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A Preliminary Investigation into the Performance of Artificial High Friction Aggregates Manufactured Using Geopolymer Cement-Based Mortars

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Abstract

Despite local and national road authorities striving to provide motorists with a durable and safe infrastructure environment, one in six UK roads are currently classed as being in poor condition. In terms of safety, Department for Transport statistics report high numbers of road incidents; 29,711 killed or seriously injured in 2023, representing little change compared to 2022. As such, reported in this paper is research aimed at developing artificial geopolymer cement mortar-based aggregate as a cost/environmentally attractive alternative to calcined bauxite for high friction surfacing applications. Work was undertaken in two distinct phases. In the first, the performance of alkali silicate-based geopolymers comprising a range of industrial wastes as binder materials was assessed using modified versions of standardized polished stone value and micro-Deval tests. In phase two, selected mixes were assessed for resistance to simulated wear by exposing test specimens to 20,000-wheel passes on an accelerated road test machine. Performance was further investigated using a dynamic friction test method developed by the Indiana Department of Transportation. Despite commercially sourced calcined bauxite aggregates exhibiting the highest performance levels, the findings from this preliminary research were generally positive, with acceptable levels of performance noted for manufactured geopolymer-based aggregates. For instance, in accordance with recommended levels of performance prescribed in BBA/HAPPAS standards, this included attainment of polished stone values higher than 65 and, following accelerated road testing, average texture depths greater than 1.1 mm. It is recognized that further research is needed to investigate geopolymer binder systems and blends of aggregate types, as well as artificial aggregate manufacturing procedures.

Keywords: geopolymer mortar; road safety; highway maintenance; calcined bauxite; high friction surfacing

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1. Introduction

A well maintained, safe and fully functional highway infrastructure is central to global economic competitiveness. High friction surfacing (HFS) is reported as being essential in road network locations such as approaches to major junctions and pedestrian crossings, and sites with steep gradients and tight bends. From 1991 to 2001, a monitoring study of 2309 road safety schemes in the UK attributed HFS as directly contributing to an accident

reduction rate of 35.1% based on a site balance of 10% rural and 90% urban roads [1]. The aggregates predominantly specified for use in HFS systems, calcined bauxite, have unique properties which give it excellent performance in terms of skidding resistance. However, its limited global availability and associated high costs and negative environmental impacts means that finding alternatives is an ongoing research focus area.

In the UK, a review of 50 years of road trial data and laboratory investigations confirmed calcined bauxite as the only aggregate to consistently offer high levels of performance over extended periods. Conversely, natural aggregates with very good resistance to polishing will abrade and wear away over time [2]. Similarly in the US, several studies have investigated potential alternatives to calcined bauxite. Work at the National Center for Asphalt Technology at Auburn University [3,4] investigated materials including granite, flint, basalt, silica sand, steel slag, emery, taconite, copper slag, feldspar, calcined kaolin and quartz. 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. In research undertaken by the Texas A&M Transportation Institute to assess sandstone as a potential HFS aggregate [5], despite good frictional properties, it did not outperform calcined bauxite. High micro-Deval mass losses were reported as a particular characteristic. Work sponsored by the Indiana Department of Transportation compared both laboratory and field performance of steel slag as a calcined bauxite alternative [6]. Lab-based results showed that friction levels were reduced by 8 and 4% for steel slag and calcined bauxite, respectively. Comparable field-based reductions after nine months of service were 45 and 20% for steel slag and calcined bauxite, respectively. In work undertaken as the Missouri University of Science and Technology [7], despite an asphalt-based alternative to epoxy being positively confirmed for HFS, the alternate aggregate types assessed (Rhyolite, Meramec and Flint) failed to outperform calcined bauxite. Encouragingly, positive findings were reported from a study exploring 30–50% by mass blends of natural sandstone or volcanic tuff aggregate with calcined bauxite [8], in which the latter was reported to absorb most of the impact energy exerted by vehicle tires, thereby offering an alternative HFS option.

Geopolymer-based materials have a potential role to play given their established environmental and performance credentials [9], as well as the emergence of codes covering their properties and use [10]. In terms of geopolymer-based artificial aggregates, a review of production methods and properties [11] reports use of a wide range of wastes with high silica and alumina contents as precursor binder materials, including fly ash, slag, silica fume, red mud, metakaolin and quarry tailings. Reported commonly used alkali activators include NaOH and Na_2SiO_3, with mixture designs varying to offer contrasting key mixing parameters including Si/Al, solid/liquid and alkali/activator ratios. To produce artificial aggregates after mixing both the solid and liquid precursors, common shaping methods include pelletization, mold casting, crushing, and hand shaping [12]. Crushing has been widely utilized as it is proven as an efficient method for crushing and processing natural aggregates into desired grades. To enhance ongoing geopolymerization and associated morphological improvements, curing and hardening processes such as cold bonding, sintering, autoclaving, coating, soaking and vacuum impregnation have all been reported as possible final steps in geopolymer-based artificial aggregate production [13]. Given the numerous material and processing options listed, not surprisingly a wide range of artificial aggregate properties has been reported. This includes ranges of density (710–1500 kg/m^3), aggregate impact value (10.03–50.47%), aggregate crushing value (18.50–49.40%), water absorption (5.51–28.30%) and crushing strengths (0.4–23 MPa) [11,12].

In terms of applications of geopolymer-based artificial aggregates, despite increasing research attention on their use in structural concrete [14,15] and asphalt pavement [16]

applications, limited work exists into its suitability for HFS. Against this background, the work reported in this paper focuses on identifying the suitability HFS using geopolymer-based artificial aggregates. Initial findings based on exposure of a range of experimental samples to simulated traffic wear are presented.

2. Materials and Methods

2.1. Geopolymer Mortar Materials

Metakaolin (Metastar 501, Imerys, UK), an anhydrous calcined form of the clay mineral kaolinite, and four industrial by-products were used to produce synthetic geopolymer aggregates in this study. The latter included silica fume (Elkem, Norway), ground granulated blastfurnace slag (Ecocem, Ireland) and iron silicate (Aurubis, Bulgaria). These binders were labeled as MK, SF, GGBS and IS, respectively. The sodium silicate activator used in combination with these binders throughout was a commercially available product Geosil 14,515 (GS). As a control, a commercially available two-part, calcined clay-based geopolymer system was also assessed in this study. The binder and liquid activator components of this system were labeled BC (A) and (B), respectively. Chemical composition and particle size distribution (in the form of the particle sizes at which 10, 50 and 90% of the material samples fall below) data of these materials is given in Table 1. The fine aggregate used was a commercially available concrete sand from Lough Neagh, Northern Ireland.

Table 1. Chemical and physical properties of binder materials used.

Binder	Chemical Composition (%)							Particle Size (μm)			Specific Gravity (g/cm^3)
	SiO_2	Al_2O_3	Fe_2O_3	CaO	TiO_2	MgO	LOI	D10	D50	D90	
Commercial	33.4	31.1	27.5	0.5	3.35	0.74	2.7	0.7	6.9	40.7	2.8
Metakaolin	55	40	1.4	0.3	1.5	0.3	0.7	0.9	2.7	8.2	2.6
GGBS	36.5	10.4	0.7	42.4	0.5	8.1	1.4	2.1	15.3	35.5	2.85
Silica Fume	96	0.8	0.8	0.5	0.02	0.5	1.35	2.5	10	47	2.2
Iron Silicate	27	3.2	46	1.8	>0.001	0.7	1.5	5.8	42	99.1	3.8

2.2. Compressive Strength Testing

Mortar cubes (50 mm) were cast in steel molds which were wrapped in polythene sheet for moisture retention. After 24 h at an ambient temperature of 20 ± 2 °C, the cubes were demolded, transferred to a sealed plastic container and stored at the same ambient temperature until testing at 28 days in accordance with BS EN 1015-11 [17].

2.3. Modified Polished Stone Value Testing

Aggregate friction test values (FTV) were recorded hourly for six hours in accordance with BS EN 1097-8 [18]. Two test specimens were tested for each aggregate sample, with the modified polished stone value (PSV) recorded as the final FTV reading at six hours.

2.4. Modified Micro-Deval Testing

Micro-Deval testing according to BS EN 1097-1 [19] is typically carried out on aggregates sized 10–14 mm, as opposed to 1–3 mm in this study. While no British Standard exists for fine aggregate testing, based on methods given in ASTM D7428 [20], 50 ± 5 g of aggregate (mass A) sized 1.18–3.35 mm was placed in a micro-Deval container and soaked in 750 mL of water at 20 ± 5 °C for at least one hour. Using steel balls with a mass of 1250 g, the test was run at 100 ± 5 rpm for 15 min. The container and steel balls were washed to remove any particles, and the remaining sample was washed over a 75 μm sieve until washings were clear. Retained samples were transferred to a metal container and oven

dried at 110 ± 5 °C overnight. Dried samples were weighed and recorded to the nearest 0.1 mm (mass B). The percentage micro-Deval abrasion loss was then calculated.

2.5. Simulated Traffic Wear and Testing for Skid Resistance and Texture Depth (UK Methods)

To replicate low speed, high friction traffic loading, accelerated wearing was carried out according to TRL Report 176 [21] using Ulster University's Road Test Machine (RTM). The machine configuration involves loading 2 pneumatic tires to 5 ± 0.2 kN and passing them over test specimens at a rate of 10 rpm with a freedom to move 160 ± 25 mm laterally. Test slabs were 305 × 305 × 50 mm in size, prepared using a 10 mm natural stone mastic asphalt mixture to which a 2 mm deep layer of the artificial high friction aggregate was applied using two-part epoxy resin. After a 24 h resin curing period, excess HFS aggregate was removed using a wire brush before exposure of the slabs to 100,000-wheel passes. Periodically, surface skid resistance values (SRVs) were assessed at room temperature using the pendulum test method in accordance with BS EN 13036-4 [22]. Mean texture depths (MTDs) were also measured using the volumetric patch technique in accordance with BS EN 13036-1 [23]. Images showing a representative test specimen and the RTM apparatus are provided in Figure 1a,b.



Figure 1. (**a**) Crushed geopolymer mortar high friction surface test specimen for use in (**b**) 195 Ulster University Road Test Machine (RTM); (**c**) INDOT Circular Track Meter (CTM); (**d**) 196 Dynamic Friction Tester (DFT); and macrotexture depth measurement via (**e**) CTPM 197 and laser texture scanner.

2.6. Simulated Traffic Wear and Testing for Skid Resistance and Texture Depth (US Methods)

Specimens were tested in wet conditions using the three-wheel circular track polishing meter (CTPM); a traffic polishing simulation approach like the method described in ASTM E660 [24]. The method used three treaded pneumatic tires of standard size 2.80/2.50 R4 at constant pressure of 36 psi to polish specimen surfaces at a rate of 89 rpm. Prepared using a 10 mm natural stone mastic asphalt mixture, test specimens measured 508 × 508 mm with a texture depth of 0.75 mm, onto which a 2 mm thick layer of the artificial high friction aggregates were applied using a two-part epoxy resin. After a curing period of 24 h, excess artificial aggregate was removed using a stiff brush. Average depths of surface texture were measured periodically using the CTPM apparatus in accordance with ASTM E2157 [25]. This involved a charge-coupled device laser displacement sensor set on a spinning arm that followed a circular path with a diameter of 284 mm. Representative mean profile depths (MPDs) were calculated by taking two profile depths from eight sectors across the testing area. Surface texture depths were also measured using a laser texture scanner (LTS). The LTS operated at a resolution of 0.015 mm across a maximum test length and width of 107.95 and 72.01 mm, respectively. During specimen exposure to CTPM, friction measurements were also recorded periodically using the Dynamic Friction Tester (DFT) in accordance with ASTM 1911 [26]. Undertaken at the Indiana Department of Transport (INDOT) research division, images of this testing approach are provided in Figure 1c–e.

2.7. Mortar Mix Design and Synthetic Aggregate Preparation

Based on previous research undertaken by the authors to identify influences of mixture design on key material properties [27], six geopolymer mortar mixtures were considered to assess the effect of varying binder types, activators and water contents on performance. As shown in Table 2, most mixes used MK, either exclusively or in combination an industrial waste (SF, IS and GGBS) at replacement levels varying from 10 to 80% by mass. One non-MK based mix comprising GGBS and SF at a replacement level of 25% by mass was also considered. As mentioned in Section 2, a commercially available two-part calcined clay-based geopolymer cementitious system was also assessed as part of this study as a control. In all instances, mortar mixing involved using a motorized table-top mixer to blend the powder and alkaline activator initially, followed by addition of the fine aggregate. In line with published guidance [28], the fine aggregate used was sized in the range 150–300 µm, proportioned at approximately 20% by mass of the total mix constituents.

Table 2. Geopolymer mortar mixture designs.

Binder Type	Binders				Activators			Water	Grit
	MK	GGBS	SF	IS	BC (A)	GS	BC (B)		
Commercial GP	-	-	-	-	1020	-	850	15	485
100%-MK	965	-	-	-	-	770	-	240	485
90%-MK/10%-SF	870	-	95	-	-	770	-	240	485
90%-MK/10%-IS	870	-	-	95	-	770	-	240	485
50%-MK/50%-IS	485	-	-	485	-	770	-	240	485
20%-MK/80%-GGBS	195	775	-	-	-	770	-	240	485
75%-GGBS/25%-SF	-	1045	350	-	-	410	-	115	485

Following a review of several methods [11,12], synthetic aggregates were produced using a crushing method. Geopolymer mortar was spread across a polythene sheet to a thickness of 3 mm, covered with another polythene sheet for moisture retention and left to harden for 24 h. Slabs were then broken up into smaller pieces and placed in a sealed

bucket at an ambient temperature for 6 days to cure. These pieces were then passed through a jaw crusher and the artificial aggregates classified as particles passing a 3.35 mm sieve and retained on a 1.18 mm sieve. These aggregates were stored in sealed plastic bags and transferred to the same sealed bucket to cure for a further 21 days.

3. Results

3.1. Compressive Strength Results

The mean 28-day compressive strength results for all geopolymer mortar mixes are compared in Figure 2. Clearly, the commercial geopolymer mix attained the highest strength (100 MPa). Reflecting the chemical and physical disparity of the binder types investigated in this study, the remaining mixes exhibited strength values in the range 35–77 MPa.

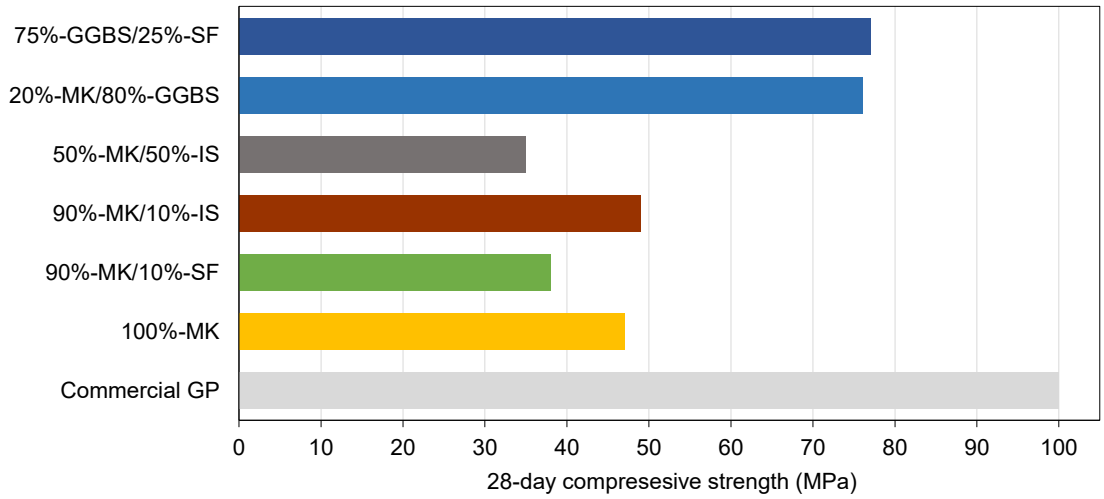


Figure 2. The 28-day compressive strength results for the geopolymer mixes considered.

3.2. DTests for Mechanical and Physical Properties of Aggregates

In the first phase of this study, work focused on undertaking PSV testing on samples coated with artificial aggregate manufactured from the various geopolymer mortar mixes considered. Two calcined bauxite aggregates (gray and buff) were considered as controls (labeled calcined bauxite 1 and 2, respectively). The raw friction tester values obtained from 0 to 6 h of testing are plotted in Figure 3a. Clearly for all specimens, a general trend of decreasing FTV with time was observed. After six hours of testing, FTVs for the geopolymer mixes ranged from 63 to 74, compared to values of 78 and 80 for the controls. Encouragingly, despite the artificial aggregates underperforming compared to the controls, all but one of the PSV results met the recommended target value of 65 [29]. As highlighted on the *y*-axis of Figure 3a, noteworthy in this regard was the fact that a wide range of low initial FTVs (81–91) were recorded for the artificial aggregates at 0 h. This compared to similar values of 96 and 97 for the calcined bauxite samples. This potentially reflected the non-optimized method used to manufacture the artificial aggregates in this phase of the work, which resulted in irregularity and lack of controlled angularity.

Given the range of low FTVs obtained at 0 h, the results are presented in Figure 3b as percentage values relative to the initial value obtained at 0 h. Results for both the calcined bauxite controls and commercial geopolymer specimens are provided in Figure 3(b-i), compared to the remaining experimental geopolymer specimens in Figure 3(b-ii). In addition, PSVs (FTV after 6 h of testing) for each aggregate type are plotted in Figure 3c. By normalizing the results in this way, the performance of the artificial aggregates was found to compete with the controls, with three mixture types outperforming the calcined bauxite specimens. PSV results for the 90%-MK/10%-IS, 90%-MK/10%-SF and 75%-GGBS/25%-SF

mixtures were 86, 83 and 83%, respectively. This was compared to values of 81 and 82% for the calcined bauxite controls.

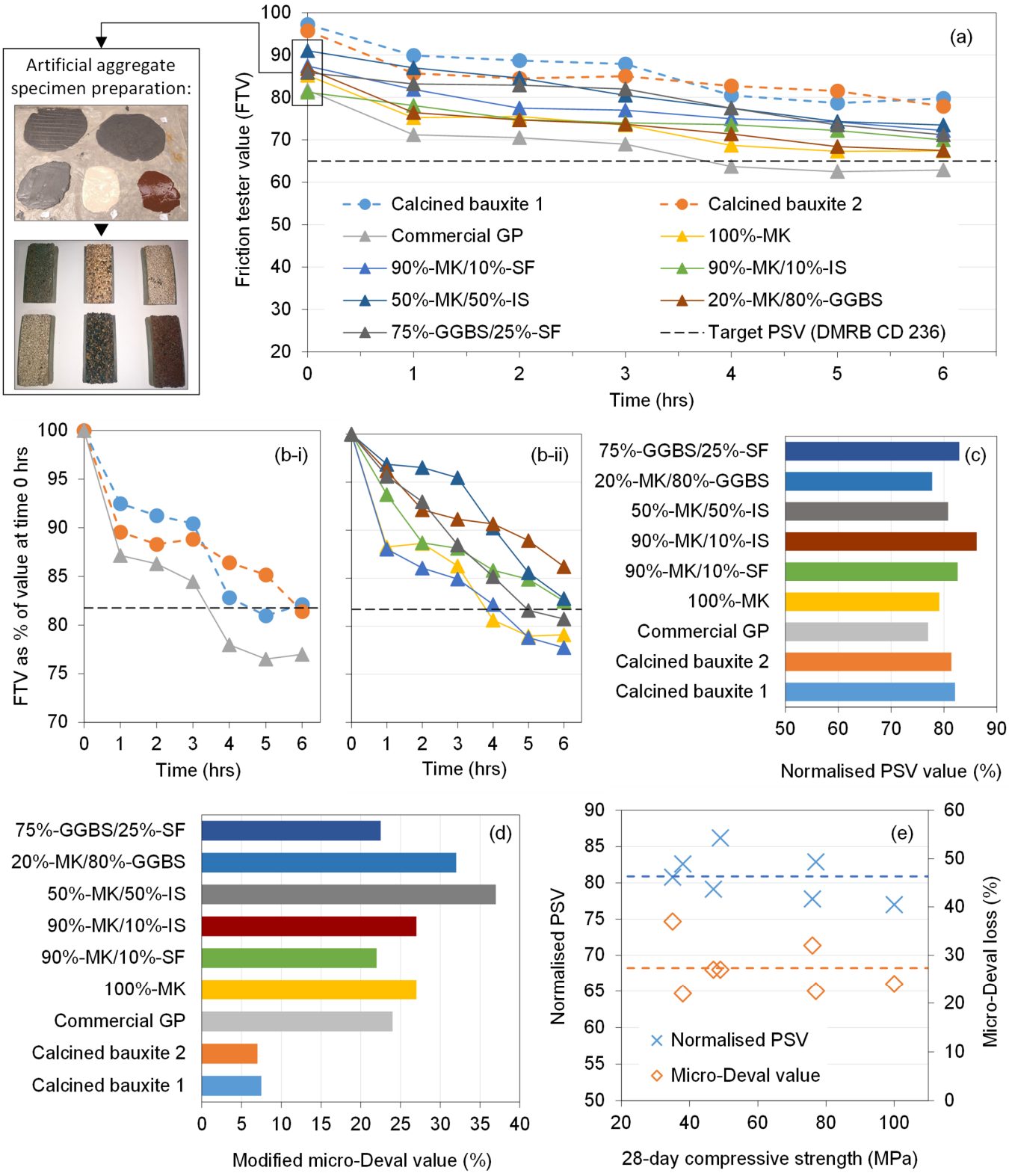


Figure 3. (**a**) Raw friction tester values (FTV) obtained from PSV testing; (**b**) FTVs as a percentage of original values at time 0 h for (i) control mixes and (ii) experimental geopolymer mixes; (**c**) percentage FTV value losses from 0 to 6 h; (**d**) percentage modified micro-Deval losses, and (**e**) relationships between 28-day strength and micro-Deval and FTV losses.

In contrast to the PSV results, findings from micro-Deval testing showed a clearer disparity between the performance of the artificial aggregates and the calcined bauxite controls, with the latter exhibiting mass losses of 7.5%. As shown in Figure 3d, this compared to much higher losses ranging from 22 to 32% for the artificial aggregate specimens.

While not feasible for the crushed calcined bauxite control aggregates, the relationship between axial compressive strength of the parent geopolymer mortars and both PSV and micro-Deval values for the corresponding manufactured aggregates is presented in Figure 3e. Despite the compressive strength of the parent mortar materials ranging from 35 to 77 MPa, no significant or skewing influence of compressive existed. The micro-Deval test was designed to assess aggregate durability and resistance to polishing and abrasion in the presence of water and is proven to offer good multi-laboratory accuracy [30]. As such, the values presented in Figure 3d were considered to represent the performance of the artificial aggregates produced, with performance variations potentially reflecting additional influences given the differing mixture designs considered, such as contrasting levels of microstructural particle packing and geopolymerization reactivity [11]. The lack of correlation with compressive strength also confirms reported findings linking the skidding resistance of HFS to other key characteristics, such as aggregate shape, hardness and surface texture [2,5,7]. Analysis of morphology or these additional physical and mechanical properties in detail did not form part of this preliminary study, however.

3.3. Simulated Traffic Wear and Testing for Skid Resistance and Texture Depth

3.3.1. UK Methods

Based on their high-ranking performance in the previous phase, three artificial aggregate types were selected for consideration in this phase of the research. This included aggregates manufactured from two MK-based mortars (90%-MK/10%-SF, 50%-MK/50%-IS) and the 75%-GGBS/25%-SF mortar. Specimens using calcined bauxite were also considered as a control. Results generated from the UK-based simulated trafficking methods were in the form of SRV and MTD; data sets proven to reliably benchmark high friction aggregates in terms of their potential in situ performance as required by BBA/HAPAS certification guidelines [29]. While a test duration of 100,000-wheel passes is typically required for BBA/HAPAS high friction surfacing testing, previous research shows that an equilibrium point is typically achieved after 20,000-wheel passes [31]. As such, in this study SRV and MTD testing was undertaken intermittently up to 20,000-wheel passes on the RTM. Performance was compared against industry SRV requirements of 70 and 65 for Type 1 and Type 2/3 applications, respectively, and MTD requirements of $\geq$1.1 and 0.9 for Type 1 and 2 applications, respectively [29].

The results obtained are presented in Figure 4, which clearly demonstrates expected trends of both decreasing SRV and MTD with an increasing number of wheel passes. The most significant contrast between the calcined bauxite control and artificial aggregates was noted for the SRV data (see Figure 4a). After 20,000-wheel passes, the average SRV for the control specimens was 75, compared to values in the range 53–56 for the geopolymer based aggregates. The latter SRVs after 20,000-wheel passes clearly fell well below the recommended BBA values of 65 and 70 [29]. As loose particles on test specimens influenced initial measurements, Figure 4b shows percentage SRV reductions from 100 to 20,000-wheel passes. The calcined bauxite controls recorded a minimal SRV loss of 1%, compared to values in the range 25–31% for the geopolymer aggregates.

Figure 4c shows recorded changes in MTD during simulated RTM trafficking. As with the SRV measurements, all specimens exhibited most significant decreases in MTD from 0 to 100-wheel passes, again attributable largely to particle loss. From 100 to 500-wheel

passes, losses generally reached equilibrium status, beyond which only minimal MTD losses were noted up to 20,000-wheel passes.

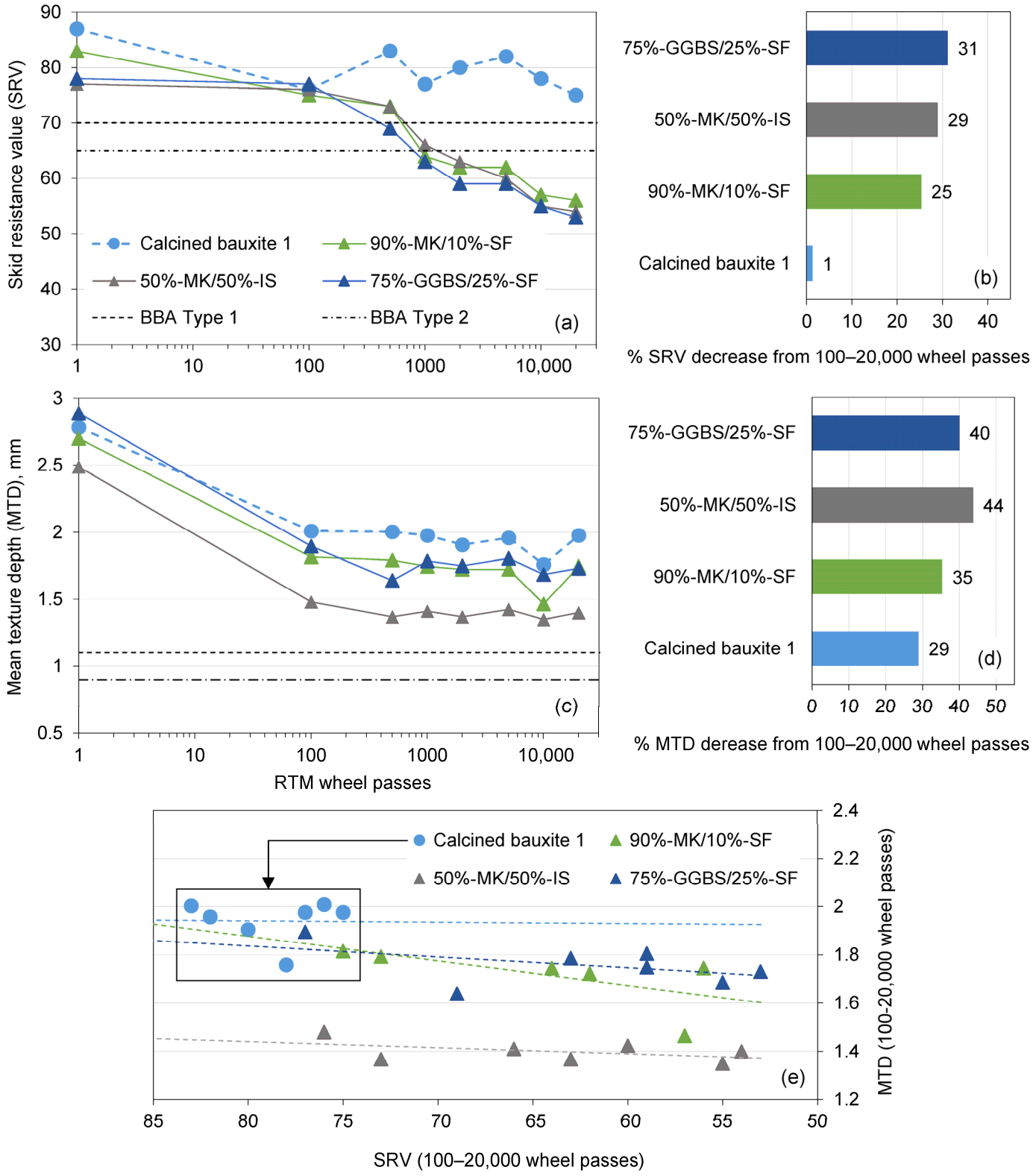


Figure 4. Results from simulated traffic wear (UK methods) including: (**a**,**b**) skid resistance values (SRVs), and (**c**,**d**) mean texture depth values (MTDs), and (**e**) relationship between SRV and MTD for result obtained between 100 and 20,000-wheel passes.

At the conclusion of testing, the calcined bauxite control was again the best performing aggregate, with an MTD of 1.98 mm (a 29% reduction from 100-wheel passes). This compared to values in the range 1.4–1.75 mm for the geopolymer aggregates (35–40% reductions from 100-wheel passes—see Figure 4d). Encouragingly, all specimen types exceeded the minimum Type 1 MTD of 1.1 mm by more than 25%.

The differences in relative performance for the SRV and MTD values is further highlighted in Figure 4e, which plots the relationship between the two data sets from 100 to 20,000-wheel passes. Clearly, SRV reductions were more significant than those for the MTD values. Also apparent from this figure is the superior performance of the calcined bauxite control specimens (highlighted by the bounding box added) relative to those with the artificial geopolymer aggregate.

3.3.2. US Methods

Based on the results presented in Figure 4, specimens using the 90%-MK/10%-SF and 50%-MK/50%-IS geopolymer aggregates were selected for further investigation. Simulated wearing was carried out according to US methods using the CTPM at INDOT. Skid resistance and texture depth results were measured after 1500, 3600, 9000, 18,000, 30,000, 45,000, 75,000, 120,000 and 165,000-wheel passes. Skid resistance results recorded using the DFT method and texture depth results recorded using both the CTM and LTS methods are plotted in Figure 4. Recommended target values prescribed by various US departments for transportation (Indiana, Illinois, South Dakota, Alaska and California) for calcined bauxite-based HFS are included in the figure for context. Based on research undertaken by INDOT [32], targets for steel slag-based HFS are also included (i.e., DFT and MPD values of 0.650 and 1.35 mm, respectively).

DFT results are shown in Figure 5a. As with the PSVs recorded using RTM testing, a significant drop in friction was noted after the first test interval of 1500-wheel passes. The general trend shows both geopolymer aggregates falling below the INDOT DFT requirements for calcined bauxite alternatives. Compared to the required value of 0.65, for instance, the 90%-MK/10%-SF and 50%-MK/50%-IS geopolymer aggregates achieved a DFT result of 0.607 and 0.583, respectively. CTM and LTS profile depth results are shown in Figure 5b, which were generally similar for each aggregate type. While higher final mean profile depths were recorded for the 90%-MK/10%-SF aggregates (2.1 mm compared to 1.6 mm for the 50%-MK/50%-IS mixes), both data sets exceeded the 1.35 mm value prescribed by INDOT for alternative HFS [32].

Figure 5c illustrates the changes in texture depth recorded by CTM across the cross-section of a 90%-MK/10%-SF aggregate test specimen. The blue and orange plots in Figure 5c indicate MPD measurements prior to testing and after 165,000-wheel passes, respectively, and show that texture depths decreased relatively evenly across the specimen. With that said, some instances existed where texture depth appeared to increase after testing, possibly reflecting aggregate loss during testing causing localized areas with deeper texture. Also provided in Figure 5c are corresponding 3D models of LTS texture depth data before and after CTPM testing, respectively. The models show that the wheel tracked area was to the right of the imaged area, with associated alterations to texture depth and aggregate particle shape apparent.

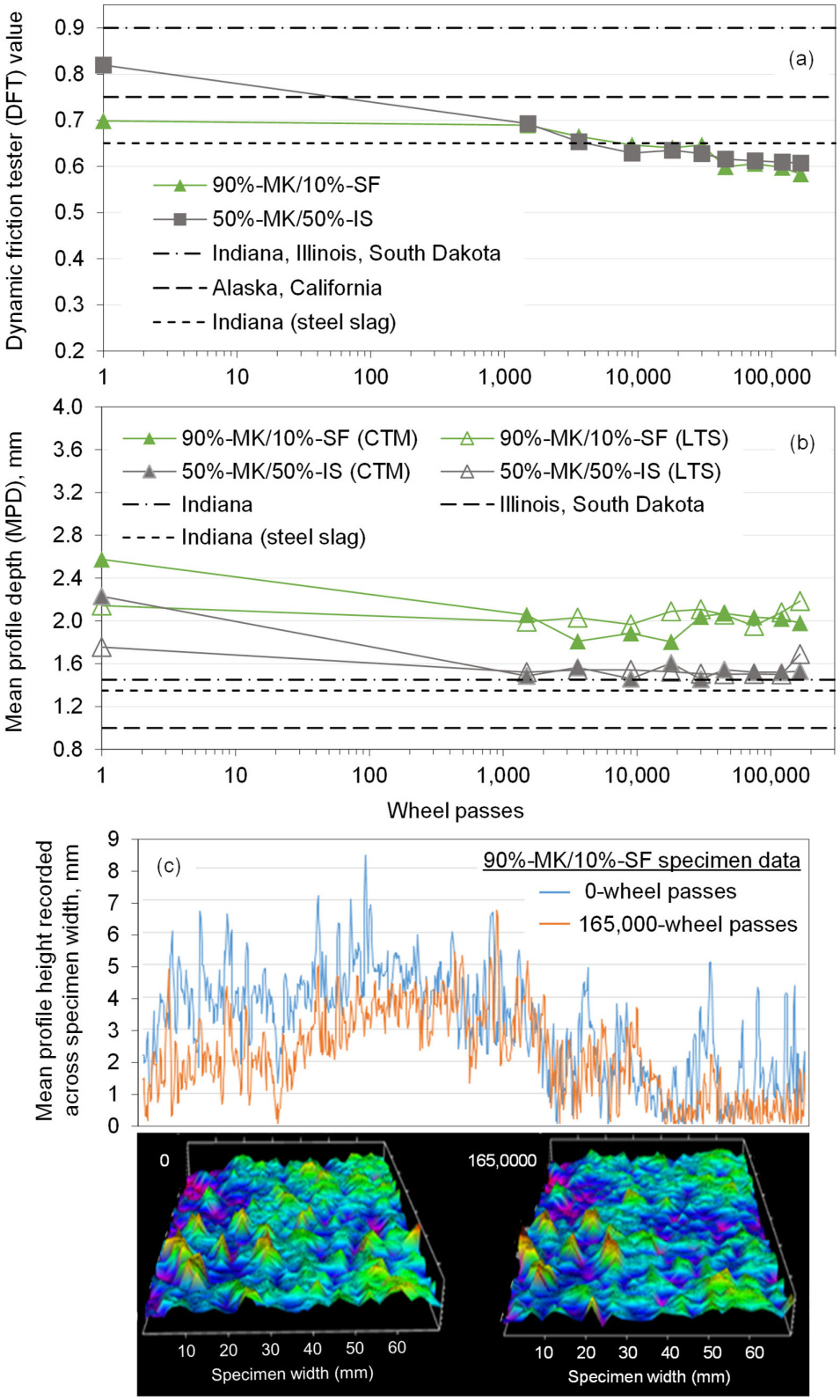


Figure 5. Results from simulated traffic wear (US methods) including: (**a**) dynamic friction testing values, (**b**) mean profile depths, and (**c**) mean profile heights recorded by the CTPM LTS across specimen surfaces and corresponding 3D models before (**bottom left**) and after 165,000-wheel passes (**bottom right**).

4. Discussion

The aim of the research reported in this paper was to undertake a preliminary investigation into the feasibility of artificial, industry waste-based, aggregates to serve as HFS for highway pavements. The aggregates considered were manufactured at a laboratory-scale using geopolymer mortars designed using various blends of metakaolin and industry wastes, including iron silicates, ground granulated blastfurnace slag and silica fume. All geopolymer mixtures were activated using a commercially available source of sodium silicate.

Testing was undertaken in two main phases. The first, considered tests for aggregate mechanical and physical properties, assessed via polished stone value and micro-Deval measurements. From this work, it was clear that the artificial aggregates performed positively, but not at the level achieved by calcined bauxite-based control specimens. In the second phase of work, testing focused on the behavior of test specimens exposed to simulated trafficking. Using established methods in both the UK and US, performance was assessed via skid resistance and texture depth measurements. From both methodologies, a trend of relatively high skid resistance losses and modest texture depth losses were noted. While the latter finding is positive, demonstrating that the geopolymer mortar materials used have the structural capacity to withstand dynamic traffic loads, the disparate relationship between texture depth losses and skid resistance losses noted is an established trend [3]. Microtexture is reported to have a greater effect than macrotexture depth on slow speed skidding resistance [33]. As results such as the DFT readings plotted in Figure 5a were undertaken at the relatively low speed of 20 kph, it is recognized that testing of this nature is likely to have a more significant effect on microtexture polishing that the overall degradation and wearing of the aggregates' macrotexture.

In this regard, a noted shortcoming of the presented study was the aggregate manufacture process adopted, which led to potentially underperforming aggregates from the outset. For example, in comparison to the undeveloped mortar crushing method adopted in this work, recent research [34] has reported novel approaches to creating geopolymer-based artificial coarse aggregates using a cut-blade mechanism. In this work a modified concrete drum mixer equipped with cutting blades was used to produce angular aggregates with rough surface textures and consistent particle sizes in the 10–20 mm. While HFS was not the intended application of this study, compared to conventional techniques, this method ensured uniform aggregate shapes with enhanced mechanical interlocking properties and high abrasion values. Recent work [34] using high-resolution profilometry reported a strong correlation (R^2 of 0.89) between the initial friction coefficient of HFS and its longer-term polishing resistance. Furthermore, based on collected texture profile information, skid resistance was found to be highly dependent on aggregate surface microtextures with wavelengths in the range 32–128 μm, with macrotexture having a less significant impact. As such, while generally positive outcomes were achieved from this preliminary study, future work will focus on alternative aggregate manufacture procedures and analytical techniques aimed at enhancing aggregate angularity and surface microtextures. Following published findings, identified additional options are to explore the effects of significantly enhancing geopolymer mortar properties such as compressive strength [35] and to consider established approaches [8] of blending alternative aggregates with known high performing materials like calcined bauxite. Whilst photogrammetry and 3D modeling was used in this study to assess particle wear during simulated trafficking at sample-level, micro-scale investigation at an individual aggregate particle level is recognized as an ongoing line of investigation that will significantly benefit this research.

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D.W., S.T.-M. and P.L.; writing—original draft preparation, A.W.; writing—review and editing, B.M.; supervision, B.M. and D.W.; project administration, B.M. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

CTPM	Circular Track Polishing Meter
DFT	Dynamic Friction Tester
FTV	Friction Test Values
GGBS	Ground Granulated Blastfurnace Slag
GS	Geosil
HFS	High Friction Surfacing
INDOT	Indiana Department of Transportation
IS	Iron silicate
LTS	Laser Texture Scanner
MK	Metakaolin
MPD	Mean Profile Depth
PSV	Polished Stone Value
RTM	Road Test Machine
SF	Silica fume
UK	United Kingdom
US	United States

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