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Influences of Surface Characteristics and Modified Asphalt Binders on Interface Shear Strength

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ABSTRACT

Weak bonding between layers of pavement leads to damages on the composite pavement. Bonding plays an important role in the durability and maintenance of composite pavement layers. The present study evaluates the factors effective in bond strength of the interface between concrete and asphalt pavements. The factors considered for this purpose include steel slag percentage in the concrete pavement, different types of modified bitumen, and rates of tack-coat. To measure the bond properties, direct shear and shear fatigue tests were carried out. In addition, texture depth and abrasion resistance were used in accordance with EN 1338 standard to measure the roughness properties of concrete pavement. The test results showed that 50% replacement of steel slag with aggregate resulted in an increase in physical properties and texture depth of concrete pavement. Moreover, the results of the shear strength test of composite pavement revealed that the optimal rate of using tack-coat varies between 0.6 and 0.9 l/m^2 and depends on the type of tack-coat. Finally, a higher shear strength was obtained for crumb rubber bitumen containing hydrated lime compared to crumb rubber modified bitumen and control bitumen.

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1. INTRODUCTION

Composite pavements have been studied for many years and implemented globally in recent century. These pavements have many advantages including long life, low maintenance necessity, and enhanced driving quality. Integrating the layers of composite pavements may result in their good performance. Sufficient bonding between layers of pavement leads less shear deformation, enhanced elastic recovery performance, and less permanent deformation [1], and thereby expecting longer life for composite pavements. On the other hand, low bonding between the layers can result in sliding the layers over each other and reducing the shear strength between pavement layers, leading to the reduced load transfer capacity. All these factors lead to the occurrence of cracking, rutting and shoving on the pavement. Previous studies have indicated that weak bonding in the interface can cause one-sixth to five-sixths reductions in pavement life [2]. Muench and Moomaw [3] reported the occurrence of separation between the layers of composite pavement due to the weak tack-coat between the layers, penetration of water into the cracks, and insufficient compaction of layers. One of the methods commonly used for increasing the bonding between the pavement layers is incorporating an interlayer of tack-coat between the pavement layers [4]. Huang et al. [5] studied the effects of surface characteristics and different types of tack coats and reported that, for the optimal tack coat dosage, the shear strength reaches its maximum value and then decreases. The study also showed that emulsion bitumen or asphalt rubber provided a suitable performance in concrete pavement [5]. Hou et al. [6] conducted a study on the modified tack coat in the composite pavement and showed that the shear strength of the interlayer with a modified tack coat increased by 69%. Also, they showed that the shear strength of the modified tack coat was higher than that of control bitumen [6].

Surface characteristics such as cleanliness, moisture, and roughness can significantly affect the adhesion of the composite pavement layers [7]. In this context,

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macrotexture (0.5 to 50 mm) and microtexture (<0.5 mm) of pavement surfaces can seriously influence interface bonding of composite pavement layers such that the shear strength will be higher if the surface is rougher [8]. Song et al. [9] indicated the effects of mixture type of underlying layer, temperature, and tack coat application rate on the interface shear strength. They found that at intermediate temperatures, tack coat application rate played a significant role in determining shear strength while at intermediate to high temperatures, surface texture depth had a significant effect on shear strength. Finally, the texture depth of underlying layer on the shear strength was affected by the tack coat rate [9].

Industrial and agricultural waste materials have adverse effects on the environment. However, using these materials has advantages because they improve the mechanical properties of the concrete pavement [10, 11]. During the road constructions, it is possible to increase the use of recycled materials instead of aggregates from mountains or riverbed. One of the recycled materials of the steel industry is steel slag. More than three million tons of steel slag is produced annually in Iran, most deposited in large quantities. Approximately, 50% of slag production in Iran is from electric arc furnaces (EAF) [12]. Allocation of this space can lead to heavy financial costs for factories. In addition to occupying a huge amount of plant space and environmental degradation, due to the presence of some heavy metals within the composition of this product, scouring steel slag can also be dangerous for groundwater resources. The desirable physical and mechanical properties of steel slag aggregate include high compressive strength and abrasion resistance, high internal friction angle, angular shape, and roughness and can be used as aggregate in pavement layers [12]. The environmental problems of slag deposits in the steel manufacturing complex, on one hand, and the lack of suitable aggregate resources in the road industry, on the other hand, necessitates replacing natural aggregates with these slags. Steel slag contains angular crushed aggregates with rough surfaces. Generally, these aggregates are 100% broken on both sides and do not have flaky or elongated aggregate. Thus, they have a proper interlock and their friction angle is high (about 45°). Saxena and Tembhurkar [13] compared the properties of fresh and hardened concrete containing 15, 25, 50, 75, and 100% replacement of coarse-grain with steel slag and wastewater. They concluded that the replacement of 50% of basalt aggregate with steel slag aggregates increased compressive strength, flexural strength, and modulus of elasticity of concrete at the age of 28 days by 33, 9.8, and 22%, respectively [13]. Studies have also been conducted on the application of steel slag in asphalt mixtures. The results of this research have shown that the use of steel slag could increase the strength of the mixture against moisture sensitivity [14-15], resistance to fatigue cracking [16], permanent deformation [15], and resistance to rutting and dynamic creep [17].

The studies conducted on the interface of composite pavement layers indicated that the type and amount of tack-coat material, as well as the surface pavement of underlying layer, are among the factors most effective on the bonding of composite pavement layers. Hence, the present was conducted to explore the possibility of using steel slag as crushed aggregates with rough texture in the composite pavement to increase the roughness and friction between concert and asphalt layers, thereby increasing the shear strength of composite pavement. Furthermore, different types of modified bitumen tack-coat with various application rate were applied to enhance the shear strength of composite pavement layers.

2. EXPERIMENTAL PROGRAM

2. 1. Methodology

This study considered two approaches for enhancing the bonding between reinforced concrete and asphalt overlay. In the first step, concrete pavement roughness can be raised to increase the bonding between the composite pavement layers because the steel slag induces a rough surface texture, a high angle of internal friction, high specific gravity, and angular shape. Therefore, the aggregates in the concrete pavement were replaced by various percentages of steel slag (25, 50, 75 and 100%). To obtain the optimum percentage, the texture depth test was performed on all specimens in compliance with ASTM E 965 and the abrasion resistance test was performed in accordance with EN 1338. In the second step, to assess the effects of different tack coats, including control bitumen and crumb rubber modified bitumen (CRMB), the crumb rubber bitumen contains hydrated lime (CR/HL), direct shear test was conducted using application rates of 0.3, 0.6, 0.9, 1.2, and 1.5 l/m^2.

2. 2. Materials and Specimen Preparation

In this study, a Superpave PG 64-16 bitumen (provided by Akam-bitumen Co.) was used to prepare specimens. In addition, siliceous aggregates with continuous gradation type 5 based on flexible Pavement design manual of Iran [18] made up the overlay layer. The physical and mechanical properties of aggregates are given in Table 1. Othman [19] used 3% of hydrated lime (HL) by mass of asphalt mixture and 15% of crumb rubber (CR) to modify the binder. In this study, the added 3% hydrate lime by mass of asphalt mixture. The CR was manufactured from waste tires by a grinding process at ambient temperature, and the size of the added CR particles fell between 0 and 1 mm. The amount of added CR was considered to be 15% of the asphalt binder [20]. The bitumen containing CR and HL was mixed for 60 minutes at a mixer rate of 5000 rpm and a controlled temperature of 175°C. The reaction time was considered to be high due to the specific surface area of material and the irregular shapes of the CR particles.

Furthermore, in this research coarse-grained and fine-grained aggregates, cement and steel slag are used. The coarse-grained size used in this study is 4.75 to 19 millimeters. In Figure 1, the coarse-grained and fine-grained curve of the existing experimental materials is presented according to ASTM C33 standard. The cement used is typical type-II Portland cement manufactured by Shahrood Cement Factory. The slag used in this study is manufactured by electric arc furnace (EAF) in Mobarakeh Steel Co., (Isfahan, Iran). The specific gravity of the slag is 3.02 grams per cubic centimeter and the abrasion of Los Angeles is 12.1%.

The mix design of concrete specimens is summarized in Table 2. These specimens were prepared using a mechanical mixer and are poured into special molds for each test. In order to compact the specimens, a standard rod and then a vibrating table was used. After mixing, the specimens were kept under laboratory conditions for 24 hours. Next, the specimens are taken out of the mold and treated in water ponds at a temperature range of 22-25℃ for 28 days. In each mix design of the three specimens, the cylindrical compressive and tensile strengths of 300×150 mm, a 100×100×500 mm prismatic beam were made to determine the flexural strength of the concrete. Also, to carry out the abrasion test using EN 1338, a specimen with dimensions of 150 mm (L) ×60mm (W) ×100mm (H) was used. Two-layer composite pavement specimens were designed using a special mold 120 mm high with an internal diameter of 100 mm. In this mold, a steel slag reinforced concrete specimen with a height of 76.2 mm and a diameter of 100 mm was placed on the lower part. Next, tack coat materials of control bitumen (PG 64-16), CRMB (PG 70-16), and CR/HL (PG 76-22) in amounts of 0.3, 0.6, 0.9, 1.2, and 1.5 l/m^2 were spread on the interface between the two layers using a brush. The asphalt mixture was then immediately poured on the concrete specimen inside the special mold and the upper layer was tapped by 125 impacts using a Marshall Hammer to reach the required air percentages corresponding to 98% of the Marshall density [21]. Figure 2 shows the construction of a two-layer composite specimen and a view of composite specimens after the opening of the mold.

TABLE 1. Physical and mechanical properties of aggregates

Test	Standard	aggregate		Steel slag	
		coarse	Fine	coarse	Fine
Bulk specific gravity	ASTM C127	2.71		3.04	
	ASTM C128		2.63		2.95
Water absorption (%)	ASTM C127	1.25	1.7	1.85	2.2
Sand equivalent	AASHTO T-167		69.5		76.4
Los Angeles coefficient	ASTM C131	18		12	

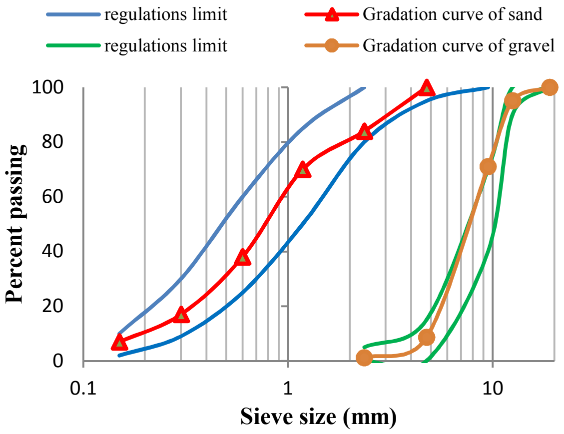

Figure 1. Gradation curve of fine and coarse aggregates

2. 3. Test Method

The abrasion resistance test was carried out according to the method specified in BS EN1338 on 28-days specimens obtained from the cutting of prismatic specimens. To evaluate the effect of underlying concrete layer properties on the friction between the reinforced concrete and the asphalt layers, a sand patch test was performed (ASTM E 965). Determining the surface texture depth based on the ratio of a certain volume of sand to the total surface covered by the material is a suitable method for asphalt and concrete pavement surfaces with a texture depth greater than 0.25 mm.

The two-layer specimens were placed in room temperature to be cooled, and after 24 hours of treatment,

TABLE 2. Mix design used in this research

Series	Cement	Additives		Gravel	Sand	Water
Control	400			987	808	160
SL-25	400	Slag aggregate	25	740	808	160
SL-50	400		50	493.5	808	160
SL-75	400		75	740	808	160
SL-100	400		100	987	808	160

Figure 2. Manufacturing composite pavement specimens

they were placed in an environment of 25 °C in a direct shear mold device. The interface of a double-layered specimen was carefully arranged in the gap between the specimens and fixed in place. After assuring correct placing of the specimens, a vertical force was applied at a speed of 50 mm/min. Finally, the device plots the applied force in terms of fixed frequency displacement and produces graphs and calculated shear strength. The direct shear fatigue apparatus consists of four semi-circular steel rings installed on Universal Testing Machine (UTM) device and used as the shear force source, with shear force loading and displacements recorded at a specified frequency during each cycle. This test was loaded using a sinusoidal cycle based on a stress control mode and performed at 10 Hz frequency and 25 ˚C on composite specimens. This test is performed three times specimen at stress level of 0.4 MPa based on shear strength test of direct shear specimens [22].

3. RESULTS AND DISCUSSIONS

3. 1. Effect of Steel Slag on Mechanical Properties of Concrete

The compressive strength of concrete specimens containing slag was determined on 28 days after curing. The test results are shown in Figure 3. The test results indicate that the compressive strength of mix concretes contains slag with 25, 50, 75, and 100% coarse grains replacement with slag increased compared to the control concrete. Generally, with the increase in the amount of aggregate replacement with steel slag, compressive strength is initially increased and then reduced. For example, the replacement of 50% aggregate with slag in the water-to-cement ratio of 0.40 resulted in a 56.4% strength increase. Substituting 100% of aggregates by slag have led to a 5.77% decrease in strength relative to the optimal amount. Because the minimum compressive strength required for concrete pavement is 27.6 MPa in the ACI 325.10R-99 code, the compressive strength of the specimens is more than the concrete pavement design criterion. There are three areas in concrete that failure in any of them lead to the failure of the specimen. One of the causes of increased compressive strength can be the pozzolanic effect of steel slag. At early ages, slag slowly reacts with the released calcium hydroxide during cement hydration and does significantly contribute to the compacting of the concrete matrix at the early ages [23].

The effect of steel slag on the concrete splitting tensile strength is shown in Figure 4. As can be seen, the overall trend of changes in tensile strength is incremental. Tensile strength increased slightly by increasing the percentage of slag as a substitute for aggregate in concrete. Meanwhile, the tensile strength of the reinforced specimens increased compared to the control specimen. Therefore, with increasing slag from 25 to 50%, the tensile strength was improved by 15%. Also, the replacement of 50 and 100% of aggregate with slag resulted in 26 and 12% increase in tensile strength, respectively. This increase is attributed to the enhanced tensile strength due to adhesion between the paste and aggregate and pozzolan reaction.

Figure 4 presents the flexural strength behavior of concrete containing steel slag. As can be observed, by increasing the amount of aggregate replacement by steel slag, the flexural strength initially increases and then decreases such that the 50% slag replacement increased by 16% compared to the control concrete. It is worth mentioning that considering the cheaper price of slag than natural aggregates, the use of slag in concrete pavement reduces the cost of construction and total expenditure.

3. 2. Abrasion Resistance and Texture Depth of Reinforced Concrete

To evaluate the abrasion of concrete, the abrasion resistance test is carried out by a rotating cylinder. Accordingly, the device conforming to EN 1338 standard was used and is applied to evaluate the abrasion of concrete (Figure 5). The surface abrasion of a concrete block with mentioned dimensions was performed by a rotating cylinder with an abrasive material under standard conditions. The worn width of the concrete specimens is shown in Figure 6. As can be noticed, there is a significant difference between the

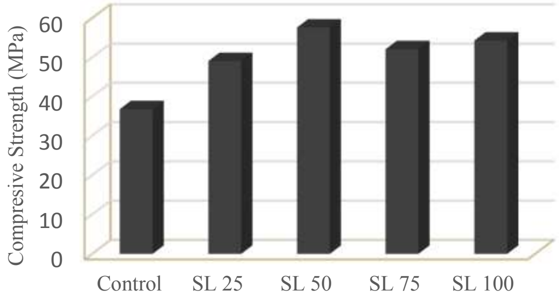

Figure 3. Bar chart compressive strength of concrete containing Steel Slag

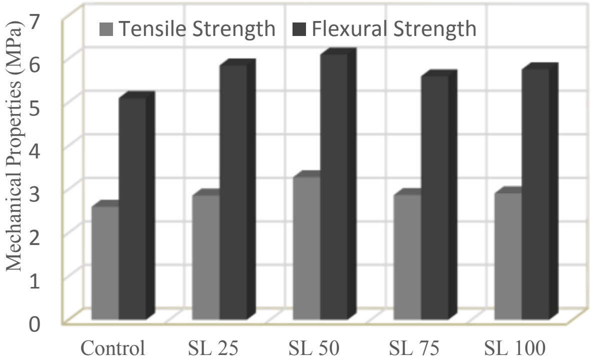

Figure 4. Bar chart mechanical properties of concrete containing Steel Slag

amount of abrasion of the control and slag-reinforced specimens. The abrasion of the concrete specimen containing 50% slag was increased by 25% compared to the control specimen. In general, the width of the wearing of the specimens is between 15 and 23 mm. Also, the abrasion of a concrete specimen containing 50% steel slag was not significantly different from steel slag with replacements of 75 and 100%. In accordance with EN1338, the specimen contained 25% of the average abrasion category (category 2) of this standard. According to this standard, specimens containing 50, 75, and 100% steel slag in the concrete pavement are in the optimal category in terms of abrasion (abrasion widths less than 20 mm). As the results show, increasing the percentage of steel slag additive increases the abrasion resistance of the specimens. A 56.4% improvement in compressive strength and 25% in abrasion resistance is associated with the optimum point of 50% slag.

Figure 7 presents the effects of steel slag on the texture depth of concrete pavement. As can be observed, there is a significant difference in terms of texture depth between specimens containing the steel slag aggregate and the natural aggregate. Thus, it can be inferred that, because of its physical properties and high wear resistance as well as its angular and broken shapes, steel slag has a greater depth of texture. In general, the texture depth of the specimens was between 0.4 and 2.2 mm, and SL-50% specimen's texture depth was increased by about 30% compared to the control specimen. The results also indicated that the texture depth of SL-75% and SL-100% specimens was increased slightly compared to that of the SL-50% specimen. A study conducted by Song et al. [9] non the optimal rate of tack coat and texture depth revealed that a higher texture depth leads to a more optimal tack coat rate, and higher shear strength is created on the interface between the upper layer and underlying layer. Therefore, in this study, to make a composite specimen, the concrete pavement reinforced with steel slag, which had a larger texture depth, was used to create a stronger bond between the upper layer and the underlying layer, resulting in greater shear strength at the layer interface. These results showed that selecting the pavement with a rougher surface, the specimen containing 50% of steel slag should be selected as an economically justified material for increasing adhesion between layers in a rigid-flexible composite pavement.

Figure 5. The test procedure of abrasion resistance according to EN 1338 and the grooved width of the specimens

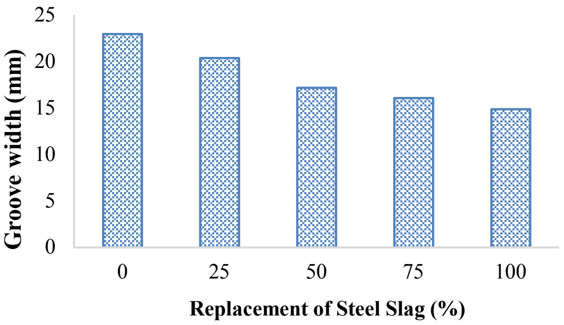

Figure 6. Effect of steel slag on the abrasion resistance of concrete pavement

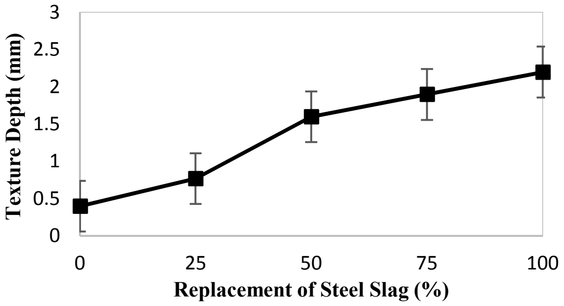

Figure 7. Texture depth results for different steel slag aggregate percentages

Therefore, according to the above results, the specimen containing a replacement of 50% slag instead of aggregate is more appropriate in terms of mechanical and abrasion properties and cost. Hence, it can be used in reinforced concrete and asphaltic pavement to increase the adhesion between the two layers and to select the lower surface with rough surfaces.

3. 3. Effects of Bitumen Type and Tack Coat Rate Between Pavement Layers

3. 3. 1. Interlayer Shear Strength and Shear Fatigue of Modified Asphalt Binders

As mentioned above, the type and rate of tack coat applied on the substrate surface of composite pavement play an important role in the shear strength between concrete and asphalt overlay. Therefore, in this study, the tack coat types including control bitumen (PG 64-16), CRMB (PG 70-16), and CR/HL (PG 70-22) were investigated. Also, the mentioned tack coat rates are 0.3, 0.6, 0.9, 1.2 and 1.5 l/m^2.

Three important factors affecting the shear strength of the pavement interlayer include friction, interlock of the aggregates, and bonding strength of layers [24]. In this research, the upper and underlying layers are composed of two different materials (the concrete base and asphalt overlay), suggesting that the bonding strength will have more effect on the friction and interlock of the aggregates. In this section, the tack coat used between the concrete and asphalt layers is analyzed and the adhesive performance of the tack coat is evaluated. Figure 8 presents the tack coat rate of control bitumen vs. the interface shear strength. As can be noticed, the higher rate of applied control bitumen increases shear strength initially and reduces it, afterward. These results show that a higher rate of bitumen usage does not necessarily mean increasing shear strength between layers. Obviously, the additional bitumen causes the surface of the concrete to be saturated and additional amounts on the surface to reduce the strength. According to the obtained results, the optimum rate of tack coat of the control bitumen is 0.9 l/m^2, at which the highest shear strength is obtained.

Temperature has an important role in the shear strength of composite pavement layers. At 25°C, the tack coat plays an important role in the shear strength between composite pavement layers. However, at a temperature higher than 60°C, the change in the use of tack coat rate does not significantly affect the shear strength [24]. Figure 8 presents the effect of the rate of using CRMB and CR/HL as tack coat against the shear strength of composite pavement. According to Figure 8, it can be seen that with increasing the amount of CRMB, the shear strength initially increases and then begins to decrease. It is important to note that when the tack coat spreads on a concrete layer, it starts to reduce slightly and does not cover the whole surface, and thereby the shear strength increases insignificantly. With increasing tack coat, the shear strength increased significantly, and this upward trend continues to some extent. When the amount of tack coat is more than 1.2 l/m^2, the shear strength is reduced significantly and the concrete and asphalt layers skid on each other.

It can be seen from Figure 8 that the optimum tack coat rate for CR/HL is 0.9 l/m^2. When there is little tack coat on the surface, the shear strength does not increase significantly. However, when the amount of bitumen spread over the surface is excessive, the two layers slide on each other with the least force. As can be seen, the amount of shear strength of the tack coat in the amount of 1.5 l/m^2 is less than the other specimens. However, in the case of using an extra tack coat on a concrete pavement, a shear sliding is created at the interface between the two layers and the shear strength decreases significantly. According to the obtained results, the shear strength of the CR/HL was improved compared with the control bitumen (PG 64-16). One of the reasons for this strength increase may be the higher adhesion of modified bitumen than normal bitumen and its proper spread is on the rough texture of the concrete pavement.

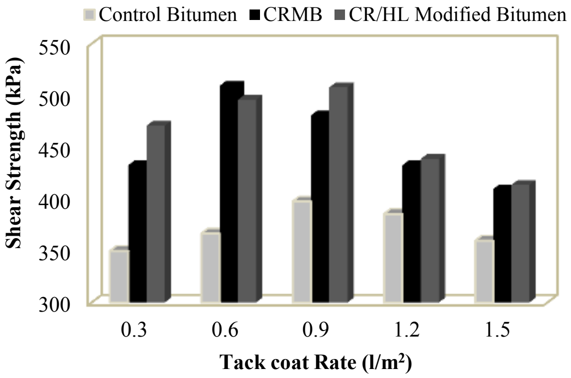

Figure 8. Effect of tack coat rate on shear strength at different tack coats

Fatigue life of concrete-asphalt composite specimen was determined for different percentages of bituminous interlayers in accordance with a 50% stiffness reduction method. Figure 9 depicts the fatigue life of concrete and asphalt specimens for 0.4 MPa stress level and different percentages of tack coat. As can be seen, the tack coat type utilized significantly affects composite pavement performance. For equal values of tack coats, the number of cycles leading to failure is increased in CR/HL modified bitumen tack coats compared to the CRMB and control specimen. The significant increase in the number of cycles leading to failure in CR/HL modified specimens confirms the fatigue parameter (G*.Sinδ) results obtained from DSR testing for modified bitumen specimens. According to Figure 9, after a significant increase in the number of cycles leading to failure at the optimal application rate, the between-layers tack coat temperature was raised due to the cyclic loading and, consequently, the tack coat became more a lubricant rather than a binder agent [22]. Certainly, the number of cycles leading to failure was increased more in field performance by increasing the amount of tack coat, because there was a longer rest period between traffic loads so that the atmosphere can overcome the heat generated between composite pavement layers [22]. The results show that an optimal value of 0.9 l/m^2 is achieved at a stress level of 0.4. For example, according to Figure 9, in a composite specimen with a CR/HL 3% tack coat of 0.9 l/m^2, the number of cycles resulted in the failure was 4746, which enhanced the fatigue life by 10% compared to that of the CRMB specimen. As can be seen, the stress level of 0.4 results for CRMB specimen and the optimum value of 0.9 l/m^2 leads to failure at a cycle number of 4480, which increase the fatigue life by 75% in comparison to the control specimen.

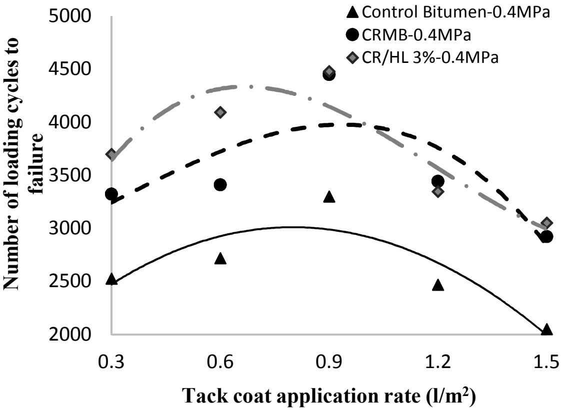

Figure 9. Fatigue lifetime results based on the 50% reduction method of different tack coat (Control, CRMB, and CR/HL) on the concrete pavement at 0.4 MPa stress level

4. CONCLUSIONS

A laboratory study was conducted to investigate the effects of surface characteristics and modified asphalt binders on the shear strength between asphalt overlay and concrete base. The main results of the present study can be outlined as follows:

- Due to the minimum compressive strength specified in ACI 325.10R-99 for concrete pavements, in this study the compressive strength of the specimens is more than the concrete pavement design criterion. Therefore, the compressive strength of concrete containing steel slag is 56% more than control specimen and a steel slag of 50% was considered as optimum value. For 50% replacement of steel slag, the tensile strength and flexural strength of concrete pavement increases by 26 and 16%, respectively.
- One of the objectives of this research is to increase the adhesion between concrete and asphalt pavement by increasing the concrete roughness using steel slag. The results showed that for 50% replacement of steel slag, the abrasion resistance and texture depth of concrete pavement increases by 25 and 30%, respectively. Therefore, 50%-steel slag was used in the concrete pavement to increase shear strength composite pavement.
- CR/HL modified bitumen is recommended as the optimal interlayer material because of its excellent adhesive performance. The optimum tack coat rate of CR/HL modified bitumen is 0.9 l/m^2.
- Generally, the shear strength order of the studied tack coats is as control bitumen< CRMB< CR/HL modified bitumen.
- The tack coat application rate also plays an important role in the shear strength and shear fatigue of the interface between the concrete base and the asphalt overlay. By increasing the tack coat application rate, the shear strength of the interface between layers was initially increased and then decreased. The optimum value of tack coat rate was 0.9 l/m^2 for CR/HL modified bitumen.

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Influences of Surface Characteristics and Modified Asphalt Binders on Interface Shear Strength

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چکیده

چسبندگی ضعیف بین لایه‌های روسازی باعث ایجاد خرابی‌های بسیاری در روسازی مرکب می‌شود. چسبندگی نقش مهمی در دوام و نگهداری لایه‌های روسازی مرکب ایفا می‌کند. این مطالعه فاکتورهای تاثیرگذار بر مقاومت چسبندگی سطح مشترک روسازی بتنی و روکش آسفالتی را بررسی کرده است. فاکتورهای درنظر گرفته شده شامل درصد سرباره فولاد در روسازی بتنی، انواع اندودهای سطحی مختلف و نرخ اندود سطحی می‌باشد. به منظور اندازه‌گیری خصوصیات چسبندگی از آزمایش‌های برش مستقیم و خستگی برشی و همچنین به منظور اندازه گیری خصوصیات زبری سطح روسازی بتنی حاوی سرباره فولاد از آزمایش عمق بافت و مقاومت سایشی طبق استاندارد EN 1338 استفاده شد. نتایج آزمایشات نشان داد جایگزینی ۵۰ درصد سرباره فولاد با سنگدانه سبب افزایش خصوصیات مکانیکی و افزایش عمق بافت رویه بتنی شده است. علاوه بر آن نتایج آزمایش مقاومت برشی روسازی مرکب نشان داد نرخ بهینه استفاده از اندود سطحی بین ۰/٦ و ۰/۹ لیتر بر مترمربع متغیر بوده و بستگی به نوع اندود سطحی دارد.همچنین مقاومت برشی بیشتری برای قیرپودرلاستیکی حاوی آهک هیدراته در مقایسه با قیر حاوی پودرلاستیک و قیر شاهد نشان داده شده است.

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