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Novel Eco-Friendly, Recycled Composites for Improved CA Road Surfaces

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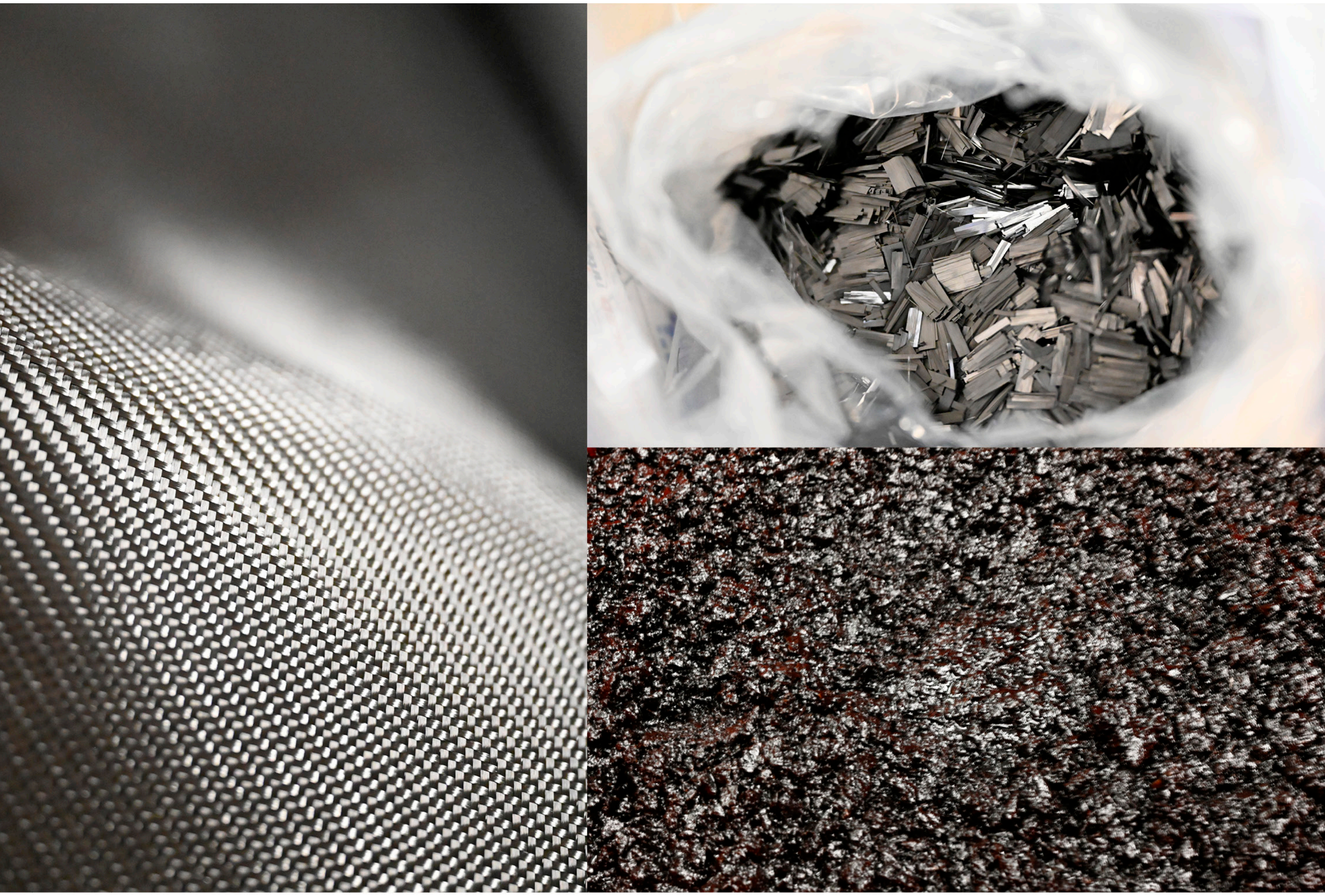

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Report 21-15

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16. Abstract

The continued use of structural plastics in consumer products, industry, and transportation represents a potential source for durable, long lasting, and recyclable roadways. Costs to dispose of reinforced plastics can be similar to procuring new asphalt with mechanical performance exceeding that of the traditional road surface.

This project examines improved material development times by leveraging advanced computational material models based on validated experimental data. By testing traditional asphalt and select carbon and glass reinforced composites, both new and recycled, it is possible to develop a finite element simulation that can predict the material characteristics under a number of loads virtually, and with less lead time compared to experimental testing. From the tested specimens, composites show minimal strength degradation when recycled and used within the asphalt design envelopes considered, with an average of 49% less wear, two orders of magnitude higher compressive strength, and three orders for tensile strength. Predictive computational analysis using the validated material models developed for this investigation confirms the long-term durability.

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Executive Summary

Section I provides the foundation for considering composites, especially recycled end-of-life products, as a viable infrastructure raw material.

Section II details the experimental and associated numerical validation tests required to develop the material test procedures that enables fast computational simulations for assessing asphalt, composite, and plastic materials as a viable product.

Section III summarizes the findings that both new and recycled composites exhibit superior performance compared to asphalt for road surfaces. A feasible product might be a hybrid composite/asphalt road.

1. Introduction

California is a world leader for safer, cleaner, and environmentally friendly vehicles, manufacturing, and technology. Yet, our roadways, bridges, and infrastructure are still constructed from the same mined materials – asphalt, concrete, and steel – and using the same polluting production facilities as commonly employed in many developing communities. This is despite the overabundance of useable plastic composite waste that must be exported to oversea landfills from our state every year. The question is, can these high-performance plastics already located inside our borders be recycled into a viable, durable, and environmentally friendly material for improved road surfaces for California? This research project will specifically address SB1 objectives 2 and 3 for cost-effective materials, methods, and advanced solutions for the application of the new materials, designs, and technologies to facilitate roads and bridges via three specific aims (i-iii):

i. Examining cost-effective recycled plastic reinforced composite materials for reducing road and bridge rehabilitation and maintenance of surfaces;

ii. Developing a finite element fatigue and wear virtual simulation specifically for plastic composite materials to address long-term road and bridge wear in order to identify the most common maintenance needs without requiring expensive and time-consuming tests;

iii. Experimentally testing select recycled composite coupon specimens and validating the simulation in (ii) and updating the research in (i) for long-term benefits and anticipated life-cycle costs.

With our student researchers, we will identify (i), address (ii), and propose solutions in (iii) to implement novel eco-friendly recycled plastic composites as a viable solution for improved California road surfaces during this 1-year period of performance (PoP). This study will also be utilized to seek additional external funding for continued research in recycled composites supporting CA SB1.

1.1 Case For Recycled Composites

The modern fiber reinforced high performance plastic composite can trace its history to the early 1900s, when American Cyanamid and DuPont created a polyester resin and Owens-Illinois Glass Co. commercially developed the glass-fiber textile fabric. This heterogeneous mix of a high strength fiber (carbon, graphite, or glass) and a rigid plastic "glue" allows the resulting single material to exhibit a performance to weight ratio up to 75% higher than traditional sheet metals and has found use in the aerospace, automotive, boating, and many consumer product manufacturing industries (Grant, 2011). For this investigation, the term plastic composite will be used interchangeably with any fiber reinforced plastic material. Unfortunately, it has also contributed to the 13 million tons dumped in the oceans each year that harm more than 700 marine animals including whales, krill, turtles, and coral (McCarthy, 2018). While plastic composites are a critical material in aerospace vehicles, accounting for well over 50% of the primary and secondary structures in some applications, as demand continues to grow at 12.5% annual compound growth rate (CAGR), so too does production of "off-fall" – composite scrap remnants from the fabrication process (Oak Ridge National Laboratory, 2016). Of the 100,000 tons of carbon fiber produced annually, 30,000 tons end up as off-fall material and less than 10% of this scrap is estimated to be recycled – Boeing for example sends up to 200 tons of recycled carbon fiber to automotive and electronics firms and is expected to increase to 500 tons by 2025 across its 11 manufacturing plants (Rybicka, 2015). This is amid a worldwide increase in demand for the plastics – 67% increase in the aerospace industry alone as of 2018 and 160% by 2033 and even more from the automotive industries which are experiencing a 4x demand during the same time period (Oak Ridge National Laboratory, 2016). Additionally, once the completed airframe, car, or consumer product has been decommissioned or retired, it is very likely to end up as waste and is not recycled — an estimated 30 to 50% of all plastic composite finish their life cycle in landfills. This represents a large market opportunity with the global composites manufacturing industry expected to top $115 billion worldwide by year 2024 (Lucintel LLC, 2019). The recycled carbon fiber reinforced plastic (CFRP) market alone is expected to grow at 13.1% CAGR from 2019 to 2024 and the market share of glass fiber (GFRP) and particulate reinforced plastics is even larger (Lucintel LLC, 2019b). Considering that recycling requires as little as 15% of the energy to obtain the fibers as production of the fibers themselves; that every ton of composite that has been produced, shipped, and is physically present in the United States, especially in the aerospace and automotive sectors constituting the Southern California landscape that have already paid the ecological price of production, it is imperative that we make the environmental argument and capitalize on the strong business incentive to recycle these materials for domestic – and especially Californian – applications (Lucintel LLC, 2019b).

Our motivation in support of SB1 objectives 2 and 3 is to investigate new materials, design, and technologies based on recycled plastic composites for facilitating road and bridge rehabilitation/maintenance and to address the long-term road and bridge maintenance and pavement/concrete rehabilitation needs. We dedicate our specific aim in (i) to examine the cost-effectiveness of recycled plastic composite materials from a business perspective for reducing road and bridge rehabilitation and maintenance of surfaces. Preliminary literature reviews indicate plastic composites have many benefits compared to traditional wood, steel, concrete, and asphalt construction materials. These polymers, both new and recycled, are: non-porous (do not absorb moisture or rot); do not conduct electricity; are sustainable and durable; are not prone to insect infiltration; are sound absorbent; are lighter than concrete or steel and about the same weight as oak wood; are an ideal candidate for use in areas of seismicity due to low self-weight; ability to absorb energy; and capable of high strains and loading rates prior to failure (Yang, 2012). Even now, plastic composites are often employed as fire retardants for steel and concrete construction projects. Using low density recycled structural plastic composite (RSPC) specifically can accelerate construction of new roads even with strict California regulations since they do not poison the soil or water as there are no carcinogens or added chemicals in the product that can leach out over time (Yang, 2012). Manufacturing of these RSPCs also reduces energy usage and related greenhouse gas emissions into the atmosphere compared to typical road-way surface production (Yang, 2012). Thus, of the more than 420 million tons of plastic and composites that are produced annually and the nearly 75% which gets thrown away, it is readily apparent that RPSCs can serve as a foundation for improved road and bridge surfaces supporting SB1 (McCarthy, 2018). Also, once the materials are used within road surfaces, their overall impervious nature allows them to be recycled almost indefinitely, similar to current asphalt road surfaces.

1.2 Current Trends in Recycled Composites

In addition to the potential life cycle cost analysis and long-term benefits of RPSC materials for roads and bridges from a business and supply perspective, it is imperative that research is conducted on the materials themselves from a performance standpoint which constitute our specific aims (ii-iii). New plastic composites for infrastructure projects have been proposed over the last few decades, although the vast majority of applications involved replacing the metal or concrete structures in bridges with an equivalent GFRP. In 2003, there were nearly 320 pedestrian and vehicular bridges made using plastic composites in this fashion and a 2002 live load test of a 221 x 32 ft composite bridge deck subject to a 35-ton dump truck test load exhibited only 297 micro-strain in the transverse direction, far less than the steel and concrete bridge deck it was replacing (Black, 2003). Because composites are specifically designed for stiffness, and for vehicle bridges this is a necessity to reduce driver anxiety, the resulting roadway is much stronger and less likely to fail (Black, 2003). As an added benefit, composite roadways are naturally corrosion resistant and less likely to experience catastrophic failure over their intended lifetime. However, replacing all 600,000 bridges and 4 million miles of roadways in the United States with an equivalent amount of GFRP would be a monumental effort and may ultimately not be feasible, currently. Nonetheless, understanding plastics and related materials through their inherent characteristics and properties may lead to a viable alternative or addition in future infrastructure projects in the context of a standalone, additive, or multifunctional support for asphalt due to their high specific strength and abundance.

Recently, progress has been made using RPSC materials for roadway surfaces. In fall 2018, researchers at UC San Diego partnered with MacRebur Ltd to install the first recycled plastic composite road surface in the United States. Working with UCSD engineers and the facilities team, MacRebur donated the recycled polymer-based asphalt to build the streets for the graduate student housing complex in order to test the long-term durability for using a non-petroleum-based binder for the road surface (Grifin, 2018). Using a similar construction method, the Shisalanga Construction company has demonstrated a 0.25-mile section in Cliffdale, South Africa in 2019 that was repaved with asphalt using high-density polyethylene to replace 6% of the bitumen binder. Just this small section alone eliminated 40,000 plastic milk bottles from ending up in landfills. The potential for these recycled plastics to improve roads is estimated to save nearly $3.4 billion in vehicle repairs and injuries in the country (Reynolds, 2019). Finally, at the University of Texas at Arlington, a study by Dr. Hossain resulted in developing a special recycled composite plastic pin for attaching roadway surfaces (Grabar, 2013). Since Texas soil conditions primarily comprise expansive clay, which permits large motions during wet and dry seasons, the roadways frequently crack requiring a nearly $10B annual budget to maintain the surfaces. With a $1M DOT grant, the research team found that by pinning the surfaces using plastic composite inserts, each insert is constructed from 500 non-decomposing plastic bottles, they could extend the life of the road surfaces from a typical 10 years up to 20 years.

As can be seen in the literature review, our specific aims to examine (i) life-cycle analysis for recycling composites domestically, (ii) new materials for improving road surfaces, and (iii) validating recycled composite materials constitute a new avenue for the future of California roads and bridges following the objectives of SB1. Our motivation is to develop and extend the limited research for RSPC materials via numerical simulation and experimental validation to be a viable alternative for improving road and bridge surfaces directly supporting California SB1, objectives 2-3. While our scope will be focused primarily on materials research for this PoP, we will continue to expand the scope of our research activities to assist the American Association of State Highway and Transportation Officials (AASHTO) to update their codes and regulations to include the use of recycled, not new, composite materials for civil infrastructure projects, primarily bridge decks and road surfaces. Thereafter, we hope that California will seek to adopt our technology as we build a cleaner, greener, and environmentally friendly future.

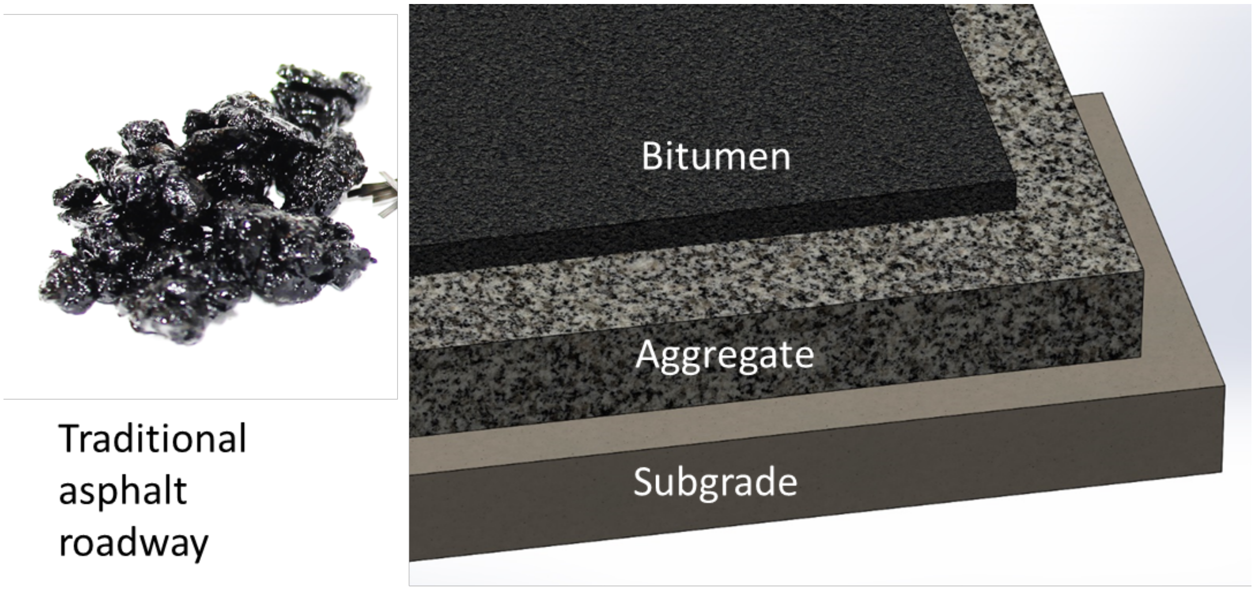
2. Methodology

Assessing the feasibility of composite road surfaces from a mechanical perspective requires comparison with the traditional (control) asphalt material. In this section, we present the experimental and numerical simulation setups for material testing on coupon-sized specimens.

2.1 Material Systems

Asphalt in the truest sense is classified as a particulate composite material, whereby aggregate is mixed with a bitumen binder and cured over time (as long as one year in some cases). Functionally, it is similar to concrete, certain masonry products, and even compressed wood particle construction boards, all of which use a variation of particles in a matrix (gravel and cement, stone and mortar, and wood pulp and glue, respectively). While the majority of asphalt consists of gravel which is highly recyclable, the bitumen binder is derived almost entirely from the viscous remnants of the petroleum refining process and thus not well suited for a more environmentally sustainable infrastructure. The resulting composite material is overlayed atop various gravel and rock subgrades to create the vast network of improved road surfaces across the United States (Figure 1). A cold mix asphalt (Aquaphalt 6.0) will be used due to its relatively uniform properties for validation studies; while it is generally lower strength than hot mix asphalt, this investigation is more focused on the general baseline validated performance as opposed to ultimate strength for which this material system is ideal.

Figure 1. Asphalt Roadway and Typical Construction



However, while asphalt is technically a composite, for the purposes of this investigation, this term refers specifically to the high-performance materials used in the aerospace, maritime, and certain terrestrial vehicle applications and not asphalt as it is commonly recognized (Figure 2). Here, long thin fibers made of glass or carbon fiber, not rock aggregate, are used to supply the strength and the binder is a polymer epoxy, not bitumen; cure times are usually less than a day as opposed to several weeks. Of particular interest are short fiber composites that dominate the marine and automobile industries as these length scales are common in both pristine and recycled applications.

Figure 2. Traditional Wet-Layup Composite with Carbon Fibers and Epoxy Matrix

In the same sense, the recycled structural plastic composite (RSPC) discussed in this investigation follows the same construction process as composite material systems, that is, fibers within an epoxy matrix, but the fibers are not pristine. Rather, they are obtained via the recycling process involving high heat that burns off the old matrix, and then reused with a new matrix (Figures 3-5). Here, it is proposed to use both carbon and glass fibers, specifically: 3/8" chopped strand construction-grade Johns Manville brand glass fiber with epoxy matrix (RS-G) and 3/8" chopped strand aerospace grade 3K carbon fiber with epoxy matrix (RS-C) where each system will have the fibers, pristine (new) and recovered (recycled), via high temperature burnoff following the American Society for Testing and Materials (ASTM) standard D 3171 – A7 which serves a dual purpose in confirming the fiber fraction (

Figure 6). All composite specimens will be 6.3% by fiber weight fraction (2.2% by fiber volume fraction).

Figure 3. Massing Composites Prior to Performing ASTM D 3171 – A7

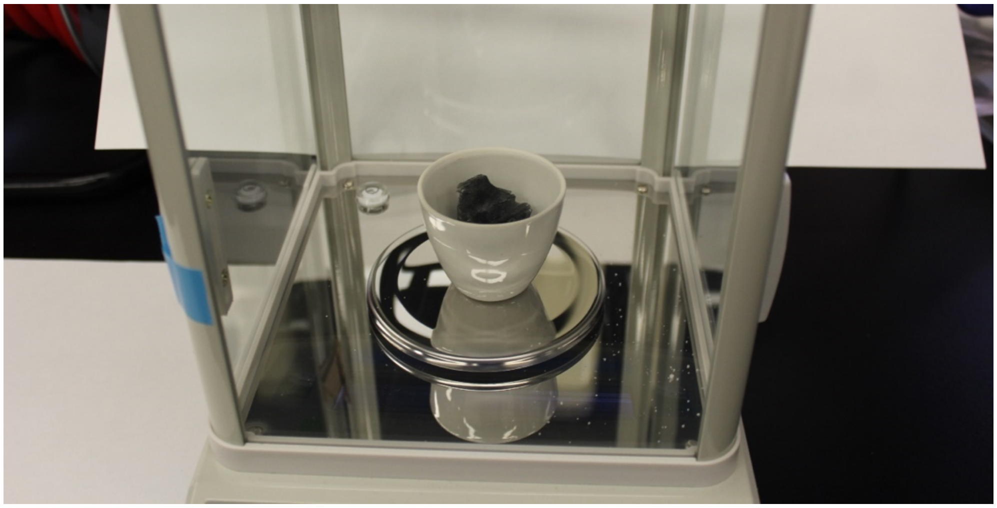
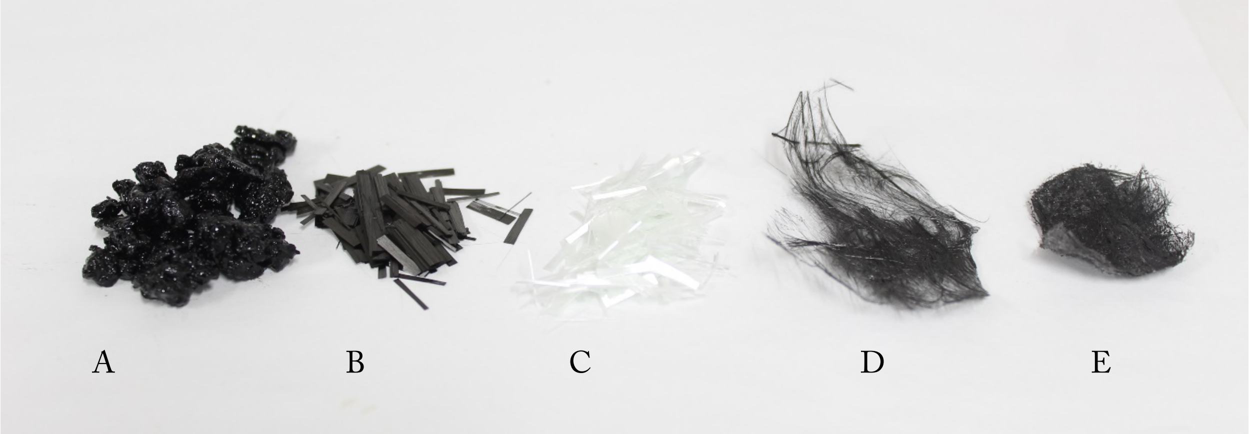


Figure 4. High Temperature Burnoff Following ASTM D 3171 – A7

Figure 5. Resulting Recycled Fibers, RS-C (left) and RS-G (right) ASTM D 3171 – A7

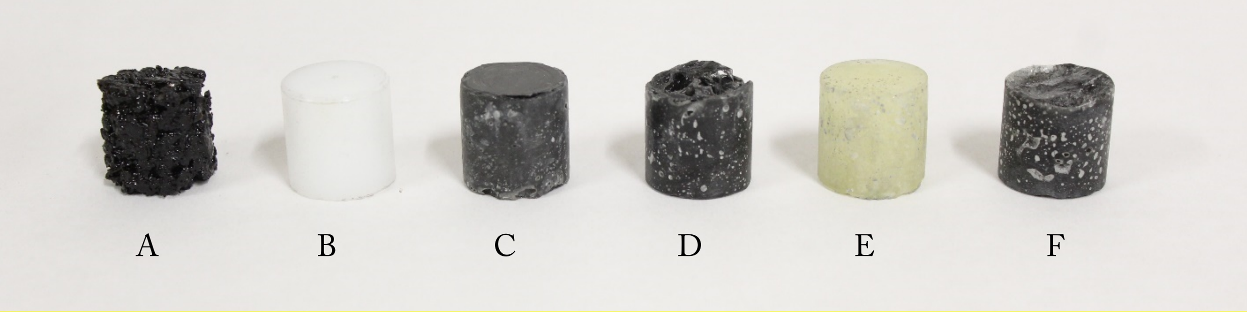
Figure 6. Raw Materials Used in the Production Process: (a) Asphalt, (b) Pristine Chopped Carbon Fiber, (c) Pristine Chopped Glass Fiber, (d) Recovered Carbon Fiber, and (e) Recovered Glass Fiber; not Shown HDPE and the Epoxy Binder



The final material of interest to this project is a standard high-density polyethylene (HDPE), one of the most common plastics used in the world and also found in everyday consumer products, from bottles to packaging (

Figure 7 7). HDPE is a homogeneous and isotropic material, not a composite, and as discussed in section 1.2, can even be used as a partial replacement for bitumen.

Figure 7. (a) Asphalt, (b) HDPE, (c) Pristine Carbon Fiber with Epoxy Matrix Composite, (d) Recovered Carbon Fiber with Recycled Fibers, (e) Pristine Glass Fiber with Epoxy Matrix Composite, and (f) Recovered Glass Fiber with Recycled Fibers



2.2 Experimental Test Setup

The performance of a traditional cold mix asphalt is compared with short glass and carbon fiber reinforced epoxy composites and high-density polyethylene (HDPE) via several test standards as shown in Table 1.

A total of 46 separate tests were run, based on ASTM standards and modified for smaller-sized specimens. This allows for specifically examining the micro/macro mechanical behavior, to be validated with finite element simulations later, as opposed to only the homogeneous macro behavior. For both RS-G and RS-C specimens, replicates were not available due to limited time in the lab to perform the requisite burn off tests to recover a sufficient supply of material.

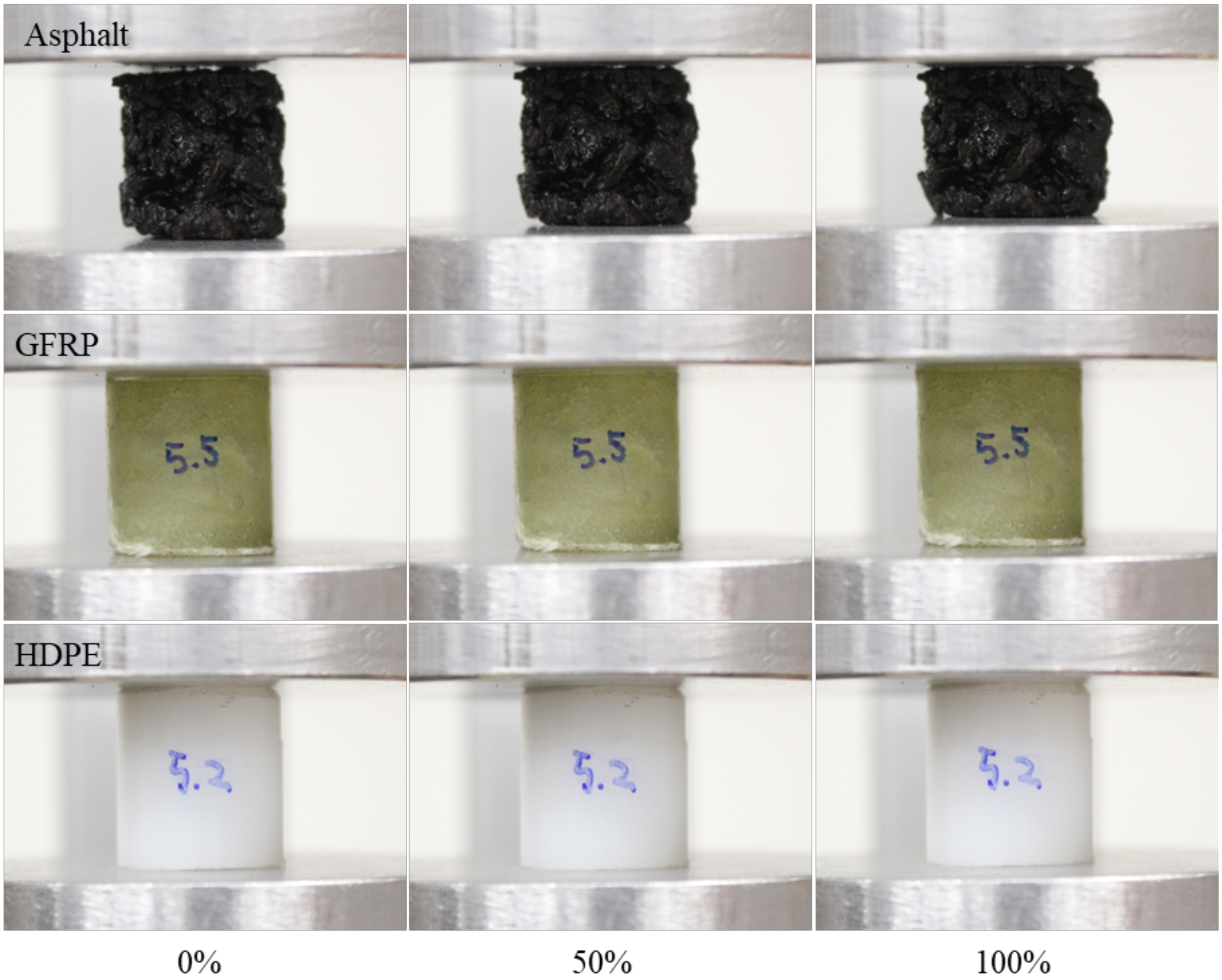
Table 1. Specimen Test Matrix

crack resistance mass (g)	Asphalt	30.2	30.5	30.6
	GFRP	18.2	16.7	18.6
	CFRP	17.4	19.4	18.1
	RS-G	16.9		
	RS-C	18.2		
	HDPE	16.4	16.3	16.1*
compression mass (g)	Asphalt	8.8	9.1	9.4
	GFRP	5.6	5.3	5.5
	CFRP	4.9	5.1	5.0
	RS-G	5.3	5.0	
	RS-C	5.2	5.3	
	HDPE	5.3	5.2	5.1
dynamic shear length (in)	Asphalt	0.7740	0.7805	0.7475
	GFRP	0.7630	0.7600	0.7735
	CFRP	0.7595	0.7710	0.7705
	RS-G	0.7545	0.7475	
	RS-C	0.7975	0.7745	
	HDPE	0.8110	0.7865	0.7565

* Omitted due to fabrication error

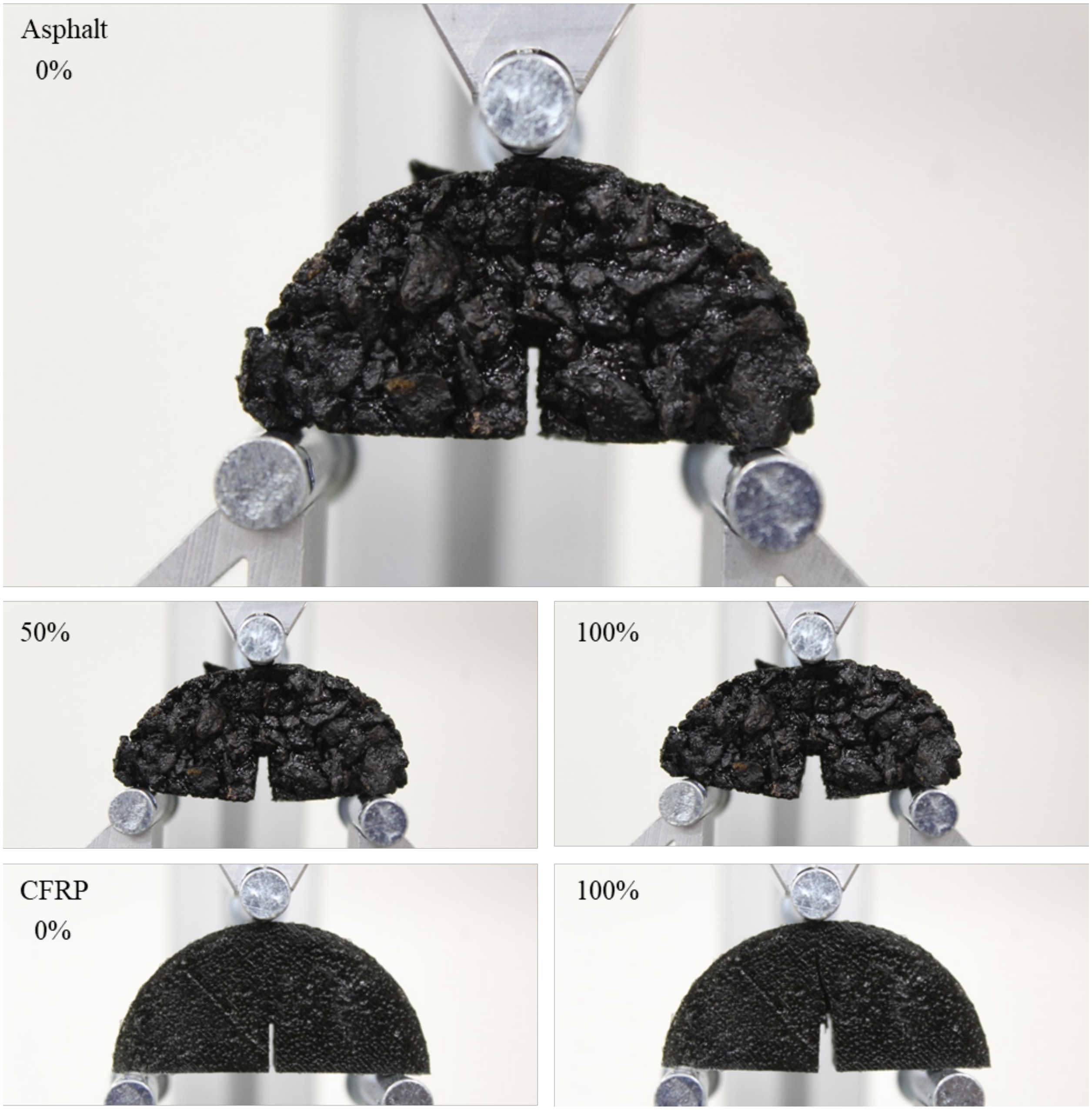
For mechanical strength, road surfaces are primarily subjected to compressive forces. This can be tested via ASTM D1074, a uniaxial compressive strength test performed at quasi-static loading rates, which would replicate a normal force on the road surface, e.g., vehicle at rest. Cylindrical specimens are used with diameters matching the height to avoid buckling effects (Figure 8).

Figure 8. ASTM D1074 for Uniaxial Compressive Strength and Modulus on Asphalt, GFRP, and HDPE at 0%, 50%, and 100% Compression



For tension and crack propagation, ASTM D8044 was used to simulate the mechanical effects of thermal loading and expansion which may lead to failure. Tensile forces are among the most critical areas of concern for asphalt since they have very little strength and hence, small cracks in their surface would lead to higher maintenance costs since the surface cannot withstand additional loads. Additionally, it is stated that higher modulus and strength in tension directly correlate to longer lifecycles (Lee, 2007). For this test, the specimen will be subject to 3-point bending with a crack defect (Figure 9).

Figure 9. ASTM D8044 Testing for Tensile Strength and Crack Propagation on Asphalt at 0%, 50%, and 100% of Failure and CFRP at 0% and 100% Failure



For the final test, providing a comparison of abrasion resistance, there is not a direct ASTM standard. Rather, there are a collection of standards from AASHTO T 279 and ASTM D3319 for accelerated polishing of aggregate samples, ASTM D6928 and D7428 and AASHTO T 327 for course/fine aggregate degradation by abrasion in a Micro-Deval Apparatus, and AASHTO T 96 Los Angeles test for small size aggregate abrasion and impact test. Most of the standards test the aggregate particles themselves with the exception of AASHTO T279. For this test, a large wheel of material is cast and spun while in contact with another spinning tire load. This would be very difficult to replicate exactly in simulation and would require having to assess the material properties of two different wear items (tire and specimen) which is not under consideration for this investigation. Thus, our proposed test is based on the T279 test but rather than making a wheel of the specimen material, we designed and fabricated a low friction plunger system that would provide a constant contact force to hold the various specimens against a hardened friction surface (Figure 10).

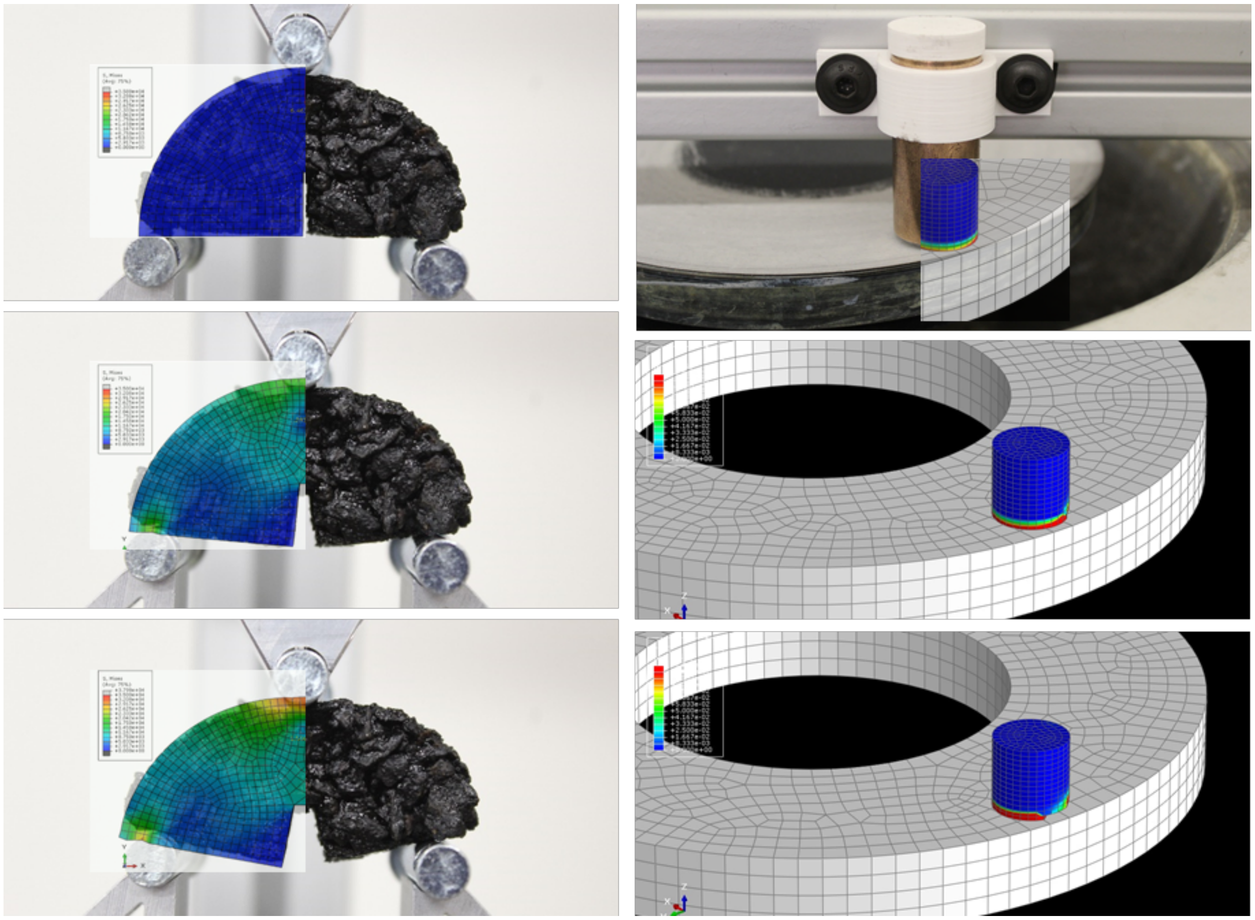
As the surface is spun at a constant velocity, this would provide an accelerated wear of the contact surface. Specimens would be the same dimensions and shape as the ASTM D1074 tests. All components were designed, fabricated, and tested in-house.

Figure 10. Accelerated Contact Surface Wear Test with GFRP

2.3 Numerical Test Setup

Experimental testing in the absence of predictive modeling would result in a set of empirical design guidelines, requiring continuous retests and/or addendums for certification of structures under new loading or use cases. This inherently slows the certification process for new and improved materials e.g., the accelerated wear test required in this investigation where the standards are not yet designed for the type of data that needs to be collected. By coupling select experimental tests with finite element analysis software, it is possible to predict the response of more complex structures, designs, and materials completely in simulation with validated models thereby accelerating development of improved road surfaces (Figure 11). The versatility of finite element simulations lends itself to examining various materials interacting with one another, such as friction in a dynamic shear wear test.

Figure 11. Abaqus Simulations of Tensile Crack and Accelerated Surface Wear Tests on Asphalt



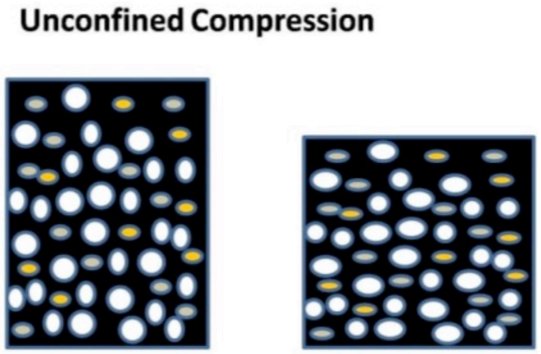
Material validation tests was performed using Abaqus/CAE for the composites and asphalt. HDPE was not a primary focus at this stage as its properties are well established and would not need to be validated. While base material properties are generally available for the asphalt (Ying, 2008 & Wang, 2014), for this experiment, material properties had to be adjusted depending on the system via empirical validation. For example, the composite systems used short fibers with random orientation for the reinforcement, for which 3/8 and 5/8 of the longitudinal and transverse modulus, respectively, are weighted (Agarwal, 2006).The composite final material properties are presented herein and in Table 2. GFRP and CFRP are assumed elastic-plastic, homogeneous and isotropic with relatively uniform random orientation of fibers and reduced modulus and strength due to the lack of unidirectional fibers typical of most high-performance composites. In both cases, fiber volume fraction (Vf) = 2.2%, an assumed void is 4.2%, and the friction coefficient is set to 0.40.

Table 2. Composite Material Properties

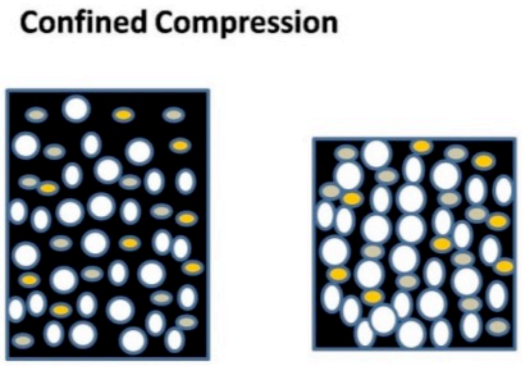
Property	GFRP	CFRP
E (GPa)	4.19	5.44
υ	0.35	0.38
σ_{ult} (MPa)	100	100
G (GPa)	1.55	1.97

Asphalt is assumed to be a crushable foam material model which allows for separate tensile and compressive plastic behavior and strengths, high deformation, and most importantly, element deletion via damage and damage evolution (crucial for modeling the shear wear tests). This model used volumetric hardening with compression yield stress ratio of 0.50, and in tension, a hydrostatic yield stress ratio of 0.08. A modulus of 495 KPa for the confined compression tests yield stress in compression value of 35 KPa. Details of unconfined versus confined compression are provided in Figure 12. A Poisson's ratio of ν=0.33 is obtained. Ductile damage evolution, with fracture strain = 0.7, stress triaxiality = 0.3, and strain rate 0. friction coefficient = 0.35.

Figure 12. Unconfined vs. Confined Compression



Gravel particulates can freely move in the bitumen binder. Volume fraction *Vf* is preserved including voids.



Particulates are brought together by removing voids at high compression. Increases the effective volume fraction. For 93.5 – 99 % increase in *Vf*, this increases stiffness *E* from 0.5 – 100 MPa (E_{gravel} is 100 GPa) .

3. Results

Details of the experimental and numerical tests are discussed in this section.

3.1 Compression Testing ASTM D8044

Compression testing the various specimens provides the static load modulus and strength (Figure 13). Here, it can be seen that for normal, unconfined compression testing, both experimental and numerical results agree, and the composites easily outperformed asphalt (Figures 13 - 14). There was minimal reduction in performance between pristine and recycled fibers with respect to ultimate load since this test primarily loaded the matrix itself and not the fiber. Some reduction in modulus would be expected since the recycled fiber has less adhesion to matrix due to charring; both were far in excess of asphalt. This was observed in Figure 14 and validated with Abaqus.

Figure 13. Comparison Force vs. Displacement, Asphalt Experimental and Numerical

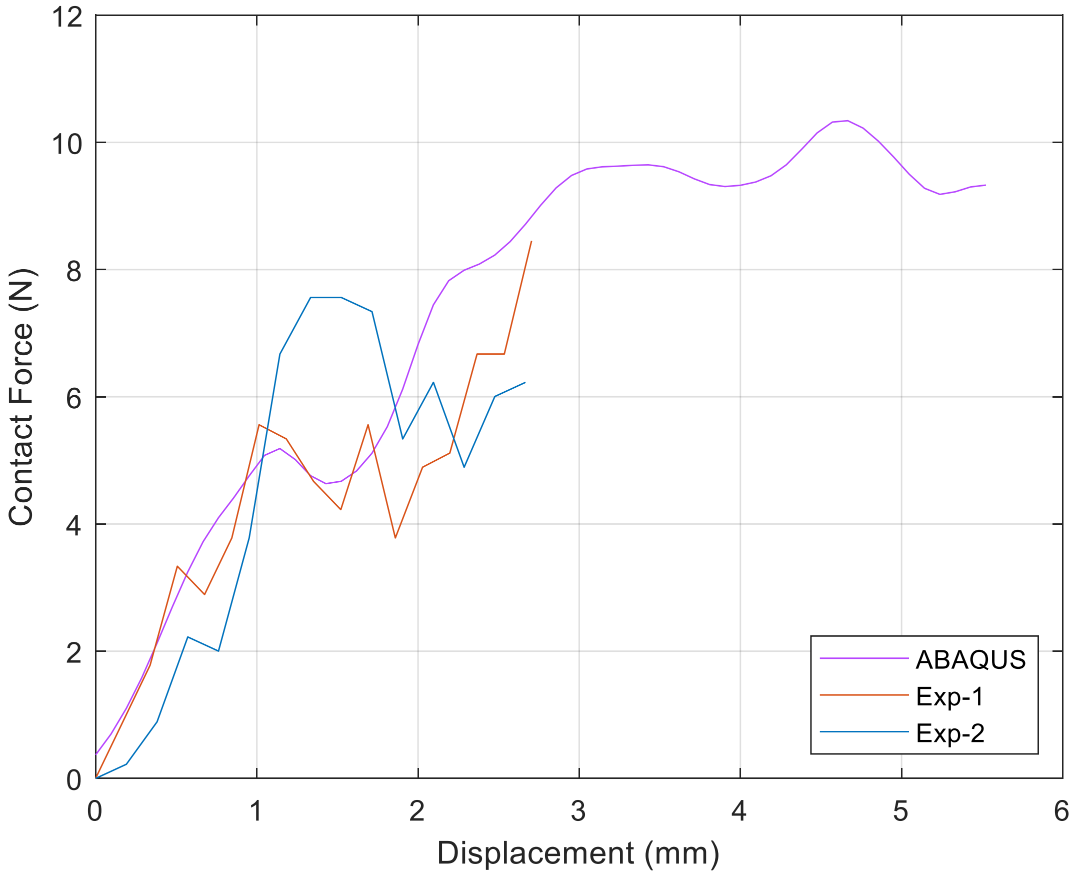
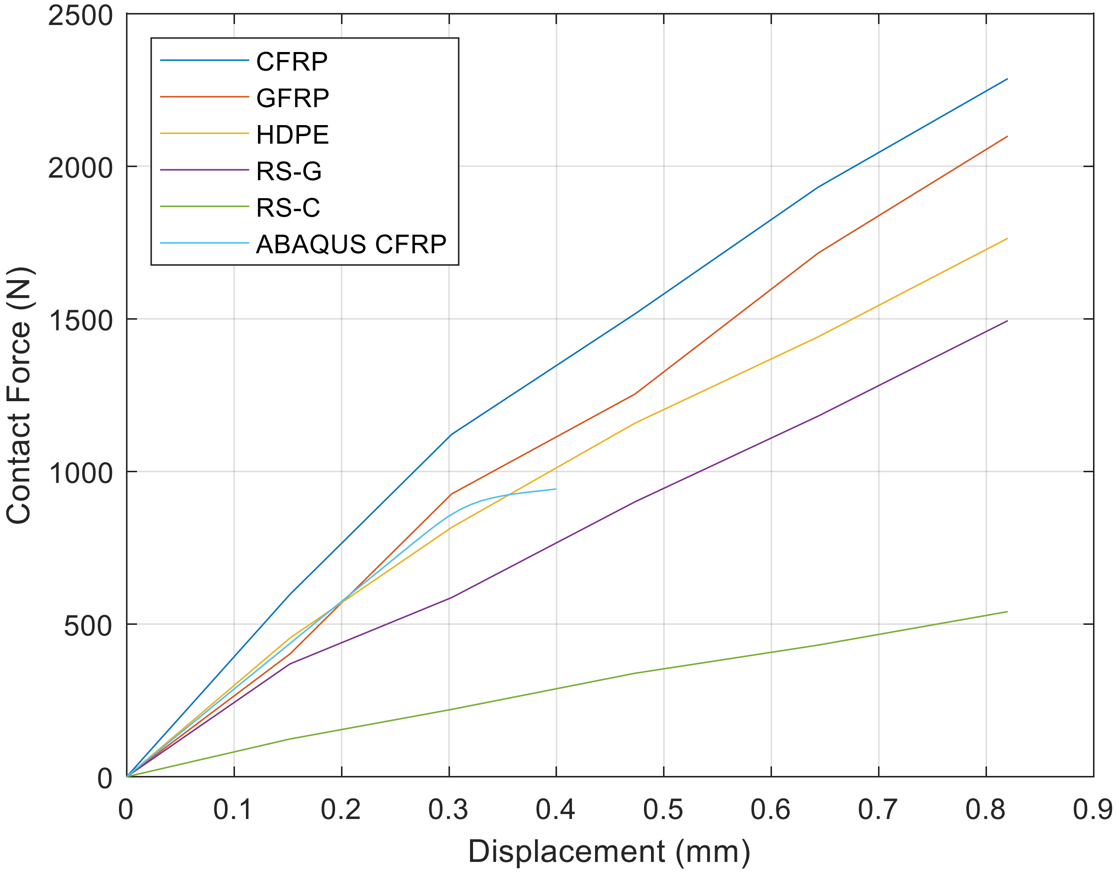


Figure 14. Comparison Force vs. Strain, Composites



3.2 Tensile Crack Propagation ASTM D1074

Three-point bend testing examines the tensile strength of the specimen with the maximum moment at midspan in direct correlation to the ultimate limit of the material. Having an additional limiting factor, a crack placed at midspan, also examines how resilient the material is post fracture. In this case, a material with higher fracture toughness (and higher tensile strength) will continue to show increasing force carrying capacity until failure in a linear relationship. This is observed for all plastic-based materials and was validated with Abaqus (Figures 15-16). Asphalt, by comparison, has relatively low fracture toughness and ultimate strength, therefore, it has a more curved force plot (Figure 17). It would be beneficial in future studies to directly measure tensile performance for asphalt to clearly identify its strength without any crack defects.

Figure 15. Comparison of Force vs. Displacement for Composites

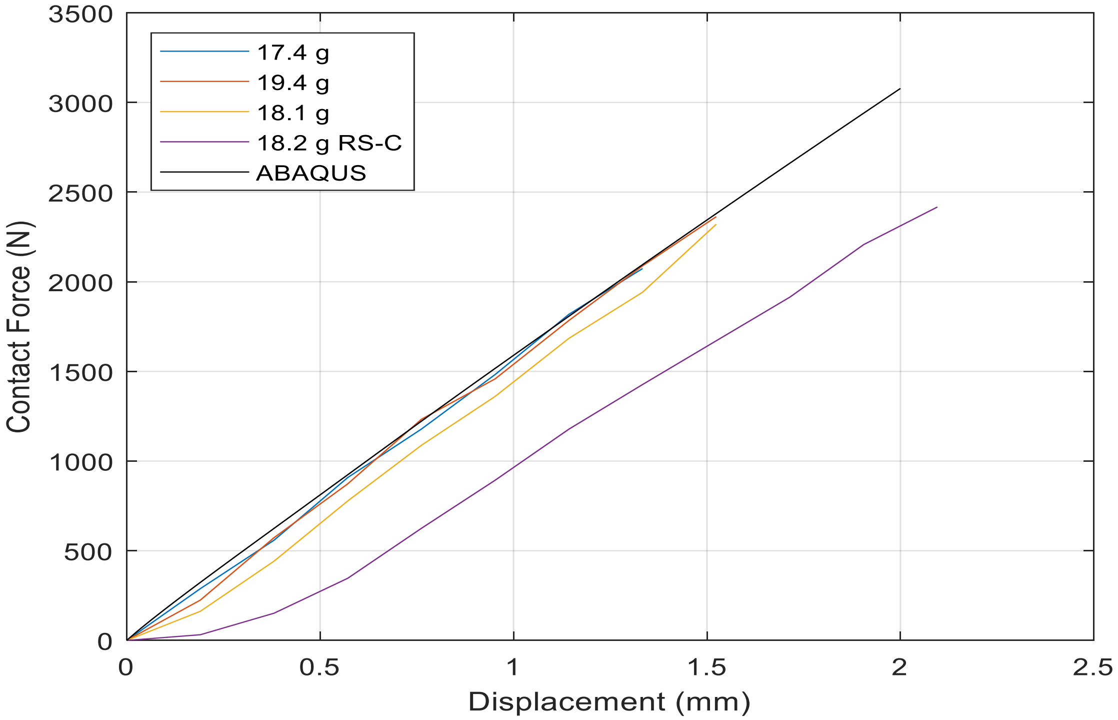


Figure 16. Comparison of Force vs. Displacement for Composites and HDPE

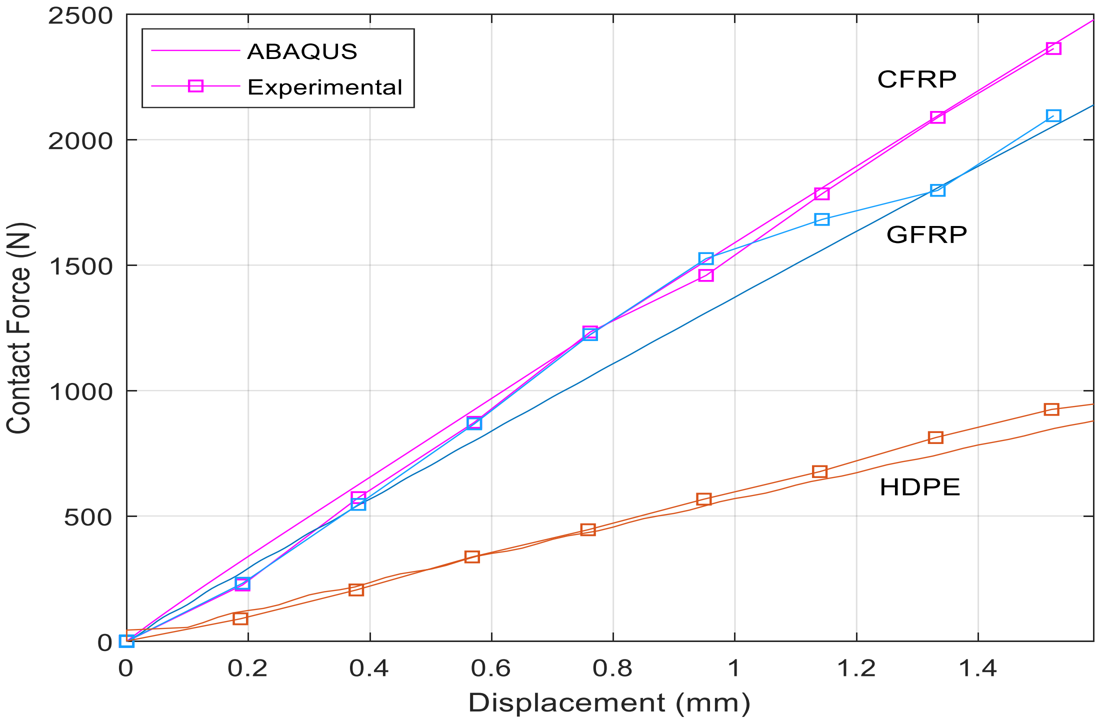
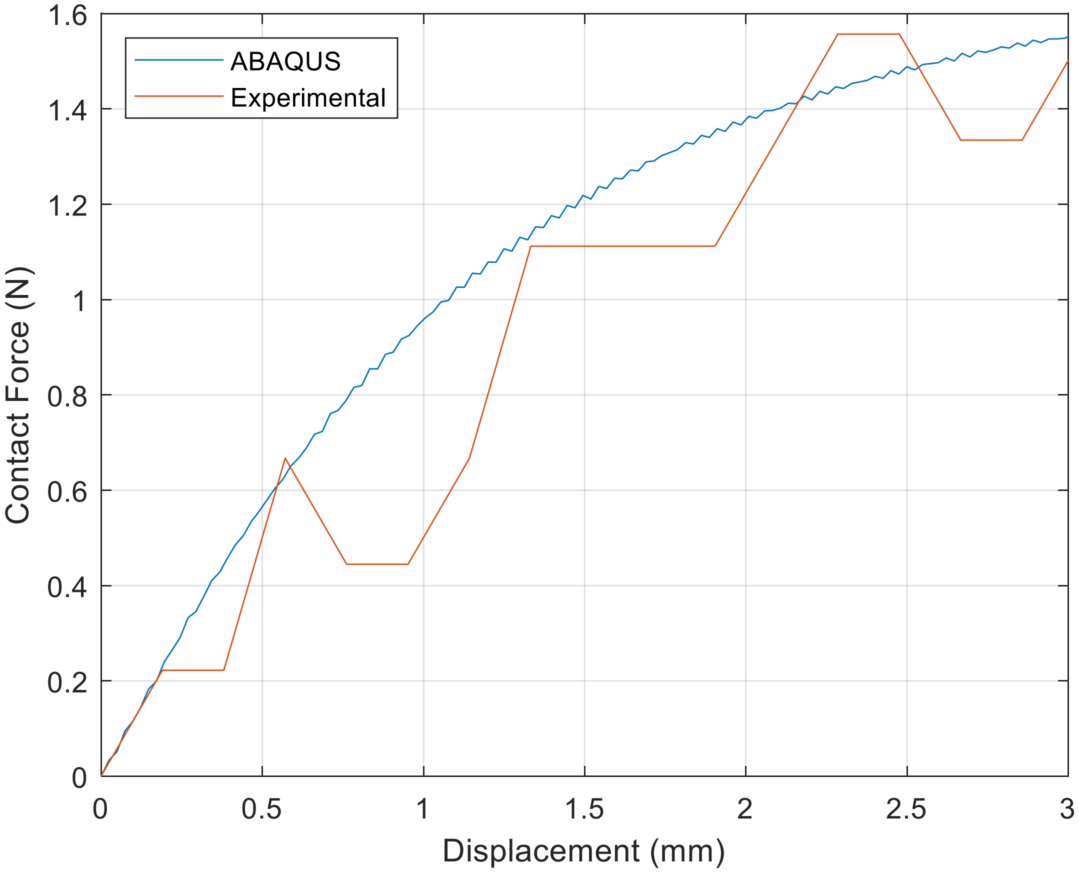


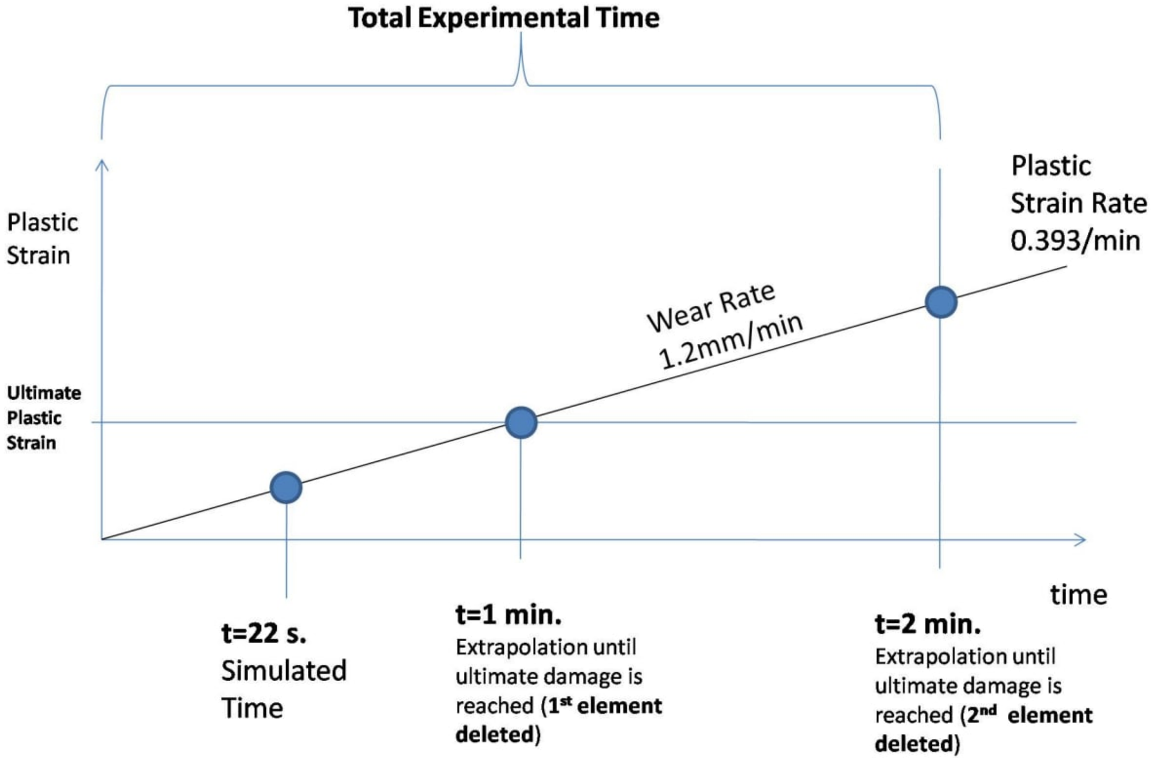
Figure 17. Comparison of Force vs. Displacement for Asphalt



3.3 Accelerated Wear

For the wear tests, the initial plan was to use element deletion as a function of time for validation but this would be highly mesh dependent; that is, the larger the element size, the higher the wear rate. Instead, the average plastic strain was used to compute the rate of damage (plasticity) since this would measure the start of plastic strain prior to element deletion. This is permissible since the plastic strain time history is mostly linear; that is, the overall response under loading for the first 22s (fairly long time under finite element explicit simulation) can simply be extrapolated to each additional minute of simulation based on the actual wear rate of each material (Figure 18). In this manner, the wear would be a progressive failure just like in the real specimen and would be independent of the element mesh size governing the deletion computation.

Figure 18. Accelerated Wear Test Loss Profile



The asphalt plastic strain time history is the average value of the first contact elements layer of 1.2 mm and given its evolution during the wear test, it should reach the ultimate plastic strain of 0.39 in 1 minute to have an average of this thickness deleted (Figure 19). After the two minutes of the accelerated wear, the first 2.4 mm are deleted for the simulation, compared to the 2.3 mm observed experimentally. This would be a minor difference of 1.2 mm/min versus 1.15 mm/min between the simulation and physical test, less than 5% difference for a validated material model.

For the CFRP wear test, the response is linear with a 0.374 value for the ultimate strain. After two minutes, it will wear 0.66 mm at a rate of 0.33 mm/min (Figure 20).

The damage for an element of 1.2 mm is highest for the first layer, with the averaged plasticity of 1.2/0.33.

Figure 19. Plastic Strain Wear Rate for Asphalt

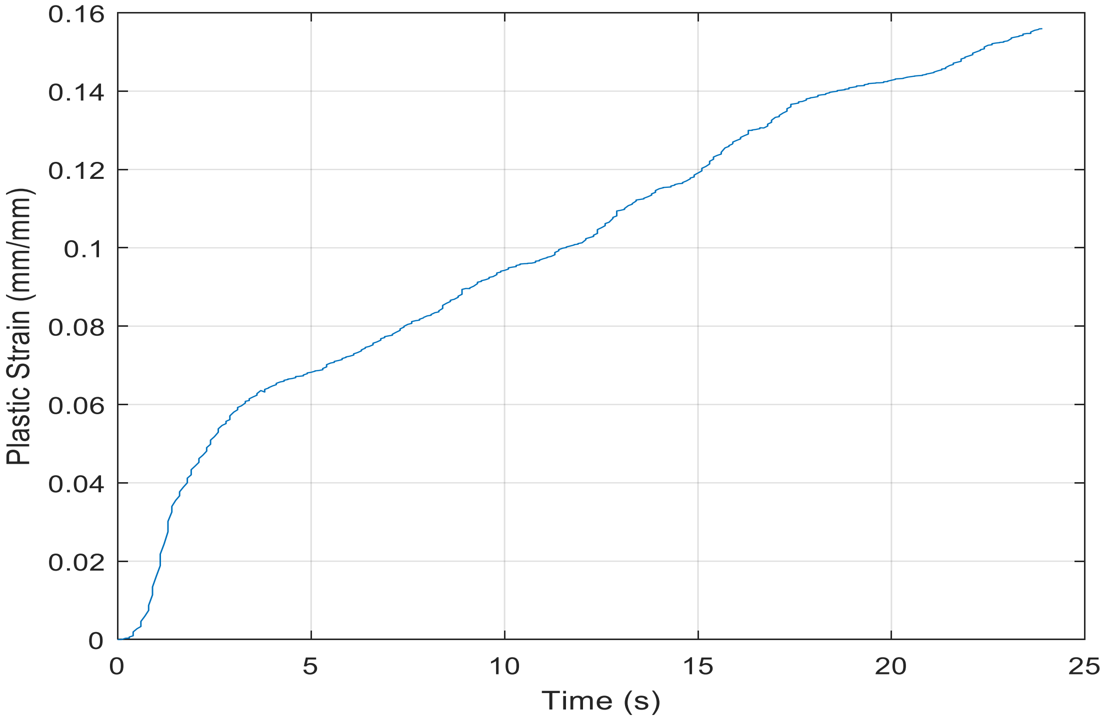
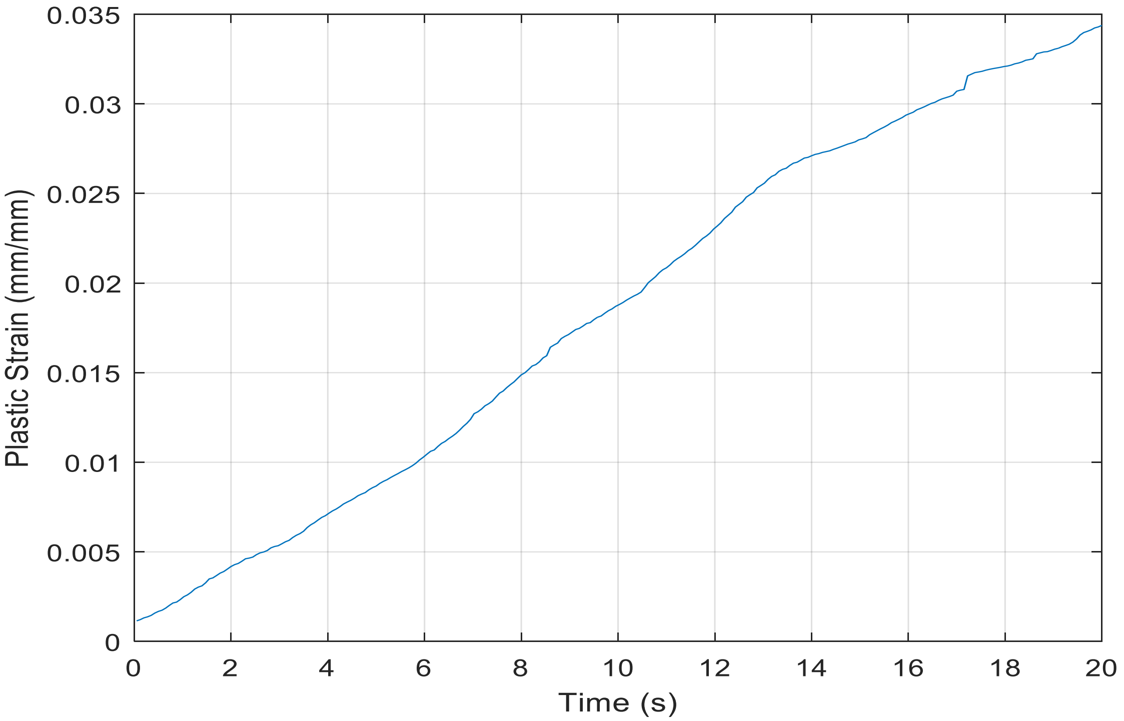


Figure 20. Plastic Strain Wear Rate for CFRP



Given the wear rate of 0.33 mm/min (for the CFRP), and from the Abaqus model, the wear rate is computed as slope (0.1) multiplied by the initial element length (1.1 mm) divided by 500 due to the accelerated spin up, with 60 s/min leading to a yield of 0.28 mm/min, which is in close agreement with the measured results (Table 3). The majority of composites have similar wear rates for all types, and half the wear of asphalt, with HDPE showing the lowest wear due to its intrinsic high wear molecular configuration. An HDPE matrix glass composite would be a future material to examine.

Table 3. Accelerated Wear Values

Material	Asphalt	GFRP	CFRP	RS-G	RS-C	HDPE
Wear (mm)	2.25	0.88	1.10	1.31	1.36	0.26

3.4 Predictive Analysis

Given the overall fit with the experimental data, it is possible to perform predictive analysis on larger-sized specimens and more realistic loading cases such as a 50 x 50 x 10 cm thick block of material subject to normal tire stresses, modeled as an analytic field with harmonic amplitude using a traction vector with pressure (normal) and shear (tangential). The pressure is assumed to be 42kPa, equivalent to a typical car with standard tires, and shear traction is proportional via the friction coefficient of 0.4 (usual friction coefficient for tires and asphalt is between 0.4-0.9). Abaqus is run in dynamic-implicit with a frequency of 10Hz over 22 seconds, simulating a vehicle braking 220 times in this accelerated damage model. Here, it is possible to see plasticity evolving uncontrollably for the asphalt model versus the composite model even when the force peak is constant, showing the overall material superiority of the composites (Figure 21). By running the analysis to compare peak deformations between both materials, it would take approximately 3000x more loading to cause the same wear-- that is, a composite road under normal operating conditions would never need replacement whereas asphalt is known to have a finite lifespan (Figure 22).

Figure 21. Predictive Loading on Asphalt Road

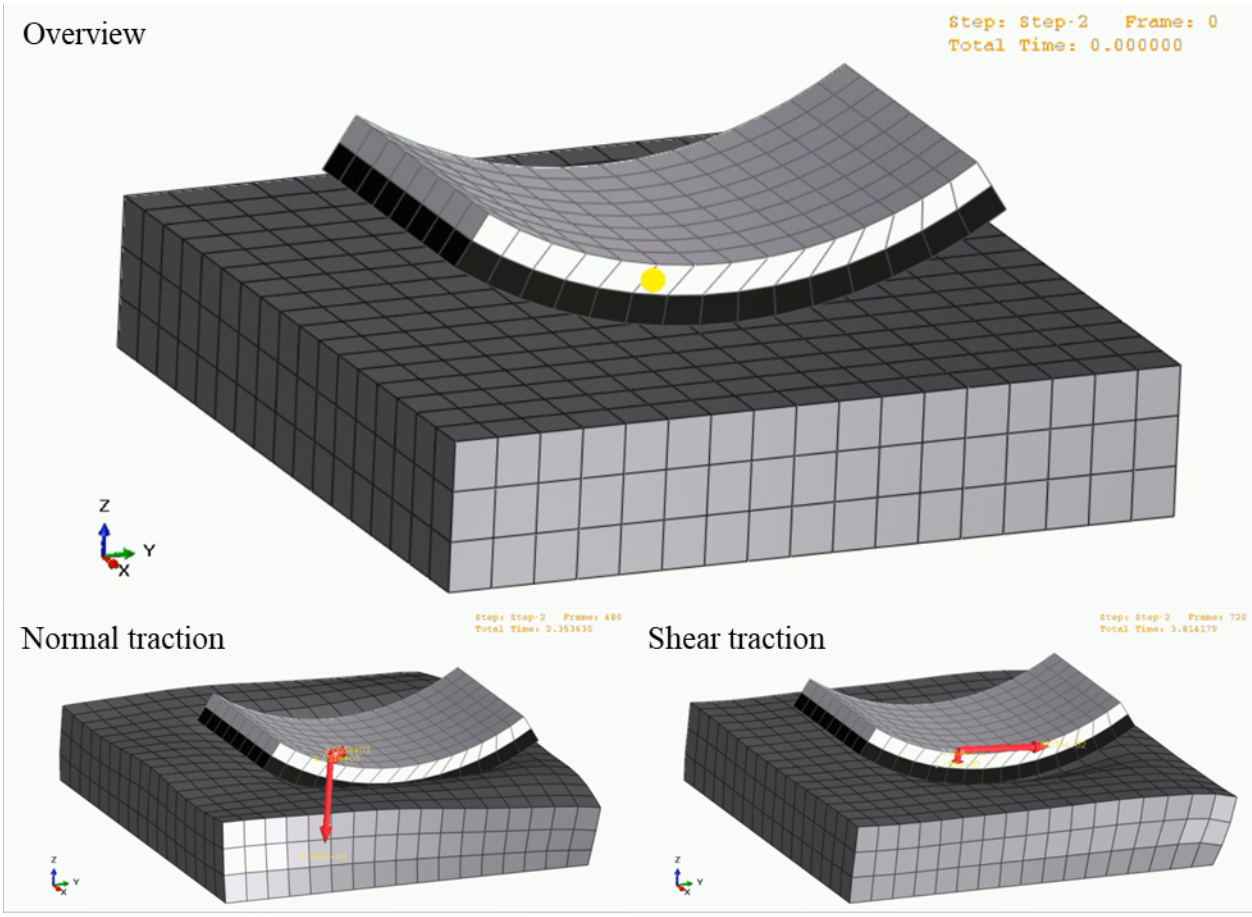
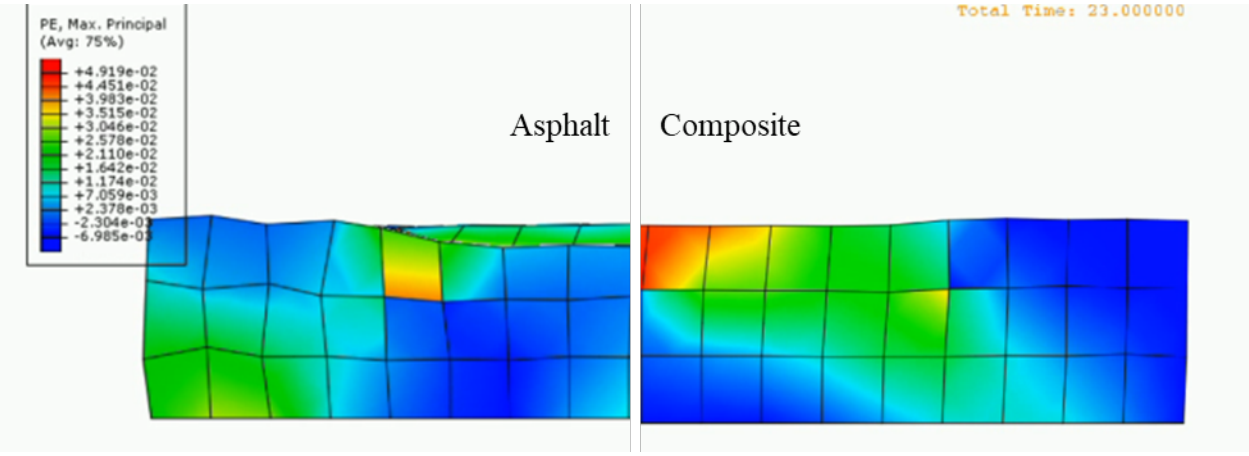


Figure 22. Comparison of Stress and Deformation of Asphalt Versus Composite



4. Summary & Conclusions

The purpose for this investigation was to examine the case for recycled composites for improved infrastructure materials. Cost per ton is roughly 100x for pristine composites compared to asphalt. However, cost per ton of disposing end of life composite is very similar to purchasing new asphalt. As such, the fact that hundreds of thousands of tons of composite materials that are produced, shipped, manufactured, and are currently at their end of life within our borders, being invoiced and shipped out of state to Asia makes little economic sense (Paben, 2020 & Sloan, 2014). Thus, from a purely economical and ecological perspective, there is justification for making use of recycled composites.

Of particular interest in this proposal is developing the validated models for examining the overall performance of asphalt and these composites. Several cases were examined and the experimental results show similar performance between the recycled and pristine materials at least within the areas of interest-- that is, ultimate strength is not the priority in infrastructure, but toughness, resilience, and wear is emphasized. Both new and recycled composites road surfaces would easily outperform pure asphalt over its lifetime. More importantly, since 100% composite construction would not be feasible for the vast majority of infrastructure projects, it should be at least considered to develop a novel asphalt composite combining both fibers and asphalt. This could lead to a new area of investigation whereby only a small percentage of the asphalt needs to be fiber reinforced in order to obtain better performance, i.e., would just 1% of the superior strength of glass fiber mixed with 99% of asphalt be sufficient to provide 20% longer lifespan? This is indeed possible as the fibers have good properties in tension and increasing the tensile strength of asphalt has a direct correlation with longer lifespan (Lee, 2007). The fiber reinforced asphalt could even be tailored to the regional needs around the United States, e.g., higher percentage of fibers for earthquake prone areas, more high strength carbon as opposed to glass for areas subject to freeze-thaw cyclic conditions, or higher glass content for marine environments.

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