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A New Materials and Design Approach for Roads, Bridges, Pavement, and Concrete

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A New Materials and Design Approach for Roads, Bridges, Pavement, and Concrete

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MINETA TRANSPORTATION INSTITUTE

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REPORT 19-35

A NEW MATERIALS AND DESIGN APPROACH FOR ROADS, BRIDGES, PAVEMENT AND CONCRETE

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EXECUTIVE SUMMARY

An increased understanding of how to improve the sustainability, durability, and longevity of road pavement materials would enable decisionmakers in the transportation industry to make environmental, financial, and other positive changes in future planning, design, and implementation. . This research comprises three studies focused on pavement materials and a fourth study that examines energy demand within the road transportation sector. These studies are as follows:

1. A techno-economic study of ground tire rubber as an asphalt modifier;
2. A computational fluid dynamics analysis comparing the urban heat island effect of two different pavement materials – asphalt and Portland Cement Concrete;
3. A new approach that modifies the surface of ground tire rubber using low-cost chemicals and treatment methods to be used in asphalt applications; and
4. An analysis of road transport energy demand in California and the United States.

In the first study, a techno-economic analysis documented that ground tire rubber (GTR) is a suitable additive for modified asphalt. In this case study, the authors provide a block flow diagram and process flow diagram for a base case (Styrene-Butadiene-Styrene) and two alternate cases (GTR and Crumb Rubber). Findings indicate lower capital and operating cost processes are needed in order to provide profitable surface-treated GTR modified asphalt. Study 2 uncovered that, despite common belief that Portland Cement Concrete (PCC) is universally a cooler pavement material than asphalt, under certain conditions – specifically higher wind velocities – PCC surface temperatures are comparable to asphalt temperatures. The third study investigates novel modified asphalt materials, which can provide transformative applications in road pavement processes. The surface of GTR is modified and its properties evaluated by contact angle measurements and infrared spectroscopy. By synthesizing new materials with a modified surface, there is an opportunity to develop asphalt composite materials with enhanced properties. This project provides a simple method to change the surface properties of GTR particles that could enhance pavement applications. Finally, in Study 4, the researchers assess how changes in oil prices affect gasoline supply and demand. Through an understanding of the responsiveness of gasoline demand to changes in price and income, policy implications for road usage in California and the U.S. can be examined. Ultimately, these four studies increase understanding of GTR and transport energy demand. They lay out important information about the future of the relationship between materials and design in the transportation industry. These findings may be used by engineers, policymakers, and others in the industry to better consider implications of decisions involved in design, creation, and modification of structures using pavement and concrete, including important roads, bridges, etc.

I. STUDY 1: TECHNO-ECONOMIC STUDY OF GROUND TIRE RUBBER

INTRODUCTION

Different binders are used in creating different types of asphalts. These different binders have different rheological properties that affect their strength as a material. These materials are styrene-butadiene-styrene (SBS), crumb rubber (CR) and ground tire rubber (GTR). The economic analysis described below compared SBS, GTR, and CR. The polymers currently used in asphalt today include Polyethylene (PE), Polypropylene (PP), and SBS. An advantage of SBS is that it has lower viscosities at lower temperatures. A disadvantage is that SBS has a high cost. Ideally, research would reveal a cost-effective, durable, and environmentally friendly polymer binder to be used as functional asphalt modifier.

Preliminary work was carried out by the principal investigator (PI), Dr. Alan Fuchs, at the University of Nevada, Reno during an earlier project. There, ground tire rubber (GTR) was modified using a vinyl norbornene (VN) polymer. This work was done as part of an NSF SBIR Phase I project. It showed significant progress in the development of a surface modification of GTR that allows for its use as an asphalt modifier. GTR is a more cost-effective material than asphalt, and its use has environmental benefits. During the Phase I project, surface functionalization was used to create hydroxyl groups on the GTR. The oxidized GTR compound, GTR-OH, was functionalized by the substitution of polyethylene glycol (PEG) groups on the hydroxy groups of GTR-OH, yielding a GTR-PEG product. Variations of the oxidation reactions found in the literature were explored, and researchers concluded, through infrared characterization, that a 1:2 GTR to KMnO_4 equivalence reaction left overnight yielded the best oxidation results; further, a reaction of GTR with PEG in a pyridine base resulted in the best PEG group substitution results.

The GTR was coated using atom transfer radical polymerization, which is a controlled polymerization technique. The materials were characterized using scanning electron microscopy and infrared spectroscopy. Asphalt binder testing and asphalt testing techniques were also used to determine separation, softening point, penetration, viscosity, and rheology. The results of this research indicated that improvements in asphalt performance were achieved with lower separation between the asphalt and the coated GTR.

Petroleum refining processes remove valuable components of asphalt binders, so high-quality asphalt binders for shingles and roads must be modified. Polymers are thus added to improve the rheological and viscoelastic properties. Styrene-butadiene-styrene (SBS) is the most prevalent additive, and it ultimately improves rutting and impact resistance in road pavement as well as asphalt shingles. Although SBS provides beneficial stability characteristics, it is a costly component in a very cost-sensitive industry; polymer modified asphalt (PMA) suppliers desire to have it at least partially replaced. Tire rubber is a possible substitute for SBS, as it consists of cross-linked synthetic and natural rubbers. Tire rubber is also a waste commodity that occupies valuable landfill space, and certain agencies already mandate its use, regardless of cost.¹

Tire rubber has already been used to replace SBS to some extent, but with limited success

and at an even higher cost per ton over SBS because of the added processing and energy required to blend it into asphalt. Tire rubber must be reduced to a very fine, micronized particle size to obtain properties comparable to SBS in asphalt.² The costs to reduce it to that form prevent it from serving as a viable alternative to SBS. GTR is a low-cost particle of intermediate size between the micronized rubber powder (MRP) and larger crumb rubber (CR). However, GTR cannot be added to asphalt without some modification, as the particles readily settle in the mixture. CR particles are so large that no amount of modification will keep them suspended in solution. A modified GTR—with its low cost and potential for excellent phase stability—would therefore be the most suitable form for an asphalt modifier.³

Polymeric Designs (PD) therefore developed a polymer coating to improve the GTR-asphalt surface interaction by chemically bonding the two phases. The monomer 5-vinyl-2-norbornene (VN) was ultimately chosen for polymerization by virtue of its thermal characteristics and its bicyclic structure, which includes two carbon=carbon double bonds. Three polymerization methods were implemented: atom transfer radical polymerization (ATRP), free radical polymerization (FR), and ring-opening metathesis polymerization (ROMP).

A review of literature showed that methyl acrylate (MA) co-polymerization with various norbornene polymers had been achieved, so polymerization with 5-vinyl-2-norbornene was tried and yielded a viable and novel copolymer: methyl acrylate/5-vinyl-2-norbornene (MAPVN). Two coating methods were implemented with a solvent to apply the copolymer to the GTR: surface polymerization and physical coating. Surface and bulk polymerization involved polymerization of the monomer units MA and VN directly onto the surface of the GTR particle using 2-(4-chlorosulfonylphenyl) ethyltrichlorosilane (CTCS) as a covalent linker between the functionalized surface and the copolymer. This process occurs in toluene until the reaction is complete. Physical coating involves the dissolution of the copolymer into a toluene and GTR mixture. In the case of physical coating, the solid material is decanted to remove all liquids and dried to obtain the coated GTR product. Samples of GTR coated by these methods were examined using scanning electron microscopy (SEM) at 5% and 10% polymer loading, respectively. Both showed complete coating at light and heavy loadings. Asphalt was modified with the copolymer coated GTR by simple mixing and was then analyzed using four ASTM International standard tests for PMA which test for separation, penetration, softening point, and viscosity.

Primary focus was placed on separation testing, as the settling of GTR during storage is a major industrial problem. MAPVN coated GTR–asphalt mixtures were tested against SBS and uncoated GTR mixtures for ASTM performance characteristics. The enhanced interface between the GTR and asphalt provides decreased particle–particle interaction, a key factor in increased dispersion. The net effect is better suspension of each particle in the heated asphalt mixture and a reduction of separation to a level well within acceptable limits. Some of the key findings for Phase I were that PD has developed a new family of polyvinylnorbornene (PVN) and PN copolymers, which can be used in modified asphalt.

BASE CASE

In our experiments, the base case modifier was SBS. This is the industry standard

polymer modifier for asphalt mixtures. It is currently used as an asphalt modifier because it can improve the physical properties without greatly increasing the high temperature viscosity. Including an SBS modifier increases the softening point of asphalt and decreases the separation. As stated previously, however, SBS is costly. A more economic substitute is desirable.

Block Flow Diagram of SBS



SBS is first measured out into a hopper, which then dumps the SBS onto an auger that transports it into a mixing tank. Liquid asphalt, in this case obtained from Bowman Asphalt, is then added into the mixing tank, which is mounted on load cells to obtain an accurate measurement of each constituent. The SBS pellets sink to a grinding mill at the bottom of the tank. The high concentration of SBS at this point in the process aids in the grinding efficiency. The grinding and mixing process adds heat. The mixture is then transported to a holding tank, where more asphalt is added to obtain the final appropriate ratio.

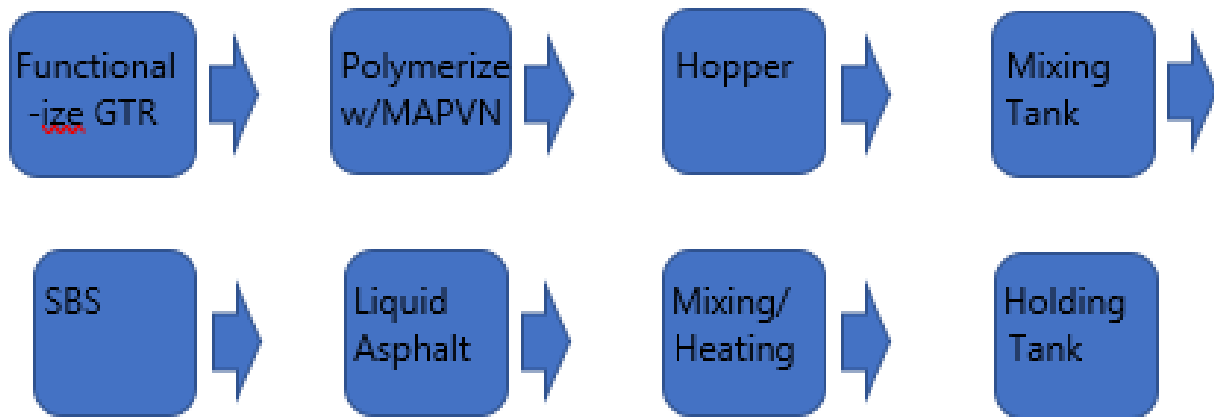
ALTERNATIVE CASES

Block Flow for Crumb Rubber



We first begin with a measured quantity of crumb rubber that is added to a hopper. The crumb rubber gets transported from the hopper and added to a mixing tank along with a measured quantity of SBS. Liquid asphalt is added to the chamber. These elements undergo mixing and heating, and the mixed material is pumped into a holding tank ("Asphalt-Rubber").

Block Flow for GTR



The first step for using GTR as an asphalt additive is chemically modifying the surface of the GTR. First, selective oxidation of the rubber C=C double bonds on the surface of the GTR particles (especially the more accessible 1,2 vinyl groups) is performed in order to introduce 1,2-diol groups. 2-(4-chlorosulfonylphenyl) ethyltrichlorosilane (CTCS) reacts with the hydroxyl groups on the GTR to form a covalent Si-O-GTR bond. This bond serves as a covalent linker between the oxidized surface and the copolymer methyl acrylate/5-vinyl-2-norbornene (MAPVN). Physical grafting is then used to polymerize MAPVN onto the GTR surface. A measured amount of the treated GTR is then placed in a hopper and transported via conveyor belt to a mixing tank. SBS and liquid asphalt are added, and everything is mixed, creating heat. Once the mixture is well blended, it is pumped into a holding tank (“Asphalt-Rubber”).

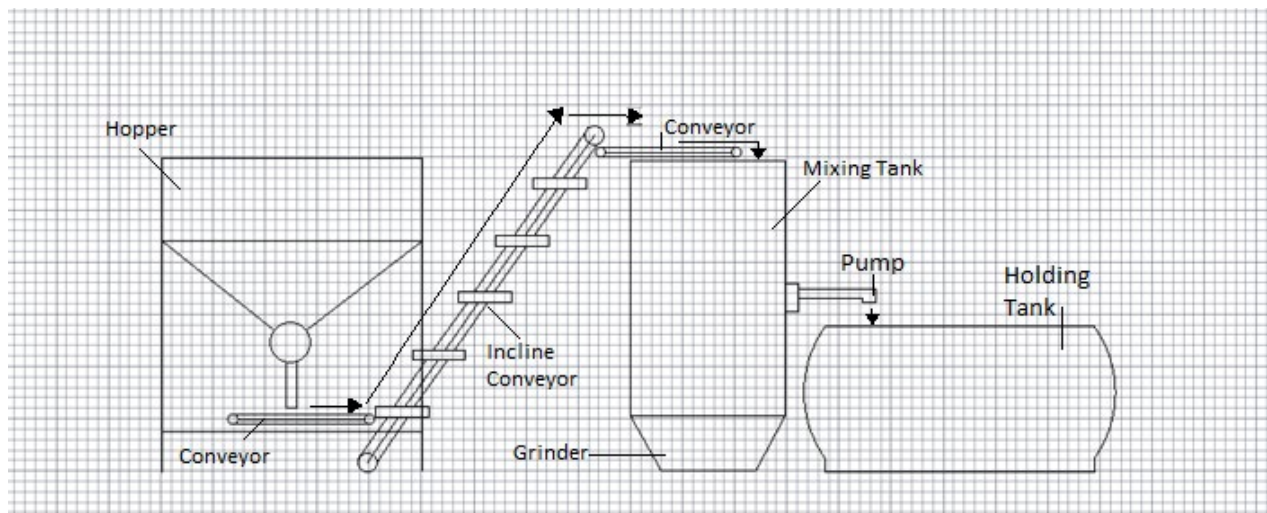


Figure 1. Process Flow Diagram

Figure 1 is a process flow schematic of the asphalt compounding system. Ground tire rubber (GTR) is conveyed to the mixing tank, where it is mixed with asphalt and transferred to the holding tank.

Table 1. Equipment Tables and Economics

Equipment	Material	Size	Capacity
Hopper	Steel	2 Cubic Yards	2000 lbs.

Equipment	Material	Dimensions
Conveyor	Metal, Rubber	1 ft × 10 ft

Equipment	Material	Dimensions
Inclined Conveyor	Metal, Rubber	1 ft × 14 ft

Equipment	Material	Capacity	Dimensions
Mixing Tank	Stainless Steel	500 Gallons	52 in. Diameter, 60 in. Height

Equipment	Material	Capacity	Dimensions
Holding Tank	Steel	550 Gallons	48 in. Diameter, 72 in. Length

Material Name	Classification	Price (\$/kg)	Flowrate (kg/h)	Annual Cost (\$)
Residuum	Raw Material	5.00	20.00	832,200
Sasobit	Product	5.00	10.00	416,100
EVA	Product	0.11	7.00	6,408
SBS	Product	4.50	7.00	262,143
Aggregate	Raw Material	2.00	7.00	116,508

Equipment and costs are provided in Table 1. Materials needed for construction and equipment dimensions are provided based on heuristics for calculating their design parameters.

Table 2. Materials Costs

Material Name	Classification	Price (\$/kg)	Flowrate (kg/h)	Annual Cost
Residuum	Raw Material	\$5.00	20.00	\$832,200
Sasobit	Product	\$(5.00)	10.00	\$(416,100)
EVA	Product	\$(0.11)	7.00	\$(6,408)
SBS	Product	\$(4.50)	7.00	\$(262,143)
Aggregate	Raw Material	\$2.00	7.00	\$116,508
				\$1,633,359

Table 2 includes the materials costs for the raw materials used in the novel asphalt mix. The cash flow diagram for this process is negative (-\$18M) at the completion of the project, indicating that lower capital cost or more efficient operating cost processes are needed in order to make this process economical.

CONCLUSIONS

Researchers conducted a techno-economic study on a process for development of new materials for pavement. A block flow diagram, process flow diagram, equipment tables, and

economic analyses were conducted. The cash flow diagram for this process is negative at the completion of the project, indicating that lower capital cost or more efficient operating cost processes are needed in order to make this process economical. Environmental costs will be considered in future research. The findings of this study indicate that GTR is an effective and economically suitable additive for modified asphalt.

II. STUDY 2: COMPUTATIONAL FLUID DYNAMICS (CFD) APPROACH

INTRODUCTION

The Urban Heat Island (UHI) effect is a phenomenon in which temperatures are higher in urban areas when compared to the surrounding countryside, due to human activities. UHI has detrimental consequences on the health and wellbeing of people living in cities worldwide. Researchers have shown that of the primary causes of UHI are the concentrated use of synthetic materials and anthropogenic activities..

One way to assess UHI is by studying the materials used in urban infrastructure such as pavements, building materials, and roofs. Various researchers have focused on the choice of materials used to build pavements and have performed experiments to study heat retention, as well as emissions associated with pavement materials.

In the present work, UHI effect is studied by simulating the surface temperatures of two different pavement materials—asphalt and Portland Cement Concrete (PCC)—on a hot summer day. Asphalt, typically darker than PCC, has lower albedo (ability to reflect light) and thus a higher temperature in the sun. A computational fluid dynamics (CFD) analysis is done to evaluate the surface temperature of these two materials at different wind speeds and ultimately compare how PCC and asphalt contribute to UHI.

DESCRIPTION

Full scale three-dimensional computational fluid dynamics (CFD) simulations are performed on pavement blocks of two different materials, asphalt and Portland Cement Concrete (PCC). ANSYS Fluent 18.2 is used as the simulation software. The steady state temperature on the pavement top surface is calculated as a function of wind speed and solar irradiation at a given place, on a given day, and at a given time. For the purpose of simulations, the location chosen is Bakersfield, California, and the date and time chosen is July 15 at 10:00 am. Wind speeds over the pavement surface vary from 0.0001 m/s (quiescent air) through 10 m/s. Figure 2 shows the simulation geometry. Wind speeds, not actually measured but as simulation only, are used as boundary conditions for simulations. The pavement block is 4 meters in length, 4 meters in breadth and has a depth of 0.6 m.

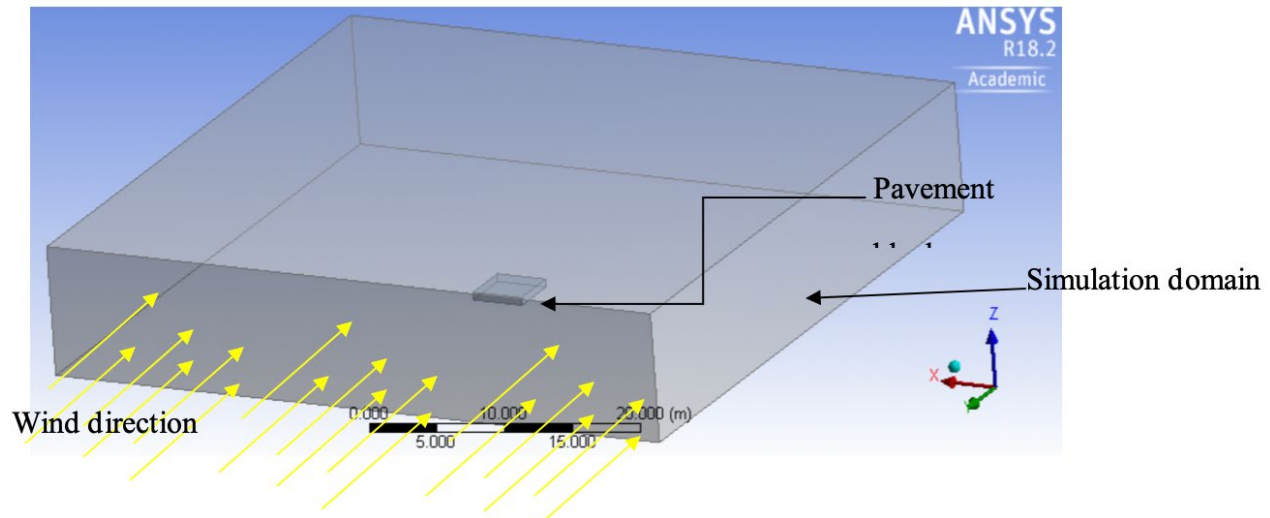


Figure 2. Simulation Geometry

The pavement block is simulated with the assumption that it is in an open space. The simulation domain is kept large enough to avoid any wall effects. As shown in Figure 2, wind is assumed to flow in one direction only. The ground temperature is assumed to be 340K (67°C). The free stream temperature used for simulations is 300K. Table 1 shows the material properties of asphalt, PCC, and ground used for the simulations.

Table 3. Material Properties

	Asphalt	PCC	Ground (Clay)
Density, kg/m ³	2240	3150	1330
Specific heat, J/kgK	750	920	878
Thermal conductivity, W/mK	0.75	0.29	2.5
Emissivity	0.9	0.54	0.65
Albedo	0.2	0.8	0.35

From wind velocity, the Reynolds number is calculated using equation (1):

$$Re = \frac{\rho v D_h}{\mu} \quad (1)$$

where Re is the Reynolds number, ρ is the density of air in kg/m³, v is the wind velocity in m/s, D_h is the characteristic length scale or width of the pavement block and μ is the dynamic viscosity in Pa.s

The Nusselt number is calculated from the Reynolds number. Equation (2) is used when flow is laminar:

$$Nu = 0.664Re^{0.5}Pr^{1/3} \quad (2)$$

where Nu is the average Nusselt number when flow is laminar, Re is the Reynolds number, and Pr is the Prandtl number.

Equation (3) is used when flow is turbulent:

$$Nu = 0.037Re^{0.8}Pr^{1/3} \quad (3)$$

where Nu is the average Nusselt number when flow is turbulent.

CFD results reveal the steady state temperature on the pavement top surface. Tables 4 and 5 show calculated values of Reynolds number, Nusselt number, and convection coefficient for asphalt and PCC, respectively.

Table 4. Convection Coefficients: Asphalt Surface

Wind Velocity, m/s	Reynolds Number	Nusselt Number	Convection Coefficient, W/m ² K
0.0001	27.38	3.12	0.5849
0.001	273.8	9.86	1.850
0.01	2738	31.2	5.849
0.1	27380	98.6	18.50
1	273800	311	58.49
10	2738000	4690	879.7

Table 5. Convection Coefficients: PCC Surface

Wind Velocity, m/s	Reynolds Number	Nusselt Number	Convection Coefficient, W/m ² K
0.0001	27.38	3.12	0.2262
0.001	273.8	9.86	0.7152
0.01	2738	31.2	2.262
0.1	27380	98.6	7.152
1	273800	311	22.62
10	2738000	4690	340.2

The steady state surface temperatures are a function of wind speeds, material thermal conductivity, and radiative properties such as emissivity and albedo.

Emissivity is the measure of an object's ability to emit infrared energy. It is defined as the potential of the surface to emit energy by radiation in comparison to blackbody at the same

temperature. Albedo, on the other hand, is defined as the fraction of incident light on the surface of a material that is reflected, and it is given by equation (4):

$$Albedo = \frac{scattering\ coefficient}{scattering\ coefficient + absorption\ coefficient} \quad (4)$$

Asphalt, typically darker in color than PCC, has lower albedo.

RESULTS

Figures 3, 4, and 5 show the steady state temperature profiles on the asphalt pavement at wind speeds of 0.0001 m/s, 0.1 m/s and 10 m/s.

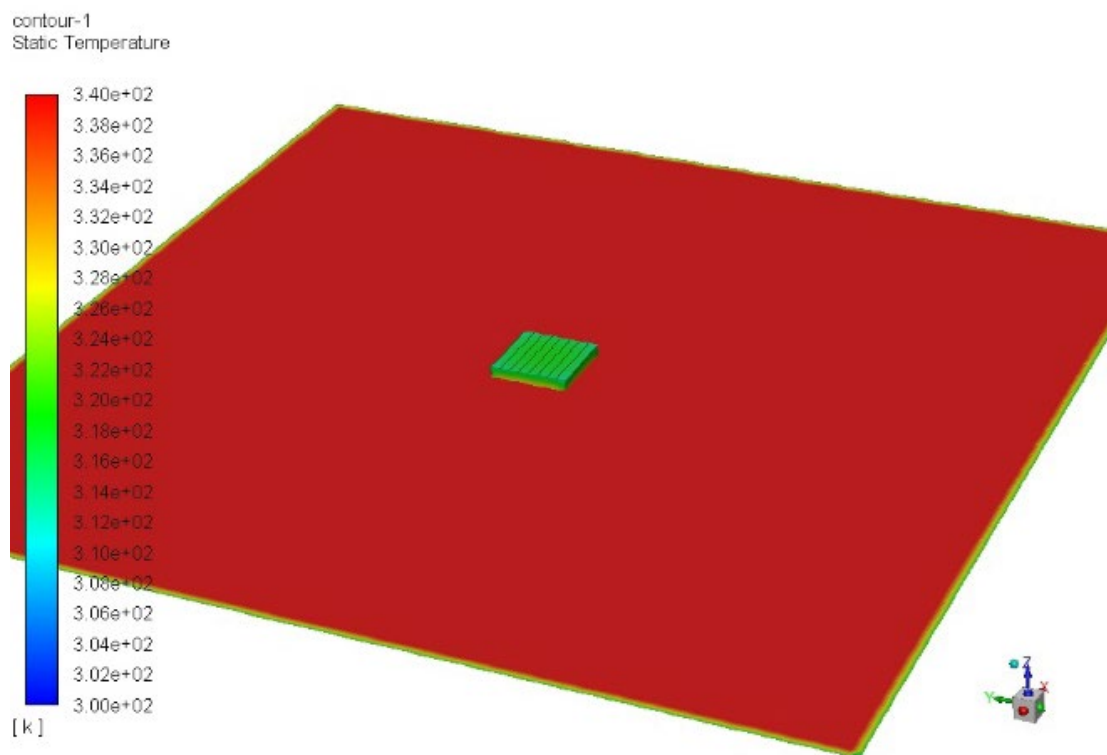


Figure 3. Temperature Profile on Asphalt Pavement: Wind Speed 0.0001 m/s

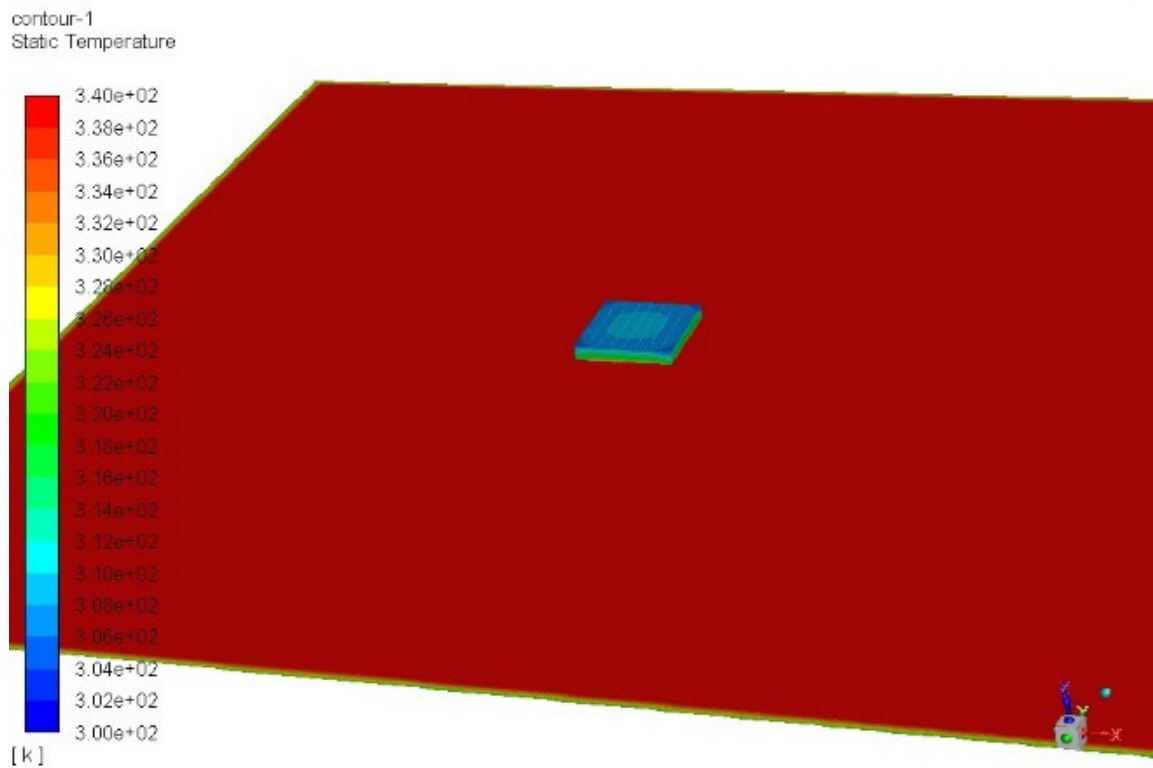


Figure 4. Temperature Profile on Asphalt Pavement: Wind Speed 0.1 m/s

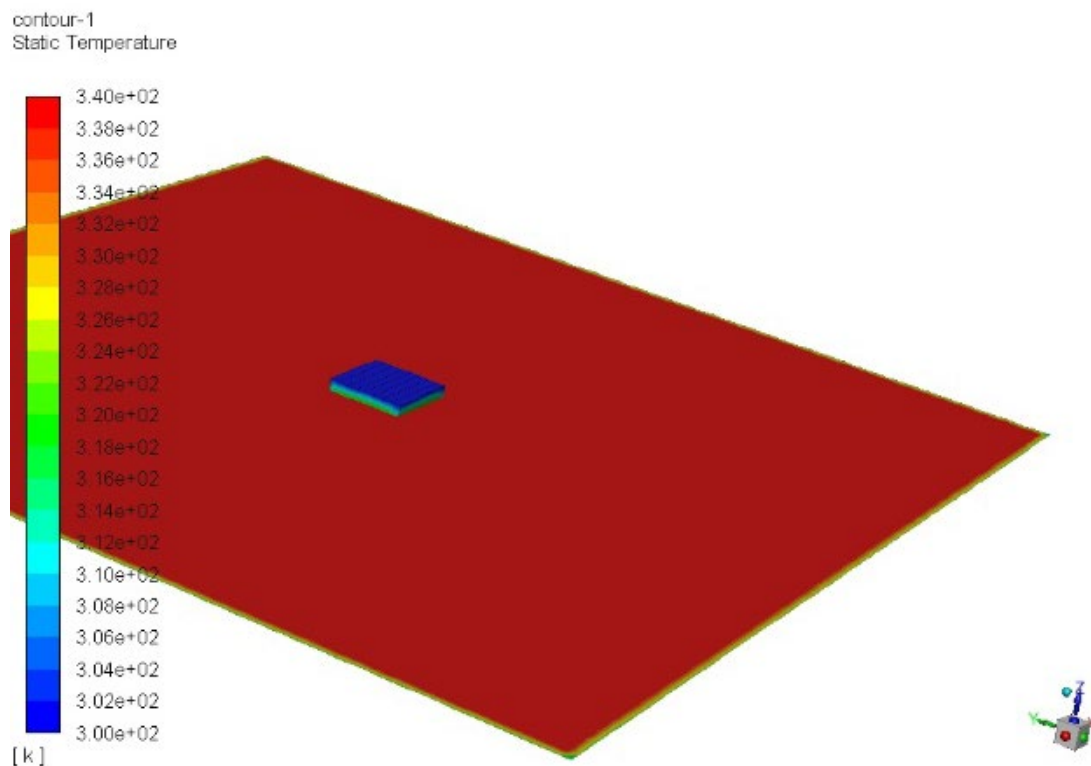


Figure 5. Temperature Profile on Asphalt Pavement: Wind Speed 10 m/s

As expected, with an increase in wind velocity, the top surface temperature reduces. The

ground temperature is kept fixed at 340K. The results compare asphalt and PCC pavement blocks with the same dimensions. Figure 4 shows a comparison of pavement top surface temperatures for the two materials.

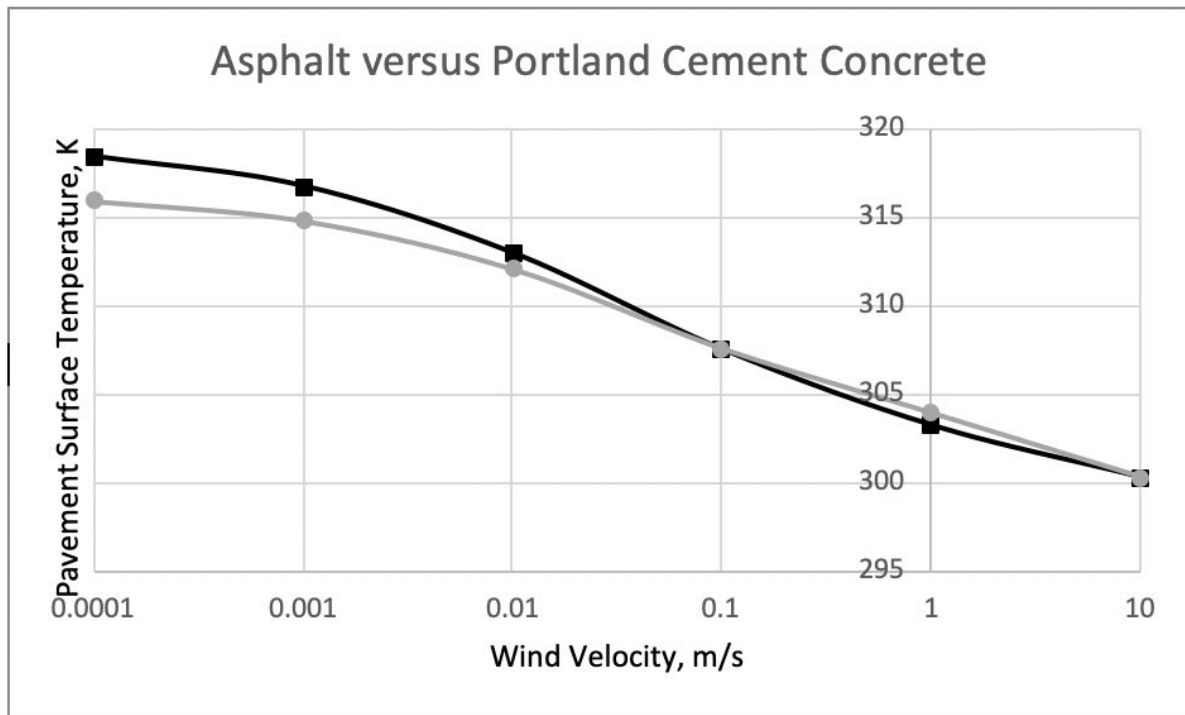


Figure 6. Pavement Surface Temperature with Wind Speed: Asphalt versus PCC

DISCUSSION

The results show that at low wind velocities (≤ 0.1 m/s) and under steady state conditions, asphalt surface temperature is always higher than PCC surface temperature. However, at wind velocities higher than 0.1 m/s, the steady state surface temperatures of the two materials are almost the same. Significantly, this result disproves that PCC is universally a cooler material than asphalt. Previous researchers typically used 0.1 as the albedo for black asphalt pavements and 0.8 as the albedo for white PCC pavements. The model uses these values as inputs. Based on observations by previous researchers, the CFD model accurately predicts asphalt pavement surface temperatures being higher than PCC surface temperatures. However, it also suggests that at higher wind velocities, asphalt and PCC pavements may contribute equally towards UHI.

CONCLUSION

CFD analyses on two different pavement materials, asphalt and Portland Cement Concrete (PCC), show that although the steady state surface temperature of the asphalt pavement is about 2–3°C higher during a hot summer day with low wind velocities (≤ 0.1 m/s), the surface temperatures of both materials are comparable at higher wind velocities. These

results contradict the common belief that PCC is universally a cooler pavement material than asphalt. This finding also suggests a need to re-examine the suitability of PCC pavements in urban settings.

III. STUDY 3: SYNTHESIS OF SURFACE MODIFIED GROUND TIRE RUBBER PARTICLES AND ITS CHARACTERIZATION

INTRODUCTION

The goal of this section of the project is to develop novel modified asphalt materials to provide transformative applications in road paving. This goal will be accomplished by modifying the surface of the ground tire rubber (GTR) and evaluating its properties by contact angle measurements and infrared spectroscopy. Synthesizing new materials with a modified surface provides an opportunity to develop asphalt composite materials with enhanced properties.

DESCRIPTION

The use of GTR as a road building material is important to the construction industry.⁴ Worn tires can be crushed to ground tire rubber (GTR) and mixed with bitumen to improve pavement performance. However, poor compatibility between GTR and bitumen entails some drawbacks: GTR dispersion in bitumen is not optimal, causing heterogeneity problems and great instability during hot storage. Interface and adhesion aspects appear to be the main factors governing this compatibility.⁵ In the past, several researchers have investigated ways to modify the surface of GTR to make it more compatible with binders and asphalt. Zhang et al. used atmospheric plasma to change the surface of GTR from hydrophobic (116°) to hydrophilic (0°) in order to enhance the compatibility of the particles with nitrile rubber vulcanizates.⁶ Fuhrmann et al. modified GTR particles with glycidyl methacrylate and methacrylic acid through photoinitiated grafting.⁷ Bulk polymerization of acrylic acid (AA) on GTR particles without any initiator was performed by Kocevski et al.⁸ Fan and Lu investigated the graft copolymerization of poly(methyl methacrylate) onto waste tire rubber powder through ozonization.⁹ Xiaowei et al. used plasma polymerization of ethanol to modify the surface of waste rubber tire. Their method decreased the contact angle from 122° to 34° .¹⁰ All these authors presented different methods to decrease the hydrophobicity of GTR particles. Some of these methods involved equipment with higher cost, such as plasma polymerization. The present work involves a different approach, which could provide an alternative to modify the surface by using low-cost chemicals and treatment methods.

METHODS

Two different samples of GTR were used. One had an average particle size of $150\text{ }\mu\text{m}$ (MD150), and the other had an average size of $400\text{ }\mu\text{m}$ (MD400). The vinyl groups on the GTR were oxidized with potassium permanganate in order to yield hydroxy groups. The samples were treated a second time to incorporate polyethylene glycol. Table 6 shows the list of samples prepared for characterization.

Table 6. List of Samples

Common Name	Particle Size (μm)	Reaction Conditions	Reference Code
GTR-OH	105	5 min, 2 eq KMnO_4	AMB1-12A
GTR-OH	105	Overnight, 2 eq KMnO_4	AMB1-15D
GTR-OH	400	Overnight, 2 eq KMnO_4	AMB1-15B
GTR-OH	105	Overnight, 10 eq KMnO_4	AMB1-19A
GTR-OH	400	Overnight, 10 KMnO_4	AMB1-19B
GTR-PEG	105	Overnight	AMB1-23A
GTR-PEG	105	Four days	AMB1-25B

SYNTHESIS

To investigate the possibility of creating GTR-infused asphalt concrete, a functionalized GTR compound was synthesized. Particles of 105 and 400 μm sizes provided by Lehigh Technologies and composed of an undisclosed mixture of 1,3-butadiene homopolymer, styrene-butadiene copolymer and 1,3-butadiene, 2-methyl- homopolymer were reacted using standard methods of oxidizing diene compounds. The oxidized GTR compound (GTR-OH) was functionalized using bimolecular nucleophilic substitution of 2-[2-(2-chloroethoxy)ethoxy]ethanol groups on the hydroxy groups of GTR-OH, yielding a GTR-PEG product. Variations of the oxidation reactions were explored, and it was concluded through infrared (IR) characterization that a 1:2 GTR to KMnO_4 equivalence reaction left overnight yielded the best oxidation results and a reaction of GTR with PEG in a pyridine base resulted in the best PEG group substitution results.

Pure GTR-OH was obtained by the following method: after the allotted reaction time, HCl (1M) was added to the reaction mixture and allowed to stir for one hour. After that, the mixture was filtered and GTR-OH solid was washed with DI water. This solid was transferred to a desiccator and placed under high vacuum conditions for 5–6 hours. Infrared spectra of GTR-OH solid after purification showed strong absorption at around $3300\text{--}3178\text{ cm}^{-1}$, which indicates that alcohol functional groups are present: see Figure 11. The purification of GTR-PEG samples was similar to that of GTR-OH purification except hydrochloric acid was used to protonate the remaining pyridine so it could be washed out with DI water. After filtration and washing, GTR-PEG samples were dried under reduced pressure, and infrared spectra showed characteristic absorption for ether functional groups at 1029 cm^{-1} as well as absorption for alcohol functional groups at 3176 cm^{-1} . See Figure 12.

MATERIALS CHARACTERIZATION

The surface modified GTR particles were studied with Fourier Transform Infrared (FTIR) Spectroscopy and by contact angle.

Contact Angle

Samples were created to test the contact angle with (deionized) water. A small portion of powder samples were placed on a glass slide. Another glass slide was used to flatten the

powder so the surface of the material would be flat, facilitating the measure of the contact angle. The contact angle measures the degree of hydrophobicity of the surface and a liquid. The contact angle data were collected using the AST product VCA Optima Contact Angle Analysis Equipment. The measurements were performed using the image analysis software provided with the instrument. Three different droplets on each sample were tested by dispensing approximately 3 μL of water from the syringe onto the solid surfaces.

Statistical Analysis

Researchers performed statistical analysis of the data, One-way ANOVA to evaluate any differences between the samples, and multiple comparisons with Tukey HSD and Bonferroni correction to compare the control with the modified samples.

RESULTS

Contact Angle

The hydrophobic or hydrophilic characteristics of the GTR particle surface were measured by static contact angle. A standard method to test wettability, the contact angle test has been used in the past to measure the wetting properties of GTR modified asphalt.¹¹ Figure 7 shows a typical test for contact angle. A droplet of water is shown in the image. Then, imaging software is used to fit the shape of the droplet to a model, and a contact angle is obtained. This figure shows a high contact angle (129.8°), and therefore, the sample is very hydrophobic. (Contact angles above 120° are considered very hydrophobic.) The chemical composition of tire rubber does not contain any polar groups, and thus, it is expected to be hydrophobic. In conjunction with the surface roughness due to particle size, this finding gives a very high contact angle. Hossain et al. (2015) obtained similar average values (114°) when testing GTR only. Some of the samples in this project presented a more hydrophilic surface. For example, the contact angle of sample AMB1-25B is shown in Figure 8.



Figure 7. Contact Angle Measurement of Sample MD400

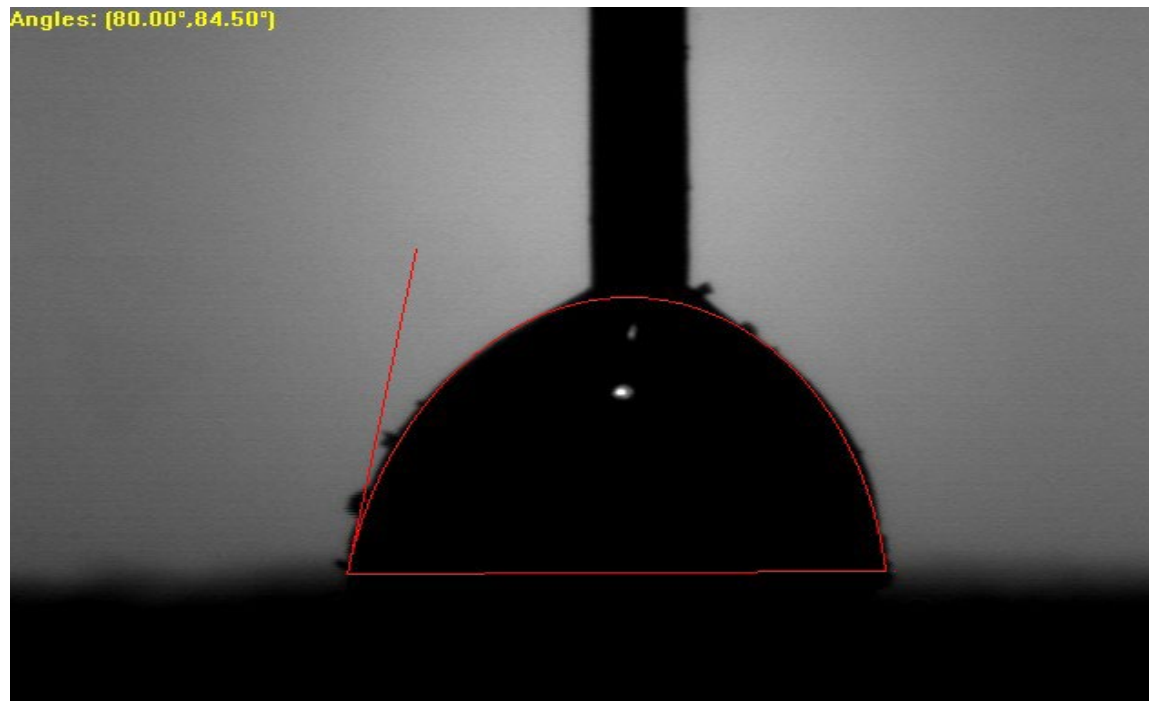


Figure 8. Contact Angle of Sample AMB1-25B

Figure 9 shows the average contact angle of the samples with 95% confidence intervals. Some of the samples seem to be less hydrophobic than the controls. In order to verify that some samples displayed a significantly different contact angle than the control, one-way

ANOVA was performed.

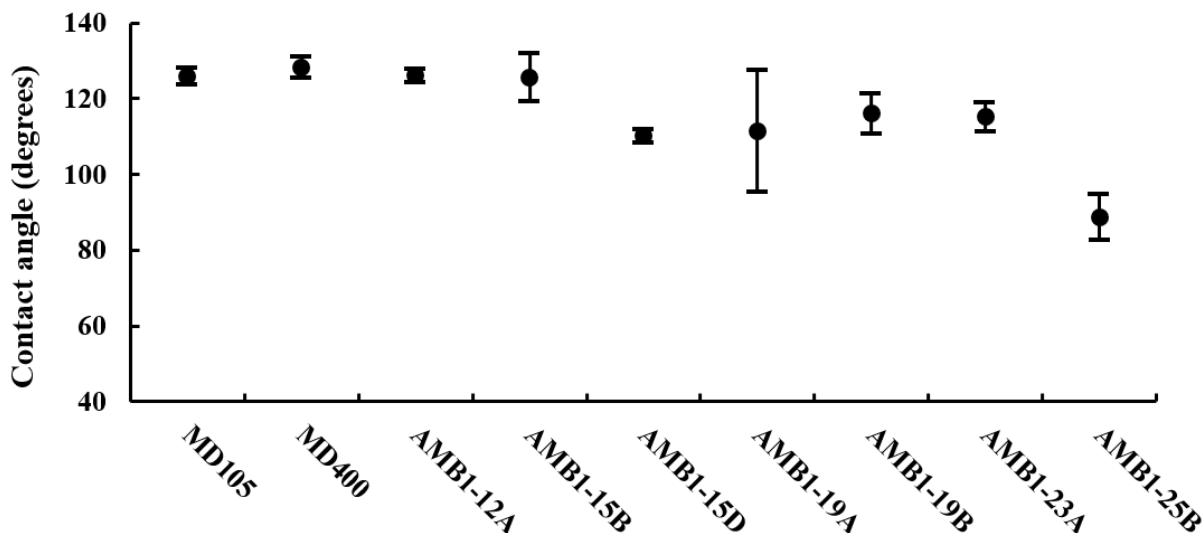


Table 7. Average Contact Angle of the Samples with 95% Confidence Intervals

Table 7 shows the one-way ANOVA results from the contact angle data. The results indicate that at least one of the samples showed a statistically significant difference in the average contact angle since its p-value is less than 0.05. The next step was to perform a post hoc Tukey HSD test. The results indicate that samples AMB1-15D ($p < .05$) and sample AMB1-25B ($p < .01$) presented statistically significant different contact angles than the control. Furthermore, sample AMB1-25B ($p < .01$) had significantly lower contact angles when compared to the rest of the treatments. Thus, the PEG substitution reaction with four nights (sample AMB1-25B) yields better results to render the surface of GTR hydrophilic.

Table 8. One-way ANOVA Results from Contact Angle Data

Source	Sum of Squares SS	Degrees of Freedom	MeanSquare MS	F Statistic	p-value
Treatment	6,821.82	7	974.5459	10.7305	1.60E-07
Error	3,632.80	40	90.82		
Total	10,454.62	47			

FTIR Spectroscopy

To study the chemical composition of the GTR particles, Fourier transform infrared (FTIR) spectroscopy was used. Kocovski et al. used FTIR to confirm the grafting of acrylic acid in GTR.¹² Fuhrmann and Karger utilized ATR-FTIR to characterize the grafting of methacrylate and methacrylic acid onto GTR.¹³ An alpha FTIR instrument (Bruker) with an attenuated total reflectance was used for this purpose. This configuration allows for the analysis of materials without any sample preparation. The attenuated total reflectance (ATR) crystal is made of ZnSe. The crystal was cleaned carefully with ethanol, making sure no residual sample remained on the holder. The spectra were analyzed for the identification of the functional groups in the samples. FTIR spectra were collected over the range from 4,000 to 650 cm^{-1} . Opus software was used to analyze the spectra.

FTIR was used to determine any chemical surface modification in the rubber particles. An Attenuated Total Reflectance accessory was used to obtain the infrared spectra of the rubber. The advantage of using ATR is that no sample preparation is needed. The high surface area of the particles increases the signal of surface groups in FTIR. The absorption bands are correlated to the chemical groups present in each sample. Thus, the functional groups attributed to the chemical surface modification would be detected with infrared spectroscopy. An FTIR spectrometer simultaneously collects high spectral resolution data over a wide spectral range. The chemical structure of ground tire rubber (GTR) was analyzed by Fourier transform infrared spectroscopy (FTIR).

Figure 10 shows the FTIR spectra of sample MD400. Samples MD400 and MD150 had similar FTIR spectra. Certain peaks correspond to certain chemical bonds in GTR. The first two peaks around 2918 cm^{-1} and 2850 cm^{-1} have been attributed to $-\text{CH}_3$ and $-\text{CH}_2$ symmetrical stretching.¹⁴ The peak around 1428 cm^{-1} has been assigned to $-\text{CH}_2$ scissoring.¹⁵ The peak at 1383 cm^{-1} has been assigned to $-\text{CH}_3$ symmetric bend.¹⁶

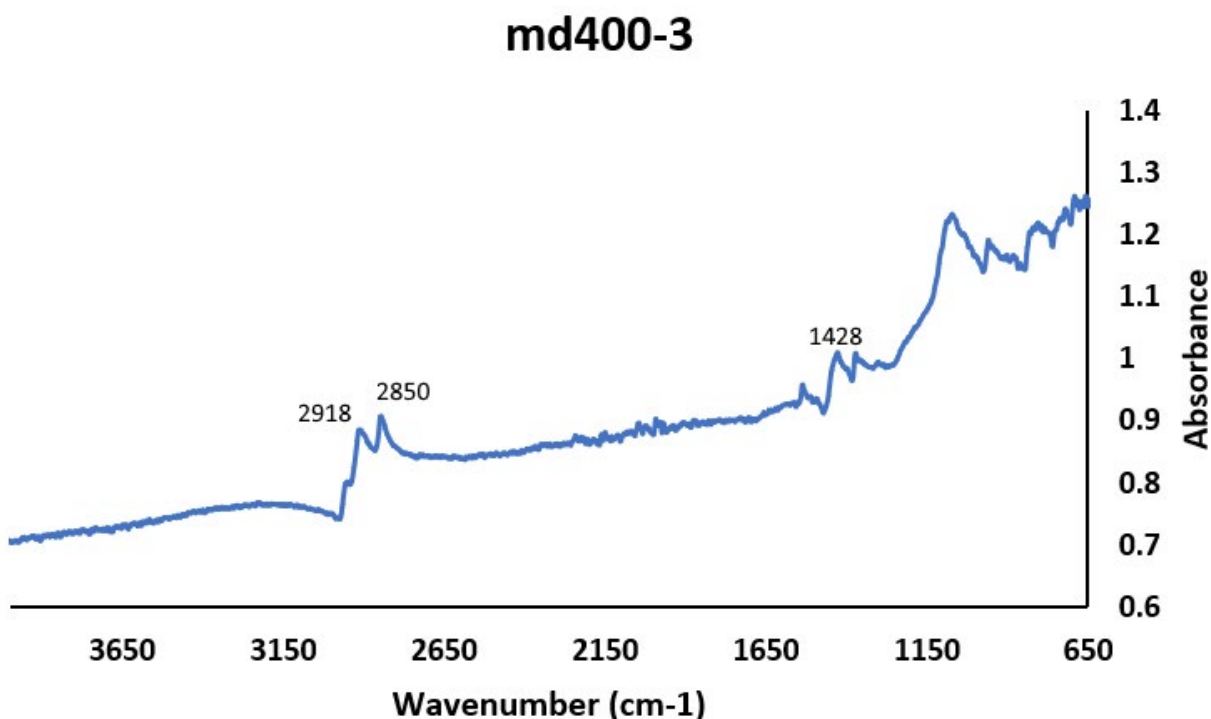


Figure 9. FTIR of Surface of Sample MD400

Figure 11 shows the FTIR spectra of sample AMB1-15D. The sample presents some of the peaks previously described and attributed to $-\text{CH}_3$ and $-\text{CH}_2$ symmetrical stretching. In addition, the broad peak around 3298 cm^{-1} has been attributed to the $-\text{OH}$ group due to intra- and intermolecular bonding.¹⁷ The peaks at 1405 cm^{-1} and 910 cm^{-1} have been attributed to $-\text{OH}$ bending. This data indicates the presence of hydroxyl groups and therefore a successful surface functionalization. The results from FTIR corroborate the increase in the hydrophilic behavior of sample AMB1-15D.

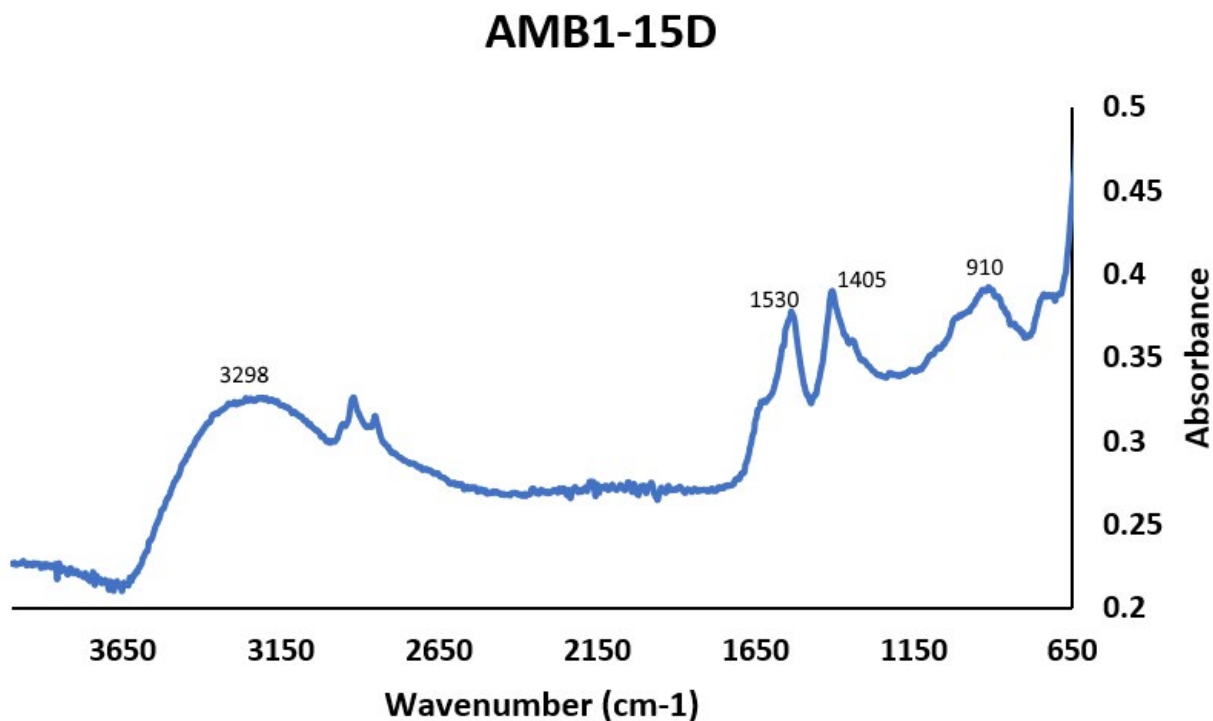


Figure 10. FTIR of Surface of Sample AMB1-15D

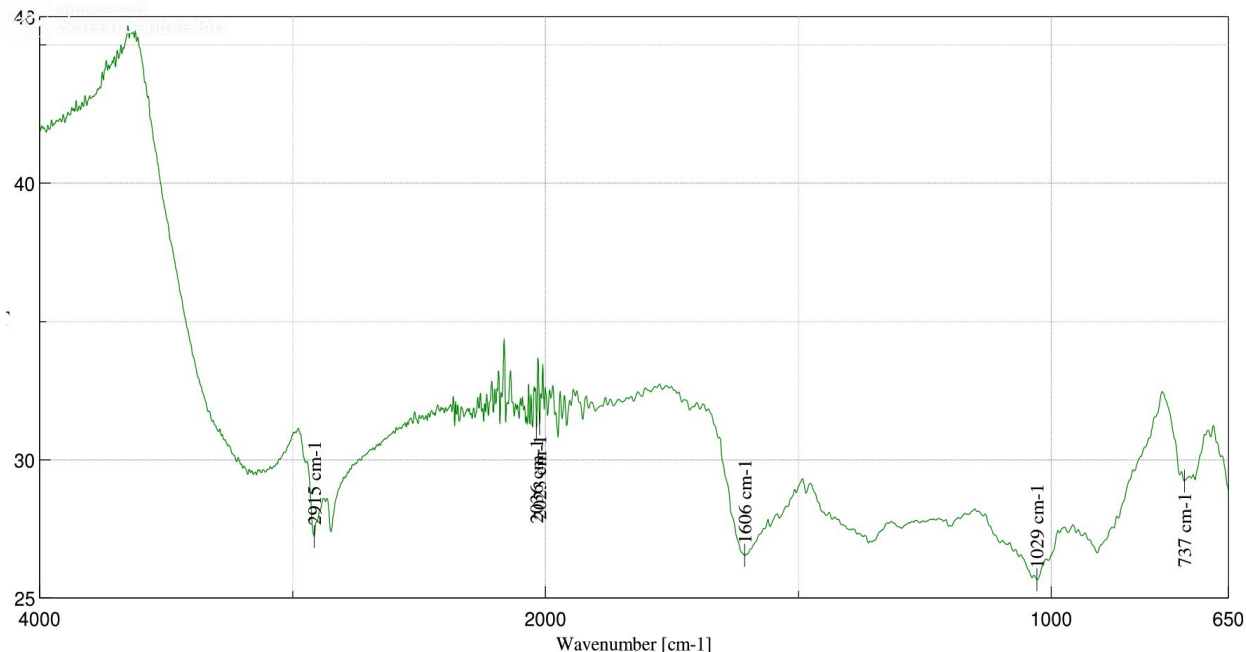


Figure 11. Infrared Spectrum of AMB1-23A (GTR-PEG)

The absorption at 1029 cm⁻¹ indicates that ether (C-O-C) bonds are present in the sample and strong alcohol (O-H) bonds can be seen in the 3300 cm⁻¹ region. Taken together, these observations show strong evidence of successful PEG surface functionalization.

CONCLUSION

The surface functionalization of GTR particles was carried out successfully. Through contact angle and FTIR, the degree of efficiency of the reaction method was evaluated, and results indicated PEG for four days provided the best results. In addition, FTIR was used to determine that the surface of modified GTR particles present hydroxyl groups. Overall, the surface modification of these materials is useful for further functionalization to improve the compatibilization of particles for the manufacture of asphalt materials. The present project provides a simple method to change the surface properties of GTR particles.

IV. STUDY 4: ROAD TRANSPORT ENERGY DEMAND IN CALIFORNIA AND THE U.S.: AN ERROR CORRECTION MODEL AND NON-LINEAR ARDL APPROACH

INTRODUCTION

Along with the examination of materials explored in the above studies, understanding the responsiveness of gasoline demand to changes in prices and income also has important implications for future transportation policy. A vast majority of studies have investigated only the broader U.S. in past decades, specifically, the 1970s and 1980s, rather than focusing on demand in more recent years or at the regional level. Our study assesses how changes in oil prices affect gasoline supply and demand in the U.S. and California specifically, using quarterly level data (first quarter of 1998 to the last quarter of 2018) with time series models to assess causality both long- and short-term. First, we estimate the price and income elasticity of gasoline sales using an Error Correction Model (ECM). Then, we use a Nonlinear ARDL Model (NARDL) to test the asymmetric relationship between income, prices, and gasoline consumption in both regions to obtain price and income elasticities of demand. Findings have important policy implications for road usage in California and the U.S.

LITERATURE REVIEW

Many studies have assessed the relationship between gas prices, income, and consumption. In the U.S., Hughes et al. argued behavioral and structural changes over the decades had changed consumers' responsiveness to changes in gasoline prices.¹⁸ The authors employed OLS with Newey-West Standard errors, simultaneous equation and partial adjustment models to assess these linkages. They found the price elasticity of demand was more inelastic in the present than in previous decades. More specifically, price and income elasticity of demand between 1975 and 1980 ranged from -0.21 to -0.34, while the period between 2001 and 2006 saw the range vary between -0.21 and -0.34. They attributed these changes to land use and vehicle characteristics. Nicol employed a different technique by using a simultaneous system of equations and cross-sectional data at the household level.¹⁹ Findings indicated that gasoline demand for both the United States and Canada were price inelastic. A more recent study employed the Autoregressive Distributed Lag (ARDL) bound testing approach to assess the long-run relationship between gasoline demand and income in South Africa. The findings, using a dataset ranging from 1978 to 2005, revealed price and income elasticities of -0.47 and 0.36, implying that gasoline demand in South Africa is price and income inelastic.²⁰ While Akinboade used an Unrestricted Error Correction Model for their analysis, Cloete and Smit used an OLS and quarterly data between 1970 and 1983 to show price and income elasticity of gasoline demand were -0.37 and 0.43 respectively.²¹ In Morocco, Belhaj used a three-stage least square estimator to assess factors driving demand for gasoline and diesel between 1970 and 1996.²² The uniqueness of this author's approach is the investigation of the role that car prices and road taxes had on demand. They found the price and income elasticity of demand for gasoline to be -0.30 and 0.50, respectively.

In Brazil, Alves and De Losso da Silveira Bueno found alcohol an imperfect substitute for

gasoline.²³ The study sought to investigate the cross-price elasticity for gasoline and alcohol using an error correction model (ECM). They also found that the price elasticity of gasoline was inelastic in the long and short run. An ECM was also used by Ramanathan to show that if gasoline demand drifts away from its long run equilibrium level, it restores itself to that level at a relatively slow rate of 28 percent.²⁴ Similarly, an ECM was applied to data between 1970 and 1989 in Kuwait to show that demand for gasoline is inelastic.²⁵ The authors also showed that income elasticity of demand is 0.47 in the short run and 0.92 in the long run. Bentzen employed an ECM to test for long and short run elasticities in gasoline demand in Denmark and found the price elasticity of demand to be -0.41.²⁶ In Greece, results of a vector autoregression (VAR) analysis were used to assess the determinants of road energy demand. In this context, Polemis found that demand for both gasoline and diesel is price- and income-inelastic.²⁷ Polemis also included dummies to capture the introduction of unleaded gasoline and significant policy changes which affected consumption. Similar findings are observed in Australia by Samimi, who showed using an ECM that there is bidirectional causality between output and energy consumption.²⁸ Interestingly, in Australia, 95 percent of adjustment in demand to the planned level in road transport occurs in five periods.

MODEL

DATA

The data used in the analyses aggregate monthly data covering the period between 1998 and 2018. Data on gasoline consumption (sales to end users, total refiner motor gasoline sales volumes) were obtained from the U.S. Energy Information Administration (EIA).²⁹ Data on personal income were obtained from the Bureau of Economic Analysis,³⁰ while gasoline and diesel prices were obtained from the EIA.³¹

ECONOMETRIC SPECIFICATIONS

Price Elasticity of Supply

The cointegration equation used in this analysis is based off Dahi and Sterner and Alves and De Losso da Silveira Bueno and is specified below:³²

$$\ln \text{Sales}_t = \alpha_0 + \alpha_1 \ln \text{Income}_t + \alpha_2 \ln \text{Price}_t + \varepsilon_t \quad (5)$$

where Sales_t is gasoline retail sales by refiners (gasoline - thousand gallons per day), Income_t is personal income in millions of dollars and Price_t is monthly retail gasoline prices (California and U.S.). The specification is run for both California and the U.S., with quarterly data used in the analysis.

The analysis follows the two-step Engle and Granger procedure, which requires that the variables are integrated in the same order.³³ The unit root testing procedure is carried out to test for stationarity, and if all variables are cointegrated, then the model can be reformulated as an Error Correction Model (ECM). Estimation of an ECM allows for inference regarding

the long and short run relationship between the variables. Estimating equation (5) tests for the presence of a cointegrated relationship, while equation (6) tests for presence of unit roots in the residual series $\hat{\varepsilon}_t$:

$$\Delta \hat{\varepsilon}_t = \gamma \hat{\varepsilon}_{t-1} + \sum_{i=0}^n \delta_i \Delta \hat{\varepsilon}_{t-i} + u_t \quad (6)$$

where $\hat{\varepsilon}_t$ is the estimated residual from (1), n is the number of lags used to approximate a white noise process $\delta_0=0$. If we cannot reject the null hypothesis that $\gamma=0$ then there is no cointegration, and we can use OLS to estimate (5). The long run elasticities are given by:

$$\frac{\partial \ln \text{Sales}_t}{\partial \ln \text{Income}_t} = \alpha_1 \frac{\partial \ln \text{Sales}_t}{\partial \ln \text{Income}_t} = \alpha_1; \frac{\partial \ln \text{Sales}_t}{\partial \ln \text{Price}_t} = \alpha_2 \frac{\partial \ln \text{Sales}_t}{\partial \ln \text{Price}_t} = \alpha_2, \quad (7)$$

where α_1 and α_2 are the income elasticity and the gasoline price elasticity, respectively.

The ECM can now be estimated as follows:

$$\Delta \ln \text{Sales}_t = \beta_0 + \beta_1 \Delta \ln \text{Income}_t + \beta_2 \Delta \ln \text{Price}_t + \gamma \hat{\varepsilon}_{t-1} + \mu_t \quad (8)$$

The coefficients in equation (8), β_1 and β_2 , are the short run income and price elasticity of sales. There is no cointegration if the residuals are integrated of order one.

EMPIRICAL RESULTS

First, ADF tests are used to assess whether variables are $I(1)$, and if they are, then cointegration tests are carried out. Unit root test results are presented in Table 8.

Table 9. Unit Root Test Results

California (1998:Q1 to 2018:Q4)					
Variable	C			CT	
lnSales	-0.034995			-2.463378	
ΔlnSales	-4.805774***			-4.943363***	
lnConsumption	-4.134417***			-4.175271***	
lnIncome	-0.779130			-2.137834	
ΔlnIncome	-8.876209***			-8.850944***	
lnPrice	-1.311719			-1.400300	
ΔlnPrice	-10.70758***			-10.72521***	
U.S. (1998:Q1 to 2018:Q4)					
Variable	C			CT	
lnSales	-0.260561			-1.927855	
ΔlnSales	-9.453665***			-9.524037***	
lnConsumption	-4.328815***			-4.823217***	
lnIncome	-1.243373			-3.033072	
ΔlnIncome	-4.453916***			-4.459513***	
lnPrice	-2.023921			-1.401016	
ΔlnPrice	-9.788286***			-9.957287***	
ADF Test Critical Values					
Without Trend			With Constant and Trend		
1%	5%	10%	1%	5%	10%
-3.5112	-2.8968	-2.5856	-4.0724	-3.4649	-3.1590

* Denote significance at 10%, ** Denote significance at 5%, *** Denote Significance at 1%.

ADF=Augmented Dickey Fuller Test, C=Constant, CT = Constant and Trend

Results indicate that all series are $I(1)$. Hence, tests for cointegration and long and short run causality were conducted, with results presented in Tables 9 and 10.

Table 10. Error Correction Model Results: U.S.

Dependent Variable: $\Delta \ln \text{Sales}_t$				
Variable	Coefficient	t-statistic	p-value	
Constant	0.2954	0.6243	0.5342	
$\Delta \ln \text{Income}_t$	-0.0188	-0.6465	0.5198	
$\Delta \ln \text{Price}_t$	0.1288**	2.0992	0.0390	
$\hat{\varepsilon}_{t-1}$	-0.0424	-1.1970	0.2349	
Adjusted R ²	0.0369			
Breusch-Godfrey Serial Correlation LM Test			0.9638	

*, ** and *** indicates significance at the 10%, 5% and 1% level

Results from the ECM model for the U.S. indicate that a 10 percent increase in the price of gasoline leads to a 1.2 percent increase in sales in the U.S. in the short run, as expected. Since the coefficient of income is not significantly different from zero, it is possible to conclude that income demand is perfectly inelastic in the short run. The income variable is a measure of economic development, indicating that sales in gasoline demand are not responsive to changes in the economy in the short run. The model was free of any violations as indicated by the LM test results. No long run cointegration results were obtained in the model.

Table 11. Error Correction Model Results: California

Dependent Variable: $\Delta \ln \text{Sales}_t$				
Variable	Coefficient	t-statistic	p-value	
Constant	0.1743	0.6695	0.5051	
$\Delta \ln \text{Income}_t$	-0.0128	-0.7025	0.4844	
$\Delta \ln \text{Price}_t$	0.1766***	4.2799	0.0001	
$\hat{\varepsilon}_{t-1}$	-0.0748**	-0.4037	0.0186	
Adjusted R ²	0.2277			
Breusch-Godfrey Serial Correlation LM Test				0.3186

*, ** and *** indicates significance at the 10%, 5% and 1% level

Results from the ECM model for California indicate that a 10 percent increase in prices causes a 1.7 percent increase in gasoline sales, hinting that supply is price inelastic for California. The findings for income are like those for the U.S., implying that economic

growth, in the short run, has no implications on gasoline sales. The ECT is negative and significant, meaning the variables have a long run relationship. The coefficient implies that 7.4% of consumption disequilibrium is corrected each quarter following shocks to gasoline prices. The model is also free of serial correlation.

Price Elasticity of Income and Price: Non-linear ARDL

Next, the long and short run, causality between price, income and gasoline consumption is assessed empirically using the recently developed non-linear ARDL (NARDL) cointegration methodology. The NARDL is advantageous in that it allows for the detection of asymmetric effects in both the long and short run and is applicable in small samples.³⁴ Causality tests are also possible when using combinations of $I(0)$ and $I(1)$ series.³⁵ The NARDL developed by Shin et al. is specified as follows:³⁶

$\Delta \ln \text{Consumption}_t$

$$\begin{aligned}
 &= \sigma_0 + \pi \ln \text{Consumption}_{t-1} + \theta_1^+ \ln \text{Income}_{t-1}^+ + \theta_2^- \ln \text{Income}_{t-1}^- \\
 &+ \theta_3^+ \ln \text{Price}_{t-1}^+ + \theta_4^- \ln \text{Price}_{t-1}^- + \sum_{i=0}^p \sigma_1 \Delta \ln \text{Consumption}_{t-i} \\
 &+ \sum_{i=0}^q \sigma_2 \Delta \ln \text{Income}_{t-i}^+ + \sum_{i=0}^q \sigma_3 \Delta \ln \text{Income}_{t-i}^- + \sum_{i=0}^q \sigma_4 \Delta \ln \text{Price}_{t-i}^+ \\
 &+ \sum_{i=0}^q \sigma_5 \Delta \ln \text{Price}_{t-i}^- + \varepsilon_t
 \end{aligned} \tag{9}$$

Consumption_t represents gasoline consumption, Income_t represents personal income (millions of dollars), Price_t represents monthly retail gasoline prices (dollars per gallon, including taxes) and p and q denote the optimal lags for the dependent and independent variables, respectively, as specified by the Akaike Information Criterion (AIC). σ_i denotes short run coefficients and θ_i denotes long run coefficients with $i=1,2,\dots,4$. Lastly,

Δ is the first difference operator and ε_t the white noise term. The long run analysis is used to measure the reaction and speed of adjustment towards the equilibrium level while the short run analysis investigates the immediate impacts of the independent variables' changes on renewable energy (production or consumption). The Wald test is used to test for long run

$(\theta = \theta^+ = \theta^-)$ and short run asymmetry $(\sigma = \sigma^+ = \sigma^-)$.

The independent variables are decomposed into their positive and negative partial sums for increases and decreases, as shown in equation 10 and 11, where x_t represents Income_t and Price_t .

$$x_t^+ = \sum_{j=1}^t \Delta x_j^+ = \sum_{j=1}^t \max(\Delta x_j, 0) \quad (10)$$

$$x_t^- = \sum_{j=1}^t \Delta x_j^- = \sum_{j=1}^t \min(\Delta x_j, 0) \quad (11)$$

The analysis in this section is finalized in three steps. First, the long run relationship between the levels of the variables Consumption_t , $x_t^+ x_t^+$ and $x_t^- x_t^-$ is explored using modified F tests. Further, $\pi = \theta^+ = \theta^-$ joint null is tested. In an illustration similar to Shahbaz, Hoang, et al. (2017), the long term asymmetric coefficients are estimated based on $L_{mi}^+ = -\theta^+/\pi$, $L_{mi}^- = -\theta^-/\pi$. Secondly, long run asymmetry ($\theta = \theta^+ = \theta^-$) and short run asymmetry ($\sigma = \sigma^+ = \sigma^-$) are tested using Wald tests. The null hypothesis of no cointegration among the variables $H_0: \pi = \theta^+ = \theta^- = 0$ is tested using the bounds test of Pesaran, Shin, et al. (2001) and implies no long run relationship. Lastly, the standard asymmetric cumulative dynamic multiplier effects are estimated using the equations below.

$$m_h^+ = \sum_{j=0}^h \frac{\partial \text{Consumption}_{t+j}}{\partial X_t^+}, m_h^- = \sum_{j=0}^h \frac{\partial \text{Consumption}_{t+j}}{\partial X_t^-} \quad \forall X = \text{Income, Price} \quad (12)$$

for $h=0,1,2,\dots$ where if $h \rightarrow \infty$, then $m_h^+ \rightarrow L_{mi}^+$ and $m_h^- \rightarrow L_{mi}^-$. The dynamic multipliers show the asymmetric responses of Consumption to positive and negative shocks in Income and Price. Results from the unit root tests indicate that Consumption is $I(0)$ while Income and Price are $I(1)$, implying the use of an NARDL. Results are presented in Tables 11 and 12.

Table 12. NARDL Results: U.S.

Dependent Variable: $\ln_Consumption$			
Variable	Coefficient	t-statistic	Prob.
C	12.1886***	5.0978	0.0000
$\ln_Consumption_{t-1}$	-0.5269***	-5.0959	0.0000
$\ln Income_{t-1}^+$	0.2174	1.0971	0.2763
$\ln Income_{t-1}^-$	0.3823	0.6788	0.4995
$\ln Price_{t-1}^+$	-0.0702	-1.6626	0.1007
$\ln Price_{t-1}^-$	-0.0637	-1.4517	0.1509
$\Delta \ln Income_t^+$	-2.0787**	-2.3026	0.0242
$\Delta \ln Income_t^-$	2.7605*	1.9682	0.0529
$\Delta \ln Price_t^+$	0.2056**	2.0208	0.0470
$\Delta \ln Price_{t-1}^+$	0.2269**	2.3270	0.0228
Adjusted R ²	0.3664		
χ_{SC}^2			[0.9635]
χ_{HET}^2			[0.0001]
χ_{NORM}^2			[0.0000]
χ_R^2			[0.5801]
W_{LR}			0.0405
W_{Sr}			0.0469

The superscripts “+” and “-” denote positive and negative variations, respectively. $\chi_{SC}^2, \chi_{SC}^2, \chi_{HET}^2$, $\chi_{HET}^2, \chi_{NORM}^2, \chi_{NORM}^2$ and χ_{RR}^2, χ_R^2 for serial correlation, functional form and heteroscedasticity and

functional form, respectively. The values in square parenthesis indicate the corresponding p-values for the tests. W_{LR} and W_{SR} represent the Wald test for the null of long term and short term symmetry for the respective variables. *, ** and *** show the significance at the 1%, 5% and 10% level respectively.

Results show that there is no long run causality running from income or prices to gasoline consumption in the U.S. Meanwhile, short run results are more complex. Point estimates indicate that a one percent increase in income in the present period is accompanied by a 2.1 percent decrease in consumption, while a one percent decrease in income is accompanied by a 2.7 percent increase in gasoline consumption. A possible explanation for this result is that wealth increases coerce consumers to purchase electric vehicles which consume less gasoline or find more efficient ways of using gasoline.

Further, a 10 percent increase in price causes a 2 percent increase in gasoline consumption in the present and previous quarter.

There is no serial correlation, though the model contains heteroskedasticity and is not normally distributed. Nonetheless, it is correctly specified, and findings from Wald tests indicate that there is asymmetry in the long and short run at the 5 percent level of significance.

Table 13. NARDL Results: California

Dependent Variable: $\ln_Consumption$			
Variable	Coefficient	t-statistic	Prob.
C	9.8355***	5.0440	0.0000
$\ln_Consumption_{t-1}$	-0.4699***	-5.0262	0.0000
$\ln Income_{t-1}^+$	0.2874*	2.0874	0.0404
$\ln Income_{t-1}^-$	0.0577	0.1632	0.8708
$\ln Price_{t-1}^+$	-0.0188	-0.5402	0.5907
$\ln Price_{t-1}^-$	0.0618	1.4983	0.1384
$\Delta \ln Price_{t-2}^+$	-0.1503**	-2.0395	0.0451
$\Delta \ln Price_{t-3}^+$	-0.2521***	-3.5861	0.0006
Adjusted R ²	0.3223		
χ_{SC}^2			[0.3608]
χ_{HET}^2			[0.0000]
χ_{NORM}^2			[0.0000]
χ_R^2			[0.8471]
W_{LR}			0.1919
W_{SR}			0.2730

The superscripts “+” and “-” denote positive and negative variations, respectively.

χ_{SC}^2 , χ_{HET}^2 , χ_{NORM}^2 and χ_R^2 for serial correlation, functional form and heteroscedasticity and functional form, respectively. The values in square parenthesis

indicate the corresponding p-values for the tests. W_{LR} and W_{SR} represent the Wald test for the null of long term and short term symmetry for the respective variables. *, ** and *** show the significance at the 1%, 5% and 10% level respectively.

Point estimates indicate that an increase in income leads to an increase in gasoline consumption in the long run. They also show that in the short run, a ten percent increase in gasoline prices two and three quarters ago leads to a 1.5 and 2.5 percent decrease in gasoline consumption in the present period. Specification tests indicate that the model is free of serial correlation and well specified, although residuals not normally distributed. There is no asymmetry in the short or long run.

CONCLUSION

Overall findings from the ECM models show that in the short run, gasoline sales are price inelastic in California and the broader U.S., with gasoline sales less responsive to price changes in the former. This implies that demand for road transportation is less responsive to changes in prices. We also find that a long run cointegrating relationship only exists in California. Results from the NARDL model show that there is no long run causality running from income or prices to gasoline consumption in the U.S. In California, higher incomes lead to higher gasoline consumption in the long run, while in the short run, consumers seem to adjust to higher oil prices by consuming less.

V. OVERALL CONCLUSIONS OF NEW MATERIALS AND DESIGN APPROACH FOR ROADS, BRIDGES, PAVEMENT AND CONCRETE

Ultimately, these four studies improve understanding of road pavement materials and transport energy demand. They lay out important information about the future of the relationship between materials and design in the transportation industry.

The outcome of the initial investigation is that a techno-economic study was carried out to assess the feasibility of a process involved in surface treating ground tire rubber (GTR) and producing modified asphalt for road and paving projects. A block flow diagram, process flow diagram, equipment specifications, and profitability analysis were carried out. This work indicates a need for lower capital and operating cost processes to provide profitable surface treated GTR modified asphalt.

In the second study, a Computational Fluid Mechanics study was carried out on two different pavement materials, asphalt and Portland Cement Concrete (PCC). Results show that although the steady state surface temperature of the asphalt pavement is about 2–3°C higher during a hot summer day with low wind velocities (≤ 0.1 m/s), the surface temperatures are comparable at higher wind velocities. These results run contrary to the common belief that PCC is universally a cooler pavement material than asphalt.

Third, the surface functionalization of GTR particles was carried out successfully. The degree of efficiency of the reaction method was evaluated by contact angle and FTIR. The contact angle results indicate that the best results were provided by the substitution reaction with PEG for four days. In addition, FTIR was used to determine that the surface of modified GTR particles present hydroxyl groups.

Finally, the economics of energy demand and gasoline sales were also investigated in this study. In the short run, gasoline sales are price inelastic in both the U.S. and California, with gasoline sales less responsive to price changes in the latter. Results from the Non-linear Autoregressive Distributed Lag Model (NARDL) shows that there is no long run causality from income or prices to gasoline consumption in the U.S. In California, higher incomes lead to higher gasoline consumption in the long run, while in the short run, consumers seem to adjust to higher oil prices by consuming less.

Our research can be used by transportation policymakers and planners to improve their understanding of road pavement materials and transport energy demand. Our work reveals, most significantly, that assumptions about GTR and PCC situational suitability and use should be reexamined. Additionally, the inelasticity of energy demand and gasoline sales in California and the broader U.S. should be considered in future transportation planning. All this information should be incorporated into decisions surrounding future urban planning, such as how the demand for gasoline vs renewable energy may influence the need for more bike lanes or public transit, as well as road construction, such as what materials are appropriate and associated costs.

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