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Study on Frictional Properties of Mineral Aggregates through a Comprehensive Experimental Program

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Abstract: The objective of this study is to analyze the frictional properties of mineral aggregates after conducting a comprehensive experimental program. A total of 15 aggregate sources from five different regions in China were selected and tested using a specially-designed device stationed at the State Key Laboratory of Tribology in Tsinghua University. A total of 4 groups of experimental tests were performed to measure the aggregate frictional coefficients under different testing conditions. In the first group, a total of 25 tests were performed to study the impact of loading levels and rotational velocities of the rolling shaft on the measured frictional coefficients. The second and third groups of tests were conducted to study the dry and wet friction at the surfaces between the aggregate specimens and the outer ring of the rolling shaft with the milled sands pretreated. The fourth group of tests was performed to measure the dry friction at the surfaces between the aggregate specimens and the outer ring with the car tire rubber pretreated. From the experimental test results for most aggregate sources, it was observed that: 1) in the second and third groups of tests, both wet and dry frictional coefficients sharply increased at the beginning, then after their peak values the dry frictional coefficients kept constant while the wet frictional coefficients decreased smoothly over the testing time; 2) the wet frictional coefficients were lower than the dry frictional coefficients; 3) the dry frictional coefficients at the surfaces between aggregates and the milled sands were smaller than those at the surfaces between aggregates and the car tire rubber. However, the second and third observations above were not true for several individual aggregates tested.

***Key words**: Aggregate; Friction coefficient; Tribology; Pavement.*

Introduction

The skid resistance of a road surface is one of the fundamental requirements in pavement engineering. Pavement surface friction is a measure of pavement riding safety and plays an important role in reducing wet-pavement skid accident. According to the reference [1], 2,766 people died and 222,455 people were injured on Canadian roads in 2003 from a total of 156,904 police reported crashes, while 42,643 fatalities and about 2.9 million injuries were reported in 2000 from about 6.3 million traffic crashes in the United States. Researchers [2] concluded that uncontrolled skidding due to inadequate surface friction contributes to 15 to 35 percent of wet weather accidents. Some researchers [3] have pointed out that an improvement in average pavement surface friction coefficient by 0.1 can reduce the wet accident rate by 13%.

Obviously, skid resistance is a crucial safety issue in pavement engineering. To improve understandings of skid resistances, many studies have been performed on pavement surfaces or concrete materials. Researchers [4] developed a laboratory procedure and testing protocol to accelerate polishing of hot mix asphalt surface to evaluate changes in frictional characteristics as a function of the polishing effect. An attempt was made to approximate the pavement surface texture with fractals [5]. Through the fractal concepts, a qualitative relationship between the pavement surface texture and the skid resistance was recognized in that study. An effort was made in China to investigate possible pavement surface to provide long-lasting skid resistance [6]. In that study, accelerated abrasion device was developed to evaluate the skid resistance of porous concrete and open-graded friction course (OGFC). It is evidently true that tests on pavement surfaces or concrete materials provide more direct and persuasive results. However, at the same time, these limitations are obvious: 1) since too many factors could impact the testing result, it is hard to identify and interpret which factors are more important than the others. For example, toughness, sizes, angularity, and gradations of mineral aggregates, air voids, cement properties, and surface textures could influences the final result. 2) It is usually expensive to directly test pavement surfaces. Therefore, this kind of tests are useful for measuring a specific concrete or pavement surface, but they have limited capability for understanding and improving design of concrete material or pavement.

Instead of directly testing pavement or concrete, some researchers [4, 7] considered that mineral aggregate properties play an important role in resisting the polishing action of traffic and providing sufficient skid resistance. For Portland Cement Concrete (PCC) pavement, the cement paste provides the initial texture, but soon after the cement paste wears away, exposing the fine aggregate surfaces. Then, the fine aggregates are exposed at the PCC surface and this controls the micro-texture frictional properties. Later, some coarse aggregate may be exposed in high traffic areas. Therefore, many states in United States of America limit softer, high polishing limestone

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Table 1. No., Names, Locations, and Properties of the 15 Aggregate Sources.

Aggregate ID	Name	Location	Polish Value	L.A Abrasion	Impact Value (%)	Crushing Value (%)
A1	Basalt	Henan	41	4.63	5	11.7
A2	Basalt	Henan	45	4.65	6	11.65
A3	Basalt	Hebei	53	5.56	8	15.27
B1	Granite	Beijing	51	9.10	29	30.63
B2	Granite	Guangdong	49	5.15	16	20.98
C1	Limestone	Beijing	31	14.61	17	18.51
C2	Dolomite	Beijing	33	6.86	13	19.52
D1	Andesite	Beijing	50	5.09	14	17.36
D2	Andesite	Jiangsu	49	8.91	15	16.3
D3	Pyroxene Andesite	Beijing	47	4.94	9	13.58
E1	Quartz Sandstone	Beijing	47	5.36	15	18.51
E2	Sandstone	Beijing	61	16.11	14	18.06
F	Ignimbrite	Beijing	39	6.34	17	20.27
G	Diorite	Hebei	51	13.11	17	15.72
H	Diabase	Beijing	46	8.43	9	16.39

manufactured fine aggregates in PCC surface layers, or they require a blend with harder silica minerals. In asphalt pavement surfaces, or chip seals, initially, the asphalt cement is on the top of the mineral aggregate and provides the initial texture, but with traffic wear the aggregates will be exposed. Unlike PCC surfaces, the coarse aggregates in asphalt pavements are most likely to be exposed at the surface and provide the skid resistance. It is evident that mineral aggregates eventually are exposed on the pavement surfaces and provide the skid resistance in both the PCC and asphalt pavements. Essentially, the skid resistance properties of the aggregates are the key to a skid resistant pavement surface.

Objectives and Scope

Based on the background discussed above, the authors believe that the following three steps are indispensable in order to improve the understandings of skid resistances:

1) Measure and interpret frictional properties of mineral aggregates before mixing;
2) Measure frictional properties of pavement sections or concrete materials;
3) Link the measured mineral aggregate frictional properties to pavement skid resistances.

This paper focuses on the first step and the main objective is to seek deeper understandings of mineral aggregate frictional properties using experimental tests. The observations from this study may be used in the further research in order to build a link to pavement skid performance which is not addressed in this paper. The experimental tests were performed on 15 aggregate sources under four testing conditions which will be introduced in the following section.

Experimental Design

Aggregate Samples

Aggregate type and geographical location have a significant effect on the skidding resistance [4]: the same type of aggregates from different locations has different properties, while the same location may have different types of aggregates. Therefore, the authors tried to select various types of aggregates that have been utilized in various pavement engineering project locations of China. As shown in Table 1, a total of 15 aggregate sources were selected: Basalt, Granite, Limestone, Dolomite, Andesite, Pyroxene, Quartz, Sandstone, Ignimbrite, Diorite, and Diabase from five different parts of China (Henan, Hebei, Beijing, Guangdong, and Jiangsu). Those 15 aggregate sources were symbolized with A1, A2, A3, B1, B2, C1, C2, D1, D2, D3, E1, E2, F, G, H, and their properties were measured as listed in Table 1. The polish value, the L.A. abrasion, the impact value and the crushing value were measured using Aggregates Testing Standards in the People's Republic of China Profession Standards [8-11], and these methods are similar to the testing methods in British Standard, European standard and ASTM standard [8-11]. According to the Testing Standards, the polish value is PSV for short, a parameter to evaluate aggregate polishing resistance. Higher PSV indicates better skid resistance. When vehicles are in emergency brake or vibrating, they may impact pavement surface. In order to evaluate this kind of contacting behaviors between vehicle and pavement, the impact value is included in the Testing Standards. The crushing value is another parameter for charactering aggregate crushing resistance. L.A abrasion is also an internationally recognized parameter of aggregate characteristics.

Testing Equipment

The laboratory equipment was specially developed to measure the frictional properties of the 15 aggregate sources. The equipment consists of nine components as shown in Fig. 1. The aggregate specimen is a cylinder whose diameter and height are 22 mm and 15-20 mm, respectively. The support frame is used to stabilize the aggregate specimen during the test. The suspension weight B is used to apply the normal force on the aggregate specimen, while the suspension weight A is to pre-stress the stress sensor. As the test starts, the outer ring will rotate with the rolling shaft and interact with the aggregate specimen. The friction force is created between the two interacted entities. Then, from the stress sensor, the frictional force can be calculated. The lubricating agent (water) is

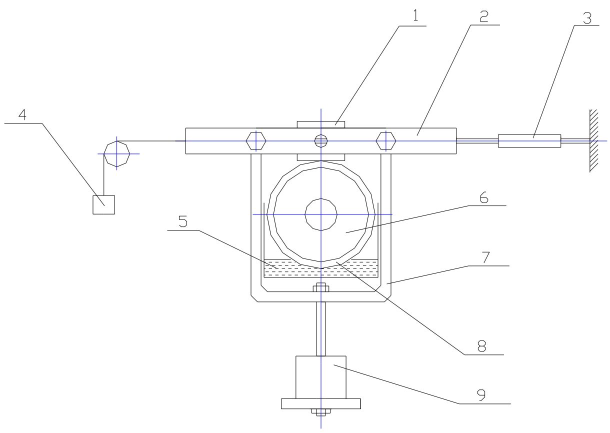

Fig. 1. Sketch Map of Testing Equipment (1. Aggregate Specimen; 2. Support Frame; 3. Stress Sensor; 4. Suspension Weight A; 5. Lubricating Agent; 6. Rolling Shaft; 7. Hook Rack; 8. Outer Ring of the Shaft; 9. Suspension Weight B).

put at the bottom of the hook rack in order to measure the frictional properties under the wet condition. Additionally, the outer ring is made of GCr15 which is a special steel with high strength and good performance. In order to increase the roughness for obtaining better testing results, the GCr15 outer ring was pretreated with the milled sands to increase the roughness in one group of tests. Additionally, in order to simulate the pavement and wheel tire interaction, the GCr15 outer ring was pretreated with tire rubbers in another group of tests. The testing results of the two groups were compared as stated in the subsequent sections.

It should be noted herein that this study was developed not to accurately predict frictional coefficients at pavement surfaces between pavements and vehicles, but to interpret and understand the frictional properties of mineral aggregates. Even though the pre-treated outer ring could not represent an actual vehicle wheel, it provided a rough surface which could be used to test mineral aggregate frictional properties. Additionally, since the rough surface had a constant frictional property, the testing results for mineral aggregates were more comparable and reliable.

Testing Conditions

In the current study, four groups of tests were performed as shown in Table 2. In the first three groups, the outer ring was pre-treated with the milled sands. The roughness of the outer ring with the pre-treated milled sands was 2.45μm. In the fourth group, the car tire rubber was attached on the outer ring to measure the frictional coefficients at the contacting surfaces between aggregate specimens and the tire rubber. In the third group, water was put at the bottom

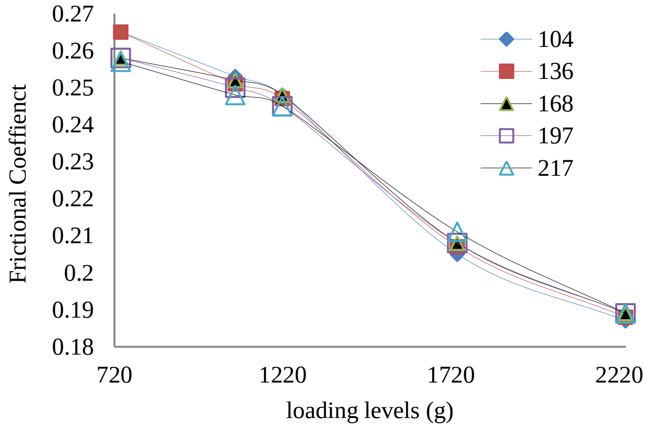

Fig. 2. Friction Coefficient vs. Loading Levels (Under the Five Rotational Velocities of the Rolling Shaft: 104, 136, 168, 197, and 217 rad/min).

of the hook rack as the lubricating agent to measure the wet friction, while the other three groups (1st, 2nd, and 4th) were designed to measure the dry friction. In the first group, a total of 25 tests were performed on the aggregate A3 under 5 levels of loads and 5 levels of rotational velocities of the rolling shaft as shown in the Table 2. In the other three groups (2nd, 3rd, and 4th), each of them had a total of 15 tests to measure the dry or wet frictional coefficients under the load level of 1220 g and 195 rad/min.

Results and Discussion

First Group Tests: Friction vs. Rotational Velocities and Load Levels on Aggregate A3

The target of the first group of tests is to study the impact of loading levels and rotational velocities on the measured frictional coefficients. As shown in Table 2, the load levels increased from 720 g to 2240 g, while the rotational velocities increased from 104 rad/min to 217 rad/min. Fig. 2 shows the measured frictional coefficients vs. the rotational velocities and the load levels. It was observed that: 1) as the rotational velocities increased from 104 rad/min to 217 rad/min, frictional coefficients were almost constants; 2) when the loading levels increased from 720 g to 2240 g, the frictional coefficients decreased by about 30%. Obviously, it could be inferred that: 1) the rotational velocities had a slight impact on the measurement of the frictional coefficients; 2) the loading levels could significantly impact the measurement. Different loading levels resulted in different frictional coefficients. It should be noted that the rotational velocities were varied in a small range from 104 rad/min to 217rad/min. If a wider range are selected in the further study, the observation may be different from the finding 1) above.

Table 2. Testing Conditions.

No.	Aggregate	Materials on the Outer Ring	Wet/ Dry	Load Level (g)	Rotational Velocity (rad/min)
1	A3	Milled Sands	Dry	5 Levels: 720/1080/1220/1740/2240	5 Levels: 104/136/168/197/217
2	All	Milled Sands	Dry	1220	195
3	All	Milled Sands	Wet	1220	195
4	All	Tire Rubber	Dry	1220	195

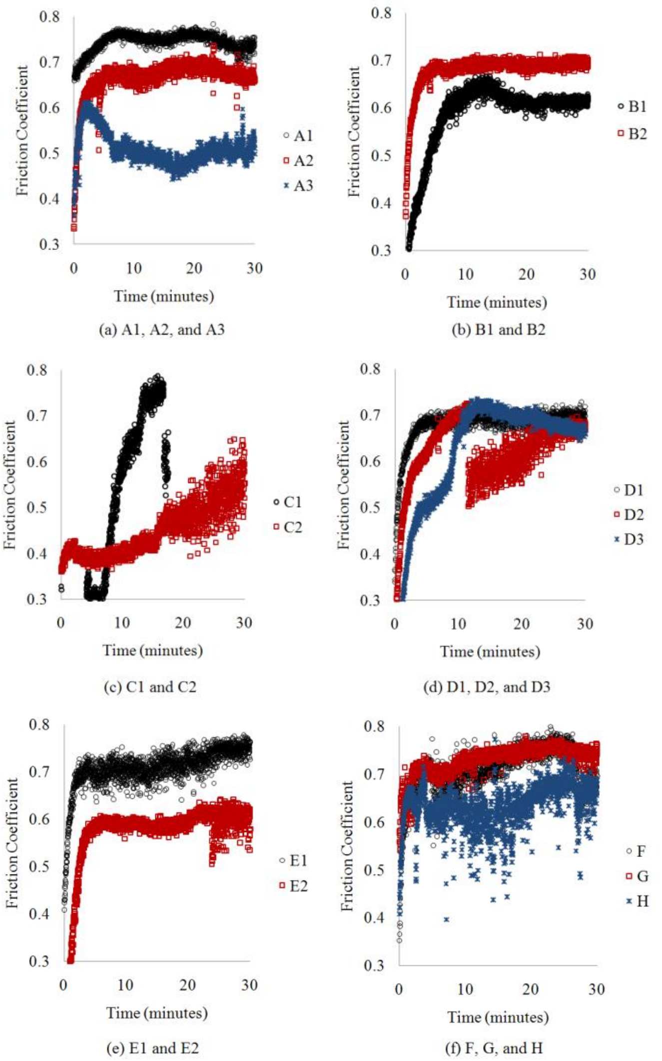

Fig. 3. Dry Friction Coefficients of the Fifteen Aggregate Sources During the Tests.

Since the first group of tests was designed to determine proper values of the rotational velocity and the loading level, the two findings above has been adequate to meet the research target.

Although the rotational velocities had minimal impact on the frictional coefficients, they must be large enough to provide the sufficient moment for rotating the rolling shaft. From several trial tests, 195 rad/min was selected for the other three groups of tests. Because the loading levels could give significant impact on the measurement results, in order to obtain the comparable results, the other three groups of tests were performed under the same loading level. As is well-known, the frictional force increases with the normal force. In other words, the larger loading level would result in the larger frictional force. Considering the scale limitation of the stress sensor, the loading level of 1220g was selected for the subsequent three groups of tests.

Second Group Tests: Dry Friction with the pre-treated Milled Sands

The second group of tests was performed on the 15 aggregate sources, where the outer ring was pre-treated with the milled sands. The target was to investigate the differences between the aggregate sources when they were polished with the milled sands. A total of 15 tests were performed under the rotational velocity of 195 rad/min and the loading level of 1220 g. Each test lasted 30 minutes. Fig. 3 is a plot of the frictional coefficients vs. the testing time. The observations were as follows:

1) As the loading time increases, the basic tendencies of Limestone (C1) and Dolomite (C2) were different from the other aggregate sources: a) During the test on C1 and C2, the frictional coefficient sharply decreased, then increased to their peak values before keeping constant; b) During tests on the remaining 13 aggregate sources, their frictional coefficients sharply increased to their peak values before keeping constants or slightly decreasing.
2) From Fig. 3 (a) three aggregate sources of Basalt (A1, A2, and A3) had completely different frictional coefficients. The authors tried to link their frictional coefficients with the corresponding engineering properties in Table 1 (such as the polish values, the abrasion values, etc.), but no clear relationships were observed. The similar findings were also observed for Granite (B1, B2) in Fig. 3 (b), and Sandstone (E1, E2) in Fig. 3(e).
3) Even though aggregate sources of Ignimbrite (F) and Diorite (G) had different types of mineralogical and engineering properties, their dry frictional properties were very close as shown in Fig. 3(f)

It should be noted that the test data of C1 and D2 were strange compared with the others. The explanations is given as follows:

1) C1 is Limestone which has less abrasive resistance. During interaction with the pre-treated outer ring, many tiny particles were dropped and resulted in abnormal frictional forces at the interaction surface. As a result, the measured frictional coefficients were abnormal. As shown in Fig. 4(c), this abnormal situation did not happen under wet frictional conditions.
2) The reason why the test data of D2 was strange was not clear. A possible reason could be that the aggregate surface was damaged during the test.

Third Group Tests: Wet Friction with the pre-treated Milled Sands

The third group of tests was performed on the 15 aggregate sources to measure the wet frictional coefficients. This group of tests was designed to study the differences of the 15 aggregate sources in term of wet frictional coefficients. Similar to the second group of tests, a total of 15 tests were performed under the rotational velocity of 195 rad/min and the loading level of 1220 g. The outer ring was pretreated with milled sands to increase the roughness. Each test lasted 30 minutes. Fig. 4 plotted the wet frictional coefficients vs. the testing time. The observations from the test results were:

1) As the loading time increases, the basic tendencies of Limestone (C1), Dolomite (C2), were different from the other aggregate sources. a) During the tests on C1 and C2, the frictional coefficient sharply decreased, then increased to their peak values, before keeping constant. b) The basic tendencies of the other aggregate sources were similar: beginning with a

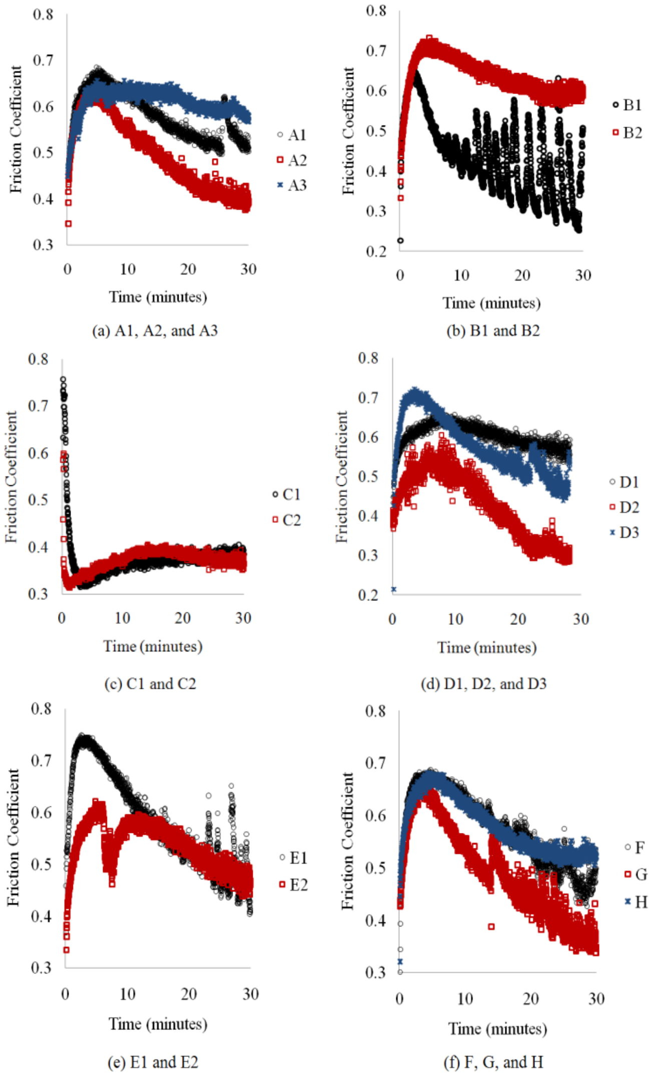

Fig. 4. Wet Friction Coefficients of the Fifteen Aggregate Sources During the Tests.

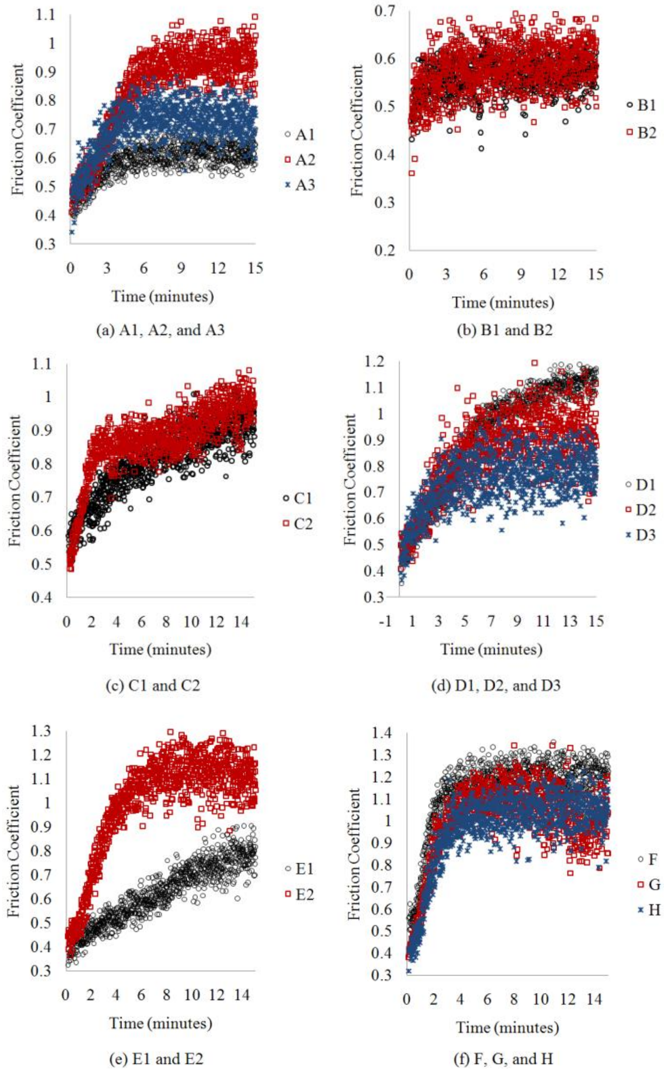

Fig. 5. Wet Friction Coefficients of the Fifteen Aggregate Sources During the Tests.

sharp increase to their peak value and then decreasing from their peak value.

2) From Fig. 4(a) three aggregate sources of Basalt (A1, A2, and A3) had completely different frictional coefficients, but there were no clear relationships between the measured frictional coefficients and their corresponding engineering properties (such as the polish values, the abrasion values, the impact values and the crushing values). These observations were also valid for Granite (B1, B2) in Fig. 3(b), and Sandstone (E1, E2) in Fig. 4(e).
3) Even though aggregate sources Ignimbrite (F) and Diabase (H) had different mineralogical and engineering properties, their wet frictional properties were very close as shown in Fig. 4(f).

It should be noted that the testing data of B1 and E1 were strange compared with the others. The authors believed that the special composition of B1 and E1 caused the abnormal observations for those two aggregate sources.

Fourth Group Tests: Dry Friction with Tire Rubber

The fourth group of tests was performed to measure the dry frictional coefficients of the 15 aggregate sources. This group of tests was to designed to investigate the difference among the 15 aggregate sources in term of dry frictional coefficients when they were interacted with the car tire rubber. Similar to the second and third group of tests, a total of 15 tests were performed under the rotational velocity of 195rad/min and the loading level of 1220 g. The outer ring was pretreated with the car tire rubber. Each test in this group lasted 15 minutes instead of 30 minutes. Fig. 5 plots the dry frictional coefficients vs. the testing time. The observations from the test results are:

1) All the measured frictional coefficients increased with the loading time before attaining a steady status.
2) From Fig. 5(a) three aggregate sources of Basalt (A1, A2, and A3) had different frictional coefficients, but there were no clear relationships between the measured frictional coefficients and their corresponding engineering properties (such as the polish values, the abrasion values, the impact values and the crushing values). These observations were also valid for Andesite (D1, D2, and D3) in Fig. 3(b), and Sandstone (E1, E2) in Fig. 5(e).

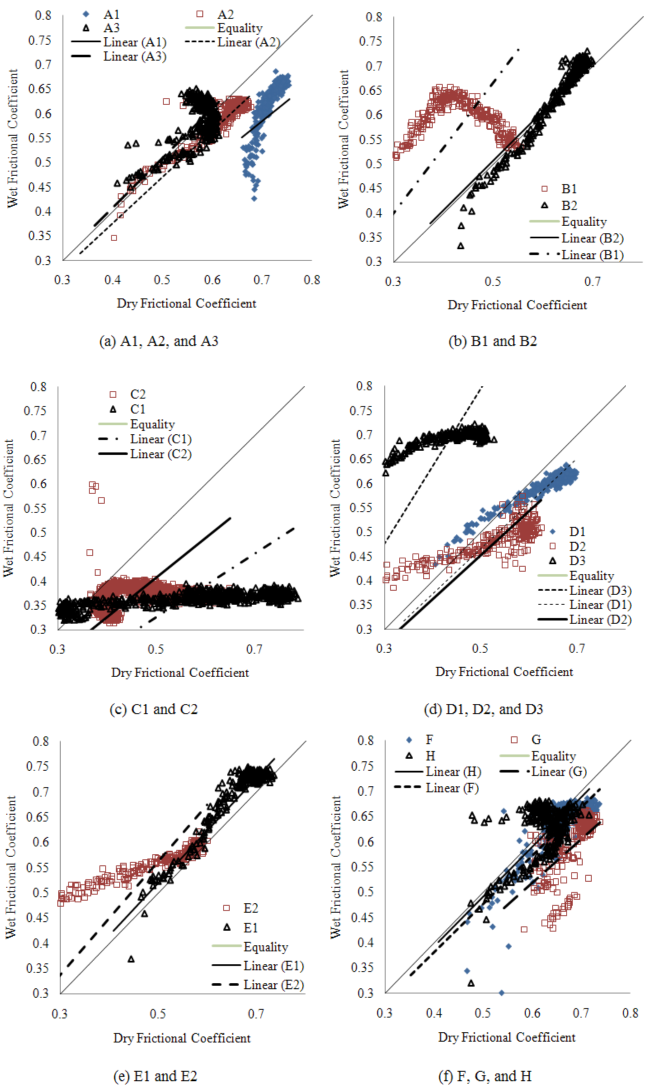

Fig. 6. Comparison between Wet and Dry Friction Coefficients at the Beginning of the Experimental Tests (Testing Time Less than 5 Minutes).

3) The two Granite aggregates (B1 and B2) had very close frictional coefficients and their curves were more flat than those of the other aggregates. Limestone (C1), Dolomite (C2) had very close frictional coefficients, but their curves increased over the testing time.

Comparison I: Dry and Wet Friction Coefficients

As discussed in the introduction, water is an important factor to impact the skidding resistance of pavement surfaces. This section presents a comparison between the dry and wet friction coefficients. Fig. 6 and 7 shows the comparison of the results:

1) At the beginning of the tests (testing time less than 5 minutes) shown in Fig. 6, even though the average wet frictional coefficients of most aggregate sources were smaller than their dry frictional coefficients, those of A3, B1, B2, D3, E1, and E2 were even larger than their dry frictional coefficients.
2) As the testing time becomes longer than 5 minutes as shown in Fig. 7, the average wet frictional coefficients of most aggregate sources were smaller than their dry frictional coefficients. However, for the aggregate source A3, the observation was contrary as shown in Fig. 7: its average wet frictional coefficient was larger than its average dry frictional coefficient by about 30%.

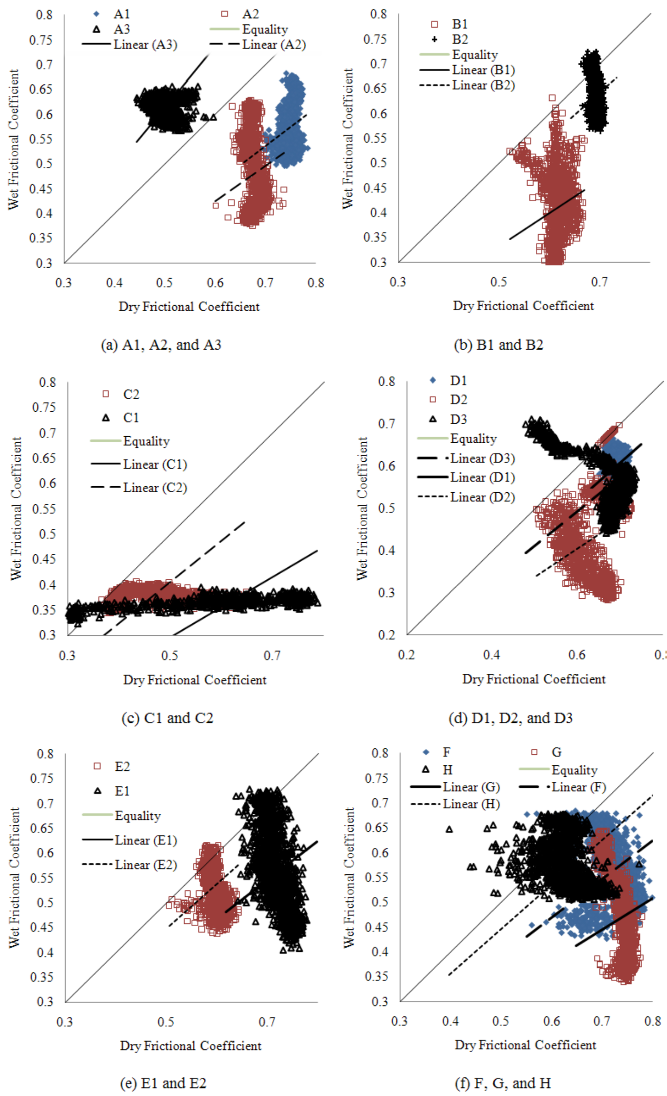

Fig. 7. Comparison between Wet and Dry Friction Coefficients at the Testing Time Longer than 5 Minutes.

Obviously, it could be concluded that: the wet friction for most aggregate sources was less than their dry friction, but this does not hold true for some aggregate sources (for example, A3).

Comparison II: Milled Sands and Car Tire Rubber

As discussed in the introduction, in reality, aggregate sources directly interact with the car tire rubbers. Fig. 8 and 9 provide the comparisons of the dry frictional coefficients from the second and fourth groups of tests. It was observed that:

1) At the beginning of the tests (testing time less than 5 minutes) as shown in Fig. 8, for aggregate sources of A1, B2 and E1, the average dry frictional coefficients with the car tire rubber were

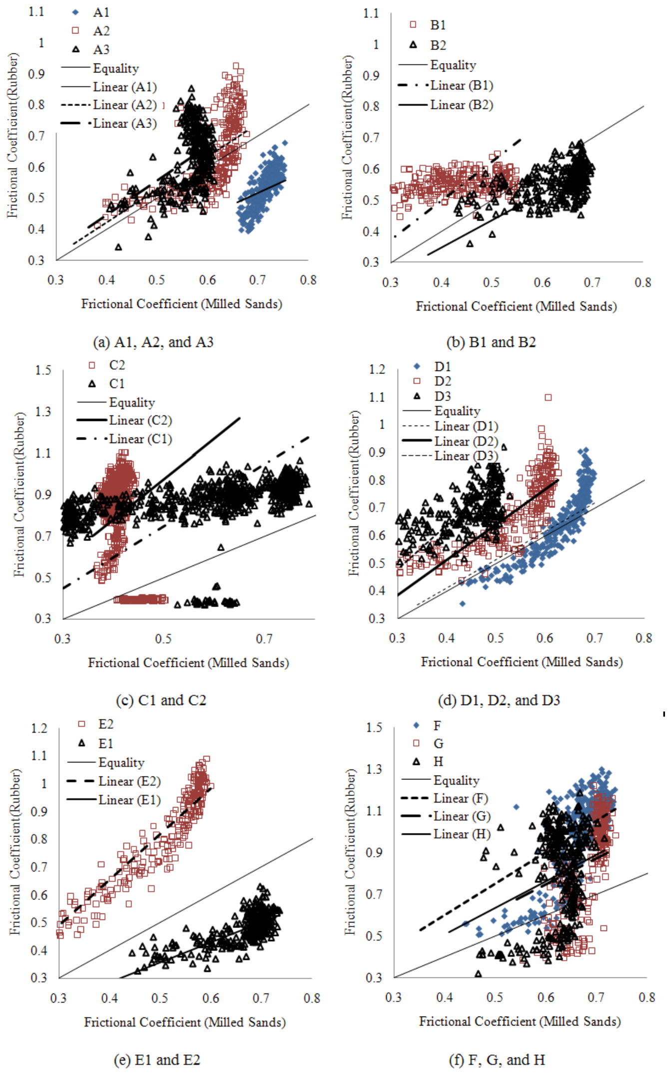

Fig. 8. Comparison between Wet and Dry Friction Coefficients at the Beginning of the Experimental Tests (Testing Time Less than 5 Minutes).

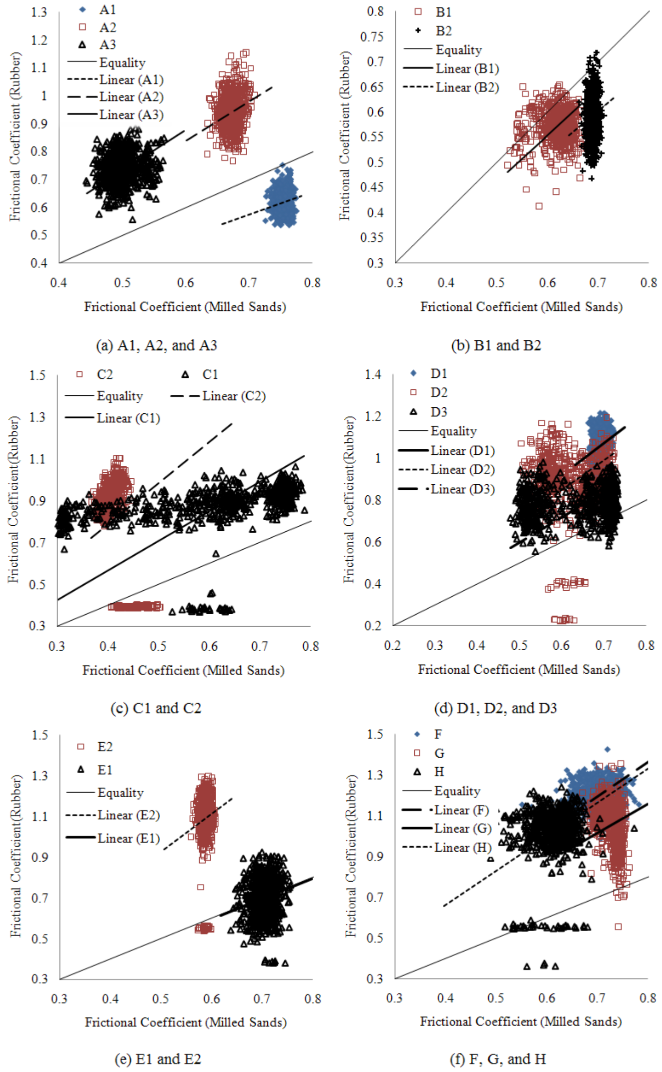

Fig. 9. Comparison between Wet and Dry Friction Coefficients at the Testing Time Longer than 5 Minutes.

even smaller than those with the milled sands. The opposite was true for the other 12 aggregate sources.

2) As the testing time becomes longer than 5 minutes as shown in Fig. 9, for aggregate sources of A1, B1, B2 and E1, the average dry frictional coefficients with the car tire rubber were even smaller than those with the milled sands. However, the opposite was true for the other 11 aggregate sources.

Therefore, it could be concluded that even though for most aggregate sources the average dry frictional coefficients with the car tire rubber were larger than those with the milled sands, the opposite was true for a few of aggregate sources (A1, B2 and E1 for example).

Summary and Conclusions

In this study, a total of 15 aggregate sources from five different regions of China were selected and tested using the specially developed device. The experimental tests were performed in four groups under different testing conditions. In the first group, a total of 25 tests were performed to study the impact of loading levels and the rotational velocities on the measured frictional coefficients. The second and the third groups of the tests were conducted to study the dry and wet friction between aggregate specimens and the steel with milled sands pre-treated, while the fourth group of the tests was performed to measure the dry friction between the aggregate specimens and the car tire rubber. The experimental test results were reported and discussed in the previous section. The following conclusions can be drawn:

1) From the first group of the tests, the rotational velocities had minimal impact on the measurement of the frictional coefficients, while the loading levels could significantly impact the measurement. Thus, it can be argued that the different loading levels resulted in different frictional coefficients. It should be noted that this finding was obtained through measuring individual aggregates instead of the pavement. Therefore, further studies are needed to validate this conclusion.

2) From the second group of the tests: a) For most aggregate sources, the dry frictional coefficients with the milled sands

sharply increased at the very beginning of the tests, then reached their peak values before keeping constant values. However, this does not hold true for the Limestone (C1) and Dolomite (C2). b) The same type of aggregates had very different values of frictional coefficients, while the different types of aggregates obtained very close frictional coefficients. For example, A1, A2 and A3 belong to Basalt, but they had very different frictional coefficients, while F (Ignimbrite) and G (Diorite) are completely different, but their frictional coefficients were very close.

3) From the third group of the tests: a) For all aggregate sources except for Limestone (C1), Dolomite (C2), the wet frictional coefficients with the milled sands sharply increased at the very beginning of the tests, then reached their peak values and finally decreased in trend. b) The same type of aggregates had the very different values of frictional coefficients, while the different types of aggregates had very close frictional coefficients. For example, A1, A2 and A3 belong to Basalt, but they had very different frictional coefficients, while F (Ignimbrite) and H (Diabase) are completely different, but their frictional coefficients were very close.
4) From the fourth group of tests, all the measured frictional coefficients increased with the loading time before attaining a steady status.
5) By comparing the wet and dry friction, the wet friction for most aggregate sources was less than their dry friction, but this is not true for some aggregate sources.
6) Even though for most aggregate sources the average dry frictional coefficients with the car tire rubber were larger than those with the milled sands, the opposite was true for a few aggregate sources.

It should be noted this research is more like rolling resistance rather than skidding resistance and the contact interface probably different from that on the real life pavement. However, this research provide Unique results of skid resistance of individual aggregates which may be used for deep understanding of real life pavement skid resistance. Future research will be undertaken to build the link between this research and the real life pavement conditions.

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