High Friction Surfacing Systems Using Blends of Natural Aggregate and Calcined Bauxite

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Abstract: High friction surfacing (HFS), bonded to a road surface at high risk locations, has been shown to significantly reduce road fatalities and serious injuries, i.e., HFS saves lives. Calcined bauxite is the preferred aggregate for use in HFS systems due to its unique ability to resist polishing and abrasion by vehicle tires. Calcined bauxite is expensive, negatively impacts the environment due to mining, production and transporting processes and has come under supply pressures in recent years. This paper investigates the potential for blending natural aggregates with calcined bauxite for use in HFS systems. The experiments involved subjecting HFS specimens to laboratory simulated trafficking and testing for skid resistance, texture depth and mass loss. The testing was carried out in laboratories in Spain and Northern Ireland. The findings suggest that there is the potential to reduce the amount of calcined bauxite used in HFS systems by replacing a percentage of the calcined bauxite with high PSV natural sandstone or volcanic tuff aggregate. The impact of this research could reduce the risks associated with supply issues to the HFS industry, reduce environmental impact by using less calcined bauxite in HFS systems and reduce costs associated with the aggregate component of HFS systems—enabling road authorities to install more systems at high risk locations to further reduce fatalities and serious injuries on their roads.

Keywords: high friction surfacing; polished stone value; calcined bauxite; blending aggregates; skid resistance; simulated trafficking

1. Introduction

The Global Status Report on Road Safety 2018, launched by the World Health Organization (WHO) in December 2018, highlights that the number of annual road traffic deaths has reached 1.35 million [1]. To put this in context, that is almost 4000 per day or 154 per hour or 2.5 lives lost every minute. Between 20 and 50 million more people suffer non-fatal injuries, with many incurring a disability because of their injury. The WHO further reported that, globally, traffic collisions cost most governments 3% of their gross domestic product.

High friction surfacing (HFS) saves lives. HFS, sometimes referred to as anti-skid, is a skid resistant surfacing system bonded to a pavement surface in areas where the risk of a vehicle skidding out of control is high. Examples would be approaches to traffic lights, pedestrian crossings, roundabouts, steep inclines and dangerous bends where sudden or excessive braking or cornering may be required. HFS systems give superior performance over other road surfacing materials in terms of skidding resistance (i.e., grip) and, as a result, increase road safety to the road user at high risk locations. Research has shown that the number of fatalities and serious injuries can be substantially reduced when HFS systems are installed at high risk locations [2–4].

The aggregate specified for use in HFS systems, calcined bauxite, is available in few locations throughout the world. Calcined bauxite has unique properties which gives it excellent performance in terms of skidding resistance. Geologically, the grade of bauxite suitable for use in HFS systems is not available in parts of the world such as Europe or North America where demand is greatest. The two main sources are China and Guyana, in South America. As a result, calcined bauxite is expensive and has negative environmental impacts due to the processes involved, in mining the raw bauxite, in the calcination process involved in altering the bauxite properties to give it unique skid resistance properties, and in the shipping and other transport costs involved to get to its desired locations around the world.

The HFS industry in the UK, USA and Ireland use refractory grade calcined bauxite imported predominantly from China. Other sources include Guyana and India. It is estimated that China produces 95% of the globe's refractory bauxite for various industries [5]. In recent years the calcined bauxite industry in China has undergone considerable change due to a range of political, environmental and economic factors. As part of Chinese government policy to clean up the environment and build a moderately prosperous society by 2020 [6], a new environmental tax law has been implemented. The new law has resulted in a series of strict environmental inspections on mineral producing facilities to reduce industrial pollution levels and crack down on illegal mining operations. Throughout 2017 and 2018 environmental inspections led to many calcined bauxite production facilities being either temporarily or permanently shut down [7].

The closures were related to the requirements for the industry to upgrade its calcining facilities, at a considerable cost. The costs associated with the Government's drive to upgrade production plants from coal to natural gas fired kilns has led to many producers being forced to close their businesses [8]. Furthermore, the crackdown on illegal businesses and the stricter controls on the use of explosives have further compounded the industry. All these factors have inevitably led to supply shortages which have resulted in price rises within the market. Calcined bauxite is predicted to experience continued tight supply and high prices throughout 2019. Although refractory bauxite is currently excluded from US trade tariffs, there is the risk over the coming years that the implementation of such tariffs, due to a US-China trade war, could lead to further price increases and volatility within the bauxite market [5].

Several studies in the US have investigated the potential use of alternative aggregates in HFS systems by comparing each aggregate's performance to that of calcined bauxite. The general conclusions from these studies show that calcined bauxite maintains higher levels of friction for longer periods of time than all other alternative aggregates investigated. The Texas A and M Transportation Institute undertook a laboratory study to compare the performance of a sandstone aggregate as a potential alternative to calcined bauxite [9]. Although the sandstone had good frictional properties, it did not perform as good as calcined bauxite. The authors also highlighted the high micro-deval mass loss as a concern for the performance of the softer sandstone. A research study sponsored by the Indiana Department of Transportation compared the laboratory and field performance of steel slag as a potential alternative to calcined bauxite [10]. After completion of cyclical polishing, the laboratory findings showed that friction was reduced by 8% and 4% for steel slag and calcined bauxite, respectively. The field data showed that, after nine months of service, the steel slag reduced friction by 45% and the calcined bauxite reduced in friction by 20%.

The National Center for Asphalt Technology (NCAT) at Auburn University conducted two studies into alternative aggregates for use in HFS systems. The first study compared the laboratory and field performance of seven alternative aggregates including: granite, flint, basalt, silica sand, steel slag, emery, and taconite [11]. The laboratory data showed that all seven aggregates performed worse than calcined bauxite. The field data found that calcined bauxite maintained higher friction levels over a 24-month period. Calcined bauxite friction values decreased from 70 to 64. Flint friction values decreased from 55 to 43. Granite friction values decreased from 55 to 40. The second study compared the laboratory performance of ten alternative aggregates including: basalt, copper slag, flint, feldspar,

three samples of calcined kaolin and three samples of quartz [12]. The laboratory data showed that calcined bauxite maintained higher friction values than all other alternative aggregates during testing.

A review of 50 years of UK road trial data and laboratory investigations also found that calcined bauxite is the only aggregate to consistently offer the highest levels of performance for the longest period [13]. Natural aggregates with very good resistance to wear will polish and become slippery over time. Conversely, natural aggregates with very good resistance to polishing will abrade and wear away over time [14,15].

In 2017, the authors considered how in-service performance of HFS could be predicted in the laboratory and investigated the 100% replacement of calcined bauxite with a range of natural aggregates. The data showed that calcined bauxite outperformed all the natural aggregates with only one natural aggregate (sandstone) just meeting the British Board of Agrément (BBA) Type 1 specification requirements required in the UK. That paper also reviewed the use and certification of HFS in the UK. The work reported in 2017 led to the data reported in this paper which investigates whether there is a natural aggregate that could be blended with calcined bauxite for use in HFS systems and still be able to meet specification requirements.

The aim of this paper is to investigate the use of locally available natural aggregates found in the UK with calcined bauxite in HFS systems. This paper considers how the results from three separate laboratory experiments could potentially impact society, the economy and the environment. The three experiments are as follows:

- Experiment 1: Subject cold-applied HFS specimens of calcined bauxite, granite, sandstone and volcanic tuff, at various blend ratios, to simulated trafficking and test for skid resistance, texture depth and mass loss.
- Experiment 2: Subject hot-applied HFS specimens of calcined bauxite and high PSV sandstone, at various blend ratios, to simulated trafficking and test for skid resistance, texture depth and mass loss.
- Experiment 3: Subject cold-applied HFS specimens of calcined bauxite and high PSV sandstone, at various blend ratios, to simulated trafficking and test for skid resistance, texture depth and mass loss.

2. Materials and Methods

2.1. Aggregates Used in Experiments

The natural aggregates used in the experiments were sandstone from three separate sources (A, B and C), granite and volcanic tuff. There were three sources of calcined bauxite used in the experiments: buff colored Chinese calcined bauxite, grey colored Chinese calcined bauxite and grey colored Guyanese calcined bauxite. Each aggregate type was tested for loose bulk density [16], particle density and water absorption [17] prior to manufacture of test specimens. The polished stone value (PSV) [18] and aggregate abrasion value (AAV) [19] were declared values by the suppliers. Table 1 shows the PSV, AAV, bulk density, particle density and water absorption data for the aggregates used in the experiments.

Local authorities often select HFS systems to be aesthetically pleasing as well as for the obvious safety reasons. For this reason, the natural aggregates selected to be blended with each source of calcined bauxite were chosen based on predicted performance and for aesthetic reasons. For example, in Experiment 1, sandstone A was dark in colour and was blended with grey Chinese bauxite. Each aggregate blend was compared against a reference specimen which was 100% of the calcined bauxite used in the experiment.

Table 1. Aggregate properties

Aggregate Type	PSV (Declared)	AAV (Declared)	Bulk Density (kg/m^3)	Particle Density—Oven Dried (kg/m^3)	Water Absorption (%)
Chinese Calcined Bauxite Buff	>70	<4	1387	2629	6.8
Chinese Calcined Bauxite Grey	>70	<4	1674	3314	1.4
Guyana Calcined Bauxite Grey	>70	<4	1745	3490	2.3
Granite	55	2	1350	2619	0.3
Sandstone A	70	7.6	1353	2716	1.2
Sandstone B	70	6.4	1296	2524	2.4
Sandstone C	67	6.3	1272	2500	1.7
Volcanic Tuff	68	6	1344	2515	0.1

2.2. Specimen Manufacture

Thermosetting, more commonly known as cold-applied HFS systems, comprise a resin binder that is applied to a road surface and acts as an adhesive to hold 1–3 mm aggregates in place which provide high levels of friction. Binder systems include epoxy resin, polyurethane, polyurea or methyl methacrylate (MMA). After the resin binder is applied, an excess of the 1–3 mm aggregates are spread over the binder. After the resin is cured the excess or loose aggregates are removed by sweeping. For Experiment 1, test plates were supplied by Aetec Laboratories, Madrid, Spain. For Experiments 2 and 3, test slabs were supplied by Ulster University, Newtownabbey, UK. The test plates/slabs were brushed clean and taped off to provide adequate formwork to hold the binder in place. The binder component, used for each specimen in investigations 1 and 3, was a two-part epoxy resin.

The two components (A and B) of the epoxy system were thoroughly mixed at a ratio of 50:50 until homogenous. The epoxy binder was then spread evenly over the test plates/slabs using a serrated edged squeegee at a coverage rate of 1.8 kg/m^2. Aggregates of various blend ratios were then spread over each test plate/slab to excess. After initial curing over-night the excess was removed by brushing. The specimens were then left to fully cure. Figure 1a shows a newly laid HFS system on an approach to a roundabout in Ireland whilst Figure 1b shows a cold applied HFS specimen prior to simulated traffic testing in Experiment 1.

(a)   **(b)**

Figure 1. (**a**) Newly laid HFS system in Ireland; (**b**) cold applied HFS specimen used in Experiment 1.

Thermoplastic, more commonly known as hot-applied HFS systems, comprise a pre-mixed rosin ester binder and aggregate thermoplastic system. The mixture is heated to high temperatures in truck mounted boilers before being discharged into buckets and applied to a road surface in strips using a screed box. For Experiment 2 the test slabs were brushed clean and taped off to provide a neat edged finish. The mixture was heated in appropriate size pans in the laboratory to the recommended laying temperatures whilst being continuously and thoroughly mixed. The heated material was then transferred to a heated screed box and spread over the slab. The screed box was combed over the

material several times to ensure even distribution of aggregate and a well textured finish. The tape was removed before the specimens were left to fully cure over-night.

2.3. Simulated Trafficking and Testing

2.3.1. Wear Simulator Turntable

The wear simulator turntable located at Aetec Laboratories is primarily used to assess the performance of road marking materials [20]. The Turntable consists of a 6.4 m external diameter table that can rotate up to a maximum speed of 120 km/h. Up to eighteen test plate specimens can be mounted on the table. Four vertically mounted approved commercial tires with pressures of 0.25 ± 0.02 MPa run freely on the table at a steering angle of $1° \pm 10'$, applying a load of 3000 ± 300 N on the test specimens from each tire.

The wear simulator has a water dispenser to apply water over the test plates and a cleaning system to keep the specimens and tires clean. The turntable is enclosed in a temperature-controlled room where testing is carried out at 7.5 ± 2.5 °C. The agreed test intervals were: 0 wheel-passes (WP), 5000 WP, 40,000 WP, 100,000 WP, 200,000 WP, 500,000 WP, 1 million WP, and 1.5 million WP. For the first 500,000 WP a steering angle of $1° \pm 10'$ was used with the remainder of testing carried out at a steering angle of $1.5° \pm 10'$. For every hour of simulated trafficking on the turntable the following test conditions were maintained: 15 min of wet trafficking at 15 km/h followed by 45 min of dry trafficking at 60 km/h. The wear simulator Turntable is shown in Figure 2a.

| (a) | (b) |

Figure 2. (**a**) The wear simulator turntable located at Aetec Laboratories, Madrid; (**b**) the road test machine located at Ulster University.

2.3.2. Road Test Machine

Appendix H of the Transport Research Laboratory (TRL) Report 176 contains a generic description of the test equipment used to perform the wear test [21]. There is only one device available for use in the UK. This is known as the Road Test Machine 1 (RTM) and is shown in Figure 2b. This equipment was identified as being suitable to simulate trafficking and so predict wear resistance. The RTM is now located at Ulster University where it is used in the UK BBA process of HFS certification. The equipment is used to test other types of asphalt and concrete products under conditions of simulated wear. This allows direct comparison of HFS data with other types of asphalt or concrete products used as a road surfacing.

The RTM equipment consists of a 2.1 m diameter table that rotates at 10 RPM or 1.1 m/s. The table has spaces for mounting ten 305 mm × 305 mm × 50 mm test specimens. These are typically asphalt slabs made using a roller compacter unto which the HFS is applied. Two vertically mounted full size 195/70R14 tires run freely on the table each applying a load of approximately 5 kN. Tire inflation pressure is maintained at 2 bar or 30 psi. During testing the tires track back and forth across the width of the test specimen generating additional stress. The RTM is enclosed in a temperature-controlled

room with testing carried out at $10 \pm 2\,^{\circ}$C to avoid deformation of the test specimen. The wear test was carried out in a dry condition with no abrasive.

The Appendix H wear test method requires initial test values and after 100,000 wheel-passes, i.e., 50,000 rotations of the table. However, test values at the start and finish of accelerated testing do not adequately show what happens during the whole period of simulated trafficking. Understanding what happens during testing offers improved insight into time related changes which relate to in-service trafficking conditions. Simulated RTM trafficking is typically stopped at regular intervals to measure changes in HFS properties.

2.3.3. Test Methods

Each test specimen was photographed and weighed to assess erosion loss and assessed for wet skid resistance value (SRV) and texture depth using the British pendulum [22] and volumetric patch technique [23] methods respectively.

3. Results

3.1. Experiment 1

This experiment involved manufacturing cold applied HFS specimens and subjecting them to 1.5 million wheel-passes of simulated trafficking on the wear simulator turntable. During simulated trafficking the turntable was stopped periodically, and the specimens tested for wet skid resistance, texture depth and mass loss. One specimen was tested for each blend ratio.

3.1.1. Skid Resistance

Table 2 and Figure 3a show the development of skid resistance for the slab specimens up to 1.5 million wheel-passes. There is a ranking of specimens before, during and after testing on the wear simulator turntable. All the test specimens followed a similar downward trend of development during simulated trafficking. Skid resistance values were initially very high for all specimens prior to trafficking, followed by a decline in skid resistance to equilibrium levels.

Table 2. Skid resistance data up to 1.5 million wheel-passes (Aetec data).

HFS Slab Ref.	Skid Resistance (PTV)							
Wheel Passes	0	5000	40,000	100,000	200,000	500,000	1,000,000	1,500,000
CB Chinese Buff 100%	112	107	94	89	87	82	79	72
CB Chinese Grey 100%	109	104	97	92	89	84	79	76
Granite 100%	97	90	77	74	69	66	59	58
CB/Granite 50/50%	102	97	87	82	79	70	70	65
Sandstone A 100%	97	92	84	84	79	76	73	71
CB/Sandstone A 50/50%	104	102	94	87	84	82	74	74
Sandstone B 100%	99	97	87	79	79	74	66	66
CB/Sandstone B 50/50%	99	102	94	92	87	79	82	75
Sandstone C 100%	102	90	89	84	79	77	74	70
CB/Sandstone C 50/50%	104	97	92	87	85	82	74	72
Tuff 100%	102	97	89	86	80	76	74	66
CB/Tuff 50/50%	104	100	89	89	79	79	72	72

Figure 3b shows the skid resistance data for the specimens ranked in order of performance after 1.5 million wheel-passes of simulated trafficking. After 1.5 million wheel-passes the specimens had undergone considerable polishing and as would be expected, the specimen containing 100% granite performed the worst. The second worst performer was the specimen containing a blend of 50% granite and 50% calcined bauxite (CB) Chinese grey. Even though 50% of the granite was replaced with 50% of the overall best performing aggregate (CB Chinese grey) it was still the second worst performer. This shows the susceptibility of granite to polishing by vehicle tires over time.
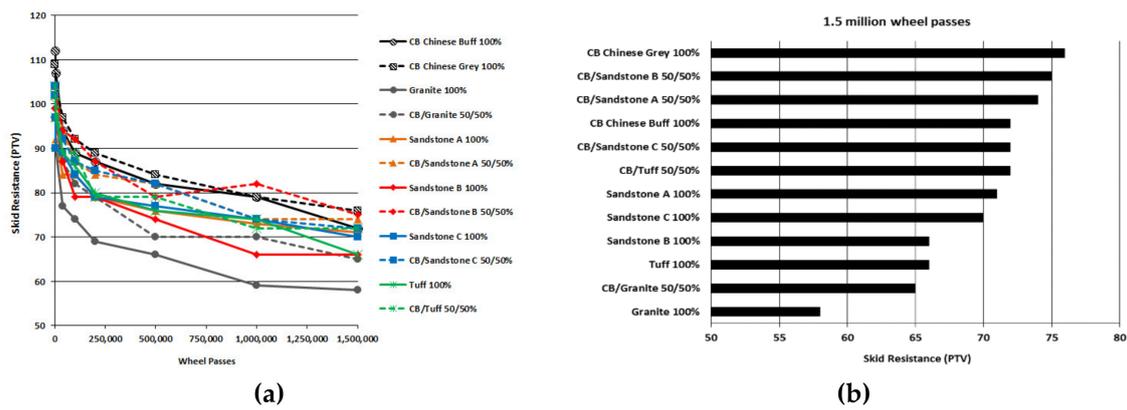
Figure 3. (**a**) Skid resistance development up to 1.5 million wheel-passes; (**b**) skid resistance ranking after 1.5 million wheel-passes (Aetec data).

Figure 3b shows that half of the worst performing specimens were made using 100% natural aggregate and one other specimen which contained 50% granite. Half of the best performing specimens contained either 100% calcined bauxite or a blend of sandstone or tuff and calcined bauxite. Two of the specimens containing a blend of sandstone and calcined bauxite out-performed the specimen containing 100% Chinese buff calcined bauxite. This shows how blending calcined bauxite with high PSV sandstone or tuff can increase wet skid resistance.

3.1.2. Texture Depth

Table 3 and Figure 4a show the development of texture depth for the slab specimens up to 1.5 million wheel-passes. Similar to the skid resistance data, there was a ranking of specimens before, during and after testing on the wear simulator turntable. All the test specimens followed a similar downward trend of development during simulated trafficking. Texture depth testing was not carried out prior to simulated trafficking due to the risk of the test sand affecting initial skid resistance values. Texture depth values were initially high for all specimens prior to trafficking, followed by a decline in texture depth levels.

Table 3. Texture depth data up to 1.5 million wheel-passes (Aetec data).

| HFS Slab Ref.	Texture Depth (mm)					
Wheel Passes	40,000	100,000	200,000	500,000	1,000,000	1,500,000
CB Chinese Buff 100%	1.8	1.6	1.5	1.5	1.4	1.3
CB Chinese Grey 100%	1.8	1.8	1.5	1.5	1.4	1.3
Granite 100%	1.4	1.6	1.3	1.3	1.2	1.2
CB/Granite 50/50%	1.6	1.5	1.4	1.4	1.3	1.3
Sandstone A 100%	1.4	1.3	1.2	1.2	1.0	1.0
CB/Sandstone A 50/50%	1.6	1.6	1.6	1.5	1.3	1.3
Sandstone B 100%	1.3	1.2	1.1	1.1	1.0	0.9
CB/Sandstone B 50/50%	1.6	1.5	1.3	1.4	1.3	1.2
Sandstone C 100%	1.5	1.4	1.3	1.2	1.1	1.0
CB/Sandstone C 50/50%	1.5	1.4	1.4	1.3	1.2	1.1
Tuff 100%	1.6	1.5	1.5	1.3	1.2	1.1
CB/Tuff 50/50%	1.6	1.6	1.6	1.4	1.2	1.1
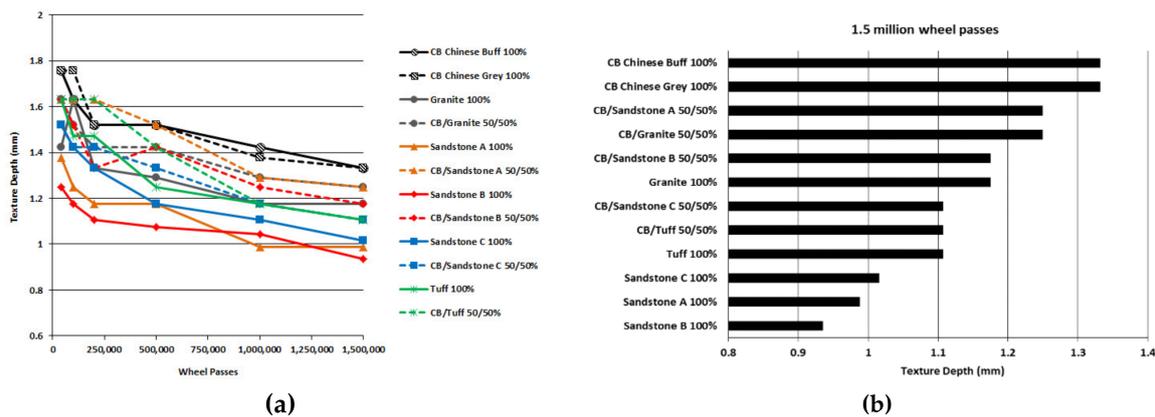
Figure 4. (**a**) Texture depth development up to 1.5 million wheel-passes; (**b**) Texture depth ranking after 1.5 million wheel-passes (Aetec data).

Figure 4b shows the texture depth data for the specimens ranked in order of performance after 1.5 million wheel-passes of simulated trafficking. The best performers were the two specimens containing 100% calcined bauxite. The three worst performers were the specimens containing 100% sandstone. The graph shows that, blending calcined bauxite with natural aggregates can increase texture depth performance during simulated trafficking.

3.1.3. Mass Loss

Very little aggregate loss occurred for the majority of specimens after 1.5 million wheel-passes. Figure 5 shows the cumulative percentage mass loss for each specimen after 1.5 million wheel-passes. This shows the specimens ranked in order of highest percentage mass loss (top) to lowest percentage mass loss (bottom).
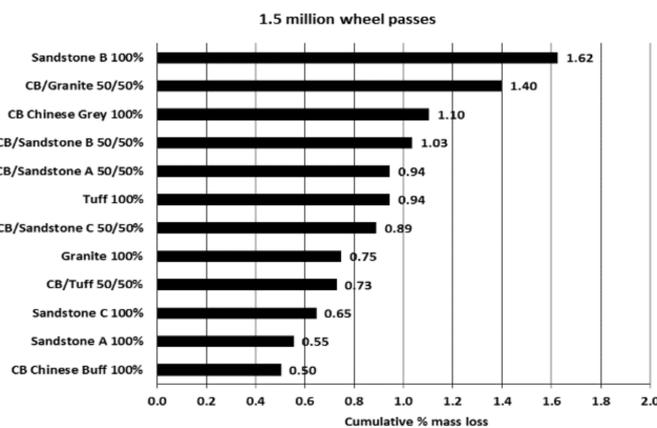

Figure 5. Percentage mass loss ranking after 1.5 million wheel-passes (Aetec data).

3.2. Experiment 2

This experiment involved manufacturing hot applied HFS specimens and subjecting them to 100,000 wheel-passes of simulated trafficking on the road test machine located at Ulster University, Northern Ireland. During simulated trafficking the turntable was stopped periodically, and the specimens were tested for skid resistance, texture depth and mass loss. Two specimens were tested for each blend ratio and the values reported in this paper are average values.

3.2.1. Skid Resistance

Table 4 shows the development of skid resistance data for all the slab specimens up to 100,000 wheel-passes. Figure 6a plots the data for the specimens made using Chinese grey calcined bauxite and sandstone B up to 100,000 wheel-passes. Skid resistance values prior to simulated trafficking ranged from 63 to 65 before increasing significantly to a range of 79 to 85 at 5000 wheel-passes. This was caused by the excess aggregate on the surface of the test specimen influencing the initial pendulum testing. This was quickly worn off exposing the aggregate held by the resin binder. After 5000 wheel-passes the specimens began to polish and as a result skid resistance values began to decline. After 25,000 wheel-passes the CB/sandstone B 70/30% specimen increased in skid resistance for the remainder of testing. After 100,000 wheel-passes the two blended specimens were comparable to the Chinese grey calcined bauxite.

Figure 6b plots the data for the specimens after 100,000 wheel-passes of simulated trafficking. Included is a dotted line running vertically at 70 PTV. This is the BBA specification limit in the UK for Type 1 laboratory specimens tested after 100,000 wheel-passes in the RTM. This shows that all the specimens in this experiment would pass the BBA test requirements for Type 1 skid resistance after 100,000 wheel-passes.

Table 4. Skid resistance data (Ulster University data).

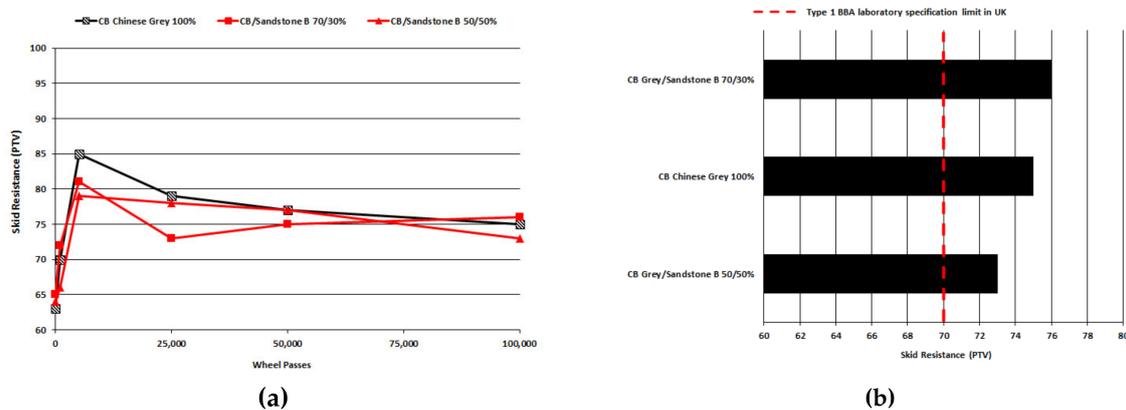| HFS Slab Ref.	Skid Resistance (PTV)					
Wheel Passes	0	1000	5000	25,000	50,000	100,000
CB Chinese Grey 100%	63	70	85	79	77	75
CB/Sandstone B 70/30%	65	72	81	73	75	76
CB/Sandstone B 50/50%	64	66	79	78	77	73
CB Chinese Buff 100%	96	85	84	82	83	79
CB/Sandstone C 70/30%	86	80	82	79	76	74
CB/Sandstone C 50/50%	96	77	80	77	76	72

(a)　　　　　　　　　　　　　　　　　　　　　　　　　　(b)

Figure 6. (**a**) Skid resistance development up to 100,000 wheel-passes; (**b**) Skid resistance ranking after 100,000 wheel-passes (Ulster University data).

Figure 7a plots the data for the specimens made using Chinese buff calcined bauxite and sandstone C up to 100,000 wheel-passes. Skid resistance values prior to simulated trafficking ranged from 86 to 96 before declining up to 1000 wheel-passes. After 1000 wheel-passes the two specimens containing blends of calcined bauxite and sandstone C increased in skid resistance up to 5000 wheel-passes before entering a downward trend for the remainder of simulated trafficking.
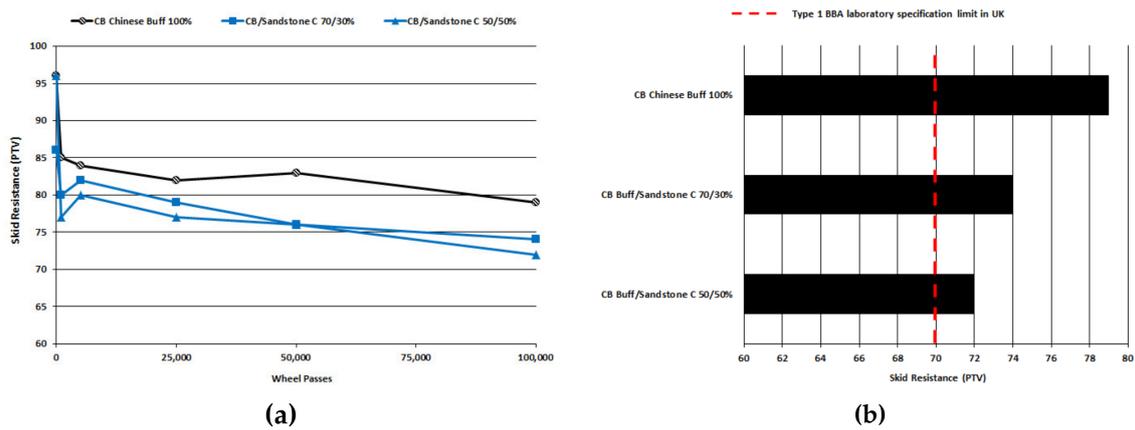
Figure 7. (**a**) Skid resistance development up to 100,000 wheel-passes; (**b**) skid resistance ranking after 100,000 wheel-passes (Ulster University data).

Figure 7b plots the data for the specimens after 100,000 wheel-passes of simulated trafficking. The specimen containing 100% Chinese buff calcined bauxite was the best performer with a PTV of 79. The next best performer was the specimen containing a blend of 70% calcined bauxite and 30% sandstone and the worst performer was the specimen containing a blend of 50% calcined bauxite and 50% sandstone B. Included in Figure 7b is the BBA specification limit in the UK for Type 1 laboratory specimens tested after 100,000 wheel-passes. This shows that all the specimens would pass the BBA test requirements for Type 1 skid resistance after 100,000 wheel-passes.

3.2.2. Texture Depth

Table 5 shows the development of texture depth data for all the slab specimens up to 100,000 wheel-passes. Figure 8a plots the data for the specimens made using Chinese grey calcined bauxite and sandstone B up to 100,000 wheel-passes. Texture depth values prior to simulated trafficking ranged from 2.6 mm to 3.6 mm. After 1000 wheel-passes all of the specimens had lost texture before entering a slower downward trend for the remainder of simulated trafficking. This was due to removal of some excess aggregate particles in the early stages of simulated trafficking that resulted in the higher volumetric based texture depth measurements obtained.

Table 5. Texture depth data (Ulster University data).

HFS Slab Ref.	Texture Depth (mm)					
Wheel Passes	0	1000	5000	25,000	50,000	100,000
CB Chinese Grey 100%	3.6	2.4	2.3	2.1	1.9	1.9
CB/Sandstone B 70/30%	2.6	2.3	2.2	1.8	1.8	1.8
CB/Sandstone B 50/50%	2.9	2.3	2.1	1.9	2.0	1.7
CB Chinese Buff 100%	3.6	2.1	2.3	2.1	1.9	1.9
CB/Sandstone C 70/30%	3.2	2.2	2.0	1.8	1.7	1.6
CB/Sandstone C 50/50%	2.6	2.3	2.2	1.8	1.8	1.8

Figure 8b plots the data for the specimens after 100,000 wheel-passes of simulated trafficking. The best performer was the specimen containing 100% Chinese grey calcined bauxite followed by the specimen containing a blend of 70% calcined bauxite and 30% sandstone. The worst performer was the specimen containing a blend of 50% calcined bauxite and 50% sandstone. Included in Figure 8b is a dotted line running vertically at 1.1 mm texture depth. This is the UK BBA specification limit for Type 1 laboratory specimens tested after 100,000 wheel-passes. This shows that all the specimens would pass the BBA test requirements for Type 1 texture depth after 100,000 wheel-passes.
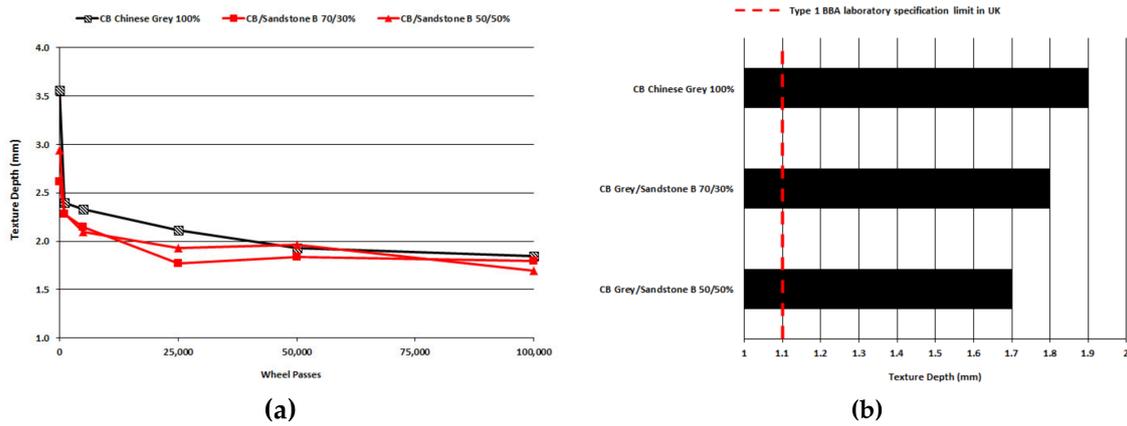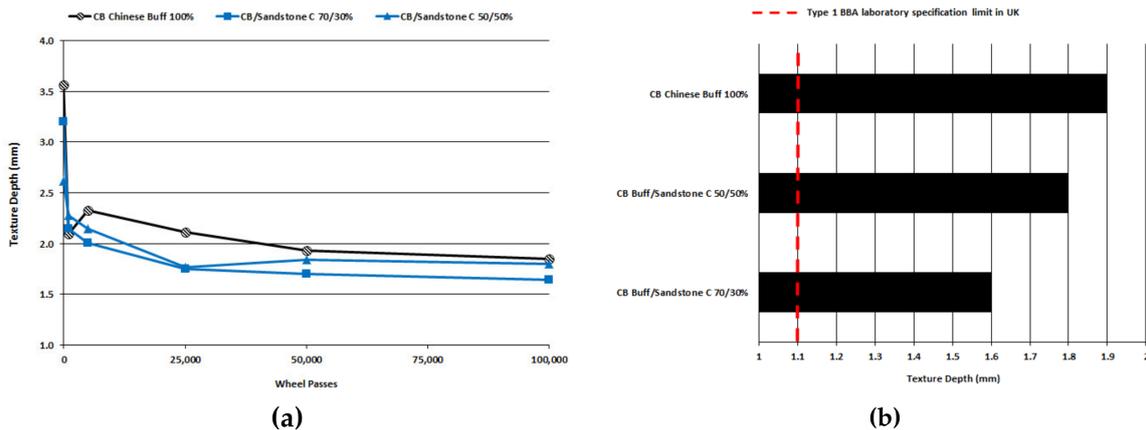
Figure 8. (**a**) Texture depth development up to 100,000 wheel-passes; (**b**) texture depth ranking after 100,000 wheel-passes (Ulster University data).

Figure 9a plots the data for the specimens made using Chinese buff calcined bauxite and sandstone C up to 100,000 wheel-passes. Texture depth values prior to simulated trafficking ranged from 2.6 mm to 3.6 mm. After 1000 wheel-passes all of the specimens had decreased sharply before entering a slower downward trend for the remainder of simulated trafficking.

Figure 9. (**a**) Texture depth development up to 100,000 wheel-passes; (**b**) texture depth ranking after 100,000 wheel-passes (Ulster University data).

Figure 9b plots the data for the specimens after 100,000 wheel-passes of simulated trafficking. The best performer was the specimen containing 100% Chinese buff calcined bauxite followed by the specimen containing a blend of 50% calcined bauxite and 50% sandstone. The worst performer was the specimen containing a blend of 70% calcined bauxite and 30% sandstone. Included in Figure 9b is a red dotted line running vertically at 1.1 mm texture depth. This is the BBA specification limit for Type 1 laboratory specimens tested after 100,000 wheel-passes. This shows that all the specimens would pass the BBA test requirements for Type 1 texture depth after 100,000 wheel-passes.

3.2.3. Mass Loss

There was no mass loss encountered for the specimens during testing, apart from the loss of a few aggregate particles at the start of simulated trafficking.

3.3. Experiment 3

This experiment involved manufacturing cold applied HFS specimens and subjecting them to 100,000 wheel-passes of simulated trafficking on the RTM located at Ulster University. During

simulated trafficking the turntable was stopped periodically, and the specimens were tested for skid resistance, texture depth and mass loss. Two specimens were tested for each blend ratio and the values reported in this paper are average values.

3.3.1. Skid Resistance

Table 6 shows the development of skid resistance data for all the slab specimens up to 100,000 wheel-passes. Figure 10a plots the data for the specimens made using Guyanese and Chinese buff calcined bauxite and sandstone C. Prior to and during simulated trafficking there was a clear difference between the specimens containing Guyanese calcined bauxite and Chinese buff calcined bauxite. The Guyanese calcined bauxite outperformed the Chinese buff calcined bauxite.

Table 6. Skid resistance data (Ulster University data).

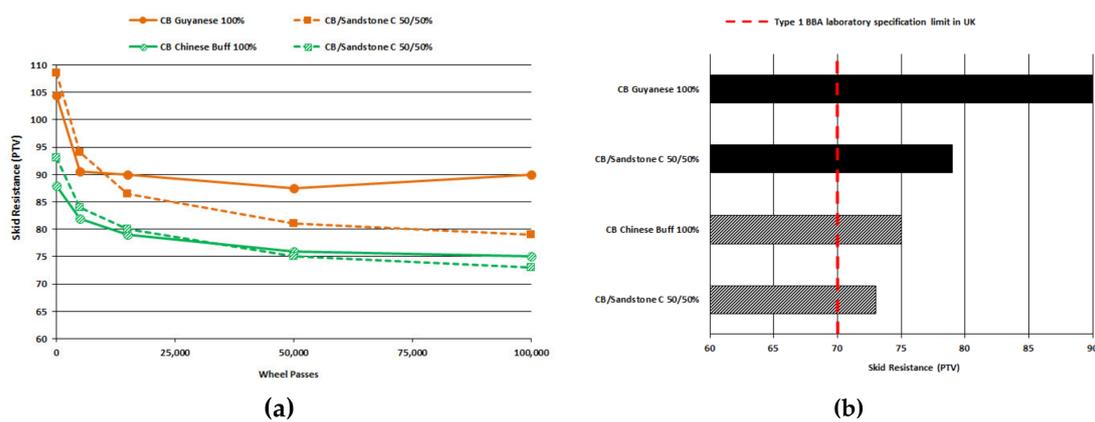| HFS Slab Ref.	Skid Resistance (PTV)				
Wheel Passes	0	5000	15,000	50,000	100,000
CB Guyanese 100%	105	91	90	88	90
CB/Sandstone C 50/50%	109	94	87	81	79
CB Chinese Buff 100%	88	82	79	76	75
CB/Sandstone C 50/50%	93	84	80	75	73

(a)   (b)

Figure 10. (**a**) Skid resistance development up to 100,000 wheel-passes; (**b**) skid resistance ranking after 100,000 wheel-passes (Ulster University data).

Figure 10b plots the data for the specimens after 100,000 wheel-passes of simulated trafficking. The specimen containing 100% Guyanese bauxite had a PTV of 90. Replacing 50% of the Guyanese calcined bauxite with 50% of sandstone C gave a PTV of 79. The specimen containing 100% Chinese buff calcined bauxite had a PTV of 75. Replacing 50% of the Chinese buff calcined bauxite with 50% of sandstone C gave a PTV of 73. Included in Figure 10b is a dotted line running vertically at 70 PTV. This is the BBA specification limit in the UK for Type 1 laboratory specimens tested after 100,000 wheel-passes. This shows that all the specimens would pass the BBA test requirements for Type 1 skid resistance after 100,000 wheel-passes.

3.3.2. Texture Depth

Table 7 shows the development of texture depth data for all the slab specimens up to 100,000 wheel-passes. Figure 11a plots the data for all the specimens that were made using Guyanese and Chinese buff calcined bauxite and sandstone C. Texture depth values prior to simulated trafficking ranged from 2.7 to 3.0 mm. After 5000 wheel-passes all the specimens had decreased sharply before entering a slower downward trend for the remainder of simulated trafficking.

Table 7. Texture depth data (Ulster University data).

HFS Slab Ref.	Texture Depth (mm)				
Wheel Passes	0	5000	15,000	50,000	100,000
CB Guyanese 100%	2.8	2.2	2.0	1.9	1.8
CB/Sandstone C 50/50%	2.7	2.1	1.8	1.6	1.7
CB Chinese Buff 100%	3.0	2.1	1.8	1.9	1.7
CB/Sandstone C 50/50%	2.8	2.1	1.9	1.7	1.6
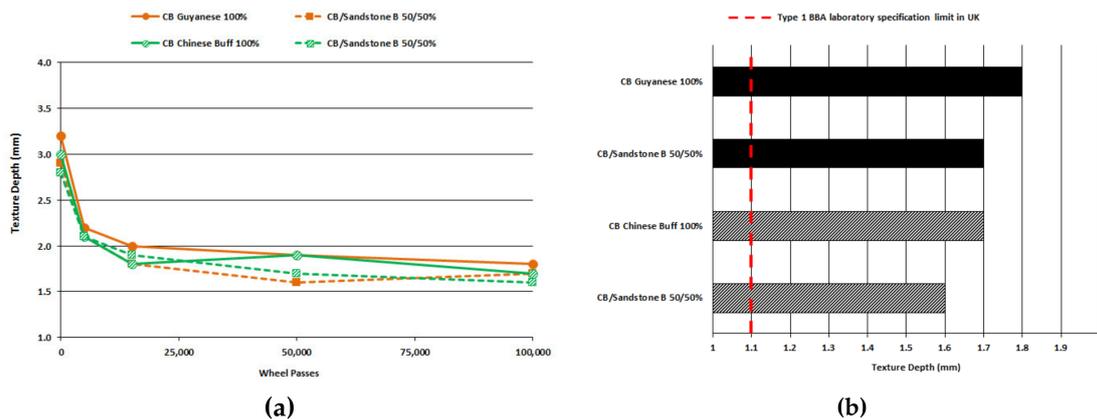
Figure 11. (**a**) Texture depth development up to 100,000 wheel-passes; (**b**) texture depth ranking after 100,000 wheel-passes (Ulster University data).

Figure 11b plots the data for the specimens after 100,000 wheel-passes of simulated trafficking. The best performer was the specimen containing 100% Guyanese calcined bauxite. The worst performer was the specimen containing a blend of 50% Chinese buff calcined bauxite and 50% sandstone C. The specimen containing a blend of 50% Guyanese calcined bauxite and 50% sandstone C had the same texture depth as the specimen containing 100% Chinese buff calcined bauxite. Included in Figure 11b is a dotted line running vertically at 1.1 mm texture depth. This is the BBA specification limit for Type 1 laboratory specimens tested after 100,000 wheel-passes. This shows that all the specimens would pass the BBA test requirements for Type 1 texture depth after 100,000 wheel-passes.

3.3.3. Mass Loss

There was no mass loss encountered for the specimens during testing.

4. Discussion

The results reported in this paper clearly show that there are natural aggregates available that can be blended with calcined bauxite and meet national laboratory performance requirements for HFS systems such as those that have been used in the UK. For many years researchers have tried to come up with alternatives to calcined bauxite in HFS systems. The approach (or mistake) was to look for 100% replacement using natural aggregates. For example, using 100% granite will not work because it will polish prematurely and become slippery to the road user over time. Using 100% sandstone will not work because it will wear prematurely over time because it is not durable enough to withstand the enormous stresses exerted on the material at high stress/risk locations where HFS systems are used. The same can be used to account for why other natural rock types do not perform in HFS. This can be seen from the results of Experiment 1, where the specimen containing 100% granite was the worst performer in terms of skid resistance. The next worst performer was the specimen containing a blend of granite and calcined bauxite. Even though 50% of the granite was replaced with 50% calcined bauxite, it was still the second worst performer. This illustrates the susceptibility of granite and other similar rock types to polishing and the risk that their use in HFS could pose to the road user.

In Experiment 1, one would expect the two control specimens containing 100% calcined bauxite to have the highest skid resistance. This was not the case. The best performer was the specimen containing 100% Chinese grey calcined bauxite with a skid resistance of 76. The next two best performers were the specimens containing blends of Chinese grey calcined bauxite and sandstone B and sandstone A with skid resistance values of 75 and 74 respectively. The 100% Chinese buff calcined bauxite specimen had the same skid resistance value as the specimens containing blends of calcined bauxite with sandstone A and volcanic tuff. In terms of texture depth, the two best performers were the two specimens containing 100% calcined bauxite. The three worst performers were the three specimens containing 100% sandstone. This illustrates the susceptibility of softer sandstone to wear and loss of texture. All the other specimens fell between these two groups.

In Experiment 2, Figure 6b shows that the specimen containing 70% Chinese grey calcined bauxite and 30% sandstone B outperformed the 100% calcined bauxite specimen by one point. The specimen containing 50% calcined bauxite and 50% sandstone B had a skid resistance of 73. Figure 7b shows the specimens ranked in order as would be expected. The 100% Chinese buff calcined bauxite specimen was the best performer with a skid resistance of 79. This was followed by the specimens containing 70% and 50% Chinese buff calcined bauxite with skid resistance values of 74 and 72 respectively. The early life friction development differs for both sets of specimens in Figures 6a and 7a. Figure 6a shows friction development increasing from 0 to 5000 wheel-passes before entering a downward cyclical trend of friction development. Figure 7a shows friction development decreasing in a downward cyclical trend throughout testing. Figures 8a and 9a shows both sets of specimens having similar trends of texture development. Both sets of data show that texture depth development stabilized after 25,000 wheel-passes and underwent minimal texture change for the remainder of testing. Figures 8b and 9b show that after 100,000 wheel-passes texture depths ranged from 1.9 to 1.6 mm. Both specimens containing 100% calcined bauxite had the highest texture depths. The experiment shows that all specimens would meet the laboratory wear test specification requirements for Type 1 HFS in the UK.

In experiment 3, Figure 10a shows both sets of specimens to have a similar trend of friction development with equilibrium being reached after 50,000 wheel-passes. Figure 10b shows the Guyanese calcined bauxite to be superior in performance to all the other specimens including the Chinese buff calcined bauxite. The specimen containing 50% Guyanese calcined bauxite and 50% sandstone C had a skid resistance four points higher than the 100% Chinese buff calcined bauxite. This illustrates potentially significant cost savings whilst ensuring performance. Figure 11a shows texture development to be similar for both sets of specimens during testing. Figure 11b shows texture depths ranging from 1.8 to 1.6 mm. The experiment shows that all specimens would meet the laboratory wear test specification requirements for Type 1 HFS in the UK.

The concept of blending calcined bauxite with high PSV sandstone or volcanic tuff compensates for the lack of resistance to wear in the sandstone or tuff by ensuring there is enough calcined bauxite in the blend to absorb most of the impact energy exerted on to the HFS by vehicle tires at high stress locations. As the tire rubber envelopes are essentially point contacts, compared to a typical asphalt or concrete road surface, the presence of calcined bauxite protects the blended particles around them. Optimizing the blend, both in terms of ratio and complimentary natural aggregate wear characteristics, ensures the longer-term survival of point contacts to maximize interfacial contact at a high stress site or during high vehicle demand driving maneuver. The correct combination of aggregates in the blend work in unison to achieve high levels of skid resistance, whilst the extremely hard calcined bauxite protects the softer sandstone or tuff particles from wearing away prematurely. These findings have potential major implications for road safety, the environment and industry supply chains.

5. Conclusions

The conclusions, and impact of this research, are that blending much cheaper high PSV sandstone or volcanic tuff aggregate with expensive calcined bauxite could:

- allow budget-stretched road authorities to lay more of these HFS systems at high risk locations which will save further lives and reduce serious injuries on our roads;
- contribute to national environmental and climate change targets by reducing carbon emissions as a result of using less calcined bauxite in HFS systems;
- reduce the risk to supply chains and over reliance on calcined bauxite as has been highlighted in China in recent years.

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