Evaluation of Bond Strength Between Old and New Pavement Overlays

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ABSTRACT

The main objective of this research was to study the factors that affect the bond strength between old pavement and new overlay. The secondary objective was to find the best tack coat material and its application rate which could be used in Jordan. A procedure was developed for determining the bond strength between pavement layers. An easy to use procedure was selected to provide a good indication of the quality of the bond. The direct shear box device normally used to test the shear in soils was developed to test asphalt pavement concrete slabs. The experiment included two types of cutback asphalts (RC250 and RC800) and an asphalt cement binder (AC) of 60/70 penetration. Bond strength was measured with a shear type device at two testing temperatures and three levels of normal pressure. Three application rates that encompassed the specification range were investigated for each tack coat type. The effects of tack coat type, application rate, testing temperature and normal pressure on the bond strength were evaluated. It was found that all of the main variables used in the test plan affected bond strength. The bond strength increases with the decreasing in testing temperature, and it increases with the increasing in normal pressure. The AC60/70 had higher bond strength than the other two cutbacks (RC800 and RC250) and the optimum application rate is (0.4 - 0.6) kgmlm2.

Keywords: Tack coat; Asphalt pavement overlays; Bond strength; Shear strength; Shear box device.

Introduction

1.1. Problem Statement

Poor bond between two layers of hot mix asphalt (HMA) is the cause of many pavement problems. Slippage failure, often occurring at locations where traffic accelerates, decelerates, or turns, is the most commonly observed problem related to poor bond between layers. It is suggested that this failure results from high horizontal stress and insufficient adhesion at the interface between layers. Other pavement problems may also be attributed to insufficient bond between layers of hot mix asphalt. Compaction difficulty, premature fatigue, top down cracking, and surface layer delamination have also been linked to poor bond between hot mix asphalt layers.

Figure 1.1 : Slippage Failure Due to Poor Bond between HMA Layers.

To achieve a good bond between layers tack coat is usually sprayed in between asphalt pavement layers. The material type can play a large role in the successful bonding of asphalt layers. The tack material can be asphalt emulsions (slow, medium, and fast setting), cutback asphalts, high float emulsions, polymer modified asphalt emulsions, and paving grade asphalt cements. The most commonly used as tack material in Jordan is cutback asphalts (RC250 and RC800).

Another factor to be considered when applying tack coat is the application rate, too much or to little tack coat can result in a poor bond. The application rate recommended by the Ministry of Public Work and Housing in Jordan is from 0.1 to 0.6 kg/m^2. So, this rang is large and the optimum tack coat application rate is not clearly determined.

1.2. Research Objectives

The objective of this research is three- folded, first: to study the factors that affect the bond strength between old pavement and new overlay. Second: to provide helpful information for the selection of the best type(s) of tack coat materials and optimum application rate(s) for Jordan. Third: to develop a test procedure for evaluating the bond strength between pavement layers.

1.3. Scope

The experiment included evaluating the effect of two types of cutback asphalts (RC250, RC800) and an asphalt cement of penetration 60/70 as a tack coat materials. Bond strength was measured with a shear box device at two temperatures (25°C and 50°C), three normal pressure levels (2, 4 and 6) psi and three application rates (0.2, 0.4 and 0.6) kg/m^2. The effects of tack coat type, application rate, testing temperature and normal pressure on the bond strength were evaluated. Figure 1.2 shows flow chart explaining how the work was done.

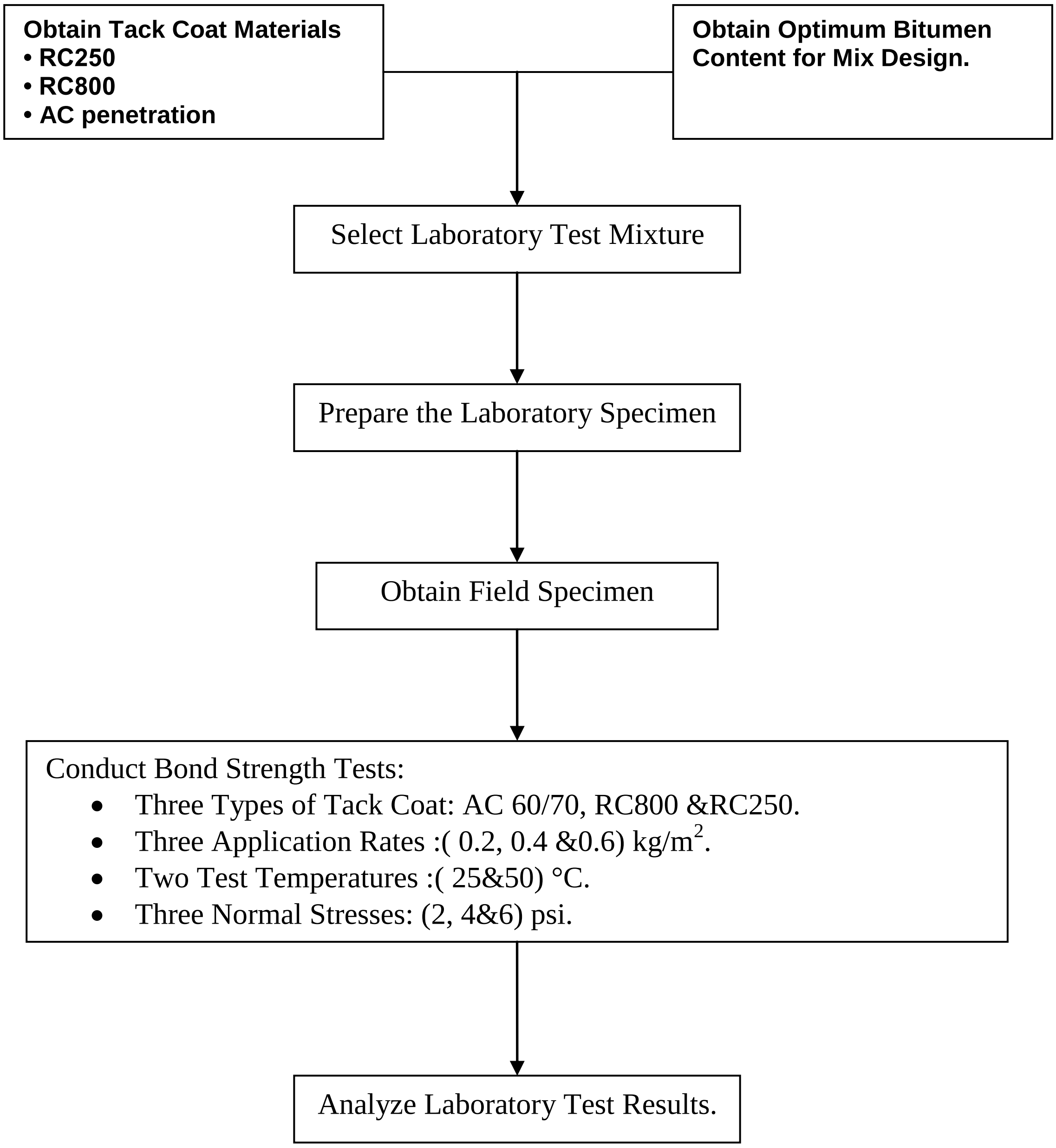


Figure 1.2: Flow Chart Represents Test Plan for the Bond Strength Project

Literature Review

2.1. Bond Strength between Hot Mix Asphalt Layers (HMA)

If the pavement layers are not fully bonded, the magnitude and location of critical strain will be different than when the layers were completely bonded (1, 2, 3). For this reason it is important to ensure a proper bond so that pavement performance can be maximized and predicted.

With pavement layer bonding being so important to the integrity of the structure, improvements to the design are necessary. These will likely lead to lower maintenance and rehabilitation costs (3, 4).From this point; the importance of tack coat clearly appears.

2.2. Tack Coat in General

2.2.1 Tack Coat Definition

Tack coat is a very light application of asphalt cement, cut back asphalt or asphalt emulsion to an existing pavement surface or between layers of hot mix asphalt to ensure a good bonding between the two layers" (1, 4, 5).

2.2.2. Tack Coat Purpose

The main purpose of tack coat is to ensure good bonding between an existing pavement surface and a new pavement surface (6, 7, 8).The lack of a good tack coat or poor adhesion can quickly lead to premature hot mix failures and cause many distresses that greatly reduce the life of the pavement surface(9, 10, 11, 12, 13, 14) .

2.2.3. Tack Coat Usage

1. Existing and New Pavement Surfaces (1, 4, 6).
2. Longitudinal and Transverse Joints (4, 5, 6).

2.2.4. Where NOT to Apply Tack Coats?

The Ministry of Public Work and Housing in Jordan (1) and others (6, 7) recommend that tack coat shouldn't be applied in the following cases:

1. If construction occur days or weeks apart.
2. Tack coat must not be applied to an area that cannot be covered by the same day's paving.
3. Tack coat must not be applied to a Pavement Reinforcing Fabric.
4. Tack coat must not be applied to a Stress Absorbing Membrane Interlayer (SAMI) unless a flush coat (fog seal plus sand cover) was placed on the SAMI. A SAMI provides an excellent bond to an asphalt concrete overlay, but the sand from the flush coat can break the bond.
5. Tack coat should not be applied to a bleeding surface.
6. Tack coats are not applied to untreated bases. They receive an application of prime coat.
7. A tack coat is not required before placing a chip seal. However, a chip seal may receive a flush coat (fog seal and sand cover) on its surface.

Several studies have been done observing the effects of tack coat and bonding. The studies have included varying temperatures, tack coat application rate, tack coat material and loading conditions.

2.2.5. Surface Preparation and Weather Conditions

The Asphalt Institute provides a good summary of weather conditions and surface preparation for proper tack application, MS-19 (4) reports that the best results are obtained when tack coat is applied to a dry pavement surface with a temperature above 25°C.

The surface must be clean and free of lose material so it will adhere, tack should not be used in lieu of cleaning the existing surface (7, 9, 12). The recommended cleaning method is to sweep the surface with a power broom (1, 12, 14).

MS-19 (4) reports that the best bond can be obtained when a tack coat is applied on a dry pavement surface.

The specification of the Ministry of Public Works and Housing in Jordan (1) recommend thus the pavement surface should be dry and clean.

West et al. (10) compared bond strengths between fine-graded and coarse-graded mixtures. They found that the fine-graded mixtures generally had higher bond strengths than the coarse-graded mixture when tested at 25°C. However, they also reported that there were significant interactions of mix type (texture) with other variables (application rate, materials used, and testing temperature), which would reverse this trend in some cases.

The literature seems to agree that a milled asphalt pavement requires higher application rates (4, 13).

Tashman et al. (13) studied the influence of the surface treatment on the adhesive bond provided by the tack coat at the interface between pavement layers. They found that milling provided a significantly better bond at the interface between the existing surface and the new overlay. The results indicated that the absence of tack coat did not significantly affect the bond strength at the interface for the milled sections, where it severely decreased the strength for the non-milled sections.

2.2.6. Sampling and Testing Tack Coat Materials

Obtain the required test report and certificate of compliance from each truckload of tack coat delivered to the project before the application of tack coat starts. Compare the test report with the specifications. Shipments may be used before sampling and testing if certificates of compliance and the test results accompanying them comply with the specifications (1, 6).

2.2.7. Application of Tack Coat

The tack coat is only used if the next layer of pavement is placed more than two days after the underlying lift. So if the lifts are placed sooner than two days, no tack coat is typically used between the layers. The reason for this is that after two days the tack coat is needed to improve the bond strength between the layers. The bonding between the layers is also improved if the surface is cleaned before placing the next lift of pavement (4).

Tack coat is applied with a self-propelled pressure distributor that is in good condition, is clean, and has been calibrated with nozzles set properly for fan overlap and not plugged. The spray bar should be capable of being set hydraulically or tied down so the bar is maintained at a uniform height from the application surface. A 1:1 dilution should be applied at 0.10-gallon/square yard. More diluted should be applied at heavier rates. A wand or hand spray nozzle attached to the spray bar can be used for applying tack to gutter faces, valve boxes, and manholes and rings. In lieu of the wand, a hand sprayer, or as a last resort a mop and bucket, may be used. Care must be taken with the wand, sprayer, and especially a mop, so that a very light coating is applied and the emulsion is not sprayed on surfaces where paving will not be used. The tack coat must be evenly distributed over the entire surface. A pneumatic roller is an effective piece of equipment used to spread the tack material uniformly (5, 15).

2.2.8. Traffic

Traffic should be kept off uncured tack coat, as well as cured tack coat, if at all possible (7, 12).

2.2.9. Measurement and Payment

Tack coat is measured for payment by mass; the unit of mass is the ton (tone). Or it can be determined from volumetric measurements. The unit of volume is the liter, to determine the volume of material used (6).

2.3. Tack Coat Types

2.3.1. Asphalt Emulsion

Since emulsions are much easier to use, they have become the most common types of asphalt used for tack (5, 9, 10), Asphalt emulsion consists of three basic ingredients: asphalt binder, water, and emulsifying agent (6, 15, 16). Other additives such as polymers are sometimes added. Polymers are either pre-blended with asphalt binder before emulsification or added as latex (6, 16).

Emulsions are typically classified by how quickly they set according to the following:

1. Slow-Setting Grades: they take longer to set than rapid-setting or quick-setting emulsions. For this reason, they are not recommended for use as a tack coat in relatively cool weather, at night, or when there is a short construction window (6, 16).

2. Rapid-Setting Grades: Rapid-setting grades of emulsion, including polymer modified emulsions, it should be considered for use at night or in cooler weather since their break time is quicker than slow-setting emulsions. Rapid-setting emulsions typically have a higher viscosity than slow-setting emulsions, so they are harder to apply and get uniform coverage. Rapid-setting emulsions can have tracking problems similar to asphalt binder because of the higher residual rate required (6, 16).

3. Quick-Setting Grades: Quick-setting emulsions used as a tack coat are made by adding a specially formulated additive to the emulsion that reduces the setting time; they are used for night work or work in cool weather as well as when rapid construction is needed. Quick-setting emulsions were originally designed for use in slurry seals and with micro-surfacing. Uniform tack coat coverage can be better obtained with quick-setting emulsions because they have lower viscosities than rapid setting emulsions and can be diluted with water (6, 16).

2.3.2. Asphalt Binder

Paving grade asphalt cements are also used for tack coats (4). The principle source of asphalt binder is the refining of crude petroleum, asphalt binder carries no charge (namely, nonionic). Any grade of paving asphalt is acceptable as tack coat material. It would be best to use the same grade of paving asphalt that is included in the asphalt concrete mix (6).

Asphalt binder should be considered for use for night work or in cooler weather because paving asphalt does not require any time to break before it can be overlaid (6).

Asphalt cements are occasionally used; however, they must be heated sufficiently to allow spray application, Asphalt cements would cool quickly, requiring application immediately in front of the paver (7).

A study was conducted by West et al. (10) similar to that of Mohammad et al. (17), but they only evaluated two types of emulsions and one performance grade binder (PG 64-

22). Bond strength at the interface was measured using a shear-testing device, which was a modified version of the Florida DOT shear tester. The researchers reported that the performance grade binder (PG 64-22) had higher bond strength than the two emulsions, which is opposite of the Mohammad et al. (17) study.

2.3.3. Cutback Asphalts

Cutback asphalts have been used as tack coat materials, but their use has significantly declined due to environmental concerns related to the volatile components (7, 16, 18). However, in Jordan, according to the specification of MPWH the Cutback asphalts have been used as tack coat materials (1) and can be used in colder climates than emulsions (7).

Cutback asphalts (liquid asphalts) are asphalts that are dissolved in a petroleum (cutter). Typical solvents include naphtha (gasoline) and kerosene. The type of solvent controls the curing time of the cutback and thus when it will obtain its ultimate strength. Rapid curing cutbacks use naphtha (gasoline) while medium curing cutbacks use kerosene. The amount of cutter affects the viscosity of the cutback asphalt. The higher the cutter content, the lower the viscosity and the more fluid it will be (18).

2.4. Tack Coat Application Rate

An excessive amount of tack coat can cause slippage, whereas too little may result in de-bonding problems (4, 7, 9, 12). Therefore, it is important to estimate the amount of tack coat that will produce the optimum outcome. The tack coat application rate should vary with the condition of the existing surface to which it is applied. In general, a tight or dense surface requires less tack coat than an open textured, raveled, or milled surface; and a flushed or bleeding surface requires less tack coat than a dry or aged surface. The proper application rate also varies with the product being applied as well as the Hot Mixed Asphalt (HMA) mixture that will be placed as an overlay (6, 10).

The proper application rate for each tack material can also be a mystery. Most specifications and construction guides provide a range for the application rate and leave it to the inspector or engineer to set the target rate (1, 4). According to the specifications of MPWH (1) the needed application rate of cutback asphalt is 0.1-0.6 kg/m^2.

Tashman et al. (13) found that slow-setting grade emulsions require higher application rates than rapid-setting grade emulsions, and rapid-setting grade emulsions require higher application rates than paving grade asphalt binders. Furthermore, dense and gap-graded Hot Mixed Asphalt (HMA) overlays require less tack coat than open-graded overlays.

The Federal Highway Administration in USA (FHWA) (7) recommends application rates between 0.23 to 0.68 L/m^2 of residual asphalt, the lower application rates are recommended for new or subsequent layers while the intermediate range is for normal pavement conditions and on an existing relatively smooth pavement. The upper limit is for old oxidized, cracked, pocked, or milled asphalt pavement and PCC pavements, the exact application rate should be determined in the field.

West et al. (10) identified the CRS-2P emulsion as the best performer in terms of interface shear strength and its optimum application rate was 0.09 L/m^2.

A world wide survey done in 1999 by the Bitumen Emulsion Federation concluded that the average rate of application was found to be from 0.12 to 0.40 kg/m^2 (4).

Mohammad et al. (17) studied six emulsions and two asphalt binders, at two different test temperatures, and the residual application rates considered were 0.00 L/m^2, 0.09 L/m^2, 0.23 L/m^2, 0.45 L/m^2, and 0.9 L/m^2. They found that, the optimum application rate is 0.09 L/m^2.

2.5. Normal Load

West et al. (10) studied the effect of normal load on the bond strength; they found that the effect of normal pressure was more pronounced at higher temperatures. This was anticipated since the stiffness of the tack coat is significantly reduced at higher temperatures and so the effect of friction at the interlayer is more evident, and as the normal load increased the bond strength increased. Also it can be clearly seen from their results that at 10°C and 25°C, bond strength was not sensitive to normal pressure and after 10 psi until 20 psi there is no significant difference in bond strength.

2.6. Test Temperature

For similar interface conditions, increased test temperature resulted in reduced interface shear strength (7).

Mohammad et al. (17) found that, the bond strength at 25°C is higher than the bond strength at 50°C, and the shear resistance at the interface decreased with an increase in temperature.

The Asphalt Institute Manual MS-19 (4) reports that the best bond can be obtained with a temperature of 25°C.

A study by West et al. (10) show that tests at 25ºC yielded shear strengths generally about five times the shear strengths at 60ºC. The tests at 25ºC were also better at distinguishing differences in the application rates.

2.7. Tack Coat Curing Time

There is no unanimous agreement in the literature on the curing time of tack coats. Some research studies and guidelines suggest that the tack coat should be cured before laying the new pavement layer (4, 8, 9). While Tashman et al. (13) found that curing time had a minimal effect on the bond strength.

The Asphalt Institute reports that tack placed too far out in front of the paver can lose its tack characteristics and would require additional tack (19).

MPWH (1) reports that tack coats placed too far ahead of the paver can lose their adhesive characteristics and any tack that is not covered in one day should be re-tacked prior to paving. No more tack should be applied than can be covered in one day (1, 4, 7).

2.8. Shear Devices

Many of shear devices were used to find the interfaces behavior of asphalt pavements.

A special attachment and loading mechanism was designed and built by Maurice Wheat (3) to facilitate the measurement of the dynamic shear reaction modulus and shear strength of the asphalt-to-asphalt interfaces when shear and normal forces are acting simultaneously and they are proportional. The test was conducted on 4-inch diameter cylindrical samples cored from an asphalt concrete pad where three types of asphalt-to-asphalt interfaces were built. For each interface, four tack-coat quantities were sprayed. On each sample, the Dynamic Shear Reaction Modulus test was conducted first. Then the Shear Strength test was conducted until the sample failed in shear at the interface.

Kruntcheva et al. (20) used an apparatus known as the Nottingham shear box to establish a realistic stress distribution at the interface. Bond stiffness and strength were assessed under repeated dynamic and monotonic static test conditions.

Washington Center for Asphalt Technology (13) used a device named UTEP Pull-Off Strength test device to test the different surface conditions and their effect on bond strength.

Another study conducted by the Washington Center for Asphalt Technology (13) to find the effect of milled sections on bond strength between pavement layers using the Florida DOT Shear Tester (13).This device is now used by the Florida DOT to evaluate the bonding of an interface if there is a question of bond integrity (10).

The Florida DOT Shear Tester was developed in 2003 by West et al. (10) to address the need for a test to evaluate tack coat strength. This tester is basically an attachment, which fits inside the universal machine. This device uses 6-inch diameter cores and the interface is placed in between the gap of the two ring sets. The gap between the two rings should be 3/16 inch. The specimen is brought to a temperature of 25°C plus or minus 1°C for a minimum of two hours before testing. When the core is placed in the ring sets it is placed so that the direction of load on the core is parallel the shear direction. The test is strain controlled and will load at a rate of 2-in/min until failure. From there the shear strength can be calculated.

A testing method that is currently being used in the UK involves testing in the field. This test is simply referred to as an in-situ torque test. A core is drilled in the asphalt and the core left in place. Then a plate is attached to the top of the core at the surface of the asphalt and a torque is applied. The torque is applied with a torque wrench so that the force can be recorded. The torque is applied to the core until it fails and the final torque applied is recorded (10).

There are several test methods that are in use today to evaluate asphalt interfaces of different layers of asphalt layers. These tests include: NCAT Shear test, Torque Bond Test, Super pave Shear Tester (SST), FDOT Shear Tester, and ASTRA from Italy.

The NCAT Shear test is a shear type test. The loading can be applied using a Marshall press or a universal loading machine. This test has many improvements over the years. One of the main improvements that it has under gone over the years was the added ability to apply a horizontal load. Similar to other methods this is a device that is placed in an MTS machine to test core samples. It is loaded at a rate of 50.8 mm/min and is tested at a constant temperature, which is maintained in the testing chamber. A schematic is given in Figure 2.14 (10).

Another study was conducted by Yildirim et al. (21) to evaluate a laboratory testing procedure for analyzing tack materials used at asphalt interfaces. The tack coat performance was to be evaluated using the Hamburg wheel tracking device and simple shear tests on laboratory samples. The shear test applied a shear load at a constant rate of 50mm/min and was conducted at 20°C. The Hamburg wheel tests were conducted at 50°C. It was found the trafficking improved the shear strength of the interfaces at 5,000 cycles. For this reason it was recommended to repeat the experiment at a higher number of cycles at a lower temperature and up to 20,000 cycles. A specific apparatus was developed for this study to hold the specimens during the testing. This was developed specifically to induce failure at the asphalt interfaces. The specimen holders were 150 mm in diameter and 50.8 mm deep. The testing of these samples used this apparatus and the Super pave Shear Tester (SST).

The effects of interface condition on the life of flexible pavements have been determined by another study by Ziari and Khabiri (22). The methodology consists of implementing a previously derived interface constitutive model into the Ken-layer program (software program) to compute the stresses and strains in typical flexible road structures. The shell transfer functions for fatigue cracking and terminal serviceability were used to estimate the pavement life.

Recasens et al. (23) conducted a study to analyze the effect of different heat-adhesive emulsions and to verify their performance in service in comparison with the response of a conventional emulsion. For this reason a new shear test device—the Laboratory Camino of Barcelona (LCB) tester—has been developed.

Methodology

3.1. General

Shear strength at interface layer of laboratory fabricated samples compacted upon old slabs of surface layer pavement separated by tack coat material was evaluated. The direct shear box normally used for testing soils was modified to accommodate square asphalt samples 10 x 10 x 5 cm.

Laboratory prepared mixture samples of 19mm Nominal Maximum Aggregate Size were compacted upon old slabs of surface coarse and they were tested at two temperatures and three normal pressure levels, three types of tack coat materials and three application rates were investigated for each tack coat material. The effects of tack coat type, application rate, testing temperature and normal pressure on the bond strength were evaluated. The attached matrix clarifies the experiment design (Table 3.1). The experiment took place in the highway lab at the Jordan University of Science and Technology.

3.2. Design of Experiment

The first phase of this study was to refine the shear box device and establish a standard procedure for conducting the test. As part of this work, it was desired to evaluate the effects of several material variables and test conditions on bond strength. The material variables of interest included tack coat material type and tack coat application rate. The test condition factors evaluated were normal pressure applied to the specimen during the bond strength test and testing temperature. See the following table 3.1

Table 3.1: Experimental Factors.

Normal Stress (psi)	Temperature (°C)	Rate (kg/m^2)	Tack
2	25	0.2	AC
4			
6			
2	50		
4			
6			
2	25	0.4	
4			
6			
2	50		
4			
6			
2	25	0.6	
4			
6			
2	50		
4			
6			
2	25	0.2	RC250
4			
6			
2	50		
4			
6			
2	25	0.4	
4			
6			
2	50		
4			
6			
2	25	0.6	
4			
6			
2	50		
4			
6			
2	25	0.2	RC800
4			
6			
2	50		
4			
6			
2	25	0.4	
4			
6			
2	50		
4			
6			
2	25	0.6	
4			
6			
2	50		
4			
6			

3.3. Experimental Devices

3.3.1. Direct Shear Box Device

Direct shear box device was modified in the engineering workshops in Jordan University of Science and Technology to test the HMA specimens, the improvements include the following:

1. Test Mould: the original was changed to another steel mold consist of two parts, the lower one (10 x 10 x 5 cm) and the upper one (10 x 10 x 6 cm) and each of them were grooved and spatial steel balls were used to minimize the friction between the moulds during the pushing process, and an U-shaped steel arm from steel was fixed on the upper mold to center the pushing force . A steel plate (10 x 10 x 1 cm) covered the upper half of the mold to distribute the normal load .
2. The proving Ring: The Ring was changed to allow it to push the upper test mold with the tested specimen, and it was calibrated to measure the bond strength between the HMA layers by using a spatial gauge .
3. Loading Arm: the arm which carries the weights was adjusted to make the applied normal load rest directly on the center of the tested specimen, and the side arms also were lengthed to fit with the adjusted molds (Figure 3.7). Other parts of the machine were left as it is (motor, the body in general, weights, etc).

3.3.2. Marshal Compacting and Mixing Devices

The automatic Marshal compactor was used in the compaction process (Figure 3.8) and small of adjustments were made to achieve the goals of this experiment, the following are the adjustments applied to the device:

1. Compaction mold: the original cylindrical mold was changed to another steel mold consist of two parts, the lower one (10x10x5 cm) to put the field specimen inside, the upper one (10x10x6 cm) to put the mixture inside and compact it by the hammer and a square steel plate (10x10x1 cm) with cylindrical steel plat (D=15cm, h=5cm) for compaction purposes .
2. Base Plate: a steel plate (20x15x1.5 cm) was fixed on the base of the device to easily fix the compacting mold.

3.3.3. Other Devices

1. The Mixing Machine: a Mechanical Mixer was used to mix aggregate with asphalt binder without any changes.

2. Ovens: A spatial oven was used to heat the materials and devices to the desired temperatures

3. Environmental Chamber (Universal Testing Machine) The environmental chamber of the universal testing machine was used to condition the samples at the needed test temperatures before testing (Figures 3.13).
4. Other Apparatuses

Some other apparatuses were used during the experimental works including Electronic caliber, steel rule, balance, brushes, steel containers, plastic containers, plastic bags, spatial keys, and thermometer for different purposes.

3.4. Materials

3.4.1. The Aggregates

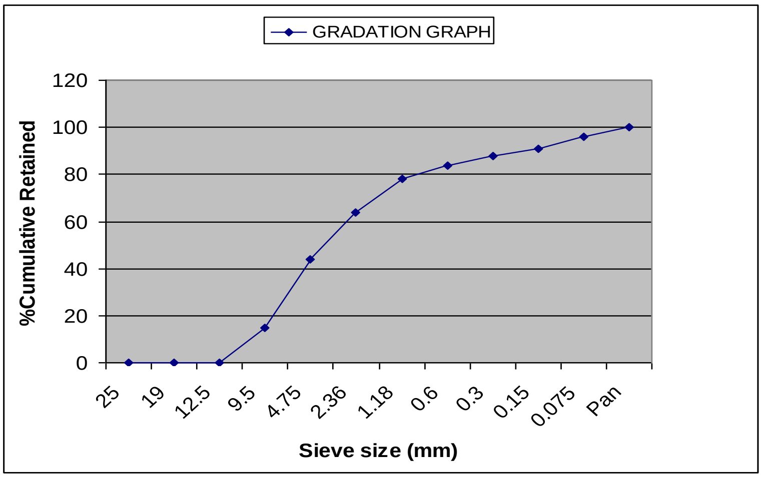
A 12.5 mm nominal maximum aggregate sieve (NMAS) size limestone aggregate gradation was selected; the aggregate was selected with high quality (Abrasion 28%). The needed weight for the basic experiments is 900 gm.

Table 3.2: Volumetric Properties of HMA.

Bulk specific gravity (Gsb)	2.66
Optimum bitumen content	4.4%
Maximum specific gravity (Gmm)	2.525
Air voids (AV)	4.3%
Voids in mineral aggregates(VMA)	13.2
Voids filled with asphalt (VFA)	67.3

Table 3.3: Sieve Analysis of Aggregate

Sieve size (mm)	Sieve size (inch)	Passing%	Retained%	Retained(gm)
12.5	**1/2**	100	0	0
9.5	**3/8**	85	15	135
4.75	**No.4**	56	29	261
2.36	**No.8**	36	20	180
1.18	**No.16**	22	14	126
0.6	**No.30**	16	6	54
0.3	**No.50**	12	4	36
0.15	**No.100**	9	3	27
0.075	**No.200**	4	5	45
Pan	**Pan**	0	4	36
Sum				900



Figures 3.15: Gradation Graph (Cumulative Retained).

3.4.2. Tack Coat Types

Three types of tack coat materials were used: two cutback asphalt (RC800 and RC250) and an asphalt binder (AC 60/70). The tack coat materials used were taken from Jordan Petroleum Refinery Company according to the specifications of the Ministry of Public Works and Housing .

3. 4.3. The Field Specimens

Field samples were taken from Sed Al Arab road ,Irbed-Jordan , and the direction of traffic was marked on the surface of these specimens (Figure 3.16), and they were cut into slabs (10x10x5 cm) .

3.5. Evaluating the Surface Texture of Field Specimens.

The surface roughness affects the bond strength. Field specimens have different textures. In order to consider this, the surface of the specimen was covered with fines passing sieve NO. 200. The fines were then removed by a straight edge and weighed. The amount of fines was used as an index of surface texture.

3.6. Marshal Mix Design

Marshal Mix design method was used to obtain the optimum asphalt content (AC); the original Marshall method is applicable only to hot-mix asphalt paving mixtures containing aggregates with maximum sizes of 25 mm (1 in.) or less. Procedures are given by ASTM1559 .The optimum bitumen content resulted according to this design was 4.4% by weight of aggregate.

3.7. Specimen Preparation for Shear Strength Testing

3.7.1. Finding the Required Number of Blows

The following procedure was done to find the required number of blows needed to obtain 4 % target air voids.

Mixing and compaction tools were put in an oven for 24 hours at 120°C followed by 2 hour at 150°C prior to mixing.

1. 900 grams of aggregate were put in an oven for 24 hours at 120°C followed by 2 hour at 150°C prior to mixing.
2. The asphalt binder (AC 60/70) was put in an oven for 3 hours at 150°C before mixing.
3. Mixing aggregate with asphalt binder at 135°C.
4. The mix was placed in the cubic mold over the field sample and compacted using the Marshal Hammer by 150, 200, 250 and 300 blows.
5. After conducting the volumetric analysis, the percent air voids was calculated for each sample.
6. The appropriate number of blows which gives Air Voids (AV) 4% was selected.

3.7.2. Preparation of Laboratory Specimen

After finding the number of blows which give the target air voids, the following procedure was followed with the constant number of blows for each specimen:

1. Mixing and compaction tools were put in an oven for 24 hours at 120°C followed by 2 hour at 150°C prior to mixing
2. A 900 gm of aggregate sample was put in an oven for 24 hours at 120°C followed by 2 hour at 150°C prior to mixing.
3. An indication about the roughness of the surface of the field samples was obtained using sand silica and steel ruler as shown in the previous Figure (3.18).
4. The surface of the specimen was cleaned using a spatial brush, Figure (3.19).

5. The required type of tack coat (pen. 60/70, RC250 or RC800) with desired amount of tack coat (2, 4 or 6 gm) was sprayed upon the field specimen by using a special brush, and it was let to cure for 30 minute for pen.60/70 tack coat and from1.5 to 2 hours for RC250 and RC800.

6. 48 gram of asphalt binder (AC 60/70) was put in an oven for 3 hours at 150°C before mixing.
7. Aggregate was mixed with asphalt binder at 135°C.
8. The laboratory mixture (aggregate + sample) was then placed above the field sample in the compaction mold and it was compacted by the Marshall hammer at 200 blows .

3.8. Testing

The improved shear box device was used in this study to test the bond strength between the field specimen and the laboratory mix as described below:

1. The environmental chamber of the Universal Testing Machine was used to condition the samples at the desired temperature for 6 hours prior to testing.
2. Both parts of the mold were placed centrally on the shear box separated by metal balls of 4 mm diameter.
3. The shear test was run at a rate = 70 mm/min and the reading was recorded using spatial gauge, see Figures (3.21, 22, 23 and 24).

Results and Analysis

4.1. Refining of the Shear Box Device

The shear box device was refined, and the proving ring was calibrated. The following equation was obtained.

Shear Load (kN) =0.0243X+0.7569…………………………………..... (Equation 4.1)

Where, X= the reading getting from the shear box device.

And it was then converted into bond strength between the old pavement and the overlay as the following.

Bond strength (kN/m^2) = Shear Load /0.01 …………………………… (Equation 4.2)

4.2. Bond Strength Results

For each combination of mix type, tack coat type, application rate, normal pressure, and test temperature, two specimens were tested and the average of these two test results were reported.

Table 4.1 presents the average bond strengths of two test specimens. And also they are shown in Figures (4.1 through 4.14).

Table 4.1: Bond Strength Results.

Tack coat type	Normal pressure (psi)	Application rate(kg/m²)	Bond Strength (kN/m²) at Test Temperature 25°C	Bond Strength (kN/m²) at Test Temperature 50°C
RC250	**2**	**0.2**	162.15	150.39
		0.4	262.98	165.60
		0.6	195.93	141.45
	4	**0.2**	240.99	165.57
		0.4	317.08	180.83
		0.6	301.29	167.09
	6	**0.2**	312.38	175.51
		0.4	458.83	258.12
		0.6	339.18	218.94
RC800	**2**	**0.2**	192.07	175.34
		0.4	389.08	193.90
		0.6	245.68	183.39
	4	**0.2**	315.53	179.66
		0.4	461.93	207.07
		0.6	455.31	191.80
	6	**0.2**	482.66	223.91
		0.4	633.45	301.02
		0.6	534.09	242.29
AC 60/70	**2**	**0.2**	278.04	179.25
		0.4	411.33	220.80
		0.6	573.97	215.89
		0.8	559.32	-------------
	4	**0.2**	402.97	218.68
		0.4	527.14	247.70
		0.6	613.71	240.78
		0.8	594.01	------------
	6	**0.2**	548.91	236.95
		0.4	739.22	340.92
		0.6	746.18	247.75
		0.8	741.92	------------

4.2.1. The Effect of Tack Coat Type on Bond Strength.

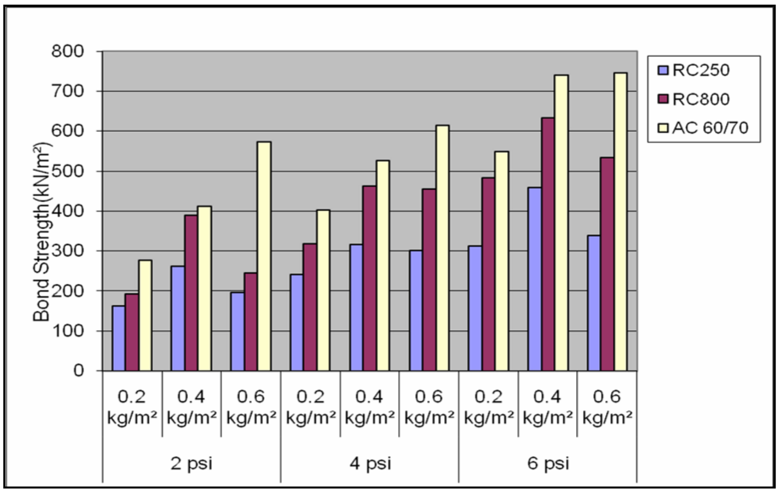


Figure 4.1.a: The Effect of Tack Coat Type on Bond Strength at 25°C.

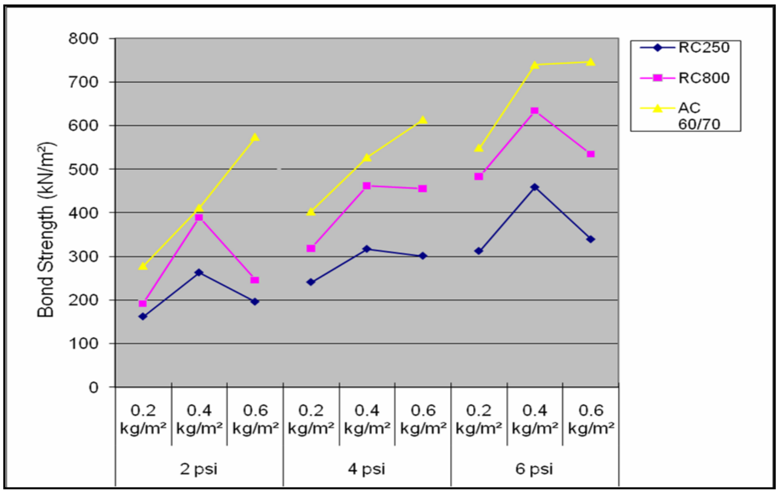


Figure 4.1.b: The Effect of Tack Coat Type on Bond Strength at 25°C.

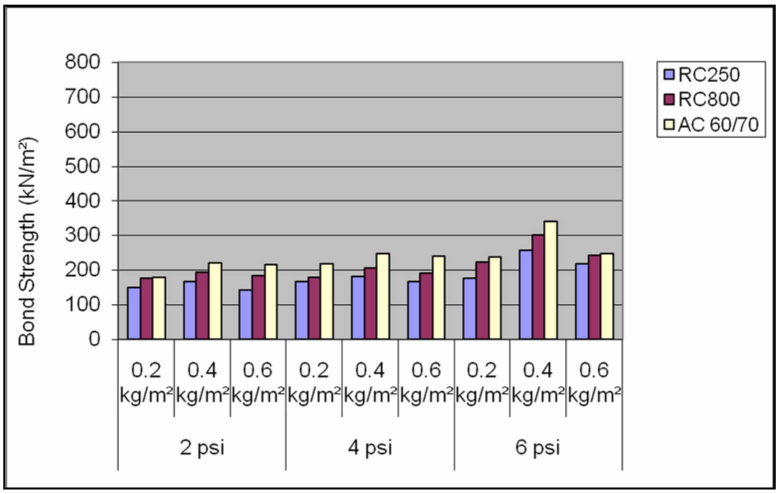


Figure 4.2.a: The Effect of Tack Coat Type on Bond Strength at 50°C.

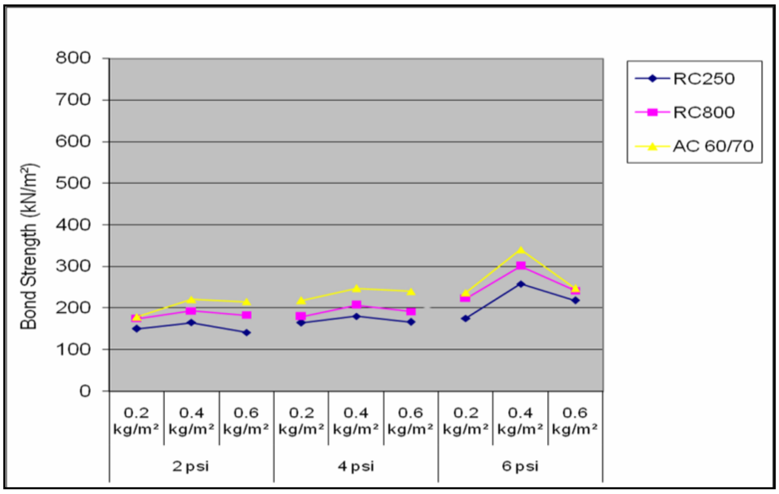


Figure 4.2.b: The Effect of Tack Coat Type on Bond Strength at 50°C.

From Figures (4.1.a , 4.1.b , 4.2.a and 4.2.b), it appears that at both temperatures, at all application rates, and under all normal stresses, the asphalt binder (AC 60/70) provides a higher bond strength than the two cut back asphalts (RC800 and RC250) especially at low temperature. The RC800, RC250 seem to give similar bond strength values. And that is due to the difference in viscosity Also, it can be clearly seen that the difference between them at high temperature is minor.

4.2.2. The Effect of Test Temperatures on Bond Strength.

The following Figures (4.3.a and 4.3.b) show the average bond strength for each test temperature. As can be seen, bond strengths at 25°C are greater than that at 50°C, so when temperature increases, the bond strength decreases dramatically. This was expected since the tack coat materials are much stiffer at the lower temperatures.

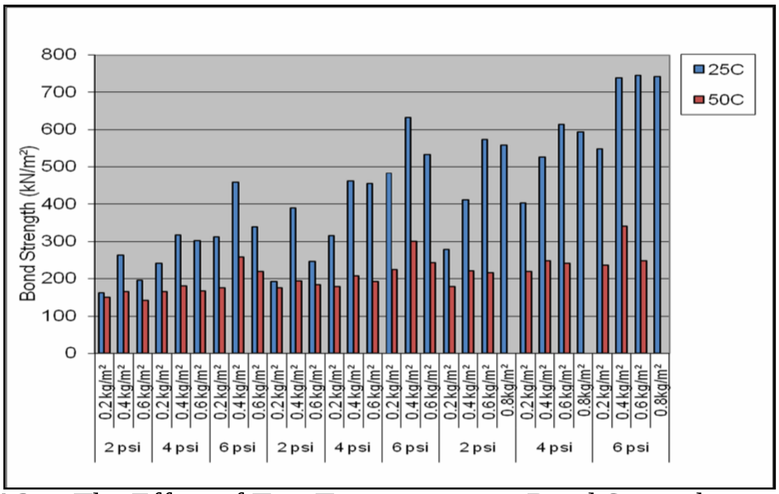


Figure 4.3.a: The Effect of Test Temperature on Bond Strength.

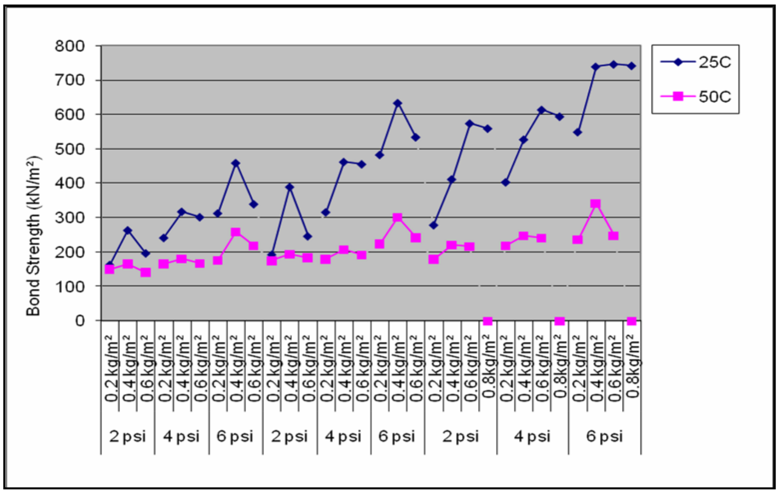


Figure 4.3.b: The Effect of Test Temperature on Bond Strength.

4.2.3. The Effect of Tack Coat Application Rate on Bond Strength.

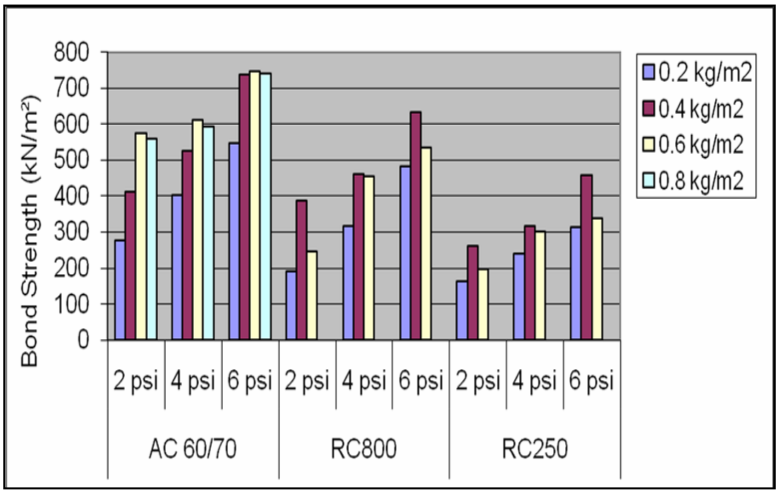


Figure 4.4.a: The Effect of Application Rate on Bond Strength at 25°C.

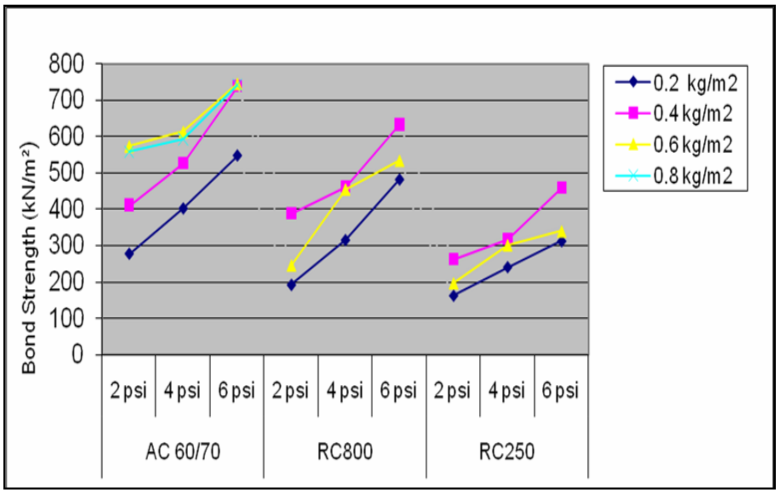


Figure 4.4.b: The Effect of Application Rate on Bond Strength at 25°C.

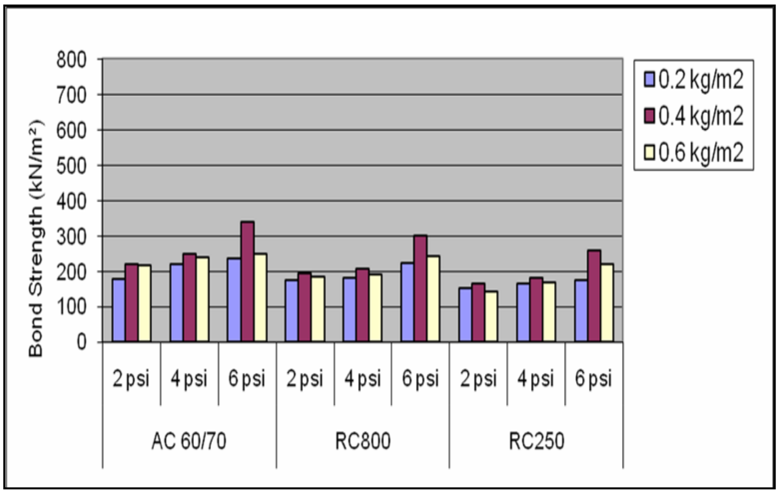


Figure 4.5.a: The Effect of Application Rate on Bond Strength at 50°C.

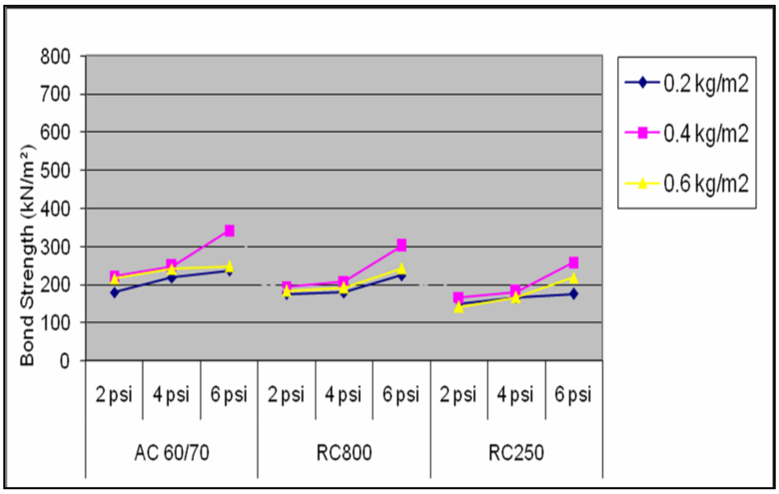


Figure 4.5.b: The Effect of Application Rate on Bond Strength at 50°C.

An interesting point that appears in the figures (4.4.a through 4.5.b) is the effect of application rate. For each tack coat material and at each normal load, the bond strengths were affected by tack application rate. The optimum application rate for the cut back asphalt materials at both temperatures was 0.4 kg/m^2, while the optimum for AC 60/70 differs according to the different in temperatures; it was 0.6 kg/m^2 at 25°C and 0.4 kg/m^2 at 50°C. Another interesting point is that at high temperatures, the application rate has not that much difference in bond strength, especially for the two cut back asphalts. That indicates that testing at high temperature is not a valid tool to predict the effect of application rate.

4.2.3. The Effect of Normal Stress on Bond Strength.

The effect of normal pressure on bond strength was significant at both temperatures. As shown in Figures (4 .6.a through 4.7.b), bond strength increases when the normal pressure increases. However, at the high temperatures, the bond strength does not change much when normal pressure increases from 2 to 6 psi.

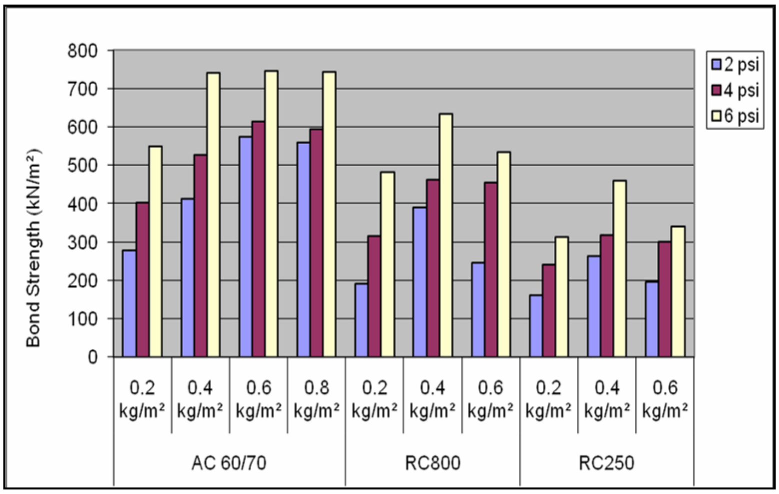


Figure 4.6.a: The Effect of Normal Stress on Bond Strength at 25°C.

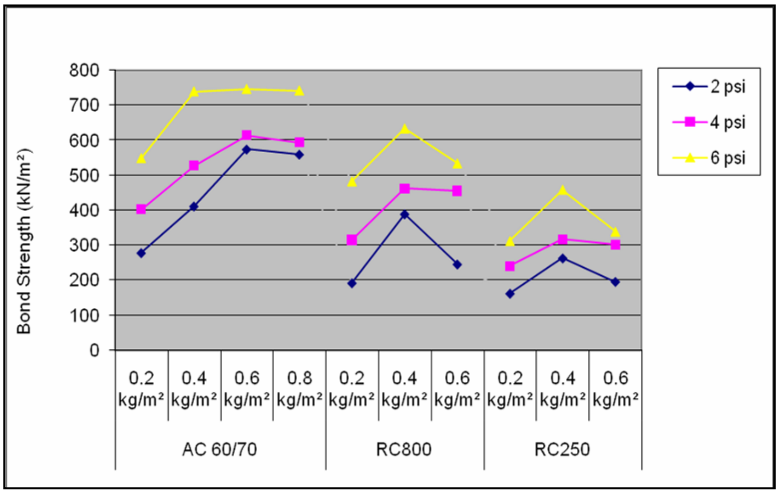


Figure 4.6.b: The Effect of Normal Stress on Bond Strength at 25°C.

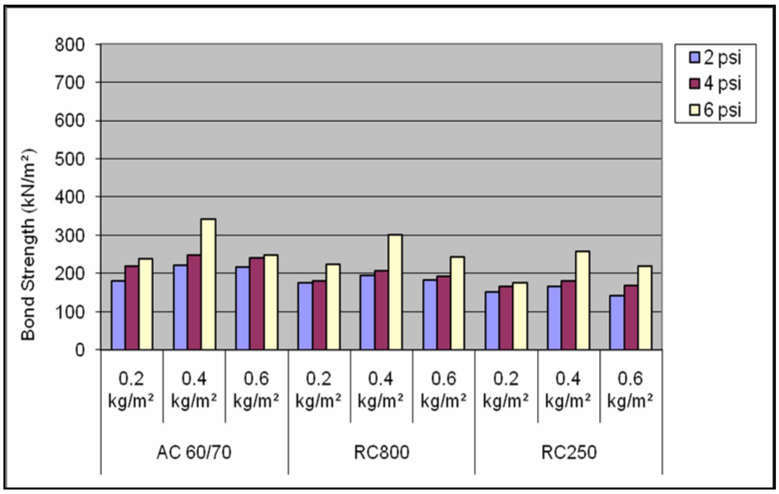


Figure 4.7.a: The Effect of Normal Stress on Bond Strength at 50°C.

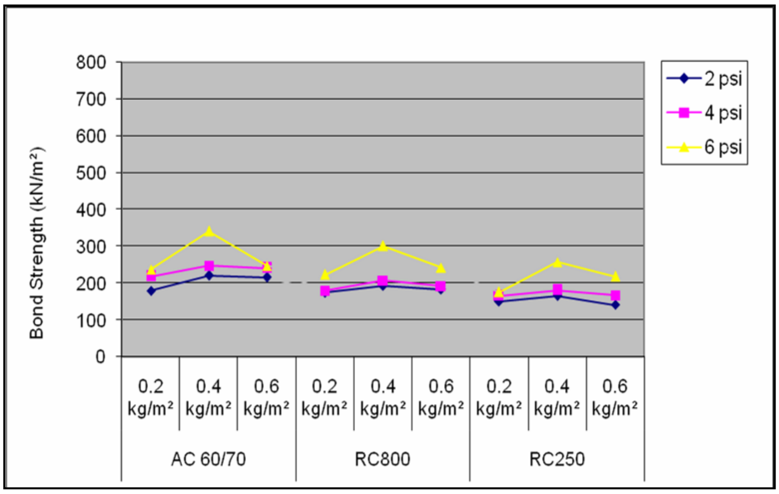


Figure 4.7.b: The Effect of Normal Stress on Bond Strength at 50°C.

4.3. Statistical Analysis of the Bond Strength Data

The effect of asphalt tack coat types, application rates, normal pressure, and test temperatures on bond shear strength were statistically analyzed using the data reported in Tables 4.1.

Analysis of the bond strength data consisted of conducting an analysis of variance (ANOVA) nested factorial design (Table 4.2).

Table 4.2: Results of ANOVA for Bond Shear Strength at α=0.05 (Nested Factorial).

SOURCE	D.F.	Sum of Square	Mean Square	$f_{\circ}$	f critical	Significance at 95%
Type of Tack Coat	2	428140.35	214070.18	101.6148	3.11	SIGNIFICANT
Application Rate (kN/m²)	6	208214.00	34702.333	16.472	2.21	SIGNIFICANT
Normal Pressure (psi)	18	453238.16	25179.898	11.952	2.21	SIGNIFICANT
Test Temperature (°C)	27	1515821.47	56141.536	26.649	2.72	SIGNIFICANT
ERROR	54	113760.94	2106.684			
TOTAL	107	2719174.93	25412.85			

Based on this analysis, the four main factors were significant (tack coat type, temperature, tack coat application rate, and normal pressure). This indicates that all of these factors influence the bond strength between two HMA layers.

Based on the F-statistics, for the four main factors tack coat type was the most significant factor followed by, temperature, application rate, and normal pressure, respectively.

Table 4.1 and Figures (4.1.a through 4.7.b) show the average bond strength for each type of tack coat, test temperature, application rate and normal pressure combination. It was found that the strength of AC 60/70 at 25°C is 1.95 times greater than the strength of RC250 and 1.43 times greater than for RC800, while at 50°C these values decrease to 1.31 times and 1.16 times respectively, this was expected due to the different viscosity of the tack coat materials and the relationship between viscosity and temperature (appendix A).

Based on the results above, the optimum rates of tack coat depend on the test temperatures and type of tack coat, they are 0.4 kg/m² for all types at 50 °C, while at 25 °C the optimum rate is 0.4 kg/m² for RC materials and 0.6 kg/m² for AC materials.

The effect of normal pressure on bond strength is shown in figures (4.6.a through 4.7.b). The bond strength increases when the normal pressure increases at both temperatures.

Table 4.3: Results of ANOVA for Bond Shear Strength at 50 °C (Nested Factorial).

SOURCE	D.F.	Sum of Square	Mean Square	f∘	f critical	Significance at 95%
Type of Tack Coat	2	30692.40	15346.2	14.08	3.11	SIGNIFICANT
Application Rate (kN/m²)	6	20007.32	3334.554	3.06	2.21	SIGNIFICANT
Normal Pressure (psi)	18	57788.91	3210.495	2.95	2.21	SIGNIFICANT
ERROR	28	30520.83	1090.03			
TOTAL	54	139009.46	2574.249			

Table 4.4: Results of ANOVA for Bond Shear Strength at 25 °C (Nested Factorial).

SOURCE	D.F.	Sum of Square	Mean Square	F∘	f critical	Significance at 95%
Type of Tack Coat	2	562838.52	281419.3	94.66	3.11	SIGNIFICANT
Application Rate (kN/m²)	6	286265.43	47710.9	16.05	2.21	SIGNIFICANT
Normal Pressure (psi)	18	539109.07	29950.5	10.07	2.21	SIGNIFICANT
ERROR	28	83240.11	2972.861			
TOTAL	54	1471453.13	27249.13			

At 50°C, all the main factors (tack coat type, application rate, and normal pressure) are significant. At this temperature, tack coat type has the greatest effect on bond strength, and then application rate and normal pressure respectively. Figures (4.1.a through 4.7.b) illustrate the bond strengths of the mixtures, at 50°C test temperatures for the three tack materials at each application rate and each normal pressure. Here it is seen that as normal pressure increases, there is an increase in bond strength. When the 6 psi normal load is applied, the bond strength for the mixture samples increases by 1.4 times compared to 2 psi. AC 60/70 provides higher bond strengths compared to the RC250 and the RC800, it provided bond strength 1.3 times greater than RC250 and 1.1 times greater than RC800 on average. About application rate, for each tack coat material and each normal load, the bond strengths have an optimum values at 0.4 kg/m² for all types at 50°C test temperatures.

Similar analyses were conducted on the bond strength results at 25°C. The ANOVA shown in Table 4.4 indicates that all main factors have significant effects on bond strength at 25°C. The Figures (4.1.a through 4.7.b) show that the bond strengths at 25°C on average, was 434.58 KN/m². Tack coat type also had significant effect on bond strength. Similar to the results shown at 50°C, it appears that the AC 60/70 provides higher bond strength than the two cut backs.

On average, when normal pressure is applied, there is an increase in bond strength. Application rates also influence the bond strength at 25°C. In general, 0.4 kg/m² application rates provided higher bond strengths for RC250 and RC800, but about AC 60/70 the optimum was 0.6 kg/m^2. (For more details; see Appendix F).

4.4. Bond Strength Results for Tile Slabs

In order to avoid surface texture effect, shear test was carried out for two samples of tiles 10 X 10 X 3 cm. tack coat was applied at different rates between the two slabs .The results are shown in table 4.5.

Table 4.5: Bond Strength of Tile Slabs at 25°C and 4psi

Application Rate (kg/m^2)	Bond Strength (kN/m^2)
0.0	47.68
0.1	47.68
0.2	48.76
0.3	50.92
0.4	52
0.5	52
0.6	53.08
0.7	50.96

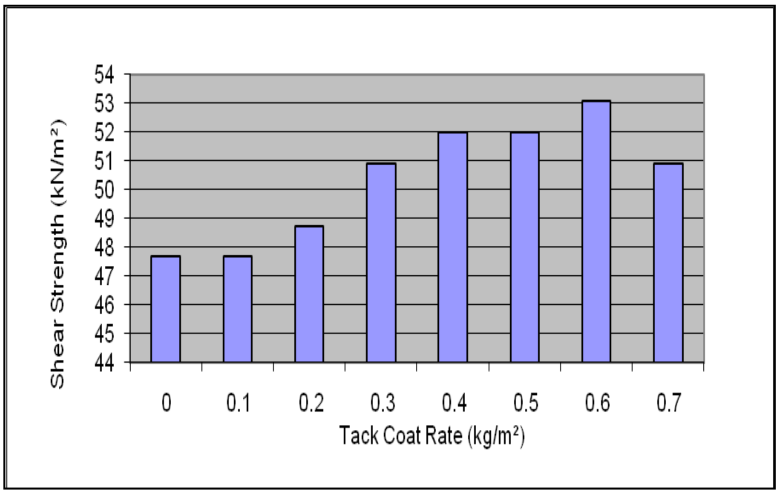


Figure 4.8: Bond Strength between Tiles at 25°C and 4 psi**.**

Table 4.5 and the figure 4.8 illustrate the effect of the roughness of the contact surface between the old layer and the new one. From the figures (4.1.a to 4.7.b) the average shear strength of AC 60/70 at 25°C test temperature was 561.4 kN/m^2 for asphalt samples, while between tiles it was about 50.4 kN/m^2, so the roughness has a significant effect on bond strength between Hot- Mix Asphalt (HMA) layers.

4.5. Summary of Findings

The bond strength between two HMA layers was evaluated using a bond strength device at 25°C and 50°C with three normal pressure levels (2, 4, and 6 psi) for each temperature. Tack coat materials selected for evaluation included two types of cut back and one type of asphalt cement as specified by MPWH.

Three application rates that are recommended by MPWH were investigated for each tack coat type.

The following findings were concluded:

1. All the factors included in the test plan had a significant effect on bond strength. Tack coat type had the most significant impact on bond strength. AC 60/70 had the highest value of bond strength.
2. The temperature had the second most significant impact on bond strength. As the temperature increases, bond strength decreases significantly for all tack coat types, application rates, and for all normal pressure levels. Bond strength tests conducted at 25°C temperatures are able to evaluate the differences among tack coat materials, and application rates, while the testing at 50°C is not capable of distinguishing between bond strength values.
3. When normal pressure increases, the bond strength increases in general.
4. The roughness of the contact surface had a significant effect on bond strength, as it increased, the bond increased.
5. The asphalt binder provides a higher bond strength than the two cut back (RC250 and RC800).
6. The optimum application rate for all material studied is 0.4 kg/m^2 at 25°C. it is the same for RC material at 50°C , while it is higher (0.6 kg/m^2) for AC 60/70 at the high temperature.

4.6. Development of Preliminary Bond Strength Procedure

Based upon the results, and considering practical application of the bond strength test, (MPWH) Ministry of Public Works and Housing should select the test conditions as (25°C) with 2 psi normal pressure.

It was shown that bond tests at higher temperatures also have merit since this is a more critical condition for which slippage is more likely to occur. At (50°C), bond strengths are low and with testing variability it would be more difficult to establish criteria to discern between acceptable and unacceptable results. On average, the bond strengths at 50°C are typically less than 44% of the bond strength at 25°C. The simplified conditions of testing at room temperature with 2 psi normal load also allow for the test to be performed in any typical asphalt lab equipped with a Marshall press.

The only additional equipment needed to perform the test is the shear box device which was developed for these tests and it can be easily reproduced in Jordan. The time to prepare a sample and conduct the test was about six hours. This very practical test set up is believed to provide a good indication of whether or not sufficient bond has been achieved in the field and provide enough sensitivity in order to rate different materials, and application rates.

Conclusions and Recommendations

5.1. CONCLUSIONS

- The draft procedure is suitable to be run at the intermediate temperature (25°C) because this temperature yielded a wider range of bond strengths for different materials than the higher temperature.
- The results of the laboratory experiment indicate that all of the main factors affect bond strength.
- In most cases AC 60/70 provided higher bond strengths than the two cut back tack coats (RC800 and RC250).
- Higher strengths were generally evident at (0.4 to 0.6) kg/m^2 application rate for all of the tack coat materials.
- The effect of normal pressure was significant and as it increased, the bond strength increased.
- Test temperature had a big effect on bond strength. On average, bond strengths were 2.0 times greater at 25°C compared to those at 50°C.
- Roughness of contact surface between asphalt layers had a significant effect on bond strength.
- The use of the draft bond strength procedure was successfully demonstrated. This study yielded several important observations.

5.2. Recommendations

Based on the findings reported in this study, the following recommendations are suggested for implementation:

- Tack coat application rates should be checked on paving projects prior to paving.
- The Ministry of Public Works and Housing (MPWH) specifications for tack coat materials and application rates are satisfactory.
- For asphalt pavement over lays, the recommended type of tack coat is AC 60/70 because of the following :
  1. It provides the highest bond strength.
  2. All three types have the same price (400 JD/ton as at 1/7/2010); so cost is not an influence.
- The simple bond strength procedure developed in this study and included in Appendix D can be used to assess the bond strength between HMA pavement layers.

There are several issues that need to be further studied:

- Road sections can be constructed as part of this study and monitored for a few years to evaluate their performance and identify any sections that do not perform well.
- Bond strength is not the only factor that affect slippage of overlay, more work is needed to better define critical conditions for slippage failures such as pavement temperature, depth of layer interface, and stress magnitudes to help set more definitive limits for minimum bond strengths between pavement layers.
- Bond strengths, tack coat types, and application rates for pavement layers on other types of surfaces and surface treatments should be investigated. More field projects with the different types of tack coat materials should also reconsidered.

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