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State-of-the-art review of interface bond testing devices for pavement layers: toward the standardization procedure

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ABSTRACT
During the past thirty years, interface bonding between pavement layers has been a topical subject worldwide to research. In this context, many researchers have developed and utilized their own devices to investigate the properties of pavement interfaces. In the absence of an international standard procedure for interface bonding, it is inevitable that testing results are not comparable in all cases. In addition, various conducted studies reveal that parameters such as temperature, loading conditions, materials and so on exert an influence on interface properties. This paper aims to deal with the matter effectively via a thorough and comprehensive review of interface bond testing to lay the groundwork for standardization procedure. For this purpose, first, a general overview of interface bond function and its impact on pavement performance is presented. Then, different types of interface bond test methods according to loading conditions are explained; furthermore, the configuration of various setups is discussed and their function is compared together. Finally, given the prior experiences, a framework for a methodical approach to a standard evaluation of pavement interfaces is presented.

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1. Introduction

Pavement is a multi-layered structure consisted of different road materials in each layer. Pavement lifts have to be bonded together in such a way that pavement act as a monolithic structure; hence, traffic and environmental stresses and strains transfer efficiently into the entire pavement structure. Adequate adhesion between pavement layers yields smaller shear deformation, stronger elastic recovery performance, and smaller permanent deformation[1], in consequence, long-lasting asphalt pavement would be expected.

The multi-layer construction of pavements especially in flexible pavements introduces weak zones at interfaces between layers, which leads to smaller shear strength obtained at these zones compared to the shear strength of the asphalt concrete mixture.[2] It is noteworthy that in real condition full bonding between adjacent layers is difficult to attain

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due to construction problems; moreover, currently assumption of either full bonding or no friction between pavement layers for analysis and design of pavements is not valid.[3]

Prior investigations reveal that weak bond at one interface can cause a predicted loss of two-fifths to five-sixths, to as low as one-sixth of the pavement life.[4] Moreover, poor interface bond strength may result in the development of the deformation within asphalt pavement, worsening the driving conditions, increasing pavement maintenance costs, and finally leading to premature distresses such as slippage, delamination, and surface top-down cracking.[5,6]

The reasons behind poor bonding are not completely realized yet but some contributing factors appear to exert an influence on debonding between the pavement layers [7]: type of base course material, low compaction of subgrade or subbase or base courses, segregation in the base course, type of bitumen of the wearing course, climate during the construction, contamination of the underlying surface, water flow between the layers, and poor or excessive tack coat application.

To provide necessary bonding between pavement layers, two methods of the adhesive bond (e.g. applying tack coat material) and mechanical bond (e.g. milling) are employed.[8] Tack coat is typically an asphalt emulsion, unmodified, or polymer-modified liquid asphalt which is normally applied to an existing or new pavement surface before laying new layer.

Due to the fundamental importance of interface characteristics and for a better understanding of its relationship with whole pavement structure, over the last few decades interface properties has been widely investigated by many researchers. To evaluate interface bonding condition, many countries and laboratories have developed their own test method and equipment.[3,5,9–13] Notwithstanding all these efforts, no international standard test method or procedure has been recognized to date. However, preliminary attempts have been made in this way.[14]

In fact, test results of various studies are often in conflict with each other and not comparable, on account of different test configurations and circumstances such as test arrangement, loading conditions, sample geometry, materials, temperature, and so on. It should be pointed out that to enhance consistency among test methods, RILEM TG 4 [7] conducted an interlaboratory experimental campaign on interlayer bonding conditions of asphalt pavements.

To address the issue, this paper hopes to pave the way for standardization procedure of interface bond testing. For this purpose, first, current test methods and procedures to evaluate interface bonding are introduced. Secondly, the main feature of each test method will be described, accompanied by a demonstration of different setups which have been developed for each method. Afterward, a debate on interface bond testing devices with different operations and their advantages and disadvantages are held. In addition, according to prior studies results of some of these testing devices are compared. Then, the previous attempts which have been made toward standardization procedure and major obstacles to achieving this target are discussed. Finally, given the worldwide experience, important features of a standard test procedure that should be taken into consideration will be demonstrated.

2. Interface bonding verification test

To get a better understanding of interface bonding evaluation, this section presents the corresponding test procedures and methods. In real condition, pavement layer interfaces are generally subjected to various loading conditions as follows (Figure 1): pure shear mode

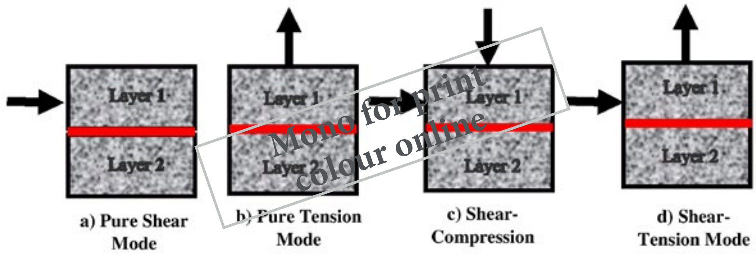

Figure 1. Different loading conditions at pavement interface.

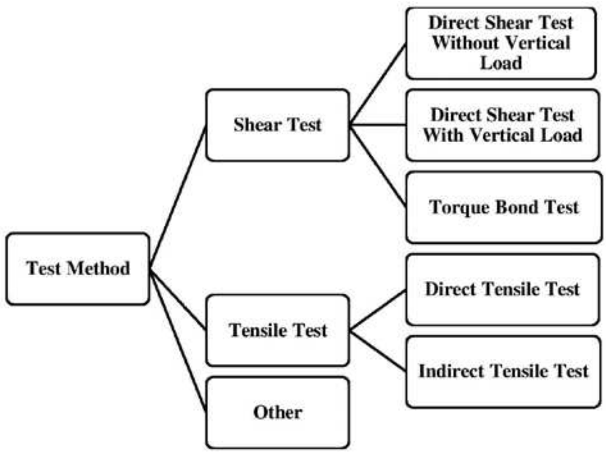

Figure 2. Types of test methods for interface bonding.

(type 1), pure tension mode (type 2), shear-compression mode (type 3), and shear-tension mode (type 4).

Pure shear or shear-compression modes usually could happen in the transverse or longitudinal direction and are typically created by traffic and/or temperature-induced shear stresses at interfaces without any joints. Type 2 loading may observe at pavement interfaces consisting of a jointed PCC and HMA overlaying. Lastly, shear-tension mode could take place at interface beneath the surface layer where the interface shear strength is relatively low. However, the latter case is rarely found in a real pavement structure.[15,16]

In light of the preceding discussion, current test methods may be grouped into different categories as illustrated in Figure 2. Choosing a certain type of test procedure depends on the problem matter, assumed loading mode and also the accuracy and repeatability of a particular test method.[14] A full description of each testing method category, together with the relevant most widely used devices will be presented in the following sections.

Note that all recognized test methods could be divided into following categories:

- Destructive tests
- Non-destructive tests (NDT) on existing pavements like Falling Weight Deflectometer (FWD) test, ground-penetrating radar (GPR), and infrared thermography.

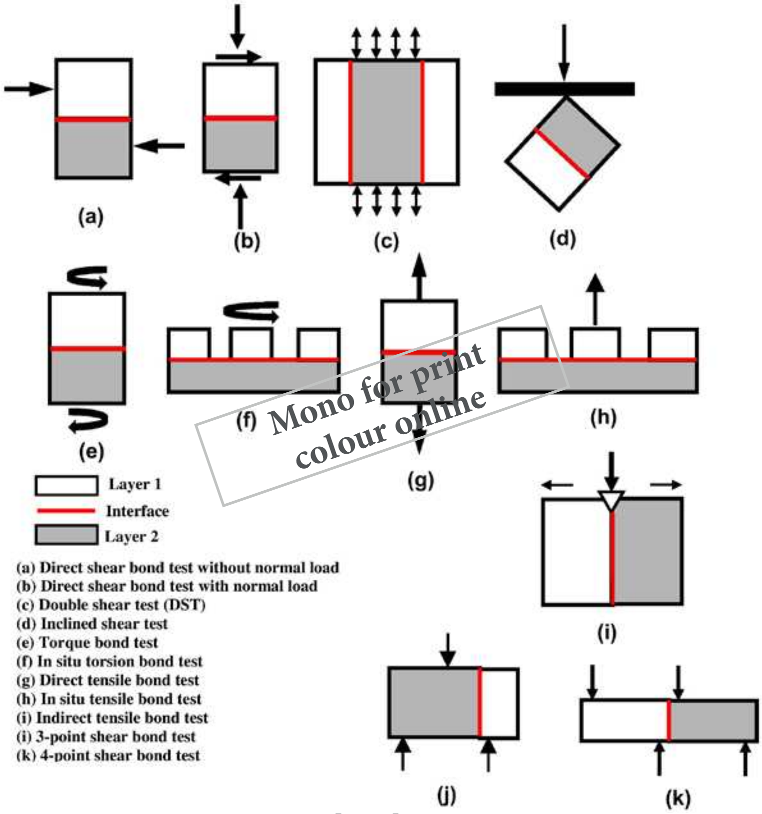

Figure 3. Schematic diagram of different test methods for interface bonding.

It should be noted that as non-destructive tests are beyond the scope of this paper only destructive testing methods are discussed here. Schematic diagram of destructive interface bond testing devices is illustrated in Figure 3.

2.1. Shear test

2.1.1. Direct shear test (with and without normal load)

The direct shear test appears to be the most commonly used test to investigate interface problems owing to its smooth operation and suitability. The construction of shear testing devices was originated from shear testing in soil mechanics and different countries and laboratories developed and built their own devices over time.[17] One of the most frequently used shear devices is the guillotine style test named the Leutner test [18] in Germany where a constant rate of shear displacement applied to a dual-layer system of cylindrical specimens until interface failure occurs. Given its rather simple configuration and easy performance, many researchers correspondingly adapted the Leutner test to make it more suitable for their purposes such as FDOT test device, LCB device, LPDS, and the modified Leutner at the University of Nottingham.[9,19–21]

Subsequent to the early developed setups, many countries and laboratories have begun to design or develop their own shear test using a similar approach during recent decades.

Table 1. List of direct shear testing devices without vertical loading.

Device name	Reference[a]
Leutner	Leutner [18]
Modified leutner	Collop et al. [21], Vaitkus et al. [6]
Layer-parallel direct shear (LPDS) (Modified leutner)	Raab and Partl [9]
Superpave shear tester (SST)	Mohammad et al. [2]
Louisiana interface shear strength tester (LISST)	Mohammad et al. [5]
Florida department of transportation (FDOT) shearing test	Sholar et al. [19]
Direct shear testing	Yildirim et al. [22], Leng et al. [23]
Modified compact shearing (MCS)	Diakhate et al. [24]
Double shear test (DST)	Diakhate et al. [25], Safavizadeh [26]
Shear test mold	Uzan et el. [27]
Interlayer reaction testing equipment	Crispino et al. [28]
Virginia shear fatigue test	Donovan et al. [29]
Simple shear test (SST)	Junior [30]
Laboratory bond interface strength device (LBISD)	Woods [31]
Interface shear test	Hachiya and Sato [32]
Shear strength test	Vacin et al. [33]

[a]Corresponding references were selected based on the detailed description of apparatus specification and configuration.

Table 2. List of direct shear testing devices with vertical loading.

Device name	Reference
ETH shear box device	Raab et al. [41]
Sapienza inclined shear test machine (SISTM)	D'Andrea and Tozzo [42]
Sapienza horizontal shear test machine (SHSTM)	D'Andrea et al. [34]
Sapienza direct shear testing machine (SDSTM)	Tozzo et al. [10]
Louisiana interface shear strength tester (LISST)	Mohammad et al. [5]
Ancona shear testing research and analysis (ASTRA)	Santagata and Canestrari [39]
Direct shear device	Romanoschi [43], Chen and Huang [44]
Shear fatigue test	Romanoschi [43]
Nottingham shear box	Carr [45]
National center for asphalt technology (NCAT) bond strength device	West et al. [46]
Superpave shear tester (SST)	Bognacki et al. [47]
Interface shear testing device (ISTD)	Al-Qadi et al. [48]
Advanced shear tester (AST)	Zofka et al. [49]
Kansas shear tester	Wheat [50]
Coaxial shear test (CAST)	Sokolov et al. [51]

Table 1 presents the list of some renowned direct shear testing devices without application of normal load.

In the literature so far, influence and application of normal stress, representing the wheel load in real condition, on interlayer bond strength has been a matter of considerable debate. [5,12,34–36] Accordingly, some researchers developed direct shear test devices incorporating the application of a normal load. Several direct shear test devices with possible applying normal load are listed in Table 2.

In a study on the importance of normal confinement to shear bond failure, Karshenas et al. [37] revealed that the use of shear bond strength data without normal confinement leads to an overdesigned pavement section, and it may be appropriate exclusively for tack coat QC/QA purposes; other studies at a similar line of research can be found elsewhere. [5,38,39] Nonetheless, the direct shear tests without normal load are widely used worldwide by virtue of its simple performance, suitability, and easy procedure for specimen production. [9,19,20,40]

Pavements in the field are subjected to a great number of cyclic loads by traffic over the course of pavement's service life. Many researchers share the view that to better simulate loading condition and evaluate interface shear fatigue behavior, dynamic loading outperforms monotonic loading.[10,12,25,42,47] This is, however, in contrast with Leng et al. [23,52] who believed that the effects of interface characteristics could be more precisely assessed by monotonic testing than cyclic testing. Given that dynamic shear tests are complex and difficult to operate, fewer studies can be found in the literature regarding the interface fatigue performance. Instead, monotonic tests are much simple to use and operate for determining the shear resistance and performance of different tack coats, provided the viscoelastic behavior of the material is not concerned.[53]

It is worthwhile to mention that since both test methods are sensitive to influential parameters such as testing temperature, loading condition, tack coat type and application rate, mixture type and so on, some preliminary attempts to link between monotonic and dynamic shear tests have been made.[10,24,54]

The effect of temperature on interface strength is well known and many studies proved this fact. Kim et al. [55] suggest that the experimental investigation for interlayer or shear behavior should be carried out at different test temperature levels rather than one fixed temperature. Romanoschi and Metcalf [12] state that all three parameters which completely describe the interface behavior, namely the interface reaction modulus (K); the shear strength (S_{max}); and the friction coefficient after failure (μ) are temperature dependent. Other researchers [11,23,27] assert that lower temperatures lead to better bonding and, therefore, increase the shear resistance, and vice versa.

2.1.2. Torque bond test

Shear behavior of interface bonding can be investigated by performing torque bond test as well. This method was originally developed in Sweden and later the British Board of Agreement has adopted this procedure as part of the approval system for thin surfacing systems.[56] This test is being used to determine bond strength between a thin surfacing layer and the underlying layer *in situ* or in the laboratory by measuring the peak shearing torque at a known temperature. In this method, torque is applied to the plate bonded to the surface of the core through a handheld torque wrench until a twisting shear failure in the bond occurs or a torque of 300 Nm is exceeded.[56]

Experimental studies show that there are several shortcomings in conventional torque bond test: (1) fixed specimen diameter, (2) mostly just applicable in the field and limited to the uppermost interface in the pavement, (3) inaccurate torque rate owing to manual operation, (4) occurrence of axial bending, and (5) application of relatively high force to twist off the surfacing.[57,58] Consequently, some researchers have developed their own devices. Table 3 lists several employed torque bond test devices in the literature.

Choi et al. [59] developed a laboratory-based manual torque bond test which is not only able to test the shear strength of any interface of the interest but also testing at various temperatures is possible. However, some limitations in the newly developed device remained unsolved. To deal with aforementioned issues, researchers at University of Nottingham [57] developed a mechanically controlled automatic torque bond equipment that is capable of conducting both quasi-static and repeated load interface testing. The apparatus uses a rack and pinion mechanism to transfer the vertical applied load or displacement and converts it into a torque or rotation, respectively.

Table 3. List of torque bond test devices.

Device name	Reference
Manual torque bond test	British Board of Agrément [56]
Laboratory-based manual torque bond test	Choi et al. [59], Pouteau et al. [53]
Automatic torque bond test	Sutanto [15]
Tack coat evaluation device (TCED)	Woods [31]
Torque-shear device	McGhee and Clark [60]
Field tack coat evaluator (A tacker)	Buchanan and Woods [61]
In Situ torsion shear test	Pouteau et al. [53]
Monotonic torque test	Diakhate et al. [3]

Table 4. List of direct tensile test devices.

Device name	Reference
Louisiana tack coat quality tester (LTCQT)	Mohammad et al. [64]
Field tack coat evaluator (A tacker)	Buchanan and Woods [61]
Tack coat evaluation device (TCED)	Woods [31]
UTEP pull-off device (UPOD)	Eedula and Tandon [65]
Interface bond test (IBT)	Hakimzadeh et al. [66]
Modified pull test	Xiao et al. [62]
Pull-off test device	Raab and Partl [67], Hachiya and Sato [32]
Schenck-Trebel test	Litzka et al. [68]
Tensile test	Santagata and Canestrari [39]

To compare the results obtained from the automatic torque bond test with those of the manual torque bond test, Sutanto [58] conducted a series of test. The results indicate higher Coefficient of Variations (COVs) for the manual torque bond test than that of obtained from the automatic torque bond test. Moreover, the results of the automatic bond test lead to 20–30% higher values in comparison with the manual torque bond test, seemingly due to previously mentioned drawbacks of the manual device.

2.2. Tensile test

2.2.1. Direct tensile test

As mentioned earlier, traffic or environmental conditions may induce tensile failure, along with shear failure at the pavement interfaces. Hence, quantifying the tensile strength of interface bonding is of great importance. Tensile tests are test procedures being used to evaluate the tensile adhesion between two bonded asphalt layers in the field or in the lab, and to quantify a failure mode by showing the weakest place in the testing system [62]. A list of some widely used direct tensile test apparatus is presented in Table 4.

Pull-off tests are the most commonly used tensile tests owing to their easy performance in the field. The normal procedure for doing the pull-off test is applying a tensile or torque load manually through a shaft or nut on tack-coated surfaces and measuring the tensile strength. The American Society for Testing and Materials (ASTM) [63] adopted a standard test method which serves as a method for measuring the tensile force required to remove two coated surfaces.

The main drawback to conventional direct tensile tests like ATacker and UPOD devices is that they are manually operated. This could, thus, lead to a non-uniform loading rate in pulling off the plate and eccentric loading effects, which obtaining less reliable results could be expected. To tackle this issue, the LTCQT (Louisiana Tack Coat Quality Tester) was designed and developed during NCHRP Project 9-40 [69] as a viable method to assess the quality of applied tack coat in the field and to compare the responses of various tack coat materials together.

In another attempt, Hakimzadeh et al. [66,70] developed a new tensile-mode Interface Bond Test (IBT) for evaluation of interface behavior between adjacent layers of asphalt pavement. The innovation in IBT is using fracture energy parameter as a promising indicator for the quality of bond achieved at interfaces between two asphalt pavement lifts and between thin layer systems. The method is simple and quick to carry out and its repeatability is acceptable. Nonetheless, the results show that crack propagation is stable just under test conditions of −12 °C and crack mouth opening displacement (CMOD) rate of 0.5 mm/min.

A mechanical pull test method was also modified and developed by Xiao et al. [62] to investigate the bonding behavior between the ultrathin surface layer and underlying asphalt layer. The results suggest that the proposed pull test is suitable for certain conditions that interface is the weakest area in the testing system. In addition, the repeatability of applied force and acquired displacement curves was satisfactory.

2.2.2. Indirect tensile test (wedge splitting test)

Despite the widely used and easy performance of pull-off test method, there exist some deficiencies in this method. For instance, giving just a single measurement (the adhesive tensile strength) which is incapable of characterizing the bond separation of materials in terms of ductile or brittle behavior, a large scattering of the results because of manual operation and so on. To address these issues, Tschegg et al. [13] introduced a new indirect tensile test method named the wedge splitting test. In this method, a slender wedge is pushed into the interface of a bilayer specimen as long as the layers are separated as a result of the horizontal component of applied force.

The major benefits of the setup can be enumerated as follows [13,71]: acquisition of precise information regarding mechanical and fracture-mechanical properties of interface, minimum experimental defect owing to special arrangement of the device, the quick performance of the test, minimum temperature loss of the specimens to avoid possible temperature influences, test procedure is applicable for prismatic and cylindrical specimens, and data obtained from the test are appropriate for FE analysis.

2.3. Other test methods

Other testing procedures to evaluate interface bonding are three-point and four-point shearing tests. To simplify the measurement procedure of the bond between the two layers, Recasens et al. [20] developed the so-called LCB (Laboratorio de Caminos de Barcelona) shear test which is a three-point shear testing capable of measuring shear strength at the interface of two adjacent layers. Furthermore, the device is employed to distinguish effects of various tack coats by testing specimens made in the laboratory and for quality control (QC) of finished works in the field. The LCB is innovative in that unlike other shear testing devices the bending moment at the interface is almost negligible, albeit rather non-uniform shear stress distribution across the interface plane.

As part of the Delft Research Project, De Bondt [72] conducted a study of the anti-reflective cracking design of asphaltic overlays. To overcome the drawbacks of direct shear tests such as shear boxes, a four-point shear testing method has been developed. As opposed to most shear test apparatus, this setup has several advantages of using simple beam-shaped specimens, removing bending moment at the interface plane, and the efficient use of loading system capacity to apply shear force. However, owing to its complex configuration, it is only appropriate for research purposes. In the subsequent section, a detailed discussion concerning interface bond testing devices is presented.

3. Discussion

The significance of interface bond evaluation has driven many researchers to extensive investigation over recent decades. According to Raab and Partl [67], bonding of the upper pavement layers under service conditions is prone to both tension mode (Mode I) and shear mode (Mode II); one should take this matter into consideration during studying interface properties.

In recent years, many European countries together with the US and Canada developed and established their own protocols and equipment to carry out interface bond testing.[17] Subsequently, theses test procedures were approved and regulated as a national standard such as the LPDS test in the Swiss standard [73], the ASTRA device complied with the European and the Italian standards [74], the torque bond test adopted by the British Board of Agreement [56], the pull-off test method validated in the ASTM [63], and recently the LISST method was approved by AASHTO as a standard test to determine the interlayer shear strength.[75] Experimental results, nevertheless, reveal that there exist pros and cons in each of these test procedures and equipment which are debated in the following.

In the subsection of 2.1.1, the Leutner device was introduced. Investigations indicate that there are several deficiencies in the device such as non-uniform interface shear stresses, the absence of normal force applied to the interface plane, and no gap width between the shearing rings of the device. Moreover, Collop et al. [40] pointed out that the test results are highly variable.

In the original Leutner shear test lack of gap between shear platens resulted in the misalignment of the interface into the shear plane, especially for specimens with irregular interfaces. To overcome this issue, Choi et al. [76] in the UK for the first time introduced a gap of 5 mm and indicated that it was beneficial for the testing. The complementary study also revealed that introduction of a 5 mm gap into shear plane decreased the variability level of the results.[21] In addition to this, for a better understanding of the role of the gap, Raab and Partl [77] conducted an experimental campaign. The results of the study revealed that the gap width does have an influence on the interface shear results, and similar studies elsewhere reinforce these results as well.[19,78] On the whole, to simplify and optimize the testing, a gap width of slightly larger than 0 mm would be adequate.

The Layer-Parallel Direct Shear (LPDS) test developed in the EMPA is an enhanced version of the Leutner test with the following advantages [9,55,79]: more versatility in the geometry, determining inter-layer and in-layer shear properties, possible uniform load distribution, and a simple and useful tool for QA and inspection testing of pavements after construction to name but a few. There are, however, several shortcomings in LPDS, namely neglect of the combined impact of horizontal and vertical loading as well as dilatancy effects, eccentricity effects, limitations on testing temperature and specimen thickness owing to ‘snow plough’ effect, and variability of the results at higher temperatures.

Shear box type tests are widely used by researchers, as both shear and normal stresses are acting at the interface. Nevertheless, there are a number of defects in this test method. According to Kruntcheva et al. [80], shear stress distribution on the interface is non-uniform due to the absence of complementary shear stresses; De Bondt [72], subsequently, solved the problem by introducing a four-point shear test setup. Apart from this, the experimental complexity associated with the normal and shear loads application should be taken into consideration. To sum up, the device could serve as a valuable tool particularly for research purposes, but for practical assessment of interface properties in the field, a simpler approach is necessary.

In a research study led by Kim et al. [55] comparison of the shear box and LPDS testing methods revealed that although the experimental results were comparable for both devices, the shear stress-deformation curve for both tests was totally dissimilar owing to the distinct shear mechanism and stress conditions imposed during the testing. Similar results are also attained elsewhere.[81]

To better simulate stress field at the interface and for possible composed application of different vertical and horizontal force magnitudes, Romanoschi [43] developed an inclined shear fatigue test in such a way that the longitudinal axis of the specimen lies at 25.5° with the vertical so that the shear stress at interface is half the normal pressure. In a similar attempt, a direct shear test called Sapienza Inclined Shear Test Machine (SISTM) [82] was designed and developed the Sapienza University of Rome, working in static conditions at a constant displacement rate. The device is similar to the device used by Wheat [50] and with a similar principle as Romanoschi device, but enhanced and more versatile than its predecessors. Later, the device has been adapted to evaluate shear fatigue performance.[83]

According to D'Andrea and Tozzo [42], the inclined dynamic machines outstrips guillotine-based shear apparatus. First, loading condition in guillotine dynamic machines in the absence of normal confinement is representative of interface points far away from the wheel, where shear stress is not strong to cause damage potential, whereas the inclined setup works in the critical range of ratio τ/σ. Second, shear testing with monotonic normal pressure is never experienced in reality.

Diakhate et al. [24,25] developed another method for interface bonding called double shear testing (DST). The test method is able to conduct shear fatigue loading on a specimen consisting of three layers bonded two-by-two with the same tack coat in the laboratory. The test has the merit of applying a relatively pure shear stress at both interfaces symmetrically. In comparison, some other shear test devices induce bending moment owing to the eccentricity effect along with shearing force. The DST setup, however, is incapable of applying a normal force to the specimen. Afterward, Safavizadeh and Kim [26] developed a modified version of DST under load control condition to study the shear fatigue characteristics of reinforced asphalt concrete.

A major deficiency in the LCB device as a three-point shearing test lies in the rotational mechanism of specimen around its support when applying vertical shear load becomes relevant. To deal with this issue, a new device named SHSTM (Sapienza Horizontal Shear Testing Machine) [34] has been designed and developed by introduction of a normal force in the horizontal direction and modifying the arrangement of supports. Compared to the shear box devices, the reversed shear box tests like SHSTM has the merit of holding the specimen horizontally in two molds, aiming to rule out the overloaded impact of the specimen and upper part of the device on shear strength.

Both monotonic and cyclic shear tests are able to evaluate and characterize the interface bonding. Shear strength is the criterion in monotonic shear test whereas, the total number of cycles to failure is the criterion in cyclic testing. Both of these properties are quite distinct from each other although they rely on test conditions such as temperature, loading rate, tack coat application rate, and the mixture type to name but a few. To find a relationship between the monotonic test results and those of shear fatigue test, Diakhate et al. [24,54] made initial attempts. The investigation showed that shear fatigue and shear monotonic behaviors might be connected by applying an 'equivalent' loading rate criterion. In fact, at each temperature, shear fatigue properties are dependent on loading rate and shear strength of monotonic test. Furthermore, Tozzo et al. [10] tried to find a linkage between the two types of tests through the sensitivity to the normal pressure. Apart from this, Diakhate et al. [25] conducted a research, aiming to overcome the time-consuming matter of fatigue tests via proposing a method to allow predicting the conventional interface fatigue law from conventional fatigue tests. The results demonstrated that predicted conventional fatigue law and the true law are in good agreement.

In the literature thus far, many experimental and theoretical investigations have been carried out to compare the results of different interface bonding devices together, considering differences in testing conditions such as failure mode, setup configuration, geometry, and so on. In the subsequent paragraphs, some of these studies are highlighted.

To determine the quality of the tack coat in the field, Deysarkar [84] conducted a research using several devices including ATAKER (shear and tension type), UTEP torque test, KMC shearing device, and UTEP pull-off device (UPOD). The results revealed that tension mode setups could better identify the quality of one tack coat independent of the surface tested.

Tashman et al. [85] researched the influence of construction factors on the bond strength at the interface between pavement layers through an experimental study. Three different test procedures, namely the FDOT shear tester, torque bond test, and UTEP pull-off test are selected for testing. The outcomes revealed that the FDOT shear tester appears to better simulate debonding at the interface caused by stress condition. Torque bond test results were consistent with those of the FDOT shear tester, whereas the UTEP pull-off test results were generally different from the other two tests.

Given that interface debonding can be caused by both shear and tension loading, Hakimzadeh et al. [70] compared the performance of the IBT test with the direct shear test (DST). The results revealed that the Coefficient of Variations (COVs) for both testing methods is in a range that provides acceptable repeatability. Besides this, it is convinced that the IBT like the shear-type test is able to differentiate between samples produced with different tack coat types and application rates. In addition, shear and tension-type tests provided different rankings in terms of tack coat types based on their performance. Studies [66,70] also exhibit that tension-type tests require considerably higher tack coat application rates than the typical range of optimum tack rate resulting from shear-type tests to create a durable adhesive bond between adjacent layers of asphalt pavement.

In order to quantify and compare interface shear behavior, Diakhate et al. [3] conducted laboratory monotonic tests under direct Double Shear (DS) test and torque test. This study showed that as viscoelastic properties of asphalt materials are more obvious at higher temperatures and low loading rate, it was difficult to find a correlation between interface shear strength values from DS tests and those from torque test. Moreover, with the torque test configuration, the interface analysis is riskier owing to non-uniform shear stress distribution across the interface and viscoelastic behavior of materials.

The above-mentioned studies are just a few examples of what have been conducted concerning the comparison of various interface bonding apparatus. For further study, interested readers are referred to elsewhere.[35,55,67,81]

A general overview of the researches done so far regarding the evaluation of the interface bonding indicates that no general agreement exists internationally on the test method, assessment criteria, and standard procedure. It is evident that each of these testing methods has their own limitations, which may result in adverse impact on the bonding assessment of pavement layers. For instance, some may suffer from load eccentricity effects. Variability of the results in some devices is relatively high. Some are manually operated, leading to unreliable results. Some are cumbersome to carry out and require complicated apparatus. Some provide very limited information regarding bonding properties.

It should be also taken into account that different criteria have been established for measurement and mechanical characterization of pavement interfaces based on failure mode (shear, tension, torsion, or combined effect) and loading mode (monotonic or fatigue). Consequently, it comes as no surprise when test results of different procedures in terms of optimal tack coat rate, or maximum required shear strength between pavement layers, for instance, contradict each other. Note different parameters like material characteristics, interface properties, field-related testing parameters, and specimen conditions might lead to significant changes in performance of interface bonding as well.

Lastly, another issue is associated with the different functions of testing devices. In this context, shear-testing devices are able to assess the bond between adjacent layers, determine the optimum tack coat dosage, evaluate shear strength of interface, drive constitutive model for the pavement interface, or perform a combination of these functions. Tensile tests, on the other hand, are used to quantify the interface tensile strength and determine bond strength of tack coats.

All things considered, the necessity for establishing an international standard procedure to measure, evaluate, and quantify interface properties is imperative. In this regard, a holistic approach to optimization of interface bonding in pavement layers to fulfill the operational requirements in both shear and tension modes under in-service conditions (traffic, environment) should be adopted.

As mentioned earlier in the introduction section of this paper, several research studies to date have been conducted so as to enhance uniformity among the various interface bonding tests toward a commonly accepted standard procedure. These efforts, however, are mainly in the context of shear or torque type tests. For instance, the RILEM TG 4 [7] conducted an interlaboratory campaign test so that compare the different test procedures for evaluation of bonding conditions of asphalt pavement under three different interface conditions as a function of varying controlling factors. In the similar line of research, Raab [14] carried out a research to develop a framework for understanding the mechanisms that control the mechanical behavior of the interlayer bond between the layers of asphalt pavements, and pave the way for the standardization of the testing of the interlayer bond.

Taking everything into account, the last part of the paper aims to provide a framework for the standardization procedure of interface bond testing based on worldwide experience as follows:

- Given the important implications of interface function both theoretically and practically, establishing a versatile and viable procedure for interface characterization is imperative. In fact, two opposite demands for a standardized procedure should be satisfied. First, meeting the requirements of highway agencies and road contractors, which is associated with high-rate production, practicality, and simplicity in the test procedure. Second, for the research purposes, which is linked with fundamental and theoretical concepts of interfaces and therefore complexity and robustness.
- A standard test method should be a multi-purpose tool, able to be work under any particular circumstances, and it should be sensitive to subtle changes in testing conditions. Furthermore, a standard device should be employed readily and requires no specific additional equipment but available in every laboratory. Specimens to be utilized for testing either fabricated in the laboratory or cored from the field should have a simple geometry, being representative and can be installed in a relatively easy way.
- As tension and torsion type tests are unable to simulate the loading conditions at the interface in the field as realistically as possible and other relevant drawbacks, it appears performing of design concepts for these test methods in standardization process would be more challenging than shear tests. A previous study [39], nevertheless, reveals that the idea of establishing holistic failure criteria for a full characterization of an interface in both shear and tension mode is attainable.
- Current assumptions of fully bonded (no slip) or completely unbonded conditions between pavement layers in pavement analysis and design are not feasible. In this regard, employing a systematic method to comply with real conditions of the interface in the pavement analysis and design procedure is quite necessary. Moreover, an ideal interface test method should provide factual data which can be applied easily for computational modeling of interfaces.
- Given the literature available thus far, the statistical investigation is considered as a key factor for evaluation of a test method, reliability of data obtained and comparing the results of different test equipments. Previous studies [86] reveal that the acquisition of analogous results during the course of experimental investigation for a specific test method under the same conditions is a challenging problem. In this context, two different parameters are usually considered: the quality of the data within each laboratory (repeatability) and among different laboratories (reproducibility). Furthermore, the COV is deemed as a statistical parameter which provides the repeatability of data obtained from a particular test method.
- Finally, the essential role of each parameter, which affects pavement interface response, such as loading, environmental conditions, materials characteristic, and interface properties to name few should be taken into consideration in standardization procedure of interface bond testing.

4. Conclusion

The discussion in this paper has given a review of interface bond testing in pavement layers toward reaching a commonly accepted standard procedure for a thorough understanding of interface characterization and evaluation. In this respect, the following conclusions could be drawn:

- Currently, there is a lack of international agreement in terms of test methods, procedures, and evaluation criteria, which engendered significant variability and even inconsistent findings available within the literature.
- Any attempt at standardization of bonding evaluation in pavement layers should meet two opposing needs: road contractors and agencies, which requires a simple and fast operation method, and researchers, which requires a precise and efficient method.
- The failure in bonding between adjacent layers could occur in both shear and tension modes under in-service conditions, which should be taken into account.
- The main feature of a standardized test method lies in the quality of the data obtained, which is assessed by repeatability and reproducibility.
- The influence of different parameters and test conditions on interface bonding properties and the interrelation between the various influential factors play a crucial role in the standardization of a test procedure.

Taking everything into consideration, this paper has only been able to touch on the most general features of an ideal standardized specification test. Clearly, further studies are needed to establish a rigorous standard procedure so that can be efficiently utilized for interface bond assessment in pavements.

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