavement and its fatigue resistance. Therefore, the base course should have sufficient stiffness, low water permeability and resistance to permanent deformation.

The subbase course is constructed for structural support. Because the subbase is subjected to lower load stresses, the material requirements for the subbase are not as strict as those for the base course.

The subgrade is the formed and compacted soil. Subgrade soils absorb and distribute the loads, avoiding their concentration in a single point to prevent potential local subsidence and cracking.

Due to the thickness, asphalt pavements are built in layers, so interfaces between layers are unavoidable. In general, the multilayer construction of asphalt pavements introduces weak zones at interfaces between layers. A poor bond between adjacent layers can lead to delamination of the pavement structure. The delamination of the pavement structure is particularly severe when asphalt pavement is subjected to horizontal surface shear forces caused by the braking and turning of heavy vehicles. Figure 1.2 compares pavement stress distribution for three different pavement layer cases: fully bonded, partially bonded, and unbonded. Lack of interface bonding may result in several types of premature damage, such as rutting, slippage, top-down cracking, premature fatigue cracking, and delamination, which can prevent the pavement from functioning as a monolithic structure. A laboratory study has shown that a weak bond of pavement interface may result in a loss of two-fifths to five-sixths of the service life, which will increase pavement maintenance costs (Canestrari and Santagata 2005). Romanoschi and Metcalf (Romanoschi and Metcalf 2001) concluded that pavement life could be reduced by up to 40% in the case of poor interlayer bonding by conducting cyclic shear tests. The conclusions obtained from the numerical analysis by software such as BISAR, ABAQUS, and AYSYS showed that service life could be dramatically reduced by at least 20%, up to 80%, and even 90% if complete debonding occurred (Kruntcheva, Collop et al. 2005, Chun, Kim et al. 2015, Cho, Mahboub et al. 2019, Jiang, Zeng et al. 2019). As a consequence, it is necessary to investigate interlayer mechanical behaviors.

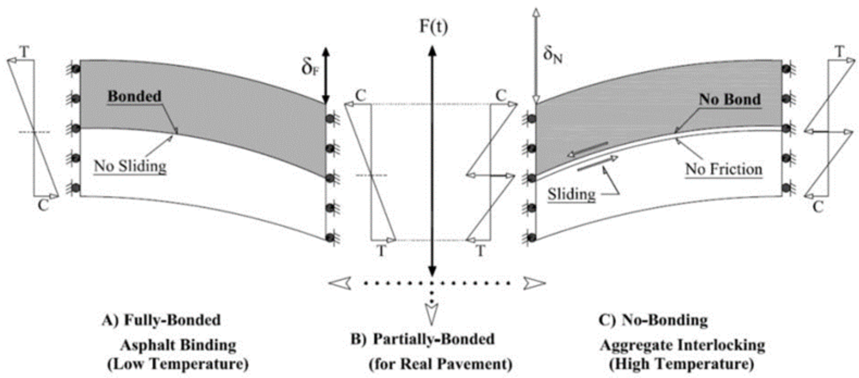


Figure 1.2. Pavement bonding stress distribution.

The pavement structure design methods can generally be classified into two groups, empirical methods, and mechanical methods. A typical mechanical design approach is based on algorithms that calculate a pavement structure's stresses, strains, and displacements. Key parameters include horizontal tensile strains and stresses at the bottom of the asphalt concrete pavement and stabilized layers, or vertical compressive strains at the top of the subgrade. Stresses and strains should be guaranteed to be less than the maximum allowable values. Currently, most of the design and analysis processes of pavements assume a complete bonding between pavement layers, leaving a lack of a systematic and mechanical approach for pavement interlayer design. However, full adhesion between pavement layers is difficult to achieve in realistic conditions due to construction problems. Only a few design methods allow the modeling of interface bond conditions using a bond coefficient between 0 (no bonding) and 1 (full bonding). However, the determination of the bond coefficient is difficult because there is no standard test procedure.

Debonding occurs when shear or tensile stress exceeds the shear or tensile strength of the material at the interface of two asphalt layers. Therefore, it is essential to evaluate interface bond strength properly and understand the damage mechanism and the distribution of stress and strain at the interface to design a durable pavement structure.

There are many reasons for poor bonding behavior, such as the type of base material, low-pressure compaction of the base or subgrade or subgrade, segregation of the base, type of asphalt in the wearing course, climate during construction, contamination of the subgrade surface, water flow between layers, weakness or overuse of the tack coat material.

Due to its fundamental importance in the pavement structure, the interlayer bonding properties of pavement layers have become a critical topic. To develop an acceptable design approach, it is necessary to establish a reliable analytical procedure to determine the shear strength of the pavement interlayer. In this field, numerous experimental and numerical studies have been carried out to evaluate the parameters affecting the interface behavior. Parameters such as normal stress, temperature, loading rate, tack coat type and application rate, aggregate gradation, compaction of asphalt layers, binder type, and surface roughness have been proved to affect the interlayer bond strength.

1.2 Problem Statement

In the past, the role of interface adhesion was neglected. Adjacent asphalt layers were considered to be completely bonded without any relative sliding. After numerous instances of early bond failures between the surface and binder layers, the importance of interlayer adhesion qualities became clear.

It is well known that adequate bonding between adjacent layers of the asphalt pavement plays a crucial role in pavement performance. It prevents sliding between pavement layers and ensures a continuous distribution of stresses and strains throughout the pavement structure. Therefore, a strong interlayer bond is required to ensure the excellent performance of asphalt pavements.

Many researchers have developed and used their equipment to investigate pavement interlayer bonding strength. Different studies show that test parameters such as temperature, loading conditions, and material properties significantly influence the interface properties. However, due to the lack of international standard protocols for interface bond strength tests, test results are inevitably not comparable in all cases.

It is worth noting that most of the previous studies have concentrated solely on the impacts of various parameters on the interface shear strength, leaving the interaction between these elements and the necessary mechanical models of interface shear strength unexplored.

To date, a comprehensive review of the available literature indicates that most studies on interface bonding properties of pavement layers have been conducted in static loading; relatively less attention has been paid to the fatigue performance of pavements. In the field, pavements are subjected to substantial cyclic loading from traffic during their service life. For this reason, static loading does not represent the actual load state of the pavement caused by the repetitive loading of moving vehicles. Therefore, the characterization of the bond behavior will be inaccurate. Due to this reason, the fatigue behavior of interfaces is getting more and more attention. Researchers are dedicated to comprehensively assessing the interlayer shear properties under repeated loading by simulating a more realistic scenario in the lab.

1.3 Objective

This PhD project belongs to the Task Group 3 “dynamic interlayer shear testing” of RILEM Technical Committee 272-PIM (International Union of Laboratories and Experts in Construction Materials 2016). It is coordinated by Marche Polytechnic University and in particular by Prof. Francesco Canestrari, Full Professor in Road, Railway and Airport Engineering at the Department of Civil and Building Engineering and Architecture of Marche Polytechnic University. The activity of Task Group 3 focused on evaluating the performance of multilayer bituminous pavements at the structural level. The interlayer characterization was studied using an innovative dynamic shear testing device.

The main objective of this research is to improve the understanding of the interlayer shear behavior of asphalt pavement.

The interface strength should be assessed to predict the interlayer failure of the pavement structure. Based on test results, use suitable parameters to characterize the interlayer bonding condition. Furthermore, establish an interlayer property decay model using the parameters obtained from the experimental results. The illustration of the research objective is shown in Figure 1.3.

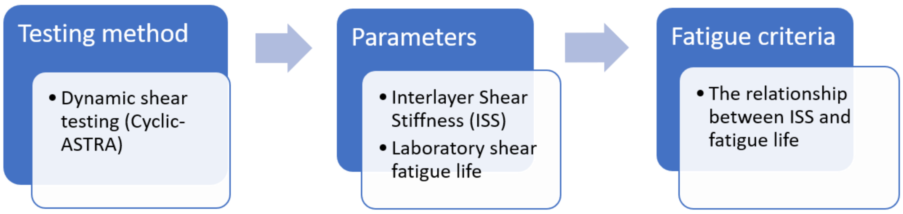


Figure 1.3. Research objective.

The following tasks were conducted to accomplish this objective:

1. Assess the debonding potential of asphalt pavement using interface shear strength (ISS) and fatigue life at various temperatures, frequencies, and loading rates. More specifically, the evaluation of both ISS and fatigue life was conducted by a newly developed testing device, called Cyclic-ASTRA.

2. Develop relationships between interface shear strength and fatigue life.

1.4 Research Approach

The overall approach taken to achieve the objective of this study included:

1. The literature review of pavement interlayer bonding strength studies, especially for cyclic shear testing methods.

2. Laboratory shear tests. For purposes of the experimental campaign, the Cyclic-ASTRA was employed for the cyclic shear test at Marche Polytechnic University. It is a development of the ASTRA (Ancona Shear Testing Research and Analysis), a static shear testing device. The Cyclic-ASTRA is reliable due to increased precision of the measurements, lower compliance of the testing equipment, and the possibility of allowing dilatancy movements perpendicular to the interface. It can apply normal stress at the interface as well.

3. Data analysis of test results.

1.5 Thesis Organization

This dissertation is composed of five chapters.

Chapter 1 covers the background, problem statement, objective, research approach, and thesis organization.

Chapter 2 gives an overview of the research background, including the effects of bonding conditions on pavement performance, a discussion of factors that affect interface shear bond strength, analysis methods of interlayer bonding property, and the introduction of static and dynamic interface performance test methods.

Chapter 3 presents dynamic shear tests conducted by Cyclic-ASTRA for interlayer shear stiffness and fatigue investigation.

Chapter 4 reports test results along with statistical analysis.

Chapter 5 summarizes the conclusions drawn from the research work and makes recommendations for future research studies.

Chapter 2

Literature review

2.1 Introduction

Asphalt pavement is a multi-layered structure constructed on the soil. The contact area between each pavement layer is defined as an interlayer. To ensure that the pavement structure can dissipate traffic load as a uniform system, the interlayer is most commonly applied by an asphaltic tack coat to increase adhesion between the pavement layers. The majority of asphalt pavement design approaches presume that all layers of the pavement are entirely bonded. However, complete bonding is difficult to achieve in engineering practice, and many pavement distress cases are related to poor bonding or debonding issues.

Since the 1970s, many research findings have shown that interlayer bonding condition has a major impact on pavement performance. A good interlayer bonding condition contributes greatly to a long pavement service life. As a result, a lot of research has been done in this area. In general, investigations focused on three aspects: theoretical analysis and modelling of interlayer bonding conditions, interlayer bond strength tests, and tack coat material.

During the last few decades, several testing methods and devices have been developed for evaluating interlayer bond strength and fatigue behavior. Influences of tack coats were studied based on material properties, application rate, curing time, and application layer condition. The effects of different interlayer bonding conditions on critical pavement responses (i.e., stress, strain, and displacement) and pavement performance were demonstrated by diverse computational analysis programs. Overall, the importance of a good bonding condition was demonstrated by all of these research findings. In the meantime, methods for assessing and developing bonding property have been discovered. Despite the fact that a variety of testing methods and devices have been used to investigate interlayer behavior, no systematic testing protocol has yet been established. Different countries recommend different standardized test methods based on distinct bond failure mechanisms and test parameters to evaluate bonding conditions in their standards. Furthermore, the effects of test parameters on testing results (e.g., temperature, normal stress, shear strain/stress amplitude, and frequency of application) need to be investigated.

This chapter provides an overview of the present research on interlayer bonding properties. The factors affecting interlayer bond strength are discussed. The mechanism of interlayer debonding is demonstrated, as well as modeling of interlayer bonding conditions. Interlayer bond strength laboratory tests developed by researchers, especially dynamic shear tests, are compared and summarized. The primary purpose of this review is to analyze the previous laboratory work on interlayer bonding property characterization, particularly test parameters, in preparation for further laboratory investigation.

2.2 Effects of bonding conditions on pavement performance

Shahin et al. (Shahin, Kirchner et al. 1986) pointed out that the maximum tensile strain is located at the bottom of the asphalt layer if the pavement layers are fully bonded. Woods (Woods 2004) calculated flexible pavement responses under different bonding conditions using the Waterways Experiment Station layered elastic analysis (WESLEA) program; the result is presented in Figure 2.1. The result indicated that the interlayer bonding condition has a substantial impact on the stress and strain distribution of the pavement. The two layers of unbonded pavement respond to loading independently, resulting in greater interface stress.

Figure 2.2 is the most common demonstration of the difference between complete bonding and poor bonding pavement structures (Gomba 2004, Chen 2011, Leischner, Canon Falla et al. 2019). As Figure 2.2a shows, in the good bonding case, the maximum tensile strain occurs at the bottom of the structure, and the maximum compressive strain appears at the top of the structure. As Figure 2.2b shows, in the poor bonding cases, tensile strains appear at the bottom of each layer whereas compressive strains exist at the top, which may cause bonding failures at the interface.

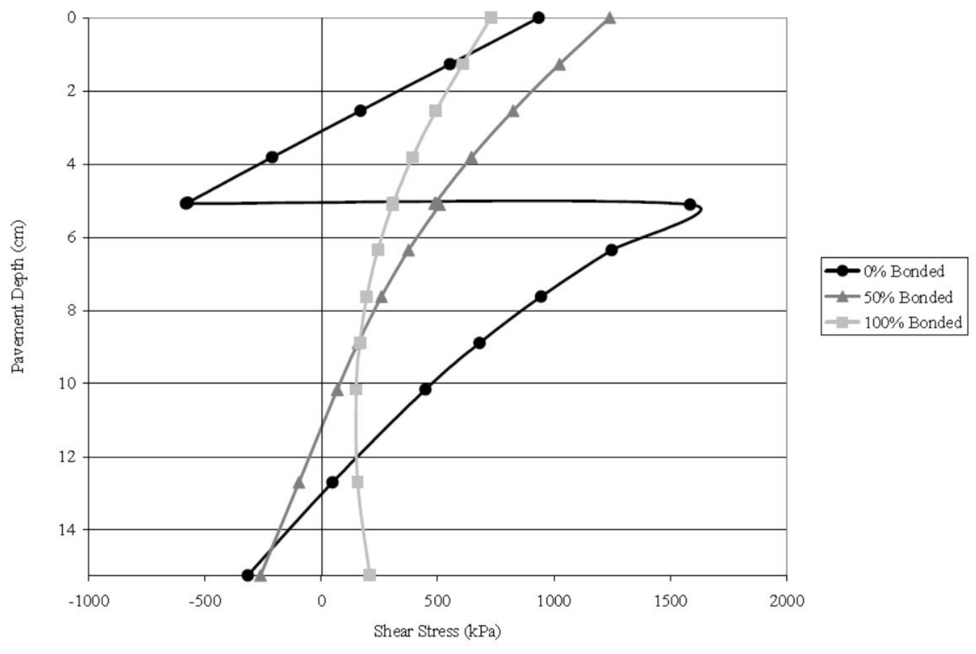


Figure 2.1. Distribution of shear stress in pavements at various interface bonding conditions.

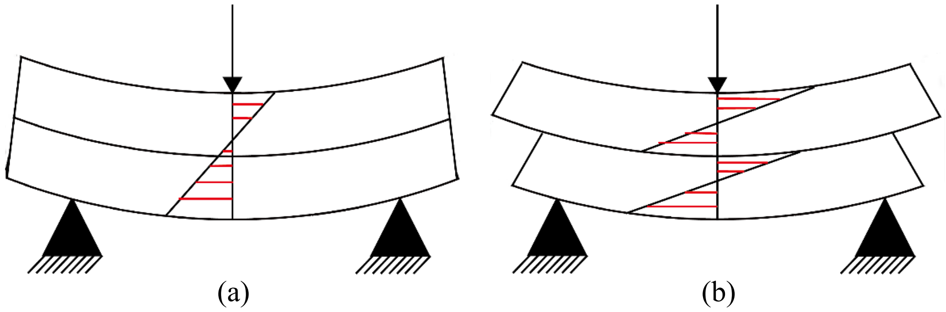


Figure 2.2. Stress distribution: a) Full bonding pavement structure; b) Poor bonding pavement structure.

Slippage cracking and delamination are two typical premature failures induced by poor bonding between an asphalt wearing course (or asphalt overlay) and the binder course (Figure 2.3). Slippage cracking is a crescent or half-moon-shaped cracking having two ends pointed away from the direction of traffic. It is more severe and commonly observed at road intersections where vehicles brake and turn direction, especially for pavements suffering heavy traffic loads. Furthermore, unrepaired interlayer debonding failure will eventually result in a total pavement failure, necessitating reconstruction and reducing the pavement's service life.

Figure 2.3. Premature failures: a) Slippage; b) Delamination.

From the 1970s, many debonding failures between wearing course and binder course have been observed in many countries, such as the United Kingdom, Northern Ireland, Austria, Poland, China, Japan, and Malaysia (Peattie 1980, Shaat 1992, Litzka, Pass et al. 1994, Hachiya, Umeno et al. 1997, Yaacob, Hainin et al. 2014, Guo, Wang et al. 2016, Jaskula and Rys 2017). The majority of them occurred on newly constructed roads that had only recently been opened to traffic. According to Khweir and Fordyce's research, bond failure of the interface may result in a predicted loss of two-fifths to five-sixths of the pavement's potential life, or as little as one-sixth (Khweir and Fordyce 2003). Other researchers' findings corroborated this conclusion (Kruntcheva, Collop et al. 2005, Cho, Mahboub et al. 2019).

2.3 Factors affect interlayer bond strength

This section discusses the various factors that affect the bond strength between pavement layers. Based on the available experimental investigations, it is concluded that there are many factors and their interactions that affect the interface bond strength, including deformation rate, tack coat type, tack coat application rate, testing temperature, and normal pressure at the interface, etc. The complexity of the interactions between these factors is one of the reasons why interface bond strength is difficult to quantify. In addition, the test methods used to measure interface bond strength lack clear standards, i.e., different researchers use different test methods, which makes it difficult to compare test results. Based on previous studies on interface bond strength, it can be determined that the interfacial bond strength depends on temperature and deformation rate. However, different research has come to varied conclusions about the impact of normal confining stress, tack coat type, application rate, and surface roughness, leaving the results unclear.

2.3.1 Tack coat

The tack coat is a thin adhesive layer that provides a solid bond between the previously constructed pavement layer and the new one. According to the production technique, tack coats can be categorized into conventional asphalt binder, asphalt emulsion, and cutback asphalt binder. Emulsified asphalt is a mixture of asphalt cement, water, and emulsifying agent. Cutback asphalt binder is produced by adding controlled amounts of petroleum distillates (such as kerosene) to asphalt cement.

The influence of tack coat on interlayer bond strength are primarily influenced by three factors, types of tack coat materials, application rate, and curing time.

In terms of the types of tack coat materials, the asphalt emulsion is the most extensively used due to its benefits of less environmental concerns, easy applicability (applied at a low temperature), and low energy consumption. Cutback asphalt binder is rarely used as a result of environmental concerns.

The application rate of tack coat is an essential affecting factor because an excessive tack coat may cause interlayer shear slippage, whereas too little may result in insufficient bond strength. Therefore, the optimal tack coat application rate is necessary to achieve proper bond strength. Generally, it is suggested to select the amount of tack-coat by considering the condition of the existing pavement surface and the bitumen content of the asphalt layers for new constructions (Canestrari, Ferrotti et al. 2013).

Despite the curing time having a positive effect on the development of interlayer bonding properties after tack coat is applied, in the literature, there was not a complete agreement on how long a tack coat should remain uncovered before the subsequent asphalt layer is placed. Chen and Huang (Chen and Huang 2010) found a slight increase in shear strength by increasing the curing time up to 45 minutes. On the other hand, in Europe, asphalt emulsions are applied underneath the paver without curing because the water in the emulsion will immediately evaporate after placing hot mix asphalt (HMA) on the tacked asphalt surface (Zhang and Technology 2017).

2.3.2 Temperature

It is well known that asphalt mixture is a temperature susceptible material. Many studies have found that temperature has a significant impact on interlayer shear strength. One of the most important conclusions is that for any interface treatment condition (i.e., with or without a tack coat, rough or smooth paving surface, dense-graded asphalt, or porous asphalt), the interlayer shear strength decreased as the testing temperature increased (Canestrari, Ferrotti et al. 2005, Canestrari and Santagata 2005, Chen and Huang 2010, Raposeiras, Castro-Fresno et al. 2013, Song, Shu et al. 2015). Temperature affects the shear strength by changing the stiffness of the asphalt binder. At low temperatures, the asphalt binder became stiff, and the effects of both the tack coat application rate and the roughness of the paving surface became less significant. At high temperatures, the viscosity of the asphalt binder reduced, and the asphalt binder flowed easier between the interlayers, resulting in a decrease of shear strength. As a result, temperature conditions must be taken into account while choosing an optimal tack coat application rate.

2.3.3 Surface conditions

Generally, for the surface conditions of an existing pavement, roughness, cleanness, and moisture are the three essential factors that influence interlayer shear strength.

Santagata et al. (Santagata, Partl et al. 2008) measured roughness characteristics at the interface by X-ray Computer Tomography (CT) and evaluated interlayer shear strength. The results indicated that higher macro-texture (higher roughness) leads to an increase in interface shear resistance. Similarly, D'andrea et al. (D'Andrea, Tozzo et al. 2013) employed a 3D laser scanner to acquire roughness parameters for interface surface characterization. It was concluded that shear resistance was stronger for higher texture peaks, probably due to a better locking between the superposed layers.

Dirt and moisture are common phenomena on road construction sites. It is recommended that tack coat materials be applied on a dry and clean pavement surface because highly contaminated surfaces have a definite negative effect on the quality of the interlayer bond. On the contrary, Canestrari and Bocci (Canestari and Bocci 1997), Raab and Partl (Raab and Partl 2016) demonstrated that the advantage of applying tack coat on a dirty surface is evident since its use restores the interlayer bond to a suitable level.

The advantage of tack coats on fine-milled surfaces is doubtable. Even to have a negative influence on the determined adhesion values, resulting in considerably lower shear forces when compared to slabs where no tack coat was applied. In the case of a milled surface, the amount of tack coat should be increased to fill the holes.

For moisture, its effect is insignificant. Sholar et al. (Sholar, Page et al. 2004) concluded that the application of water to the surface of the interlayer significantly reduced the shear strength of the specimens compared to equivalent specimens without water. However, other investigations indicated that the difference in shear strength between samples under dry and wet conditions was not significant (Raab and Partl 2004, Pasquini, Cardone et al. 2014, Zaniewski, Knihtila et al. 2015).

2.3.4 Normal stress

It is indicated that an increase in the normal stress leads to an increase in the peak shear stress (Canestrari and Santagata 2005, West, Zhang et al. 2005, Tozzo, Fiore et al. 2014). Moreover, researchers pointed out that the effect of normal stress should be considered with other test parameters such as temperature and tack coat application rate. Most of the interface shear strength was derived from the tack coat material. Only when the application rate of tack coat material decreases, an increase in the normal stress can result in a more significant contribution of roughness and aggregate resistance leading to the slide resistance at the interface.

And for the temperature, interlayer bond strength increases as normal stress increases, especially at a higher temperature. Because at higher temperatures, the effect of internal friction on bond strengths was more significant than the effect of tack coat materials, and the internal friction is dependent on the level of normal load and surface texture. At lower temperatures, bond strength was not very sensitive to the normal stress.

2.3.5 Summary

This section discusses factors that affect interlayer bond strength, such as tack coat, temperature, surface condition, and normal stress. A short conclusion for each factor is shown in Table 2.1.

It should be noted that this section aims at evaluating affecting factors based on laboratory research work. Other affecting factors related to construction quality existing in engineering practice, such as compaction quality of the new paving layer and the maintenance of the tack coat, are out of consideration of this section.

Table 2.1. Effect of different factors on interface bond strength.

Factor	Effect
Tack coat application rate	The optimal tack coat application rate provides proper shear strength
Tack coat curing time	Provides a slight increase in shear strength
Temperature	As temperature increases, shear strength decreases
Surface roughness	Surface roughness increases shear strength
Surface cleanliness	A clean surface provides higher shear strength
Surface moisture	Unclear
Pavement material	Coarser gradations provide higher shear strength than finer gradations
Normal stress	As normal pressure increases, shear strength increases

2.4 Theoretical analysis of interlayer bonding property

2.4.1 Mechanical models of interlayer bonding failure

Since the significant effects of bonding conditions on pavement performance have been widely reported, studying the interlayer debonding mechanism is necessary. Generally, the bonding failure of the pavement interlayer under moving vehicle loads and other stresses would be categorized into three separation modes, as Figure 2.4 depicts.

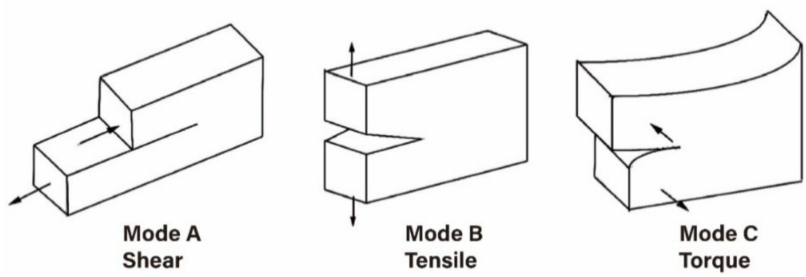


Figure 2.4. Interlayer distress modes.

Bonding failure mainly occurs when the traffic-induced shear, tensile, or torque stress exceeds the bonding strength of the interlayer material. However, it should be noted that, in reality, the bonding failure is associated with a combination of several damage modes. It could be described as follows:

- Interlayer debonding caused by shear stresses combined with tensile stresses;
- Top-down cracking caused by surface shear and tensile stresses;

- Rutting caused by normal and shear stresses.

Therefore, for the evaluation of interlayer bonding property, considering different loads directions is closer to the practice.

2.4.2 Interface strength components

Uzan et al. (Uzan, Livneh et al. 1978) described interface bond as the combination of adhesion of asphalt binder, friction between the surfaces of pavement layers, and mechanical interlocking of the aggregate particles at the interface. Canestrari et al. (Canestrari, Ferrotti et al. 2005) stated that interlayer shear resistance was contributed by residual friction, inner cohesion, dilatancy, and tack coat adhesion.

2.4.3 Modeling of interlayer bonding conditions and pavement response

Due to the rapid development of computer technology, many researchers used multilayer elastic and viscoelastic computer programs (i.e., BISAR, ADINA, FlexPAVE™, ABAQUS, and ANSYS) to analyze pavement response under different interlayer bonding conditions. Among them, finite element methods provide more precise and complex modelling of tyre-pavement contact pressure, load area, and interface conditions. These factors were proved to have significant influences on the mechanical response of the pavement structure (Wang and Al-Qadi 2009, Al-Qadi and Wang 2011, Jiang, Zeng et al. 2019).

Most research studies are dedicated to demonstrating the impact of debonding or poor boding conditions on pavement service life according to transfer functions such as fatigue cracking and permanent deformation. Regardless of the software utilized, the results were comparable and in agreement. The conclusions showed that service life could be dramatically reduced by from at least 20%, up to 80%, even 90% if complete debonding occurred (Kruntcheva, Collop et al. 2005, Chun, Kim et al. 2015, Cho, Mahboub et al. 2019, Jiang, Zeng et al. 2019). Some other studies focus on the shear stress distribution along the bonded interface under traffic loading, such as the position of maximum longitudinal shear stress and transverse shear stress (Wang 2014, Cho, Karshenas et al. 2017, Li, Wang et al. 2017).

As demonstrated above, the interlayer bonding condition should not be simply assumed to be two extreme states: full bond or full slip. Therefore, different computer programs use different models to characterize interlayer bonding conditions more accurately.

Uzan et al. (Uzan, Livneh et al. 1978) proposed one of the most prominent models, which is based on Goodman's constitutive law (Goodman, Taylor et al. 1968), using interlayer shear stiffness K to characterize interlayer behavior. As Figure 2.5 presents, considering the interlayer as a thin layer of the thickness (h), the shear stress (τ) at the interface can be expressed as follows:

$$\tau = K\Delta\mu \tag{2.1}$$

where $\Delta\mu$ is the horizontal displacement of the two faces at the interlayer; K is the interlayer shear stiffness expressed in MPa/mm or kPa/mm.

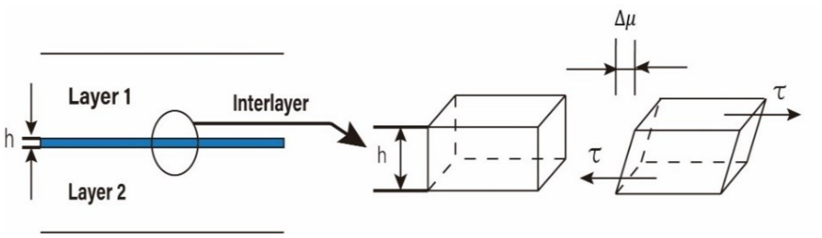


Figure 2.5. Modelling of interlayer bonding condition.

In this model. the larger K means the better interlayer bonding condition. When K=∞, the interlayer is fully bonded. When K is close to 0, the interlayer tends to be entirely smooth. Moreover, threshold values of K were measured by researchers to evaluate bonding conditions. Uzan et al. (Uzan, Livneh et al. 1978) studied different K values for the uppermost interface of a multi-layered pavement system. It was observed that when K varied between 1 and 10^2 MPa/mm, the distribution of stresses and strains at the bottom of the upper layer significantly varied. As Figure 2.6 shows, when the K value increases, the strain is close to the value of a fully bonded interface. Also, the tensile strain at each layer's bottom decreases when the K value increases. Thus, it is applicable to characterize interlayer bonding conditions by K value.

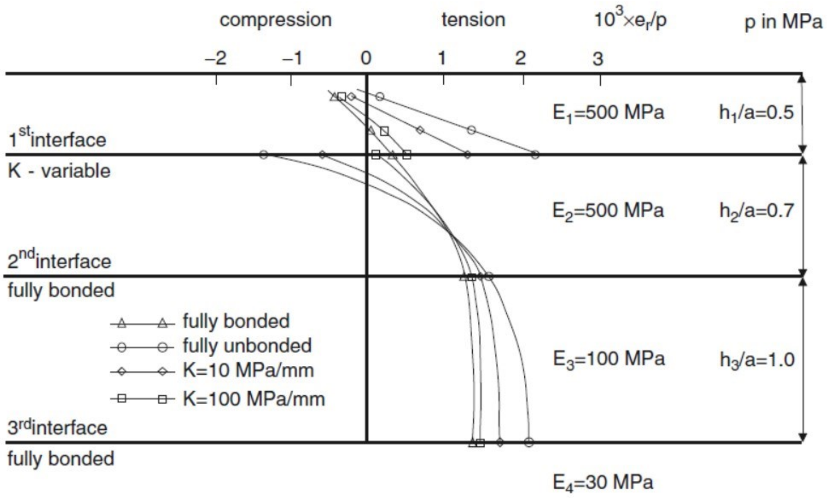


Figure 2.6. Distribution of strain vs. depth.

This model is adopted by many pavements analysis programs to characterize interlayer bonding conditions and calculate the stresses and strains in pavement structures under traffic loads. For the very popular calculation program BISAR, parameter AK called shear spring compliance was employed, defined as the ratio between the relative horizontal displacement between the layers and the shear stress acting on the surface (Crispino, Festa et al. 1997), which is the reciprocal of the interlayer shear stiffness.

Therefore:

$$AK = \frac{1}{K} \tag{2.2}$$

where, AK is the shear spring compliance, m^3/N. AK is between 10^{-8} and 10^{-12} when it represents a partial bond condition.

Since it is difficult to input an accurate and easy-expressed value to define the bonding condition in the user's interface, BISAR 3.0 adopts another two parameters to define the bonding condition more specifically. The friction coefficient α and reduced shear spring compliance ALK (m) which are derived from AK are introduced.

The relationship between α and AK is expressed as follows:

$$\alpha = \frac{AK}{AK + \frac{1+\nu}{E} \cdot a} \tag{2.3}$$

where, α is the dimensionless friction coefficient (α is between 0 and 1 when α = 0 means total friction, when α = 1 means complete slippage), a is the radius of the load circle (m), E and ν are the elastic modulus (Pa) and Poisson's ratio of the layer right above the interface, respectively.

The relationship between ALK and AK is expressed as follows:

$$AK = ALK \cdot \frac{1+\nu}{E} \tag{2.4}$$

The specific meaning of each variable symbol in the equation is the same as the above.

The specific meaning of each variable symbol in the equation is the same as the above.

Because of the user-friendly interface and approximately precise expression of bonding conditions, BISAR has gained popularity in solving stress, strain, and displacement problems in layered pavements. It is also widely used to compare other elastic or viscoelastic pavement programs.

EverStressFE is a software developed at the University of Maine for the 3D Finite Element Analysis of Flexible Asphalt Concrete Pavements. It allows users to choose locally refined mesh to obtain more accurate solutions. Like BISAR, it defines interface conditions by interface stiffness IS (N/mm^3) based on the Goodman model. The interface condition can be defined as a complete bond, completely debonded, or partial bond. For the input value of IS, a value of 0 means debonded entirely. The larger value of IS, the better the interlayer bonding condition. However, the EverStressFE can only define bonding conditions limited to two interfaces at most; other interfaces are defined as full bond by default. Jiang et al. (Jiang, Zeng et al. 2019) employed EverStressFE to calculate mechanical response and estimate the fatigue life of pavement structure under two extreme bonding conditions, one with full slip and the other with complete continuity, respectively. Li et al. (Li, Tang et al. 2020) compared EverStressFE and BISAR 3.0, two programs from the viewpoint of modelling, load application, calculation processing, and result treatment. It was reported that the two programs have certain comparability in analyzing the interlayer bonding problem of asphalt pavement.

In FE programs, conventional no-thickness interface elements were used to model the interfaces. As Figure 2.7 shows, for a fully bonded condition, tractions at the interface are presented as:

$$\begin{Bmatrix} \sigma_n \\ \tau_s \\ \tau_t \end{Bmatrix} = \begin{bmatrix} k_n & 0 & 0 \\ 0 & k_s & 0 \\ 0 & 0 & k_t \end{bmatrix} * \begin{Bmatrix} \delta\mu_n \\ \delta\mu_s \\ \delta\mu_t \end{Bmatrix} \tag{2.5}$$

where,

n, s, and t = normal (n) and tangential (s and t) coordinates in Figure 2.7;

σ_n = normal traction;

τ_s and τ_t = tangential tractions;

k_n, k_s, and k_t = normal and tangential stiffnesses;

$\delta\mu_n$, $\delta\mu_s$, and $\delta\mu_t$ = displacements at the interface.

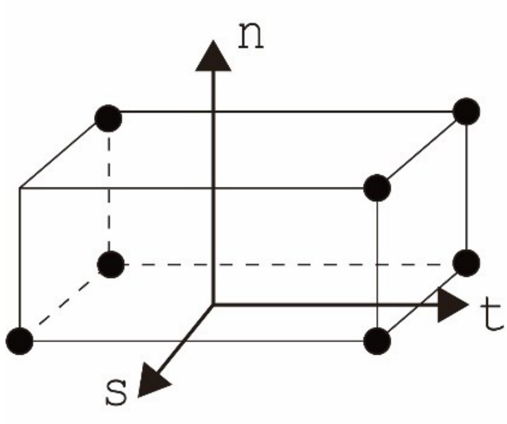


Figure 2.7. Interface elements (upper and lower nodes are separated with a thickness for demonstration only).

ADINA is a three-dimensional Finite Element (FE) software that allows users to calibrate the interlayer condition by its library of elements and material models. As Figure 2.8 exhibits, Chun et al. (Chun, Kim et al. 2015) used ADINA to define interlayer contact between the Asphalt Concrete (AC) layer and the base layer by employing translational spring elements and setting spring constants. In their research, two bonding conditions, poor bond and good bond were modeled by ANDINA. Translational spring elements were used to connect the bottom of the AC layer and the top of the base layer at the nodes in perfect contact. Three spring constants, K_t, K_s, K_n, were used to characterize the stiffness along with the three different directions for simulating the partial bond condition. K_t and K_s represented the stiffness in the interlayer plane (x and y directions), while K_n represented the stiffness perpendicular to the interlayer plane (z-direction).

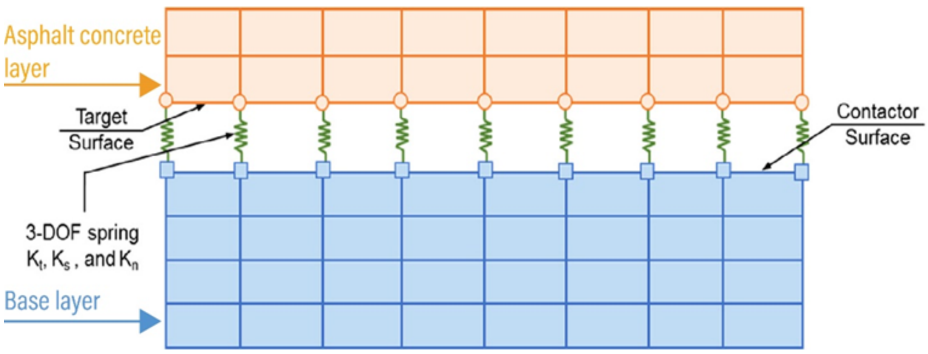


Figure 2.8. Interlayer modelling for the partial bonding condition.

Friction model is a critical factor of the simulation of the interface contact state in ABAQUS. A simple friction model (Coulomb model) assumes that the resistance to movement is proportional to the normal pressure at the interface. The Coulomb friction model is defined by the friction coefficient μ, which represents the ratio between shear stress and contact vertical pressure. It can be expressed as:

$$\mu = \frac{\tau_{\max}}{\sigma} \tag{2.6}$$

where, τ_{max} is the maximum shear stress and σ is the normal stress at the interface.

The friction coefficient was varied from 0.0 to 1.0 corresponding to a friction angle between 0 and 45°.

The Coulomb friction model may be further improved by defining the maximum allowable tangential stress (τ_{max}) before movement occurs at the interface (elastic slick model).

2.5 Laboratory Interlayer bond strength tests

It should be noted that this work focuses on destructive laboratory testing for interlayer bond strength measurement; non-destructive tests such as the Falling Weight Deflectometer (FWD) and Ground Penetrating Radar (GPR) are not covered.

Generally, laboratory test methods can be divided into two categories: static tests and dynamic tests. Based on load mechanisms, test methods can be grouped into three categories: shear test, tensile test (pull-off test), and torque test. In addition, the wedge splitting test is also considered as an interlayer test method, but it is conducted to study crack propagation or fracture rather than slippage.

The tensile test measures the tensile adhesion between the two layers; the result does not include aggregate interlocking or friction. As a result, it is frequently used to assess tack coat materials. During the torque test, a torque load is applied to the top of the specimen until a twisting shear failure in the bond occurs.

Compared to other methods, the direct shear test allows for a more comprehensive assessment of the factors affecting the interface shear strength, such as adhesion, friction, and interlock forces. Therefore, in this section, shear test is mainly introduced.

2.5.1 Static test

Static testing evaluates interlayer bonding properties at failure and is used for bond strength assessment. In this section, several essential static tests are reported.

Since the 1990s, a growing number of testing equipment for evaluating bonding strength have been developed. Among them, the Leutner test (as Figure 2.9 shows), proposed by the University of Karlsruhe (Leutner 1979), was one of the first standard shear testing methods from Germany. Despite the fact that it was static testing without the application of a normal force, the simple settlement (which could be performed with a universal testing machine) and relatively quick test procedure made it one of the most popular interlayer bond testing devices. It was adopted or modified by many countries over these years (e.g., Austria, Germany, and Switzerland). Based on the Leutner test device, devices such as Layer-Parallel Direct Shear (LPDS), FDOT test device, LCB device, and the modified Leutner at the University of Nottingham were developed (Partl and Raab 1999, Sholar, Page et al. 2004, Miro Recasens, Martinez et al. 2005, Collop, Sutanto et al. 2009).

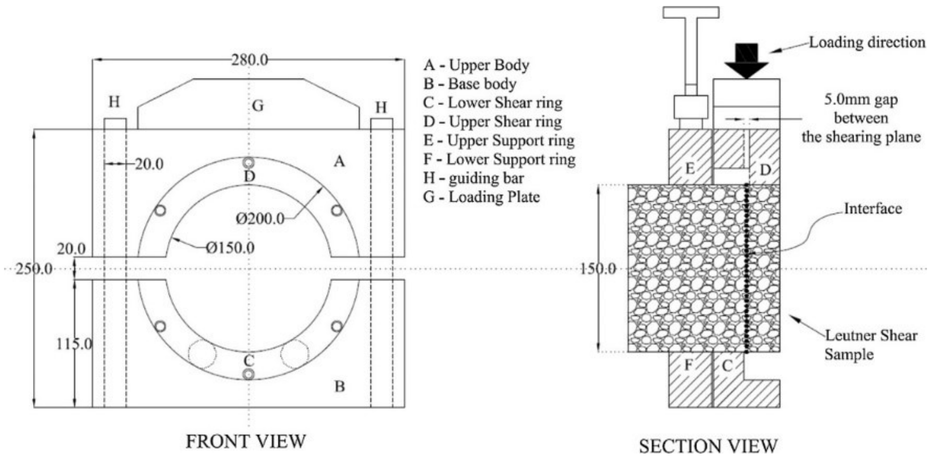


Figure 2.9. Schematic diagram of Leutner test.

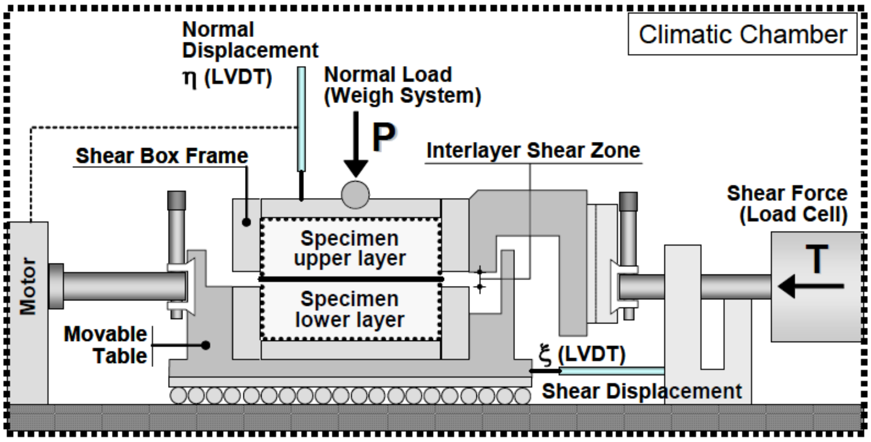
To apply normal stresses to simulate the actual stress state in pavements caused by vehicles, other devices such as Ancona Shear Testing Research and Analysis (ASTRA) device, National Center for Asphalt Technology (NCAT) device, and Romanoschi device were proposed and used to study the interface bond strength. The characteristics of these devices are listed in Table 2.2. The details of each device's normal force application are summarized in Table 2.3. Figure 2.10 presents illustrations of these devices that can apply normal stress.

Table 2.2. Characteristics of static shear testing devices.

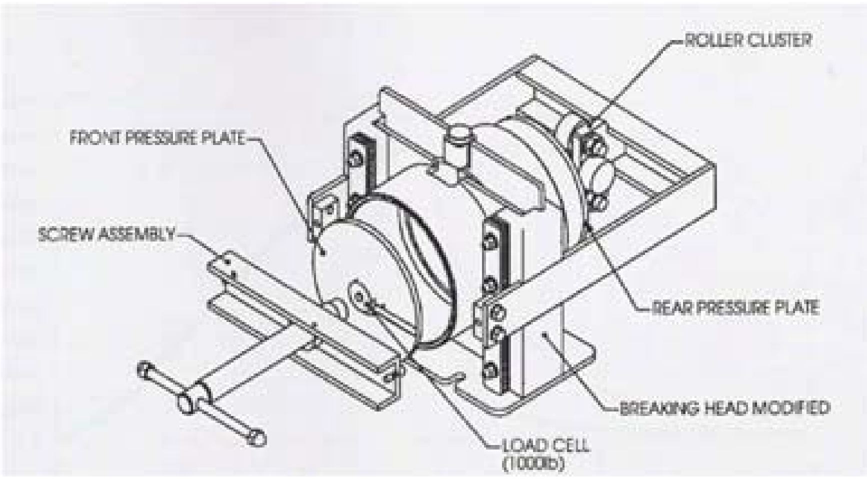
Device	Characteristics
Leutner shear test device	Specimen: cylinder 150 mm or 100 mm Gap width: 1 mm Deformation rate: 50.8 mm/min Temperature: 20 °C (standard), for research 10 °C to 40 °C Result: force/deformation diagram, max force (shear stress)
LPDS device	Specimen: grinder 150 mm Gap width: 2 mm between the yoke and the pneumatic clamp Deformation rate: 50 mm/min Temperature: 20 °C (standard), for research 40 °C Result: force deformation diagram, max force (stress), stiffness (max force/max slop of the force/deformation curve) in kN/mm
LCB device	Specimen: cylinder 100 mm Deformation rate: 1.27 mm/min Temperature: 5 °C to 45 °C Result: force deformation diagram, max force (stress)
ASTRA device	Specimen: rectangular, max cross section of 100×100 mm and cylindrical with diameter from 94 mm to 100 mm Gap width: diameter of particle diameter of the test specimen Deformation rate: 2.5 mm/min Temperature: variable in climatic chamber, standard temperature condition is 20 °C Result: data-file with shear force, horizontal and vertical displacement related to time
NCAT device	Specimen: cylinder 150 mm Gap width: 4.8 mm Deformation rate: 2.5 mm/min, 12 mm/min, and 50.8 mm/min Temperature: 10 °C, 25 °C, 60 °C Result: force deformation diagram, max force (stress)
Romanoschi device	Specimen: cylinder 95 mm Gap width: 5 mm Deformation rate: 12 mm/min Temperature: 15 °C, 25 °C, 35 °C Result: force deformation diagram, max force (stress)

Table 2.3. Normal load application conditions.

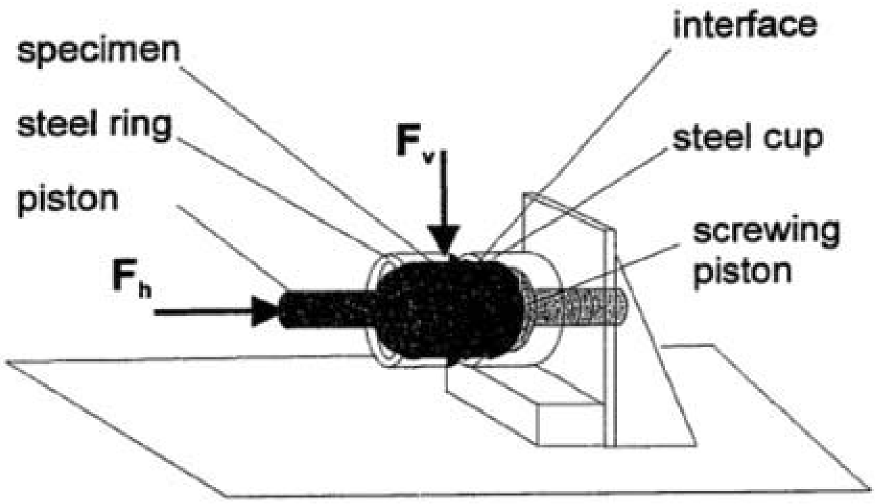
Device	Normal load
Leutner shear test device	None
LPDS device	
LCB device	
ASTRA device	0, 0.2 (for standard condition), and 0.4 MPa, applied by a lever and weight system
NCAT device	0 to 550 kPa, applied by screwing the front pressure plate to the steel cups using a latch fastener
Romanoschi device	0 to 550 kPa (138, 276, 414, and 522 kPa)



(a)



(b)



(c)

Figure 2.10. Illustration of: a) ASTRA device; b) NCAT device; c) Romanoschi device.

2.5.2 Dynamic test

Dynamic testing aims at evaluating the service life of pavement based on bonding failures. Unlike static shear tests, specimens are subjected to repeated loading conditions. It assumes that failures at the interlayer occur under fatigue caused by cyclic loading, which is more realistic in engineering practice. Although dynamic tests show an obvious advantage, for this reason, they are not as numerous as static tests because of the comparably sophisticated and longer experimental procedure.

Currently, some researchers have developed various dynamic test devices. Differences exist in design, loading mode (stress or strain-controlled), loading frequency, testing temperature, and normal stress application for the test equipment. Therefore, dynamic tests were conducted in different parameters. This section gives an overview of the world's dynamic shear testing devices.

Donovan et al. (Donovan, Al-Qadi et al. 2000) developed the Virginia shear fatigue test to optimize the application rate of tack coats for geocomposite membranes and overlaid bridge decks (Figure 2.11). The device measures the number of shear load cycles until the interface failure happens. During the test, a cyclic shear load of 0.1 second half-sine wave with a deflection of 0.4 mm is applied, followed by a relaxation period of 0.9 second. The maximum shear strength at each cycle and the maximum shear strength versus the number of cycles to failure are recorded.

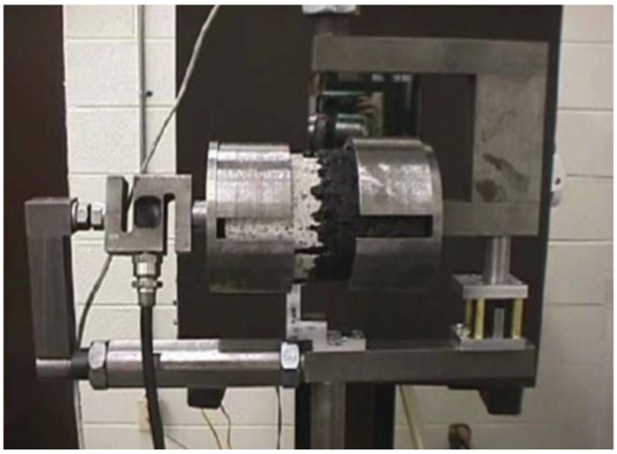


Figure 2.11. Virginia shear fatigue test.

Carr (Carr 2001) designed a direct shear box to test slabs under repeated shear loads combined with a normal load. The non-uniform interface stress distribution of the equipment is a disadvantage that requires proper assumptions to interpret the results.

Romanoschi and Metcalf (Romanoschi and Metcalf 2001) proposed a laboratory test configuration for shear fatigue testing of asphalt concrete interlayer to simulate repetitive loading from moving vehicles. The specimens were subjected to normal and shear loads in this test, respectively. To include the normal forces, the setup allows the longitudinal axis of the test specimen to be at an angle of 25.5° to the longitudinal axis. The shear stress at the interface is half the normal pressure at this angle. The minimum value of the vertical load was 10% of the maximum load at a frequency of 5 Hz. The total time was 0.2 s, and the pulse length was 0.05 s. The simulated vehicle was passed at a speed of 50 km/h. These fatigue tests were performed at 25 °C on two types of interfaces (with and without adhesive coating). Four normal stresses (0.50, 0.75, 1.00, and 1.25 MPa) can be selected to be within the range of normal stress values encountered at the actual pavement interface. Figure 2.12 shows a schematic of this test. The elastic and permanent displacements normal and tangential to the interface are recorded for each cycle, and the cyclic test is stopped when the permanent shear displacement at the interface reaches 6 mm, or when it is determined that the number of load cycles corresponding to the 6 mm permanent shear displacement can be extrapolated.

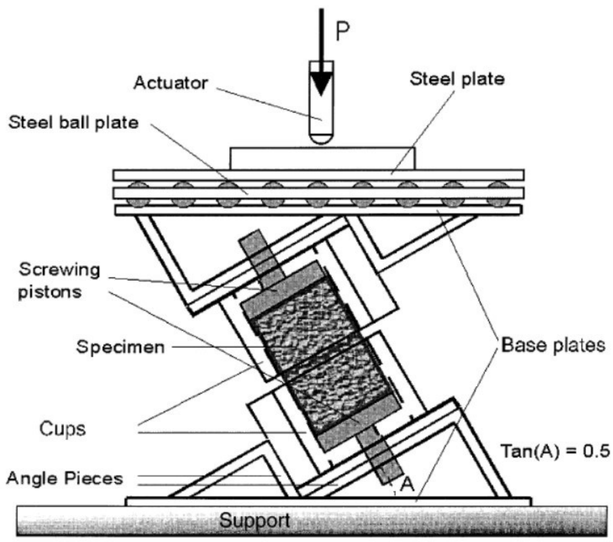


Figure 2.12. Schematic of shear fatigue test.

The direct shear test apparatus developed at the Illinois Transportation Center (ICT) is designed to apply shear forces in the vertical direction and normal forces in the horizontal direction (Figure 2.13). Both monotonic and cyclic fatigue tests can be performed with this equipment. Interface shear strength is evaluated using a monotonic loading mode at a 12 mm/min constant displacement rate. This device has two test modes for evaluating tack coat performance: cyclic mode, which assesses performance based on the number of cycles before failure, and monotonic mode, which assesses tack coat strength based on the peak load before failure.

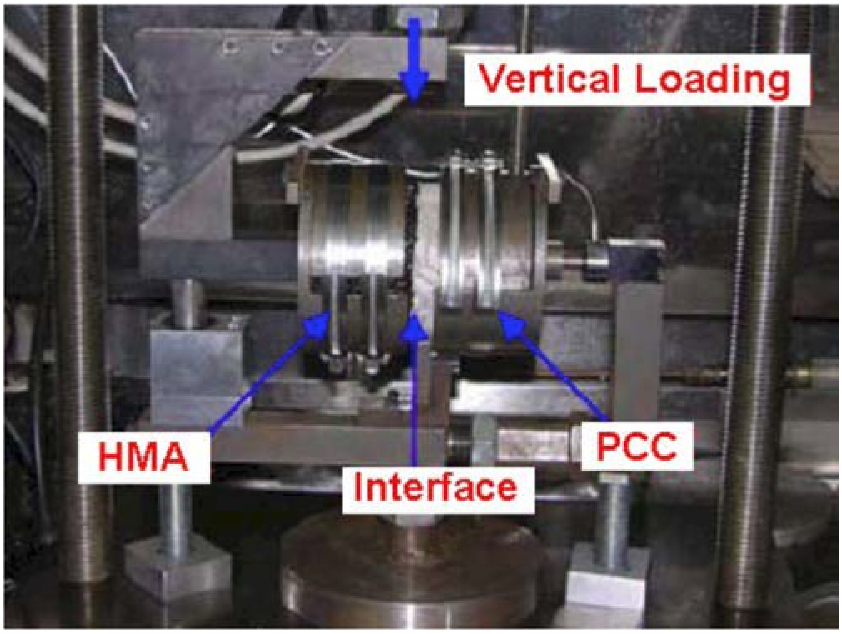


Figure 2.13. Direct shear test apparatus developed at the Illinois Center for Transportation.

Wheat (Wheat 2007) developed the KSU bond strength tester (Figure 2.14) to investigate the effect of various tack coats based on the interlayer bond strength. Two test modes are available to evaluate the bond strength of tack: cyclic mode, using a vertical actuator with a maximum displacement of 10 mm and a displacement rate of 0.05 mm/s; and monotonic mode, which is performed at six different frequencies (25, 10, 5, 1, 0.5 and 0.1 Hz) with sinusoidal loads. The angle between the specimen axis and the actuator axis can be adjusted from 0° to 45°. The shear strength test uses a vertical actuator with a maximum movement of 10 mm and a displacement rate of 0.05 mm/sec. Normal displacement is measured by two LVDT, while radial displacement is measured by one LVDT.

Figure 2.14. KSU bond strength test device.

Frisvold & Bennert (Bognacki, Frisvold et al. 2007) analysed some severe slippage failures at Newark Airport by testing cores with the Superpave shear tester (SST). The SST is a bi-axial loading device that simultaneously provides the sample with dynamic shear and axial loading (normal stress or confining stress). In this study, the tests were carried out using the Constant Stress Ratio mode to potentially allow the change in sample height when a failed interface lets the top and bottom lifts slide over the top of each other. A pulse load was applied for cycles of 0.5 s, with a rest period of 1 s and a stress ratio of 1.25 (vertical stress = 18.75 psi; horizontal stress = 15 psi).

Al-Qadi et al. (Al-Qadi, Carpenter et al. 2008) developed a tack coat shear test device to evaluate the tack coat bonding performance between the pavement layers. The test can be performed in a monotonic loading mode to measure the maximum shear load and corresponding shear displacement to evaluate the interface strength. In addition, the equipment can be used to perform fatigue shear tests by applying cyclic loads at different frequencies, thereby simulating field conditions.

D'Andrea et al. (D'Andrea, Tozzo et al. 2013) and Tozzo et al. (Tozzo, D'Andrea et al. 2014) at the Sapienza University of Rome developed Sapienza Inclined Shear Test Machine (SISTM) and Sapienza Horizontal Shear Test Machine (SHSTM) respectively. The devices apply shear and the normal load to the specimen during the test. Figure 2.15 depicts the SISTM working scheme, while Figure 2.16 depicts the SHSTM working system.

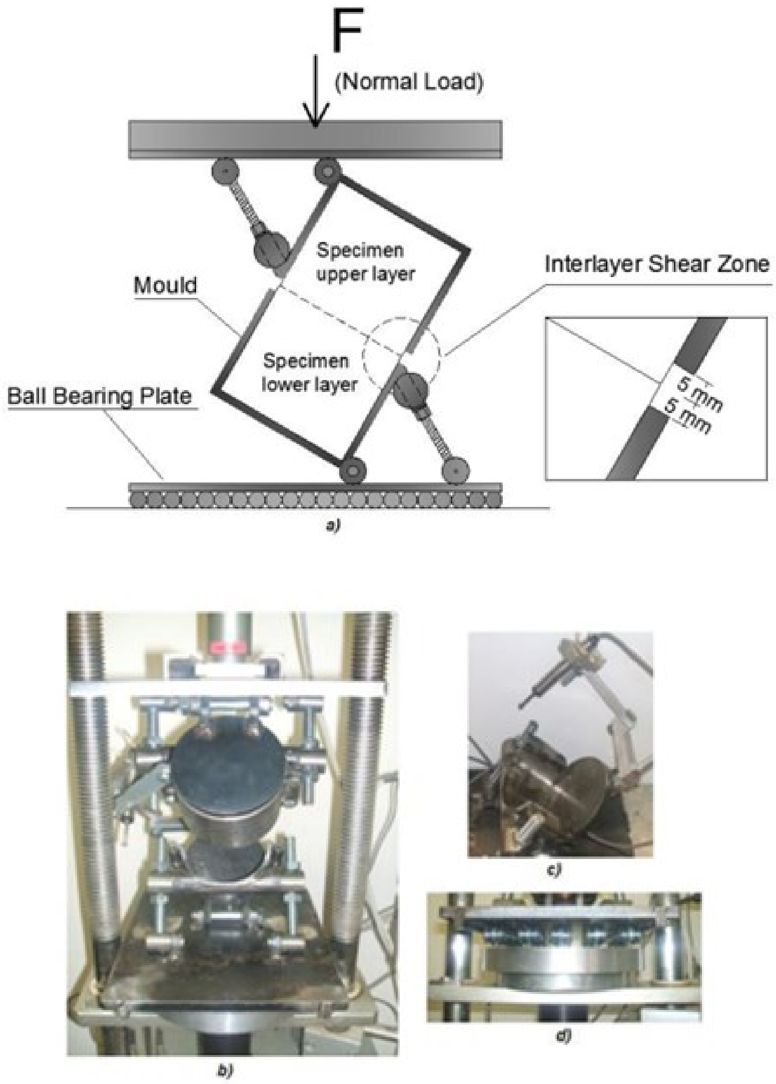


Figure 2.15. SISTM: a) the working scheme; b) the device; c) the LVDT; d) the ball bearing plate.

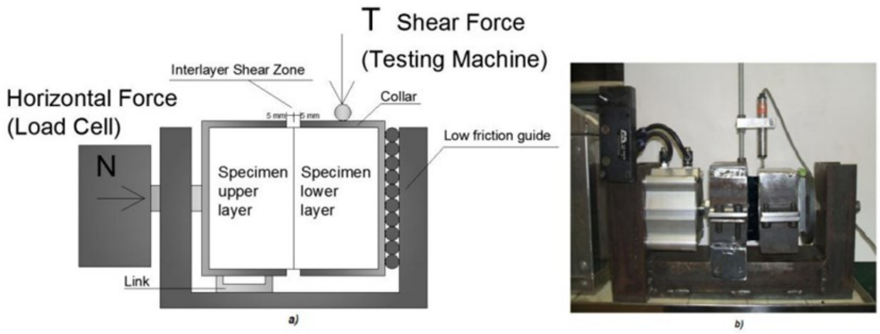


Figure 2.16. SHSTM: a) working scheme; b) the device.

In the United States, at the University of Tennessee, a research team has developed a direct shear fatigue device. This device includes four semi-circular steel rings mounted to an MTS machine able to apply shear force in the vertical direction. Song et al. (Song, Shu et al. 2016) conducted tests using a sinusoidally cyclic stress loading mode at 10 Hz and 20 °C. The stress levels were chosen based on the shear strength of the composite specimens; usually, the corresponding stress ratios are approximately 0.3 and 0.6. Two methods were employed to analyze the results from the shear fatigue test: the traditional 50% stiffness reduction method and the energy approach. The direct shear fatigue test setup is shown in Figure 2.17.

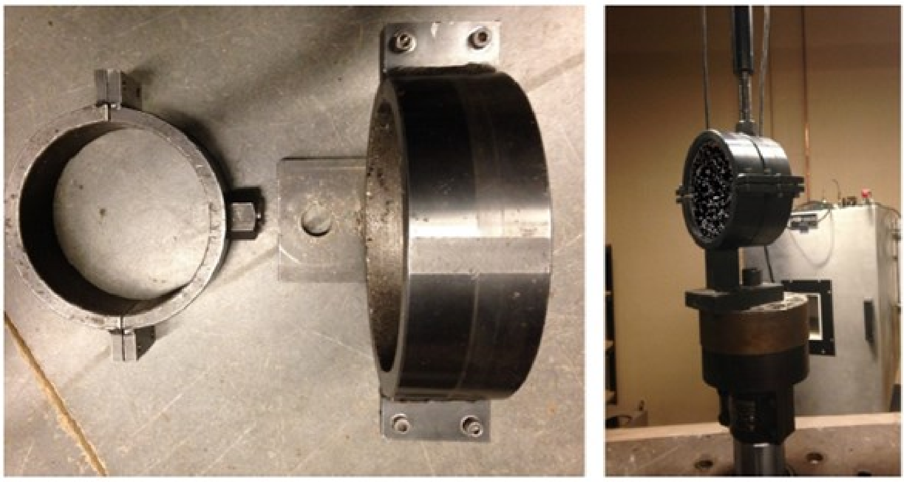
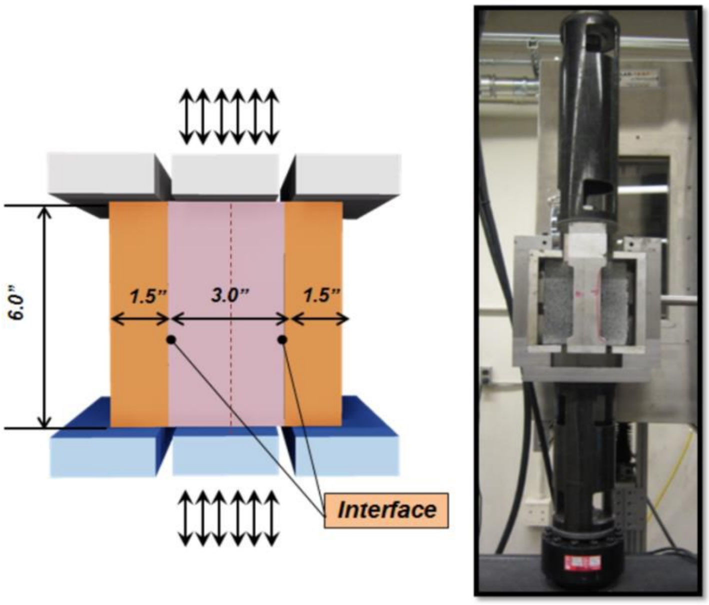


Figure 2.17. Direct shear fatigue test set up.

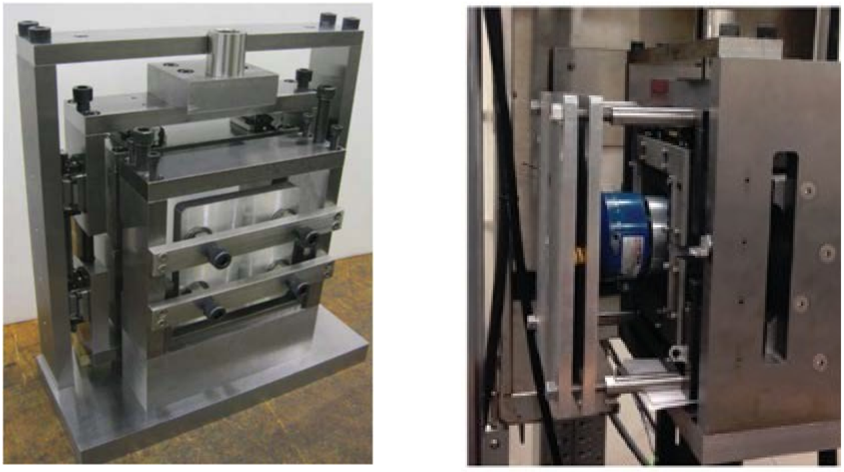
The Double Shear Tester (DST) was developed at North Carolina State University. The advantage of the DST is that the two interfaces experience relatively pure shear stresses. However, the effect of bending moments generated by the eccentricity of the shear load can be found in single interlayer tests. The DST attempted to solve this problem, but it was practically impossible to generate crack extension at both interfaces. Figure 2.18 (a) presents a schematic illustration of a DST specimen and the loading mechanism, and Figure 2.18 (b) shows the DST installed in a Materials Test Systems (MTS) loading frame.



(a) (b)

Figure 2.18. DST: a) Schematic illustration of Double Shear Tester; b) Double Shear Tester installed in MTS.

The Modified Advanced Shear Tester (MAST) was also developed at the North Carolina State University to investigate the shear properties of uniform asphalt mixtures and interlayer interfaces and resolve the problems inherent in many of the devices currently used for shear testing (Figure 2.19). A distinctive feature of MAST is its ability to control the initial normal stress applied to the specimen. MAST is designed in such a way that it can test not only different specimen geometries, such as cylindrical and square specimens but also obtain digital image correlation (DIC) images from the area of the specimen surface close to the interface.



(a) (b)

Figure 2.19. MAST: a) Schematic view; b) MAST installed in the MTS machine.

In Germany, Falla et al. (Falla, Gerowski et al. 2018) and Leischner et al. (Leischner, Canon Falla et al. 2019) developed the Dresden Dynamic Shear Tester (DDST) to characterize the interlayer shear stiffness at different temperatures, stress levels, and frequencies. As Figure 2.20 demonstrates, it is designed to be driven by a universal testing machine (UTM) with temperature and relative humidity control. The test program consisted of two phases. The initial phase was an amplitude sweep to determine the shear strain below the interface in the linear viscoelastic zone. The strain sweep was performed at four temperatures (-10 °C, 10 °C, 30 °C, and 50 °C) with a normal load of 900 kPa and a frequency of 1 Hz. The test was finalized when the shear amplitude reached a threshold value (dependent on temperature), or the shear load exceeded 6 kN.

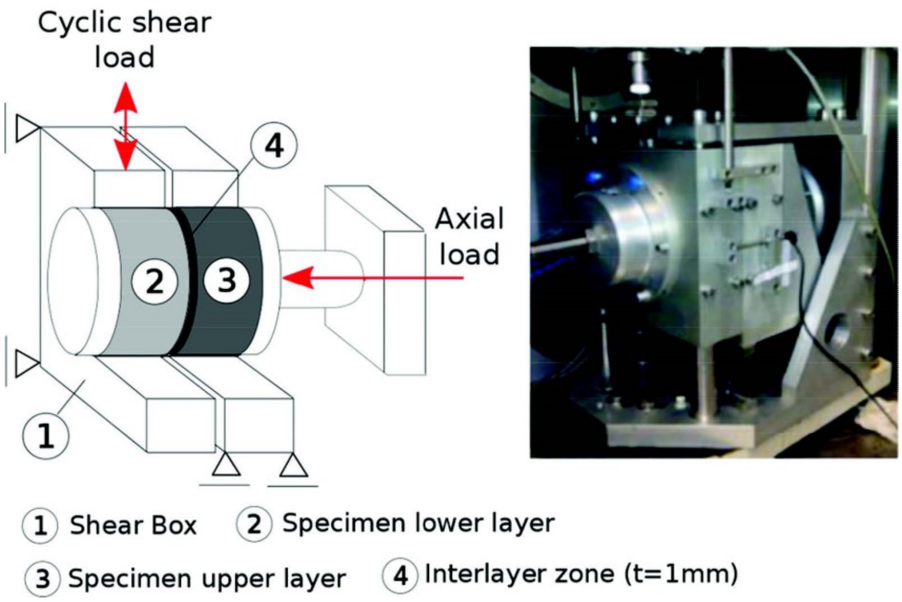
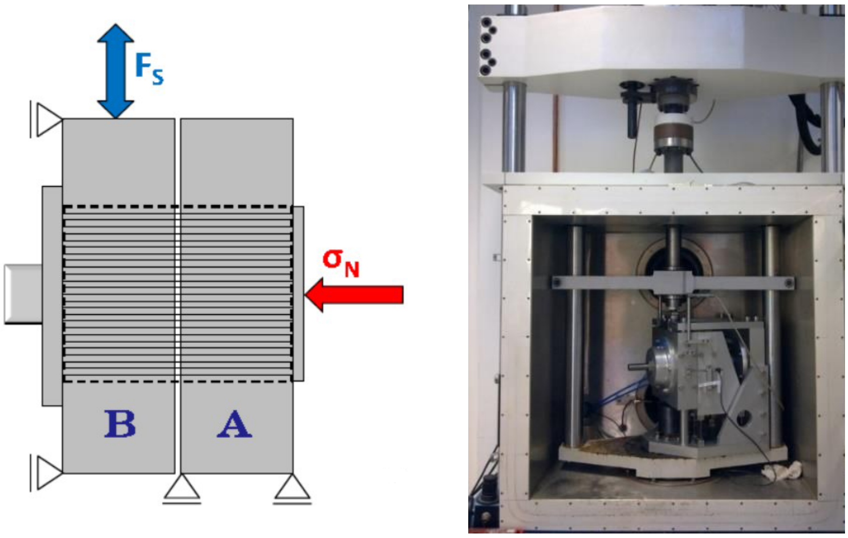


Figure 2.20. Dresden Dynamic Shear Tester.

The second phase was a frequency sweep. It was performed at strain levels within the linear viscoelastic zone. All tests were run in controlled-strain mode. Four temperatures (same as before) and four normal stresses (900 kPa, 600 kPa, 300 kPa, and 0 kPa) were chosen. The shear oscillation varied from 0.1 to 10 Hz in five steps: 0.1 Hz, 0.3 Hz, 1 Hz, 3 Hz, and 10 Hz. The interlayer shear stiffness was presented in master curves by back-calculation of testing data. The test data was processed by coupling a Fourier-assisted finite element method with an optimization algorithm.

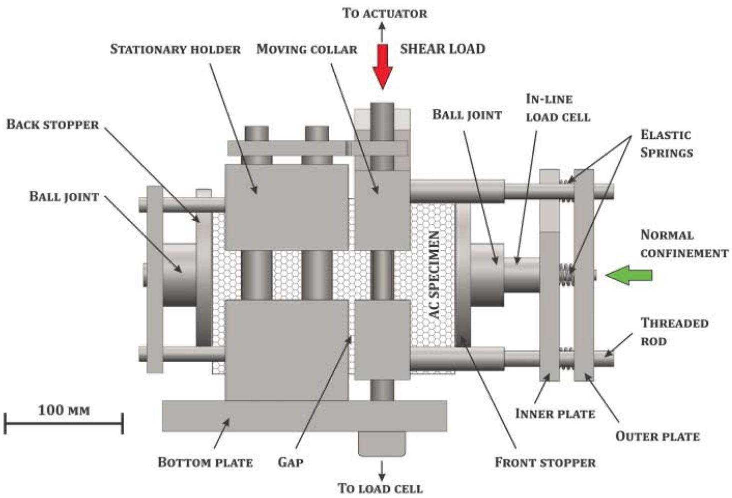
Hristov (Hristov 2018) developed cyclic testing of the interlayer bond (CTIB) device to determine interlayer shear stiffness, taking surface condition (degree of contamination and roughness), acceleration, and braking of traffic loading into account. The effects of different tack coat application rates were compared, and an optimal amount of tack coat was decided. The test procedure started always at a temperature of T = -10 °C, normal stress = 0.9 MPa, shearing frequency f = 10 Hz and a maximal shear displacement = 0.03 mm. For each specimen, it ended at T = 50 °C, normal stress = 0.9 MPa, f = 10 Hz and a maximal shear displacement = 0.15 mm. The whole experiment was conducted at four different temperatures. The specimen was loaded with five normal stresses at each temperature. Six frequencies at the corresponding number of load cycles changed successively during each normal pressure. The whole procedure of simultaneous and consecutive process runs was fully automated, and no manual interference was required. The duration of the whole procedure for one specimen lasted 11 hours and 43 minutes. Figure 2.21 presents the schematic view and photo of the CTIB device.



(a) (b)

Figure 2.21. CTIB device: a) schematic view; b) CTIB installed in the servo hydraulic testing machine.

In Poland, Zofka et al. (Zofka, Maliszewski et al. 2015) developed the Advanced Shear Tester (AST), shown in Figure 2.22. In the study, Zofka introduced the concepts of constant normal load (CNL) and constant normal stiffness (CNS). The authors clarify that while the CNL condition is more realistic because the normal stress remains relatively stable during shear, the CNS condition is more suitable as a test condition because the normal stress varies considerably during the shearing process. It is worth noting that the normal stress at the top of the asphalt layer is not always constant due to moving vehicle loads, especially in the case of heavy vehicles traveling at slow speeds on a thin pavement layer. In addition, CNL conditions may not fully explain the dilation phenomenon of the asphalt material.



(a)

(b)

Figure 2.22. Advanced Shear Tester (AST) device: a) Schematic view; b) Testing device.

In China, Li and Yu (Li and Yu 2014) developed a shear fatigue test under repetitive loads at an angle of 45° to simulate shear force in both horizontal and vertical directions (Figure 2.23) by a universal test machine (UTM), which can automatically record the load bar displacement and force for each cycle of the load application action. The shear stress and shear displacement of each specimen at failure were first identified, then four levels of stress were selected to perform the shear fatigue test. Fatigue tests were performed in a stress-controlled mode at a frequency of 10 Hz with a sine form and a temperature of 25 °C. A fatigue prediction model was developed based on the test results.

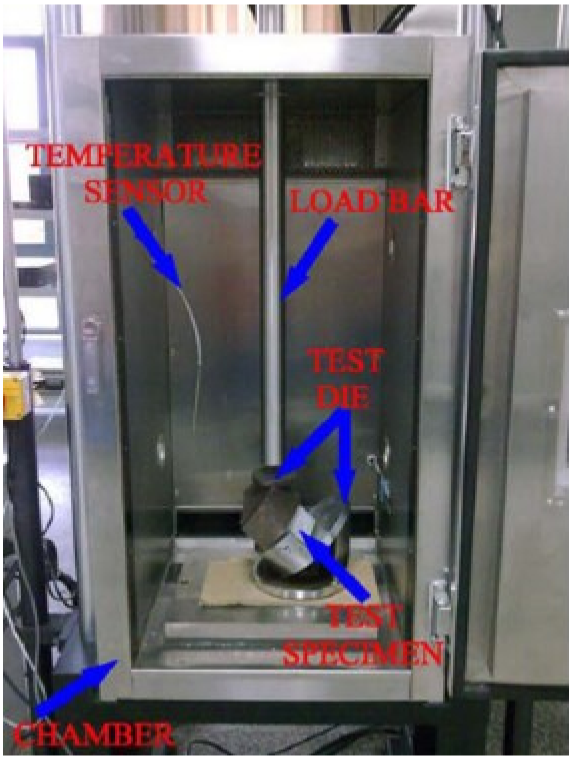
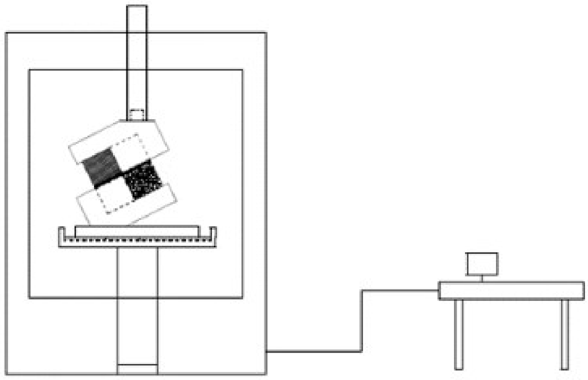


Figure 2.23. Configuration of test apparatus.

Also, in China, Li et al. (Li, Liu et al. 2014) developed a test apparatus that applies horizontal and vertical stress (Figure 2.24). The test apparatus was used for interlaminar shear fatigue testing to evaluate the interlaminar shear fatigue of asphalt overlays on rigid pavements. The test apparatus consisted of a loading system, a compression block, a support block, and a support platform. The lower end of the loading bar is associated with the pressure block, while the support block is set on the support platform. A steel ball held by a bracket is placed between the support block and the support platform. The shape of the groove of the press block is the same as the shape of the groove of the support block. The pressure block and the support block are inclined 26° in the same direction to simulate the actual shear state of the pavement structure under the extreme condition of emergency braking of the vehicle.

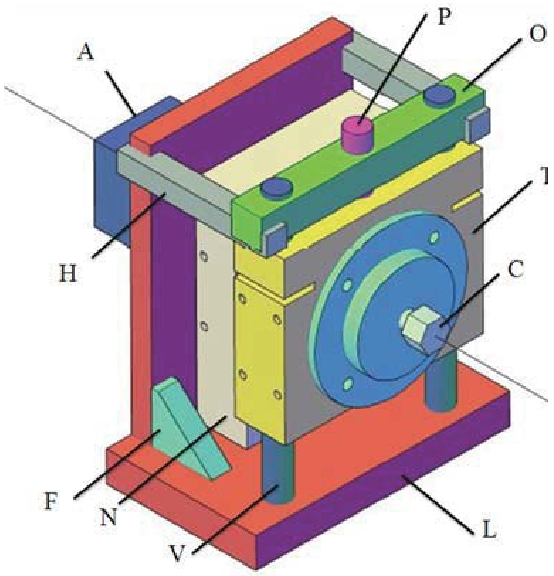


(a)

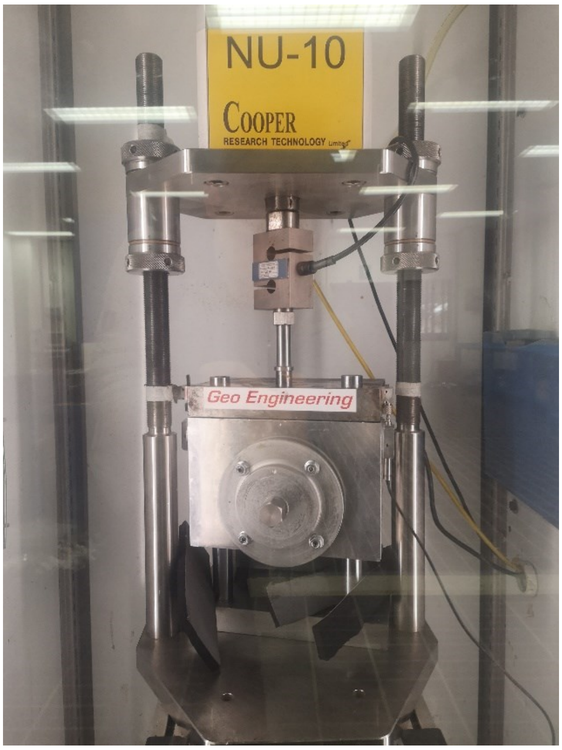
(b)

Figure 2.24. a) Schematic diagram; b) Photo of the special-purpose test apparatus.

In Italy, a new cyclic shear test device was developed at Marche Polytechnic University, namely Cyclic-ASTRA. It is a development of the ASTRA (Ancona Shear Testing Research and Analysis), a static shear testing device. Figure 2.25 shows its working scheme and the device installed in the machine. Cyclic-ASTRA can test both interlayer shear stiffness and fatigue life, and a series of test programs were carried out by it to verify its precision of measurement (Ragni , Ragni, Graziani et al. 2019). In this study, Cyclic-ASTRA shear tests were carried out at 10 °C and 20 °C. The gap between the two shear boxes was set at 10 mm. A sinusoidal (haversine) cyclic load was applied at a frequency of 5 Hz without involving a normal load. Based on the average ISS of the double-layered specimens measured with the static test, four stress amplitudes were used. The ratios between the applied amplitudes and the measured ISS were 0.29, 0.37, 0.44, and 0.51. Two LVDTs were used to measure the shear displacement parallel to the layer interface. The data acquisition system recorded the shear load and the relative interface displacement for each cycle. The results of dynamic tests demonstrated that Cyclic-ASTRA equipment allows characterizing the interlayer properties in terms of stiffness and resistance to repeated loading (cumulative damage). Because of the enhanced precision of the measurements, lower compliance of the testing equipment, and the ability to allow dilatancy movements perpendicular to the interface as well as the application of normal stress at the interface, the Cyclic-ASTRA device's results are very encouraging.



(a)



(b)

Figure 2.25. Cyclic-ASTRA: a) Schematic view; b) Cyclic-ASTRA installed in the temperature chamber.

Besides the cyclic shear test, in France, Ragni et al. (Ragni, Takarli et al. 2020) assessed the shear fatigue behavior by the shear-torque test. An acoustic emission (AE) technique was introduced to evaluate the damage evolution occurring in the interlayer during the test. The study aimed to improve the interlayer failure criteria based only on stiffness evolution. The result showed shear-torque fatigue loading led to delaminating of the double layers. The location and development of AE were utilized as a metric to quantify the interlayer damage.

Attia et al. (Attia, Di Benedetto et al. 2020) developed 2T3C Hollow Cylinder Apparatus (2T3C HCA) to characterize the interface between asphalt concrete layers. This device can apply torsion and tension-compression to hollow cylinder samples. Normal and shear stresses can be applied independently with monotonic or cyclic loading. Digital image correlation (DIC) was employed to measure the displacement at the interface.

2.5.3 Comparison and connection between static and dynamic shear test

Currently, the shear test is the most widely conducted test for interlayer bonding property evaluation. Between static shear test and dynamic shear test, many researchers supported the latter because it can simulate loading conditions as in the field and evaluate interlayer shear fatigue performance from a dynamic point of view (Diakhaté, Millien et al. 2011, Tozzo, Fiore et al. 2014, D'Andrea, Tozzo et al. 2016). Although dynamic testing is more complicated and challenging to conduct, the test results can reveal the decrease of shear stiffness and the accumulation of plastic deformation at the interface. Monotonic testing is suitable for evaluating the effects of different interface treatments (i.e., tack coats, milling, geosynthetic-reinforced) on shear strength due to its relatively fast and straightforward experimental procedure. However, monotonic testing results only express maximum interlayer shear stress, which is unreliable for shear fatigue performance evaluation.

From the cyclic results, master curves can be retrieved, which enable predicting the shear stiffness for all combinations of temperature and strains and stresses of interest based on limited testing (Raab, Partl et al. 2017). Moreover, the results from cyclic testing are valuable for both interlayer bond property evaluation and modelling purposes.

Compared with the fatigue test, the static test takes advantage of obviously spending less time. Therefore, many researchers were interested in developing a model to describe shear fatigue properties from the results of the static shear test. Diakhaté et al. (Diakhaté, Phelipot et al. 2006) studied the shear fatigue behavior of tack coats and intended to connect the shear fatigue and monotonic shear behaviors. Although the specimen can be tested by static and dynamic shear tests at the same temperature, the conversion of other testing parameters between the two tests, such as shear displacement rate to load frequency, is unclear.

One of the difficulties is finding the connection between fatigue test loading frequency and displacement rate of the static test. Szydło and K Malicki conducted the Leutner test and shear fatigue test to study the correlation between test results (Szydło and Malicki 2016). Their research indicated that significant correlations exist among the selected test parameters of interlayer bonding property and suggested that it is possible to build regression models for interlayer bonding durability based on the results of the static shear test.

Isailovic´ and Wistuba evaluated the interlayer bond properties by both Leutner monotonic shear test and cyclic direct shear test based on Leutner testing device. The test results were compared to investigate whether the shear strength obtained from monotonic shear tests can be used as an indicator for fatigue performance or not. The monotonic shear test was conducted with a shear displacement rate of 50 mm/min at 20 °C. The cyclic shear fatigue test was conducted with a gap width of 1 mm at 20 °C and used displacement amplitude sweep tests to determine three displacement amplitudes. Three types of asphalt mixtures and three types of tack coat materials were used to combine ten bond types for the specimens. It was shown that only part of the results from the monotonic shear test agreed with results from the cyclic shear test. Therefore, the static test cannot take the place of a dynamic test to evaluate shear fatigue life.

2.6 Influence of dynamic test parameters on results

Although many researchers have explored the influence of testing factors, especially temperature, the comprehensive influence of dynamic test parameters combining temperature, frequency, and normal stress on interlayer bonding properties is not clearly illustrated yet. These parameters are closely related to the pavement environment and load conditions in reality. For this reason, it is necessary to conduct a thorough investigation into the influence of these parameters.

The shear stiffness at the interlayer zone was strongly influenced by the temperature, frequency, and normal load. The influence of temperature is the most obvious; it is well-known that the interlayer shear stiffness decreases significantly with temperature increase. At high temperatures, the friction between two interlayer surfaces and interlocking between aggregate particles contribute more to the interlayer shear stiffness than the tack coat. Therefore, the normal load has a more evident positive influence on interlayer shear stiffness at high temperatures.

Higher shearing frequencies also positively affect the interlayer bond shear stiffness. At a high frequency, the asphalt concrete material performs more rigidly.

2.7 Summary and discussion

Interlayer bond property plays a critical role in the performance of pavement structures. In recent years, the recognition of the importance of interlayer bonding to pavement performance has prompted a great deal of research into the factors affecting the interlayer bond property and test methods. The cyclic shear test has gained popularity due to its advantage of simulating repeatedly moving loads.

This chapter gives an overview of the research background, including the effects of bonding conditions on pavement performance, a discussion of factors that affect interface shear bond strength, analysis methods of the interlayer bond property, and the experimental characterization of the interlayer bond property.

The shear test is the most commonly used method for estimating bond strength. The interlayer shear test can better simulate realistic interlayer damage and is relatively simple to perform.

Accuracy is also an essential issue in the evaluation of pavement structures. There are limitations in each test, which may adversely affect the assessment of the interlayer bonding forces. In most cases, some testing devices can only consider loads in a single direction and cannot accurately simulate the load-carrying capacity of pavement interlayers. Some test methods are manual, resulting in unreliable and poorly reproducible results. Combining several different tests may be an ideal solution to alleviate this problem.

Interlayer bond performance is influenced by several factors, including material properties, construction conditions, etc. The effects of different factors on interlayer bond performance are more complex in the field than in the laboratory.

Chapter 3.

Experimental program

3.1 Introduction

This chapter describes the experimental work carried out in this research.

This chapter describes the materials, the preparation of specimens, the testing device introduction, the testing program, and the conclusions of the experimental work.

3.2 Materials

The double-layered slabs for the interlayer shear strength test were prepared in the laboratory at Marche Polytechnic University. The same asphalt concrete (AC) mixture was used for the lower and upper layers.

The asphalt concrete mixture contains a Styrene-Butadiene-Styrene (SBS) polymer modified bitumen, coarse aggregate, limestone fine aggregate, and filler supplied by the asphalt mix plant of Pavimental company in Loreto, Italy. After production, the mixture was transferred to the university and stored in several paper bags in the laboratory, as Figure 3.1 shows.

Figure 3.1. Asphalt concrete mixture.

Table 3.1 shows the grading of the AC. The main characteristics of the SBS polymer modified binder are listed in Table 3.2. Figure 3.2 depicts the grading curve of aggregates.

Table 3.1. Grading of the AC.

	Sieve (mm)	Remains (g)	Percent (%)	Total Bin (%)	Passing (%)
	20	23.1	2.5	2.5	97.5
	16	27.8	3.0	5.4	94.6
	10	183.5	19.5	24.9	75.1
	8	132.9	14.1	39.1	60.9
	4	141.5	15.1	54.1	45.9
	2	145.9	15.5	69.7	30.3
	1	106.7	11.4	81.0	19.0
	0.5	61.9	6.6	87.6	12.4
	0.25	22.4	2.4	90.0	10.0
	0.125	22.1	2.4	92.3	7.7
	0.063	19.1	2.0	94.4	5.6
Bottom		53	5.6	100.0	0.0

Table 3.2. Basic characteristics of the SBS polymer modified binder.

Characteristics	Standard	Unit	Value
SBS polymer content by weight	-	%	4.75-5.25
Penetration (25°C; 100 g; 5s)	EN 1426	0.1 mm	45-80
Ring and Ball softening point	EN 1427	°C	65
Elastic recovery (25 °C; 5 cm/min)	EN 13398	%	80
Dynamic viscosity @ 135 °C	EN 12595	Pa·s	0.4
RTFOT at 163 °C			
Mass loss	EN 12607-1	%	0.5
Penetration	EN 1426	0.1 mm	60
Ring and Ball softening point	EN 1427	°C	8

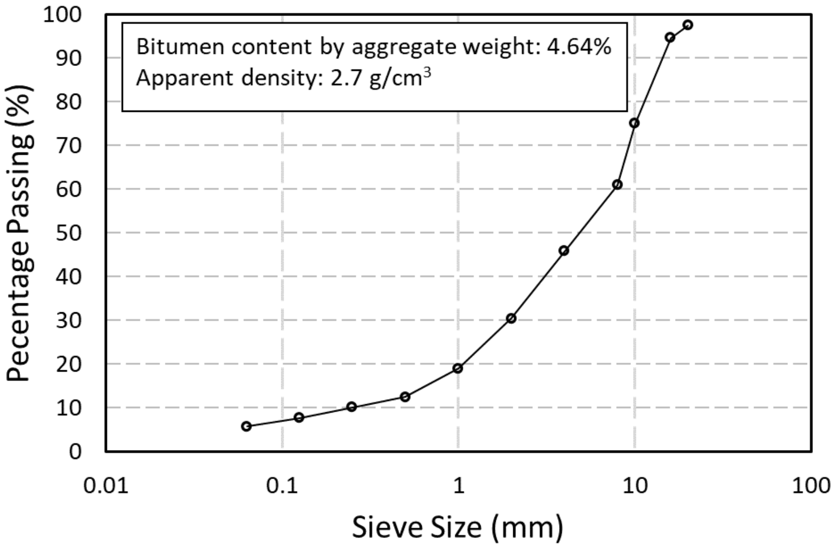


Figure 3.2. Grading curve of aggregates.

3.3 Slabs preparation and properties

3.3.1 Slabs preparation

The double-layered square slabs were compacted in the laboratory in a stainless-steel mould (Figure 3.3) using a roller compactor according to EN 12697-33. The roller compactor (Figure 3.4) is a pneumatic device used for compacting a bituminous mixture by simulating in-situ compaction in the laboratory. Two knurled nuts can be used to adjust the slab's final thickness. The volume of the mould is cross-sectional area multiplied by the height of the material; therefore, by compacting a certain mass, the slab density can be easily found. During the cycle, four different pressure levels can be applied. The first pressure can be varied between 0 and 2.5 bar, simulating the compaction effect of a paver. And the other three pressures are between 0 and 1 bar, representing the compaction performed by the roller in the field. For each pressure, the number of passes of the rollers can be fixed between 0 and 100. The roller compactor skips the corresponding pressure by setting the number of cycles to zero.

Figure 3.3. Roller compactor mould.

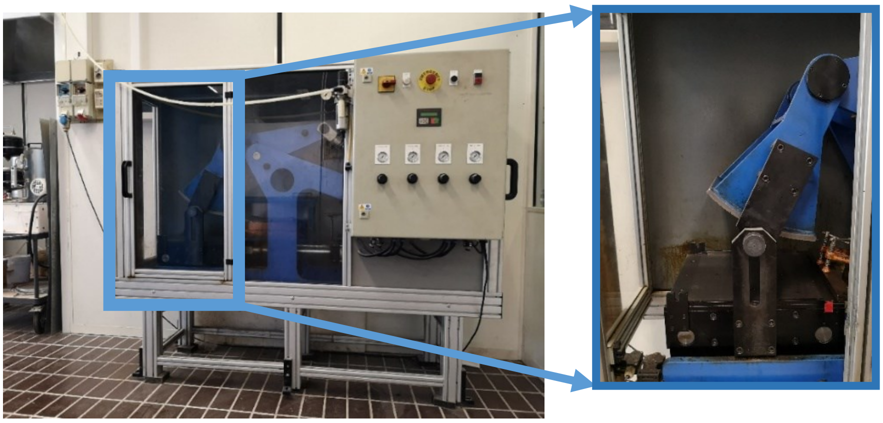


Figure 3.4. Roller compactor.

Before compacting slabs, the density of the slab needs to be calculated. According to AASHTO T 312 (2019), four asphalt concrete replicates were compacted to test slab density. Therefore, the procedure established:

1. Two bags of materials were taken (to avoid second time heating, the mass of each bag is around 10 kg).

2. For each bag, took 2 replicates for gyration compactor (each one was 4.5 kg weight); left 1 kg for bitumen extraction, for the calculation of bitumen content and aggregate grading curve.

3. For the gyration compactor, compacted two specimens with 150 mm diameter. The mode was gyration times control (200 gyrations). The material was heated at 160 ℃ for 3 hours in the oven before the compaction. And the moulding was heated for 30 minutes before starting to compact.

4. During the compaction of the specimen, the height of the specimen was recorded at least every five gyrations.

The gyration compactor and specimens are shown in Figure 3.5. The result is presented in Figure 3.6.

(a)

(b)

Figure 3.5. Slab density calculation: a) Gyration compactor; b) Specimens.

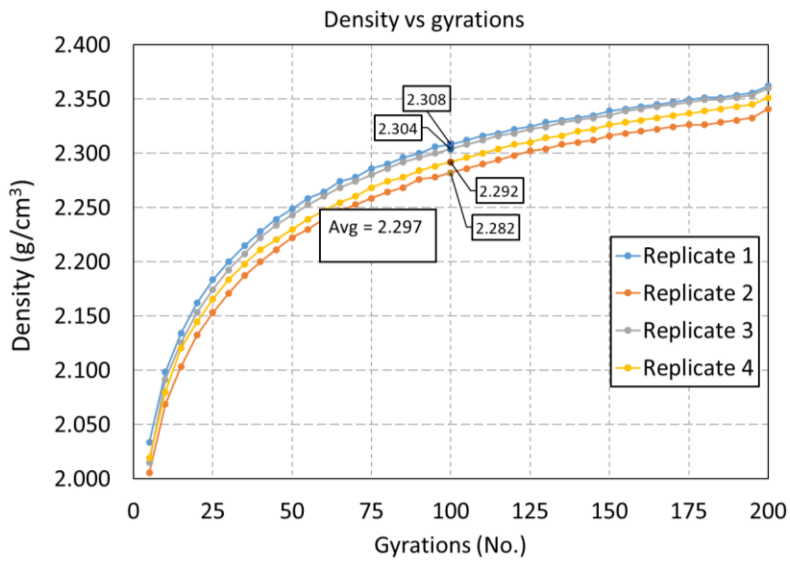


Figure 3.6. Density of specimens by means of gyratory compactor.

The structure of each slab is double-layered with a dimension of 305×305×80 mm^3. The thickness was 40 mm for each layer. According to the density of the asphalt concrete, the amount of material for each layer is 8.547 kg. Before compaction, the asphalt concrete was heated in the oven at 170 ℃ for three hours. Then the under course was compacted at room temperature. After the underlying system was restored at room temperature for more than 24 hours for cooling, the same amount of asphalt concrete heated in the oven at 170 ℃ for three hours in advance was laid to compact the up course. There were 32 slabs prepared for the following tests. All the slabs were not applied with a tack coat. The compaction direction and serial number were marked on the surface of each slab. Four specimens (ø95 mm) were cored from each slab. The process is shown in Figure 3.7. The slab and cored samples are shown in Figure 3.8.

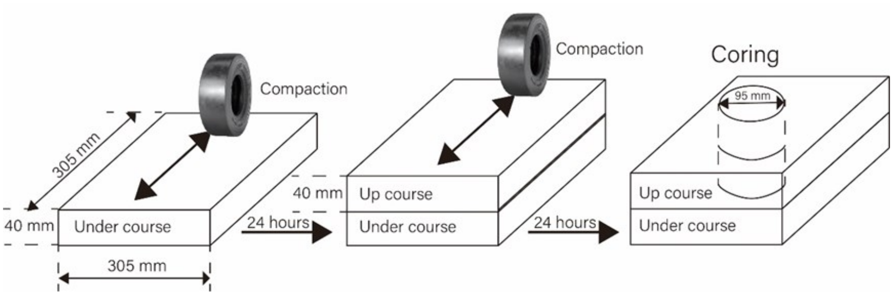


Figure 3.7. Specimens' preparation.

Figure 3.8. Specimens' preparation: a) Slab; b) Specimens.

3.3.2 Specimens' properties control

To check the slab quality, 20 specimens with the diameter of 95 mm were cored from the double-layer slabs to measure the bulk density of the mixture according to AASHTO T 312 (2019). The average bulk density of the slabs is presented in Table 3.3.

Table 3.3. Properties of specimens.

Number of the specimen	m_1 (g)	m_2 (g)	Bulk density (g/cm^3)	Average density	Density by AASHTO T 312 (2019)	Air void content (%)
7.1	1300.5	735.6	2.302	2.288	2.297	8.41
7.2	1300.2	731.9	2.288			
7.3	1286.7	720.8	2.274			
7.4	1299.2	731.4	2.288			
11.1	1299.1	737.100	2.312	2.297		
11.2	1300.1	734.700	2.299			
11.3	1284.8	726.700	2.302			
11.4	1281.5	717.700	2.273			
14.1	1295.300	732.000	2.299	2.296		
14.2	1298.800	734.900	2.303			
14.3	1296.500	732.200	2.298			
14.4	1281.700	720.600	2.284			
16.1	1288.100	727.200	2.296	2.309		
16.2	1280.100	726.300	2.311			
16.3	1294.800	733.300	2.306			
16.4	1297.200	738.100	2.320			

3.4 Leutner test

Before the cyclic shear test, the shear strength of specimens was measured by the static shear test. Shear tests were performed by the Leutner equipment (Figure 3.9), according to European Standard EN 12697-48. A LVDT transducer was added to compute the relative displacement between the lower and the upper part of the Leutner device. Leutner tests were conducted at a temperature of 20 °C, applying a constant shear displacement rate of 2.5 mm/min across the interface of the double-layered specimen. A total of seven specimens were tested.

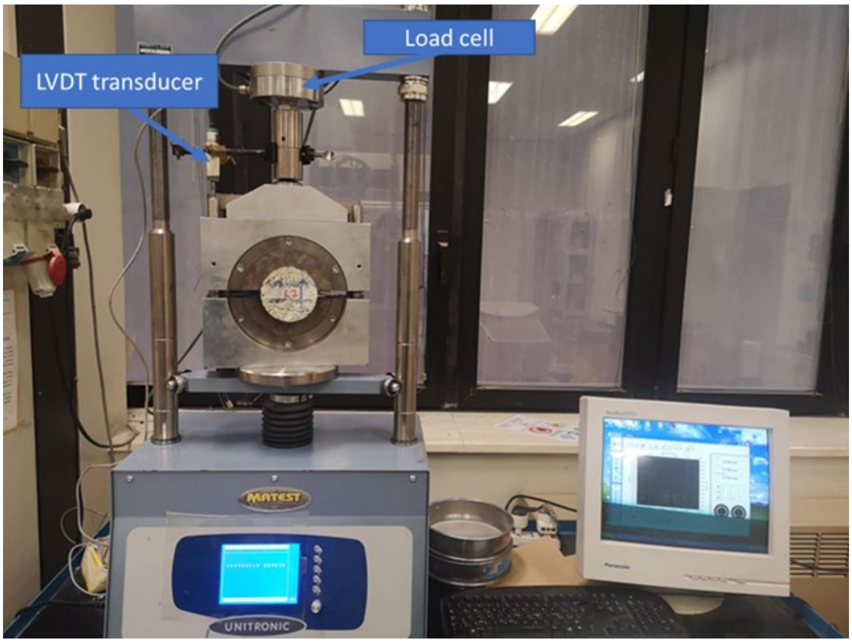


Figure 3.9. Leutner testing device.

3.5 Cyclic-ASTRA test

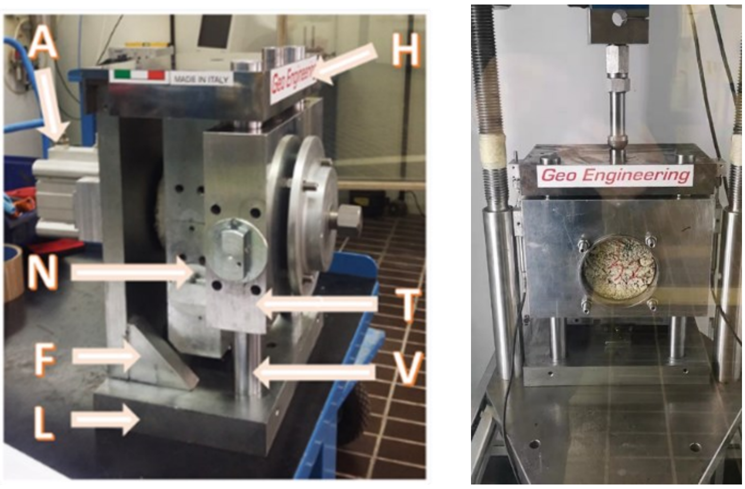
3.5.1 Test device

The Cyclic-ASTRA testing device is designed for the cyclic shear test at Marche Polytechnic University. It is a development of the ASTRA (Ancona Shear Testing Research and Analysis), a static shear testing device.

For all the tests carried out in the lab, the Cyclic-ASTRA with specimen was installed into a servo-pneumatic universal testing machine equipped with a climate chamber.

The scheme of the Cyclic-ASTRA device is shown in Figure 3.10 (a). It consists of two half-boxes (T and N) separated by an adjustable gap. The half-box T moves on two vertical guides (V), fixed to a base (L), and allows the application of a vertical load parallel to the interface. The half-box N can slide horizontally (perpendicular to the interface) along a low friction precision guide, fixed to the base L. The device also allows applying a prefixed horizontal load (perpendicular to the interface) through a pneumatic actuator (A). The horizontal load is static because a dynamic application would lead to the higher complexity of the test frame. The base L is stiffened using two triangular elements, F. The two vertical guides are connected through a horizontal plate H, linked to the base L (the plate H has the purpose of stiffening the base).

The specimen was glued and fixed inside two steel rings covering its up course and under course tightly between the rings existing a gap of 10 mm where was the position for the interlayer of the specimen. The rings were fastened with Cyclic-ASTRA by sixteen screws. Cyclic-ASTRA can apply both dynamic vertical load and static normal load together to the specimen. The test is conducted in a temperature chamber to control the temperature. Vertical shear displacement data was collected using two LVDT introducers. The device during the test is shown in Figure 3. 10 (b). The specimen glued in the ring with a gap width of 10 mm is shown in Figure 3. 11.



(a) (b)

Figure 3.10. Cyclic-ASTRA device: a) Scheme; b) Cyclic-ASTRA in a temperature chamber.

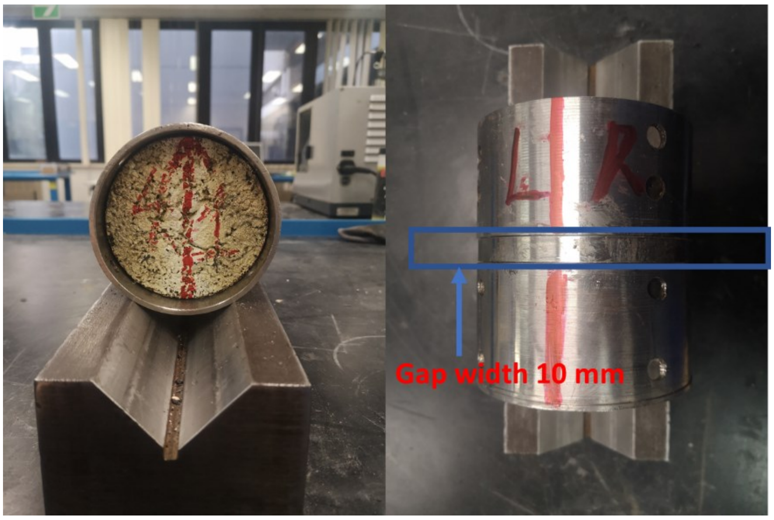


Figure 3.11. Specimen glued in the ring.

The load and the interface displacement were recorded for each cycle during the test. As Figure 3.12 shows, two LVDT transducers (M924681AL51-01 and M924681AL51-02) were mounted vertically (parallel to the interface) to measure the interface shear displacements. The shear load was recorded by the data acquisition system.

Figure 3.12. LVDT used in the tests.

3.5.2 Test program

In this study, ten specimens were tested. The Leutner testing apparatus was used to assess the interlayer shear strength of seven specimens. The Cyclic-ASTRA device was used to assess the interlayer shear stiffness (ISS) and shear fatigue life of three specimens.

For both ISS and fatigue life measurements, the gap between the two shear boxes was set a 10 mm, a sinusoidal (haversine) cyclic load was applied to the specimen, and two LVDTs were used to measure the shear displacement parallel to the layer interface. The data acquisition system recorded the shear load and the relative interface displacement for each cycle.

For the measurement of ISS, it was conducted at two temperatures (10 and 30 ℃, began at 10 ℃), three frequencies (5, 1, 0.2 Hz, from 5 to 0.2 Hz); for each frequency, there were 20 cycles; for each temperature, three stress amplitude was applied, 0.4, 0.8, 1.2 kN for 10 ℃ and 0.2, 0.4, 0.8 kN for 30 ℃. Testing started from the lower temperature, lower stress amplitude, and the higher frequency.

The measurement of fatigue life was carried out at 10 ℃, the stress amplitude was 3 kN, and the frequency was 5 Hz.

Figure 3.13 demonstrates the test program.

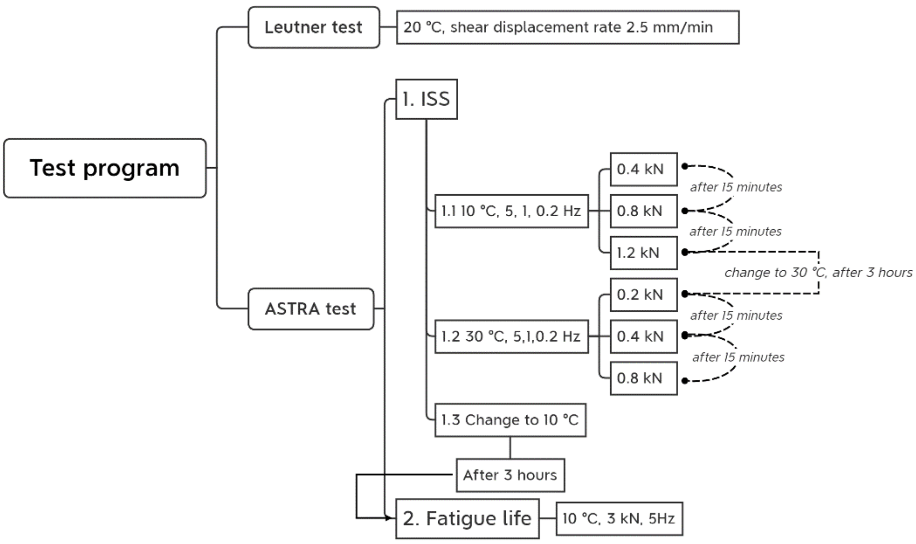


Figure 3.13. Laboratory test program.

3.5.3 Test procedure

Before the test, the specimen was fixed inside Cyclic-ASTRA, and the device was in a climate chamber for conditioning. After the specimen had equilibrated with the test temperature for more than 3 hours, the test was started and the load was applied to Cyclic-ASTRA by the servo-pneumatic universal testing machine.

As Figure 3.14 shows, the servo-pneumatic universal testing machine was controlled by universal software on the computer.

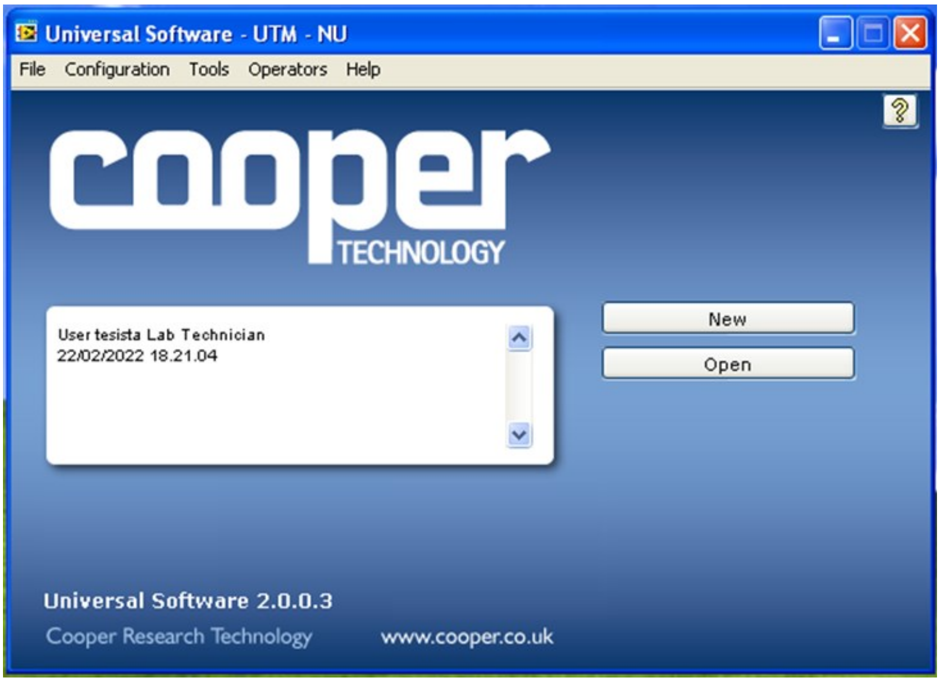


Figure 3.14. The interface of universal software.

To set up the test on universal software, for both interlayer shear stiffness test and fatigue test, first of all, selected test configuration and input specimen dimensions. The interface of the universal software is shown in Figure 3.15.

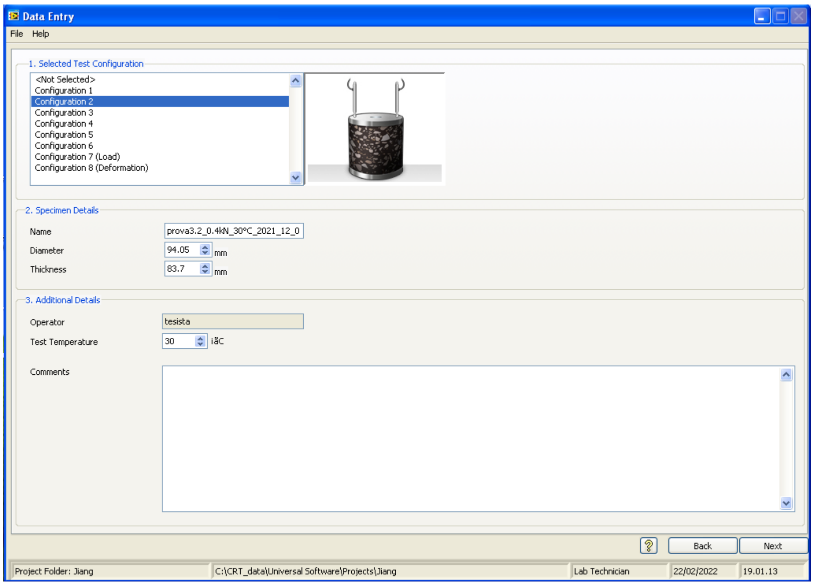


Figure 3.15. Configuration selection and specimen details.

For the interlayer shear stiffness test, as Figure 3.16 shows, the control method was load controlled; three stages were set up to apply the same sinusoidal (haversine) waveform cyclic load at three different frequencies, and between each stage applied 0.03 kN static load.

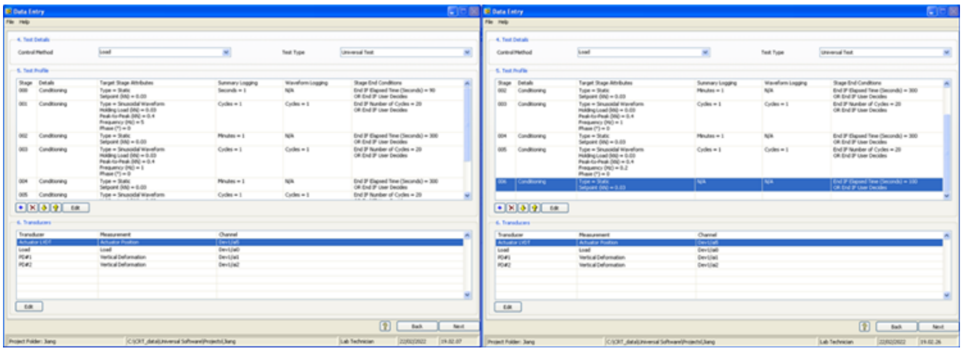


Figure 3.16. Shear stiffness test profile set up.

For the interlayer shear fatigue test, as Figure 3.17 shows, the control method was load controlled, one stage was set up to apply the static load for several seconds, and one stage was set up to apply the sinusoidal (haversine) waveform cyclic load until the interface failure of the specimen happened. Since the fatigue test took a much longer time than the stiffness test, the result was not recorded for each load cycle but for more dispersed cycles, as Figure 3.18 shows.

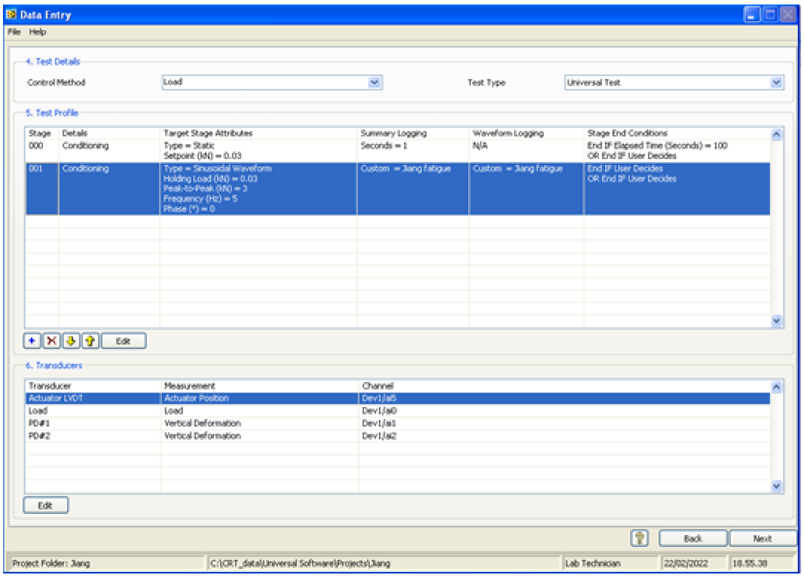


Figure 3.17. Shear fatigue test profile set up.

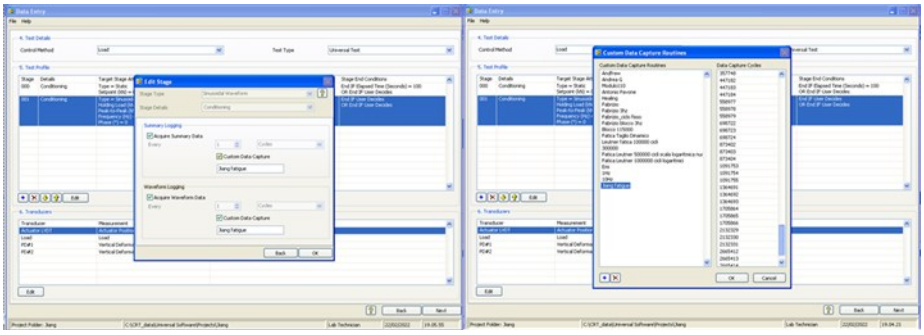


Figure 3.18. Shear fatigue test data capture set up.

To reach the desired load amplitude quickly, it is necessary to adjust the start peak to the peak factor. It is a percentage of the peak output; in a load-controlled test, it is a percent of the peak load output (Figure 3.19). As a pneumatic system, there is not exactly a linear relationship between the start factor value and the actual load achieved due to the dynamics of the system. This is because of air flow restrictions and the compressibility of the air and will also be affected by the loading frequency. The best way to tune is by empirically using tests on similar samples for the same test to determine which start factor gives the quickest rise to the target amplitude without much overshoot.

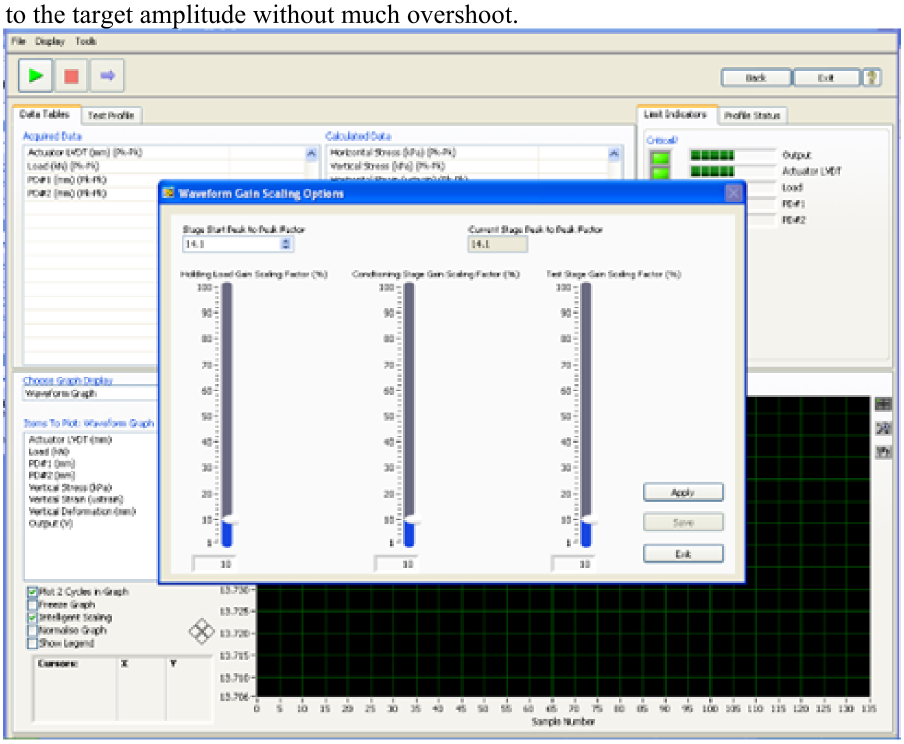


Figure 3.19. Stage start peak to peak factor set up.

Chapter 4.

Test results and discussion

4.1 Leutner test results

Seven specimens were tested by Leutner shear device. Figure 4.1 shows one of the test results, and Figure 4.2 shows the specimens after the test. Table 4.1 presents the summary of the Leutner test results.

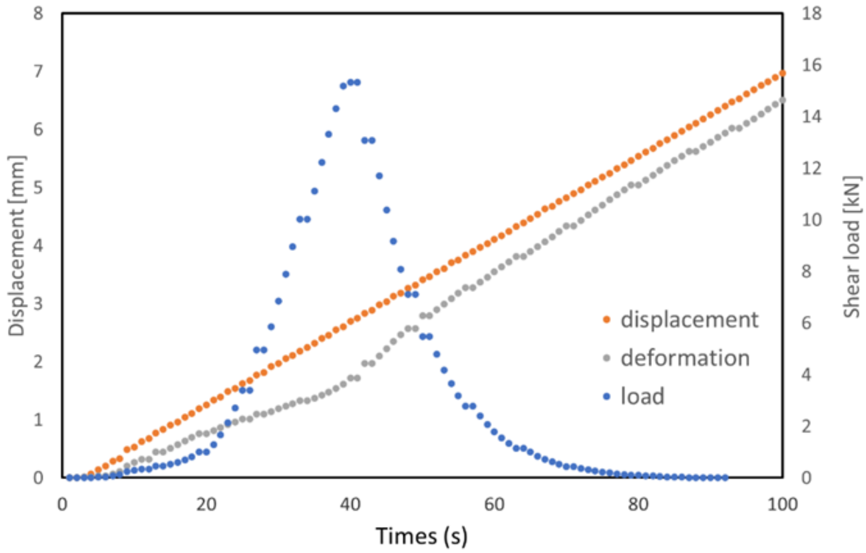


Figure 4.1. A Leutner test result.

Figure 4.2. Specimens after Leutner test.

Table 4.1. Leutner test results.

Specimen ID	τ_{peak} (MPa)
1.1	1.82
1.2	2.14
1.3	0.97
1.4	1.12
2.1	1.89
2.2	1.87
2.3	1.47
Average	1.61
Standard deviation	0.44

4.2 Interlayer shear stiffness test results

4.2.1 Calculation of interlayer shear stiffness

This study employed interlayer shear stiffness to evaluate interface shear characteristics. During the shear stiffness test, the load frequency changed from 5 Hz to 1 Hz then to 0.2 Hz. For each frequency, there were twenty sinusoidal waveform load cycles.

The interlayer shear stiffness (k) can be defined as follows:

$$k = \frac{\tau}{\mu} \tag{4.1}$$

where τ is the amplitude of applied shear stress and μ is the amplitude of the relative deformation at the interface.

To calculate the stress and deformation amplitude, the sinusoidal components of the measured stress and strain signals shall be analysed. The stress wave consisted of a constant compression (creep component) and a sinusoidal wave. The separation of the creep component from the periodic component of the measured signals was
obtained by using a moving average filter. It can be defined as follows:

$$y_{ma}[n] = \frac{1}{N} \sum_{i=-N/2+1}^{i=N/2} y[n+i] \tag{4.2}$$

where y (·) is the discrete-time signal (either stress or strain) and y_{ma} (·) is its moving average over one period (N=100). The periodic component y_p [n], which is measured stress/deformation harmonic, is calculated as follows:

$$y_p[n] = y[n] - y_{ma}[n] \tag{4.3}$$

According to the Fourier series, a periodic waveform can be expressed as follows:

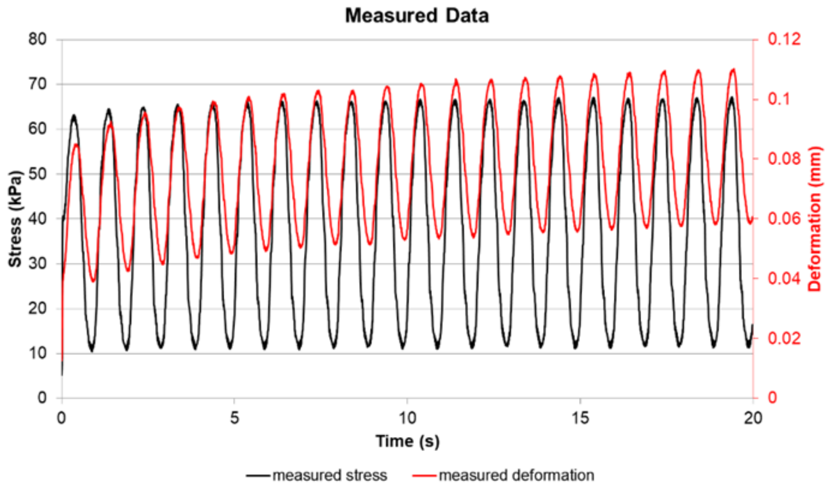
$$f(t) = \frac{1}{2} a_0 + \sum_{n=1}^{\infty} (a_n \cos n\omega t + b_n \sin n\omega t) \tag{4.4}$$

The amplitude of each sinusoidal component is calculated as follows:

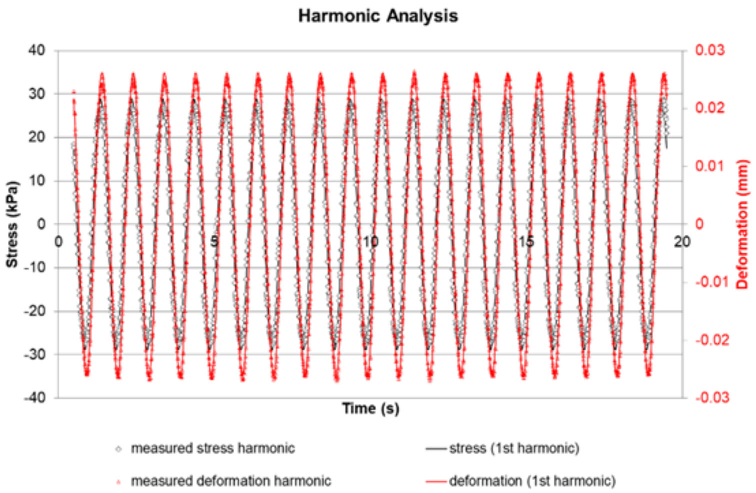
$$c_n = \sqrt{a_n^{\,2} + b_n^{\,2}} \tag{4.5}$$

Only the first harmonic component (n = 1) was employed to calculate stress and deformation amplitude. Therefore, the interlayer shear stiffness was calculated using Eq. (4.1).

Figure 4.3 shows an example of the measurements conducted with the Cyclic-ASTRA device. In particular, the shear load and interlayer relative displacement time histories are reported. The test was carried out at a frequency of 1 Hz.



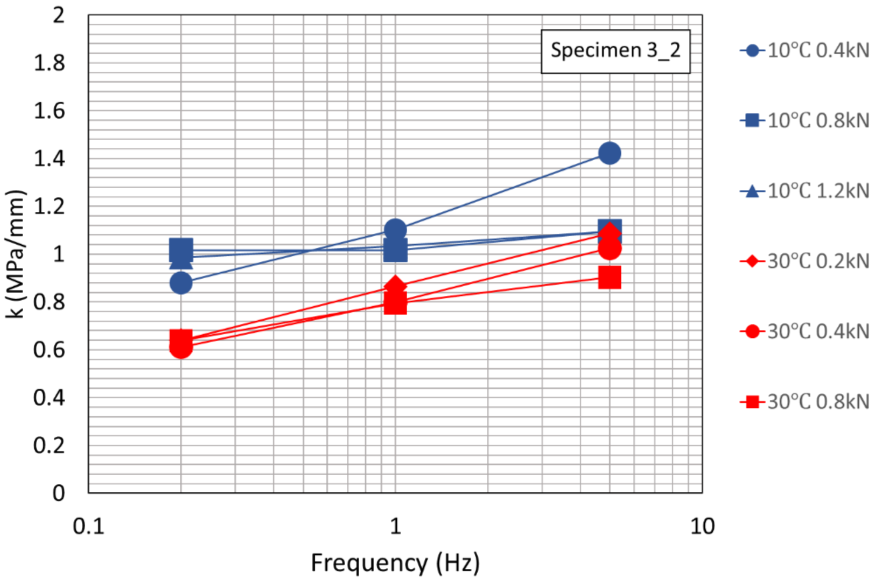
(a)



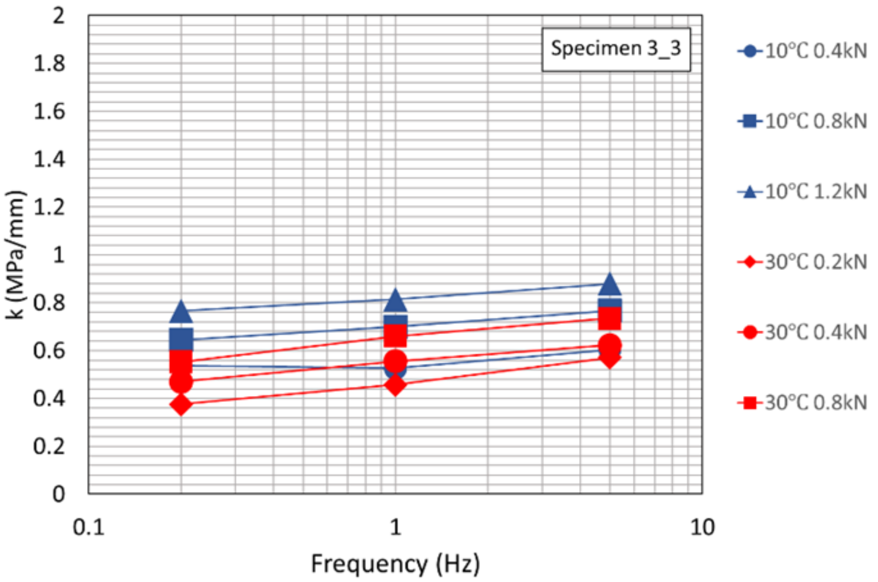
(b)

Figure 4.3. Example results: a) Evolution of measured stress and deformation at 1 Hz; b) Evolution of stress and deformation at 1 Hz.

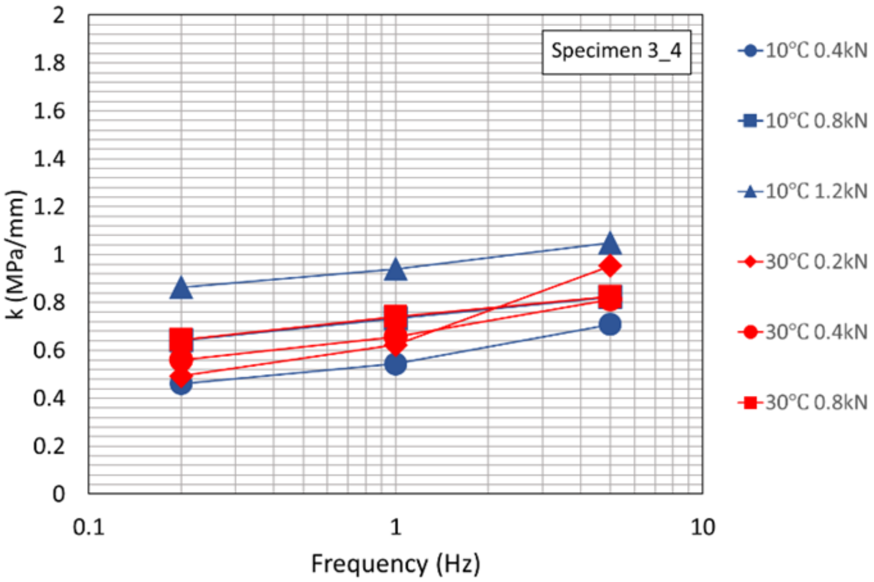
Figure 4.4 presents the results of interlayer shear stiffness tests at different frequencies and temperatures.


Specimen 3_2
k (MPa/mm)
Frequency (Hz)
10°C 0.4kN
10°C 0.8kN
10°C 1.2kN
30°C 0.2kN
30°C 0.4kN
30°C 0.8kN

(a)


Specimen 3_3
k (MPa/mm)
Frequency (Hz)
10°C 0.4kN
10°C 0.8kN
10°C 1.2kN
30°C 0.2kN
30°C 0.4kN
30°C 0.8kN

(b)

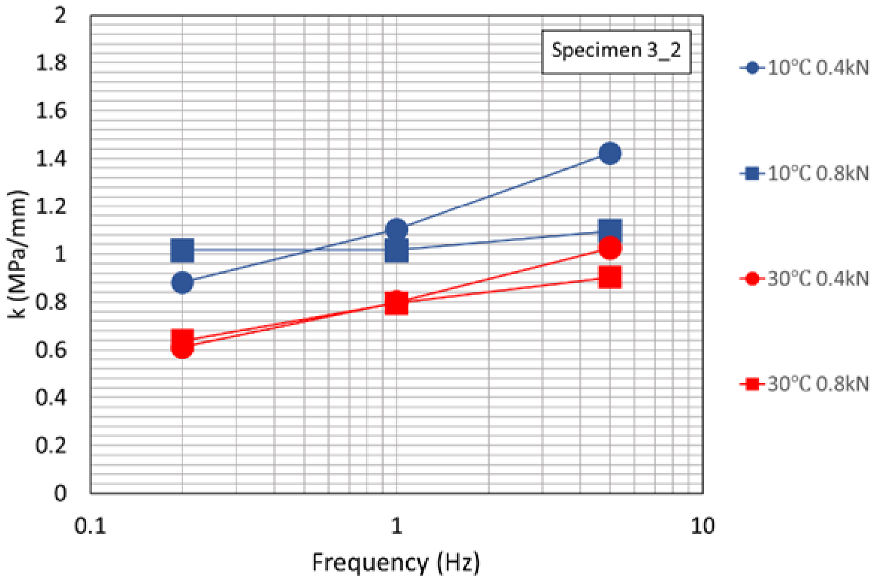


(c)

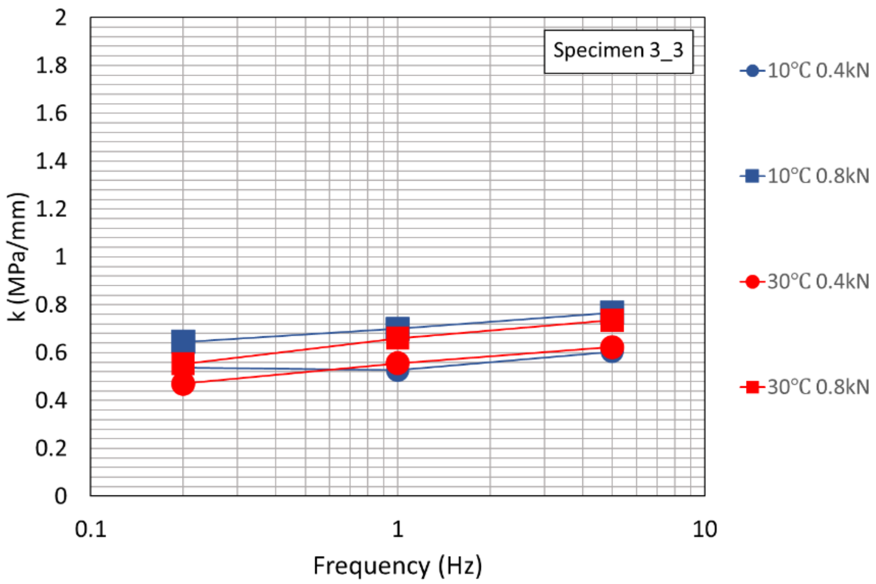
Figure 4.4. K values of specimens: a) specimen 3_2; b) specimen 3_3; c) specimen 3_4.

4.2.2 Effect of temperature

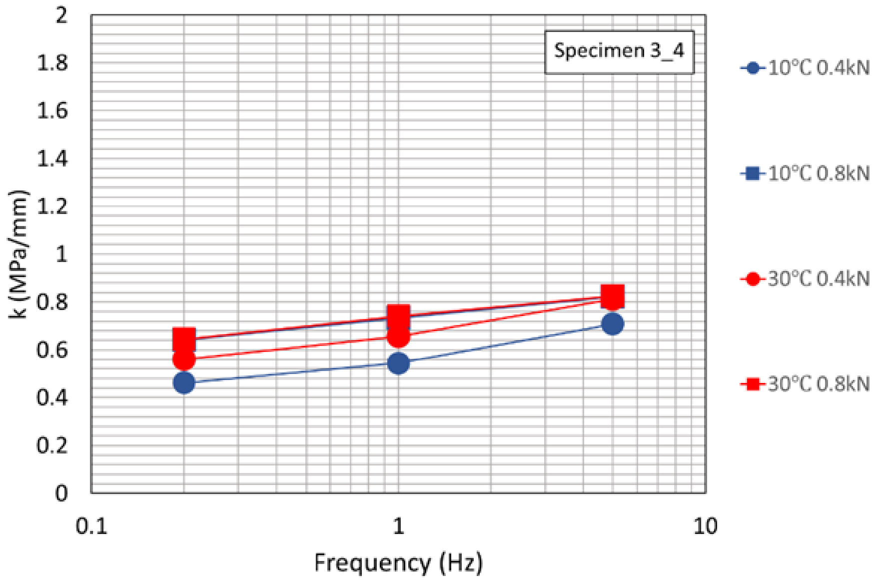
It is well known that asphalt mixture is a temperature susceptible material; many researchers had concluded that the interlayer shear strength decreased as the testing temperature increased. This phenomenon was also observed in this study. As Figure 4.5 shows, the experimental results demonstrate that when the temperature increased from 10 to 30 °C, the shear stiffness of the interlayer bond decreased significantly with the increase of temperature.


Specimen 3_2
10°C 0.4kN
10°C 0.8kN
30°C 0.4kN
30°C 0.8kN
k (MPa/mm)
Frequency (Hz)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0.1
1
10

(a)


Specimen 3_3
10°C 0.4kN
10°C 0.8kN
30°C 0.4kN
30°C 0.8kN
k (MPa/mm)
Frequency (Hz)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0.1
1
10

(b)



(c)

Figure 4.5. The effect of temperature: a) specimen 3_2; b) specimen 3_3; c) specimen 3_4.

4.2.3 Effect of load frequency

This study involved three frequencies, from 5 Hz, 1 Hz, to 0.2 Hz. Testing started from the high frequency to the low frequency. The interlayer shear strength was affected by the load frequency. The experimental results indicate that the shear stiffness of the interlayer bond increased significantly with the increase of load frequency.

4.2.4 Effect of load amplitude

In this study, for each temperature, three levels of shear stress amplitudes were applied to the specimen. However, in terms of the test results, the effect of load amplitude is unclear by far. It could be due to the ununiform quality of testing specimens, especially the air void content was not constant.

4.3 Interlayer fatigue test results

Compared to the interlayer shear stiffness test, the interlayer fatigue test took much more time. Since the connection between them is not well-established, it is necessary to conduct fatigue tests. The fatigue test takes longer because the specimen is not instantly broken from the interlayer zone. Usually, the fatigue failure process consists of three stages. Figure 4.6

presents a typical shear fatigue behavior. As it shows, the shear fatigue process is divided into three regions:

Region I has a rapid increase of the interface shear displacement;

In Region II, microdamage occurs and accumulates in the interlayer, leading to the deterioration of the interface, and the micro damages gradually connect into the net by load repetitions;

In Region III, the interface is further deteriorated. The damage impairs the structural integrity of the specimen, and the shear displacement of the interface increases at an accelerating rate until complete damage.

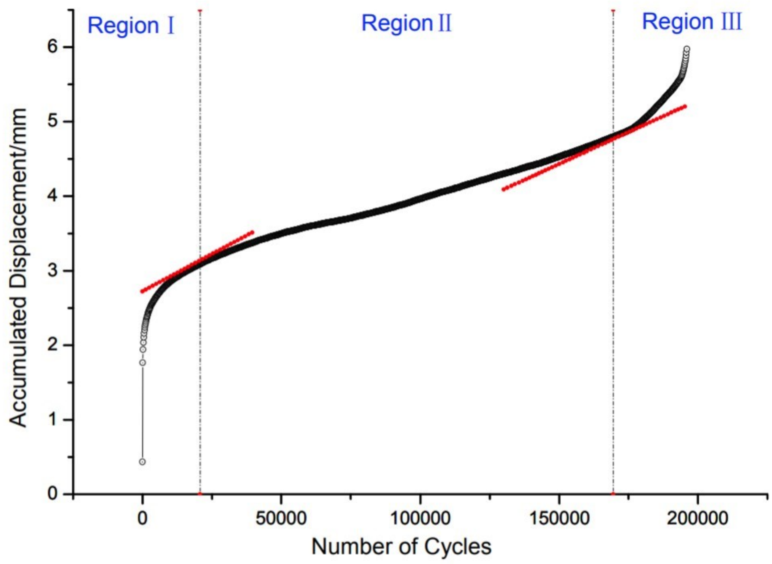
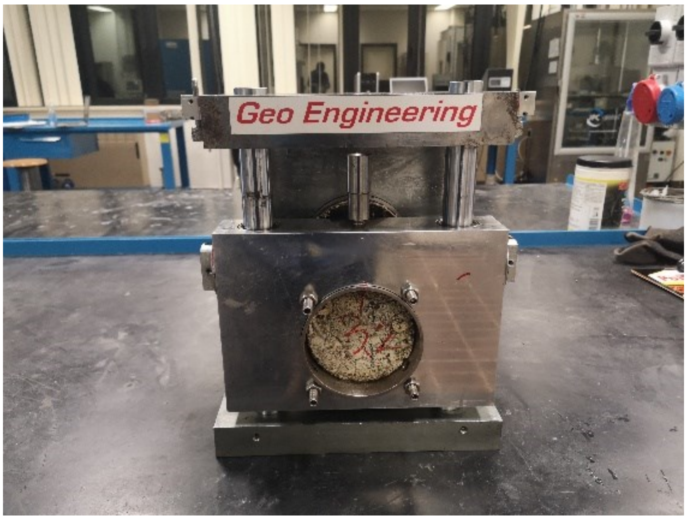


Figure 4.6. Shear fatigue failure process.

After the specimen is broken from shear damage, the number of loading cycles is recorded. The number of cycles to failure N_f can be defined by getting half of the initial force when the test is displacement control or getting half of the initial displacement when the test is load control. If they are not constant, it can be defined as getting half of the initial shear stiffness (the 50% reduction of the interface stiffness).

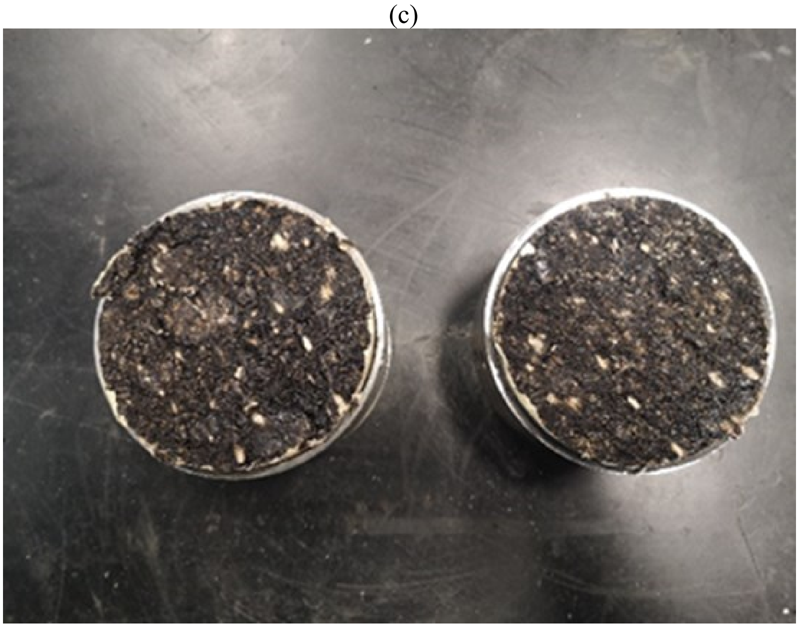
In this study, interlayer shear fatigue tests were carried out on three specimens. Figure 4.7 presents a specimen after interlayer fatigue failure.



(a)

(b)

(c)



(d)

Figure 4.7. Shear fatigue failure of a specimen.

It was observed that all the specimens were broken from the interlayer zone. Figure 4.8 shows the evolution of permanent deformation at the interlayer with the increase of the number of load cycles.

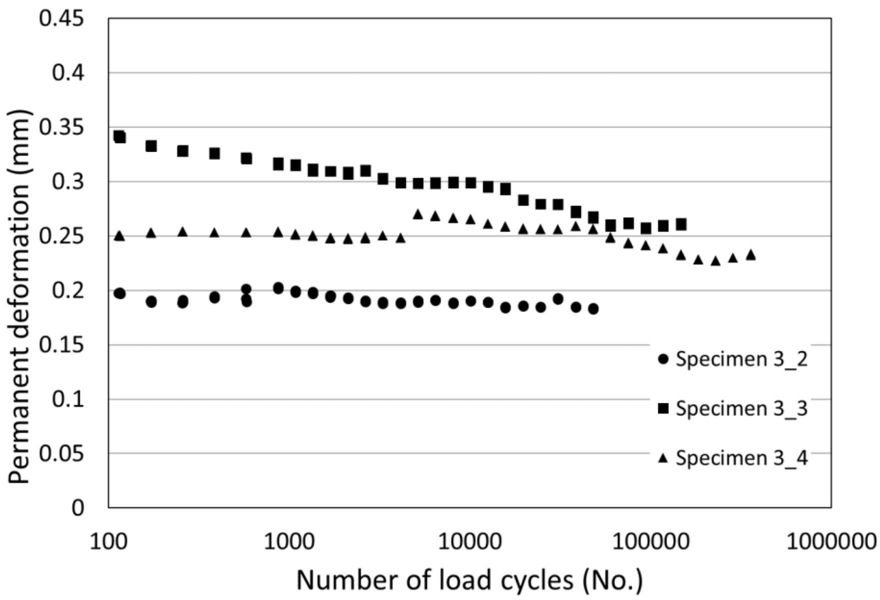


Figure 4.8. Permanent deformation at interlayer.

It can be observed that the deformation was not increased as expected. Instead, every curve was flat. The interlayer shear stiffness k can be calculated by vertical stress and deformation. Figure 4.9 shows how the k value changed with the load cycles.

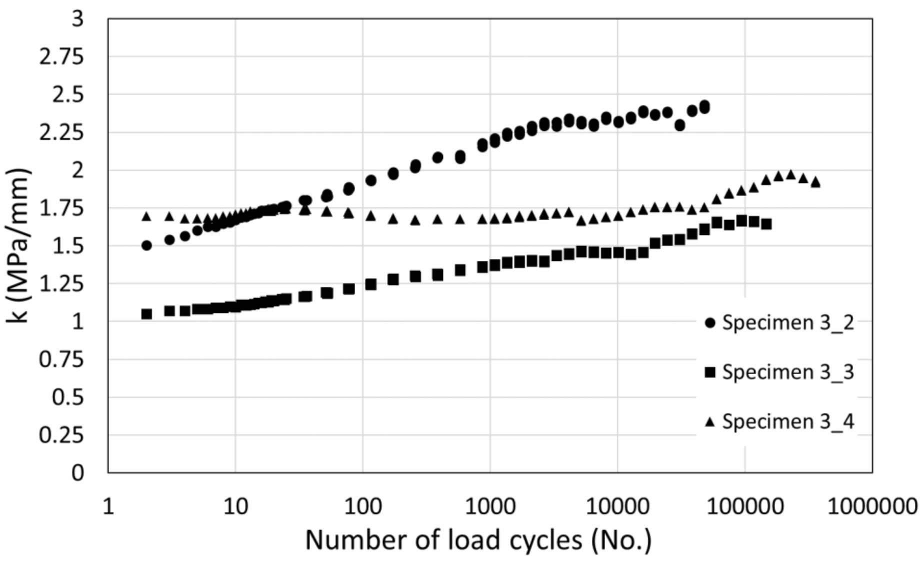


Figure 4.9. K value varied with load cycles.

The results indicate that the K value was fluctuant and finally decreased as the specimen was broken. This result could be caused by the specimen not being fixed inside the device.

4.4 Conclusions

This chapter summarises the experimental activities to investigate interlayer shear behavior carried out by Cyclic-ASTRA at the Marche Polytechnic University. The ISS and shear fatigue life of specimens were evaluated in this research. For ISS, the effects of testing parameters such as temperature, load frequency, and load amplitude were studied.

According to the test results, the following conclusions were drawn:

1. For interlayer shear stiffness, despite the effect of load amplitude was not clearly illustrated, the effects of temperature and load frequency had been observed. It can be concluded that the shear stiffness of the interlayer bond decreased significantly with the increase of temperature and it increased significantly with the increase of load frequency, the conclusions agreed with previous studies in this field.
2. For interlayer fatigue life, since the permanent deformation of the specimen during the test was not increased as expected, it needs further investigation. This phenomenon may be caused by the specimen was not fixed inside the device.

3. To solve these problems above, it is necessary to improve the accuracy of the Cyclic-ASTRA device.

Summary of the overall experimental study

Chapter 5.

Conclusions and recommendations for future research

This thesis investigated the interface behavior of asphalt pavement layers using an experimental approach.

To complete the research work, first, a comprehensive overview of the existing knowledge on the significance of interface behavior in asphalt pavements was carried out.

Next, experimental activities were carried out in the laboratory to evaluate the property of interlayer bonding in different conditions. Laboratory experiments were performed by the lab-designed shear test device Cyclic-ASTRA under dynamic loading conditions. Several influential parameters were incorporated to assess the influence of each factor on interface shear strength. The interlayer bonding behavior was evaluated by interlayer stiffness and fatigue life. The influence of each parameter on interlayer shear stiffness was investigated. Then, the relationship between ISS and shear fatigue life was investigated in this study.

Based on the experimental work conducted in this study, the following conclusions have been drawn:

1. The importance of standardized test methods for interlayer properties evaluation

Currently, there is a lack of international agreement on test methods, procedures, and evaluation criteria for the evaluation of pavement interlayer shear strength. Some popular test methods have the advantage of being fast and straightforward, but lack precision and validity. As a result, for the same test parameter, there are inconsistent or even significantly different conclusions in the literature. This thesis was also developed in the framework of the RILEM Technical Committee 272-PIM "Phase and Inter-phase behavior of bituminous Materials", which organised an interlaboratory test aimed at comparing different prototype equipment currently employed to obtain the dynamic shear characterisation of multilayer bituminous systems. Therefore, the final target of the research is to develop standardized test methods. In order to obtain a standardized test procedure, the influence of different parameters and test conditions on the interlayer bonding properties and the interrelationship between the various influencing factors will be investigated. In this way, the quality of the obtained data can be guaranteed and the resulting data can be evaluated by repeatability and reproducibility.

2. Interlayer shear stiffness
    - The impact of temperature on interlayer shear stiffness was clearly observed. The interlayer shear stiffness decreased significantly with the increase of temperature.

- Higher load frequencies have a positive effect on the interlayer bond shear stiffness. At high frequencies, the specimen performed more rigid. The shear stiffness of the interlayer bond increased significantly with the increase of load frequency.
- The effect of load amplitude was not discovered in this study. It could be due to the ununiform quality of testing specimens, especially the air void content was not constant.

3. Interlayer fatigue behavior
    - The evolution of the force (or displacement) against the number of cycles can be divided into three stages. Include a rapid increase of displacement at the beginning of the test, a quasi-stationary displacement increment, and then a rapid increment of displacement at the end of the test.
    - However, in this study since the permanent deformation of the specimen during the test was not increased as expected, it needs further investigation.

Based on the results of this study, the following recommendations for future research are listed:

- Improve the accuracy of Cyclic-ASTRA shear test device in order to ensure the repeatability and reproducibility of test results.
- Study the effect of normal stress on interlayer shear strength.
- Study the relationship between interlayer fatigue behavior and interlayer monotonic behavior, build regression models for interlayer fatigue life based on the results of static shear test.
- Test both field cores and laboratory-fabricated specimens to verify the shear test device and observe the field shear performance.
- Based on the experimental test results, establish a mechanistic prediction model for interface debonding failure using a computational analysis program.

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