

## SUSTAINABLE BIO-COMPOSITES FOR HIGHWAY INFRASTRUCTURE: FEASIBILITY OF MATERIAL SUBSTITUTION IN EXISTING PRODUCTS

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The U.S. Forest Service regularly removes tons of dead biomass from federal forestlands to control and prevent devastating wildfires. Every year thinning young trees and brush, as well as removing dead biomass from the forest floor generates large quantities of low-grade woody material for which there is little use. Currently this biomass is either burned on-site, or at facilities to generate electricity. Finding a sustainable long-term utilization scheme for this material may generate a steady demand for this material and improve the economics of fire prevention. In this project the feasibility of substituting non-renewable materials currently used in a wide variety of highway infrastructure products, with sustainable composites utilizing low-grade woody biomass is investigated as potential alternative to burning. Devices such as traffic signs, road markers, and guardrails are installed on public roadways in high volumes. Until now, there have been no clear guidelines established for systematically assessing the viability of full or partial material substitution with more sustainable alternatives. A conceptual framework is presented, outlining necessary input information, inquiries, practical steps, and decision points necessary to determine if material substitution in a product or its individual components is viable. This procedure can assist entrepreneurs and small-scale businesses willing to enter the market, and provide opportunities in rural regions affected by the decline in the forest products industry. The application of this procedure is demonstrated on three selected highway products. Potential benefits to the environment, the economy, and local communities are discussed.

*Keywords:* Wood plastic composites; WPC; Highway infrastructure; Sustainable materials; Woody biomass; Forest fuel; Urban waste

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### INTRODUCTION

Forest thinning and burn fuel removal from congested forestlands is a common practice used to maintain forest health and safety. In particular, the western states of the US are plagued with seasonal wildfires of high intensity. Although small-scale seasonal forest fires are considered natural events beneficial for forest health, the large amount of fuel accumulated on the forest floor due to a century of artificial fire suppression has created an environment in which any uncontrolled wildfire can rise to catastrophic proportions. Each year the US federal government spends billions of dollars to fight, mitigate, and prevent forest fires on federal lands, increase a forest's lifespan, and thus improve carbon storage benefits (Daly 2008; Barnard 2009; Hudiburg et al. 2009). These

operations create large volumes of low-grade woody biomass. An interagency memorandum of understanding between the US Department of Agriculture (USDA), Department of Energy (DOE), and the Department of the Interior (DOI) (2003), defines woody biomass as trees and woody plants, including limbs, tops, needles, leaves, and other woody parts, grown in a forest, woodland, or rangeland environments that are the by-products of forest management (USDA 2008). In healthy forests woody biomass becomes a source of needed nutrients (Eisenbies et al. 2009); however a century of artificial forest fire suppression has resulted in accumulations that the ecosystem can no longer process. Its low grade renders it nearly useless as raw material for most traditional forest products. The slash material has low bulk density, and therefore is expensive to handle and transport. As the scale and costs of forest fire prevention increase in response to this increasing threat, so does the pressure to find sustainable ways to utilize biomass that is generated in burn fuel removal operations.

In the state of Oregon alone, approximately 4.25 million acres (about 15% of state forestlands), could produce one million bone dry tons (BDT) of woody biomass from thinning of forest stands yearly, reducing the risk of catastrophic fires for over 20 years (Bowyer et al. 2006). Harvesting western juniper - considered an invasive species in Oregon's rangelands, logging slash in other timber harvests, and urban wood waste could provide an additional one million BDT of biomass (Bowyer et al. 2006). In 2005, about one million tonnes of forest residue were generated in the state (Milbrandt 2005).

Currently low-grade woody biomass from forest operations is most commonly collected in slash piles and burned onsite releasing substantial amounts of CO<sub>2</sub> into the atmosphere (Krankina 2010). Recently, research efforts have been focused toward efficient harvesting methods and in-situ processing for cogeneration fuel conversion (Han et al. 2010; Harrill and Han 2010). However, with the volatility of fuel economics and increasing concerns regarding CO<sub>2</sub> emissions, the long-term feasibility of this approach may soon be questioned. The economics of fire prevention operations might improve substantially if the patterns of utilization of the harvested material were diversified, creating consistent demand for bio-particles. Particularly, finding a steady market for products made from low-grade wood fiber might offset the costs of removal operations and provide desirable path for carbon sequestration (Mason et al. 2006; Winandy et al. 2005).

One alternate way to utilize this low-grade biomass is as filler in hybrid wood-plastic composites (Wolcott and Muszyński 2008). This path of utilization is the focus of this paper.

Fillers are often added to materials that are more expensive in order to lower the cost. In any industry using high volumes of plastic products, even moderate amounts of inexpensive fillers replacing petroleum-based polymers translate into significant savings. Filler content may also significantly alter the physical and mechanical properties of the resulting composite. Early research on waste-wood-derived fillers have shown a combination of high performance, low cost, and reduction of mold cycling times (English et al. 1996). The presence of wood particles in a plastic matrix can result not only in a less expensive material, but also improve the stiffness of the composite when compared to an unfilled plastic alone (Taylor et al. 2009). WPCs made with recycled and second generation materials have been shown to have equal or better mechanical properties,

water resistance, and dimensional stability against composites using virgin materials (Youngquist et al. 1994).

WPCs have primarily been developed for outdoor materials such as residential decking and railing systems, windows, siding, roofing, pallets, and furniture; hence there has been a lot of environmental testing to develop this material class (Rowell 2007).

Since wood plastic products are manufactured in a similar manner to 100% plastic products (Wechsler and Hiziroglu, 2007) startups or conversion to WPC production would not require major capital investments (Taylor et al. 2009). This low cost of entry into the WPC market can benefit rural communities, allowing business growth in areas affected the most from the decline in the forest products industry. These communities, originally created as centers for forest products industries, are strategically located in the heart of the forestlands where the woody biomass is generated. For the time being they are also a repositories of workforce with unique expertise and skills related to forest operations and forest products manufacturing, although with time these assets may be lost to migration or generation change.

One of the potential outlets for wood plastic composites utilizing low-grade woody biomass is public infrastructure, in which a great variety of standardized products is used in substantial volumes. Of particular interest are highway systems, which use a wide variety of roadside hardware and safety products on roadways and their perimeters.

### **Highway Products**

Highway products include a variety of fixed and mobile devices on roadways and their perimeters. Examples include: mileage and sign posts, traffic dividers, work zone barricades, signage, manhole guards and protector rings, snow fences, retaining walls, sound barriers, guardrails, and various crash protection systems. Hundreds of highway products can be present on every mile of roadway, each differing in material, size, function, applicable regulations, and manufacturing processes.

#### *Types of highway products*

The National Cooperative Highway Research Program (NCHRP) Report 350 (Ross Jr. et al. 1993) covers several categories of highway features: 1) longitudinal barriers such as bridge rails, guardrails, median barriers, transitions and terminals; 2) crash cushions; 3) breakaway or yielding supports for signs and luminaries; 4) break away utility poles; 5) truck-mounted attenuators; and 6) work zone traffic control devices. Other categories of highway products not included in NCHRP Report 350 include erosion control devices, pavement markings, and paving materials.

Every highway product must be approved by the regional Department of Transportation in each state, based on criteria that are deemed critical for its use on public roadways (AASHTO 2010; ODOT 2010). The National Transportation Product Evaluation Program (NTPEP), an organization of the American Association of State Highway and Transportation Officials (AASHTO) provides reports to state departments of transportation on testing performed on highway products. Each state maintains a list of qualified products approved for use along its highway system.

## **Markets and Volumes**

There is a significant market for highway products. A study conducted by Thompson et al. (2010), estimated that nearly 455,000 tubular markers are purchased annually in the eight western states of the US (Washington, Oregon, California, Idaho, Utah, Nevada, Arizona, and Montana). The estimated annual volume of in-road reflectors is over 1.2 million units (Thompson et al. 2010). A rough estimate by a local distributor of traffic supplies concludes that in a high volume year, about 800,000 pavement markers are sold in Oregon alone (Parsens 2009).

Thompson et al. (2010) estimated that these two relatively small products alone account for an approximate 867 tonnes of plastic deployed yearly along the western state's highways.

Sound barrier walls represent a large market as well. There were over 2,506 linear miles of barriers constructed in the US by the end of 2007, with an estimated cost of over \$3.35 billion (FHWA 2007).

Most highway products and their components are currently manufactured from non-renewable materials of substantial carbon footprint: concrete, metals, petroleum-based plastics, or from treated wood. Even if only some of these materials can be replaced with wood plastic composites filled with low-grade woody biomass, it is clear that highway products can become an effective outlet for substantial amounts of the material generated in fire prevention and other forest operations across the US, while displacing substantial volumes of petroleum-based plastics. An example of successful utilization of wood plastic composites with low-grade biomass content in highway related products has been traffic and Forest Service sign panels and posts made with *Altree*<sup>TM</sup>, a material developed by New Mexico based P&M Signs Inc. (Ginsberg 2010).

Highway-related products differ by size, function, and manufacturing processes currently in use, and they are regulated by different standards. However, despite their variety, some necessary material characteristics can be easily predicted. For instance, virtually all highway products are exposed to outdoor climate conditions and/or ground contact throughout their entire service life. The feasibility of substituting current materials with more sustainable alternatives in these products must be assessed carefully, case by case and against multiple criteria.

In the absence of clear guidelines, an assessment such as this may be a daunting task for entrepreneurs and small-scale businesses willing to enter the market.

## **OBJECTIVE**

The objective of this paper is to outline a conceptual framework for systematic assessment of the potential replacement, or partial substitution of materials used currently in highway related hardware, with sustainable woody biomass-based composites. It is designed to guide the decision making process on whether WPCs, using low-grade woody biomass, are a suitable material substitution in products and components currently made from non-renewables such as concrete, metals, or 100% petroleum-based plastics. Specifically, this methodology examines if a material substitution for a product, or its components, necessitates substantial changes in its design and manufacturing process.

## **PRODUCT DEVELOPMENT VERSUS MATERIAL SUBSTITUTION**

Evaluating the use of WPCs filled with low-grade woody biomass in a highway product requires consideration of many factors. NCHRP Report 350 describes the stages of product development from design to product implementation of products and features related to highway safety. These guidelines are however of limited use when material substitution in existing products is considered, which is the focus of this project.

In contrast to new product development, material substitution in a product requires consideration of the extent and cost of necessary changes in the existing manufacturing process, and whether the product made with the new material will be able to meet the standard performance criteria as well as the original.

The procedure by which the feasibility of material substitution in a product can be assessed is summarized in the diagram in Fig. 2. The primary concerns are:

- 1) the effect of replacing the original material with WPC or simply adding low-grade biomass filler to the original plastic formulation on the manufacturing process,
- 2) the effect of the substitution on the critical material and product properties and functions defined in the product standards, and
- 3) the cost-benefits balance of the substitution. The cost-benefits analysis must be considered in the broader context of sustainability of the material substitution with bio-based composite.

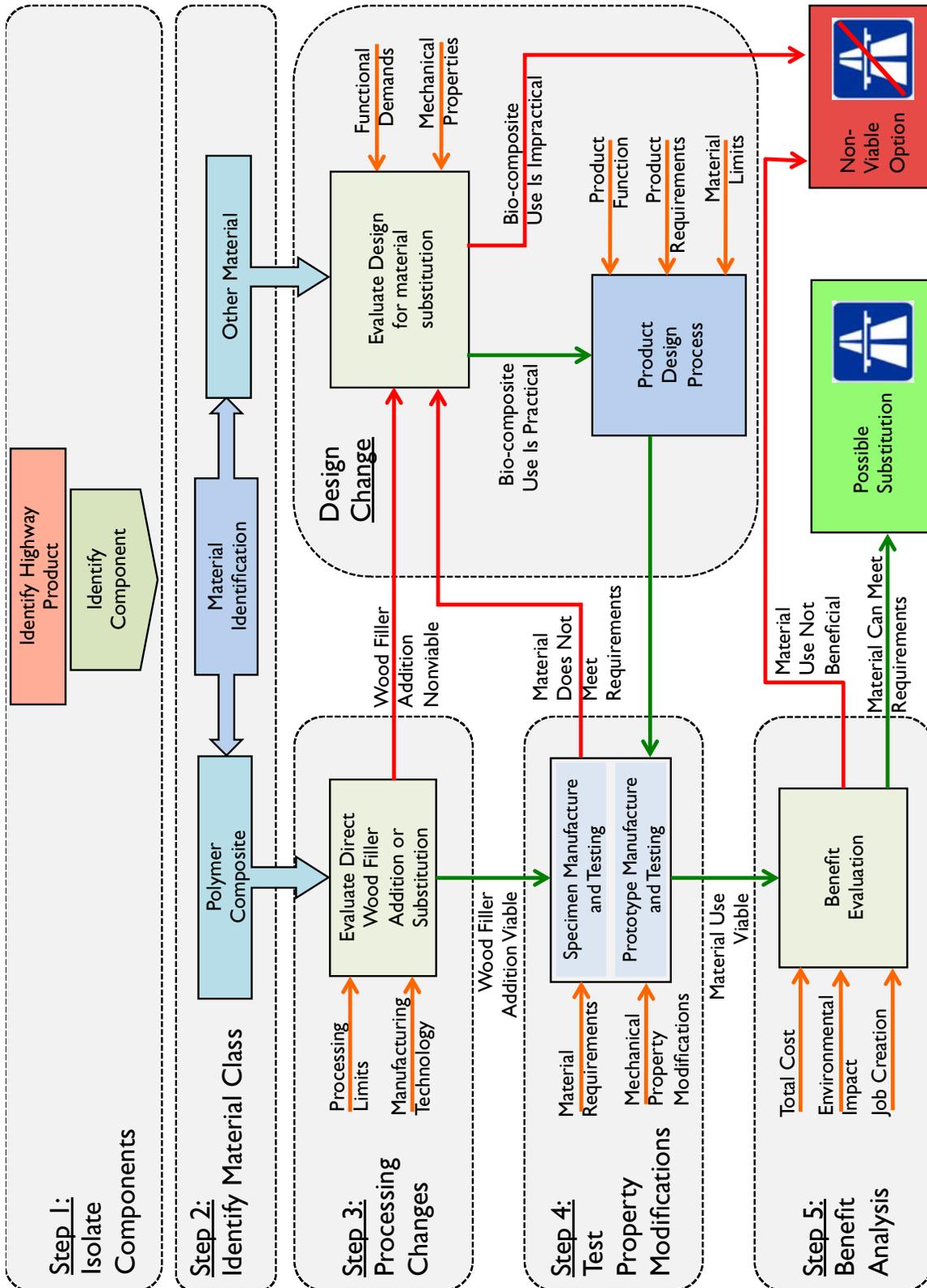
## **PROCEDURES FOR THE FEASIBILITY ASSESSMENT OF MATERIAL SUBSTITUTION**

In order to address these concerns a step-by-step assessment procedure has been developed to guide the decision making process. The assessment process may be summarized in the following five steps, illustrated in Fig. 2.

### **Step 1: Isolate Product Components**

In this step, the design of the candidate product should be carefully considered and for multi-component products each component should be assessed individually.

Products related to highway infrastructure may be comprised of many component parts, each made of different materials. Some parts, such as reflective surfaces, or fasteners cannot possibly be replaced with counterparts made from wood plastics. Similarly, material substitution in products and parts made currently of concrete or steel will require major changes in the product design and manufacturing processes. However, for the numerous parts and products currently manufactured from virgin plastics, adding moderate amounts of wood particles as a filler material may not require significant changes in processing.



**Fig. 1.** A diagram summarizing the procedure for the feasibility assessment of material substitution with bio-composites

## **Step 2: Identify Currently Used Material**

Individual products and components should be divided into two categories based on material type:

- A) Products or components made from polymer composites may be good candidates for direct material substitution. They can be potentially made with minimal changes to their manufacturing process or design by a direct addition of woody particles in their formulations.
- B) Products or components made from other materials such as metals, solid wood, and concrete may either require major changes in both manufacturing process and design – or may not be suitable for substitution at all.

## **Step 3: Analyze Processing Constrains**

In case of components currently made of polymer composites (category A from step 2) the effects of incorporating low-grade woody biomass fillers in the formulation on the manufacturing process need to be considered. Process characteristics and parameters may limit the practicality or the amount of bio-based filler that can be incorporated within a material.

For instance, woody biomass subjected to temperatures above 200°C undergoes rapid thermal degradation and therefore cannot be compounded with materials which must be processed above that temperature (Clemons 2002; Klyosov 2007). The individual process and the specific processing equipment can also limit the maximum amount of the filler that may be added to the composition. The addition of fillers affects the viscosity and flow characteristics, and may change the efficiency of the manufacturing process. At this stage, the decision must be made whether the adjustment of the process is practical or even possible.

## **Step 4: Analyze Effect on Critical Material and Product Properties**

Highway products and their components in which biomass filler content causes no major changes to their manufacture must now be tested for compliance with the critical standard criteria. Although most of the product standards specify functional requirements for the entire products, small-scale material testing can be used as an indicator of material properties before prototype and full-scale product prototype testing is preformed. The addition of particulate fillers affects many physical and mechanical properties of the material. This is particularly true for organic fillers derived from woody biomass. It is important to note however, that not all material properties are affected to the same degree. Some properties affected may not be critical for required performance criteria. The following distinctions should be made:

- A) WPC formulations whose properties compare favorably with the requirements critical to the functional performance characteristics of a product/component may be considered for prototype trials.
- B) Composite formulations missing the mark by a small margin may be considered for prototype trials after moderate changes of the product/component design, aimed at compensating for the loss of property (e.g. modification in the cross section dimensions).

- C) Composite formulations missing the material requirements by a substantial margin shall be considered unfit for the material substitution. In this case, different composite formulations, major changes in manufacturing processes and/or major changes in the product/component design should be considered.

For composite formulations meeting the material requirements, prototype testing according to prescribed testing protocols is the ultimate technical criterion for the product's acceptance.

- A) Prototypes meeting the product performance criteria should be further subjected to cost-benefit analysis.
- B) Prototypes missing the mark by a small margin may be considered for slight adjustments in the composite formulation or design.
- C) Prototypes missing the functional performance criteria by a substantial margin shall be considered unfit for the material substitution. Again, different composite formulations, major changes in manufacturing processes, and/or a major change in the product/part design may be considered.

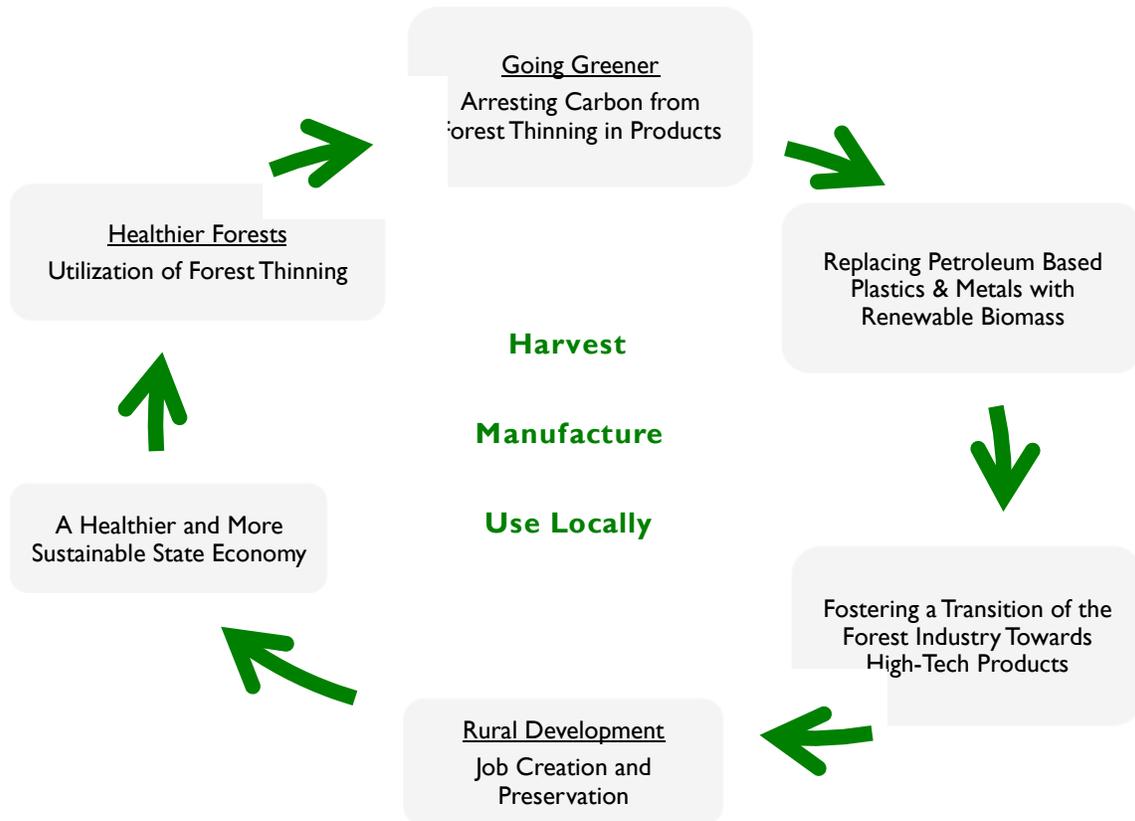
### **Step 5: Cost-Benefit Analysis**

Prototypes meeting the functional performance criteria for the product must be subject to a cost-benefit analysis, and also considered in the broader context of sustainability.

Sustainability is often defined in the broader perspective of joint environmental, economic and community objectives (from the Oregon Sustainability Act (2001)). Therefore, in this project, the sustainability of material substitution in highway products is measured not exclusively in terms of direct savings on their ticket price, but is assessed in the context of benefits to the environment, local economies, and communities. In fact, these benefits are best assessed in collaboration with local community administrations at state, county, or municipal levels. These entities are also typically responsible for the health and safety of public forests, maintenance of public infrastructure as well as creating local job and business opportunities.

Manufacturing bio-composites does not generally require overwhelming capital investments and is suitable for small to medium-scale businesses. It is reasonable to assume that the relatively low entry costs for establishing a small-scale WPC operation, and the recent push toward sustainable materials may help create new business opportunities. This will contribute to the economic development of rural areas affected by the decline of the traditional forest products industry. Additionally, the small-scale and potential mobility of such an operation, and the dispersed nature of the target resource base, can provide the means to reduce costly long distance transportation of raw materials. The synergistic nature of the potential benefits is schematically summarized in Fig. 2.

Though there is potential for positive outcomes from the manufacture of regional bio-based products, a number of additional assumptions outside the scope of this paper must be tested to assess overall feasibility, and should be examined before a full-scale manufacturing operation commences.



**Fig. 2.** Schematic representation of synergistic nature of the potential benefits of utilization of renewable low-grade woody biomass in products related to public infrastructure

## EVALUATION OF POTENTIAL MATERIAL SUBSTITUTION IN THREE HIGHWAY PRODUCTS

The following sections illustrate the flow of the evaluation procedure for three highway products: raised pavement markers, tubular markers, and sound walls. They represent an assorted selection of components commonly present on the US highway system and a range of uses: small items, permanently fixed on the pavement in substantial numbers that collectively sum to a large volume of material; portable items deployed temporarily and reused frequently; and large-scale fixed roadside features. While the following sections outline specific steps that would be proper for each of the selected products, the actual analysis leading to qualification or disqualification of the substitution in each case exceeds the scope of this paper.

### Raised Pavement Markers: Botts' Dots

Raised pavement markers (also known as Botts' dots) are used to mark lanes providing visual and tactile lane division (Fig. 3). They represent a class of small-size fixed items, which can be used in hundreds of uniform units per mile. The type

considered here is a simple round, domed marker. It is made from a non-reflective material and mounted with a bituminous or epoxy adhesive to an asphalt or concrete surface (ODOT 2010). The California Department of Transportation estimates that there are about 20 million Botts' dots on its roadways today (Caltrans 2010). That is enough to form a continuous line of Botts' dots stretching the length of US Interstate 5 from the US-Mexico border all the way to Tacoma, Washington.



**Fig. 3.** Raised pavement markers

*Step 1: Isolating components*

Botts' dots are relatively simple single-component products.

*Step 2: Current materials*

Currently, Botts' dots are made from ceramics, or thermoplastics such as polycarbonate, polyester, acrylonitrile butadiene styrene (ABS), and polypropylene (PP) (TSSCO 2010a).

*Step 3: Processing constrains*

Ceramics and polycarbonate matrixes have processing temperatures generally too high for the inclusion of wood particles, which would decompose above 200°C. Of the thermoplastic materials currently used in Botts' dots manufacturing only polypropylene and ABS have melting temperature low enough to be considered. In fact, polypropylene is a common matrix in commercial wood-plastic composites (Clemons 2002). Woody biomass may also be mixed with polyester resin (Caulfield et al. 2005).

Polypropylene, ABS and polyester resins are compatible with wood fillers, and WPC parts using these matrices can be mass produced by injection molding (Hunnicut 2007; Bouafif et al. 2009). Specific processing constrains and optimal filler loading ratios to achieve the desired material properties need to be determined.

#### *Step 4: Analyze Effect on Critical Material and Product Properties*

The critical properties for pavement markers are bond strength to pavement, hardness, resistance to repeated compressive loadings, resistance to water absorption, and color stability (Caltrans 2006).

*Small coupon testing:* The effect of adding woody biomass filler in the original polymer on these critical properties of the composite may be established through preliminary tests on small samples and coupons and compared with reference specimens of the original materials. Particularly, hardness, water absorption, and resistance to outdoor weathering of material specimens may be examined with standard tests designed for plastics such as ASTM D785, ASTM D570, and ASTM D1435.

At this stage using recycled plastics in the formulations may be considered. The results will help determine the viable range of filler content in the original polymer. If the compressive strength, resistance to water adsorption and discoloration of the new composite material compare favorably with that of the original materials the new formulations may be considered for prototype trials. If the composite formulations miss these requirements by a substantial margin they shall be considered unfit for the material substitution in Botts' dots. In this case, different composite formulations, major changes in manufacturing processes and/or major changes in the product/component design should be considered.

*Product testing:* Full-size prototypes molded of the composite formulation determined in the tests on small coupons will be subjected to tests prescribed by the local department of transportation. Every state has different specifications for pavement markers. Although not extensively different, the target state's department of transportation publications must be consulted.

Prototypes meeting the product performance criteria should be further subjected to cost-benefit analysis.

### **Tubular Markers**

Tubular markers are used to guide traffic, indicate obstacles or hazards, for both temporary and permanent applications (Fig. 4). These are items typically deployed temporarily and re-used multiple times. Commonly found in construction areas, they need to withstand impacts without damage to the markers or vehicles that strike them.

#### *Step 1: Isolating components*

Tubular markers may comprise of two to four components: the vertical, thin-walled tube is held in place with a heavy base, or occasionally an assembly that fastens it to the pavement.

#### *Step 2: Current materials*

In many products the heavy base is already made from recycled tires, so there is no need to consider material replacement here. The marker tube is made from HDPE, LDPE, urethane or PVC (TSSCO 2010b; Western Safety 2010). The fasteners are typically metal, and will not be a good candidate for material substitution either. Therefore, we will focus on the assessment on the tubular part.



**Fig. 4.** Tubular markers

#### *Step 3: Processing constrains*

All three polymers currently used to manufacture the vertical marker tube are commonly used in manufacturing of wood plastic composites for exterior use, though HDPE dominates the market. Both recycled and virgin plastics are used (Clemons 2002). Injection molding of the thin-walled tube (often less than 1/8"), may be a technological challenge, because adding the filler increases the viscosity and related shear characteristics of the molten mixture (Li and Wolcott 2005).

#### *Step 4: Analyze Effect on Critical Material and Product Properties*

The FHWA Manual on Uniform Traffic Control Devices (MUTCD) governs the standards for tubular markers. They need to be flexible and withstand multiple impacts without damage to itself or a vehicle. They must be bright orange in color, and have wide, reflectorized bands adhered to them (FHWA 2009; ODOT 2009). Additional requirements may need to be met based on an individual state's department of transportation.

The substitute composite material needs to remain very compliant and tough. Thus, it can be assumed that this product is not a candidate for inclusion of high percentages of wood filler. Unless a plasticizer is added to the composition, brittleness and elastic modulus of WPCs increase as the load of wood filler increases.

*Small coupon testing:* Preliminary tests can be made on small samples and coupons. Testing should include mechanical characteristics, durability, resistance to discoloration, and ability to accept adhesives. Using standard test methods designed for plastics (e.g. ASTM D638, ASTM D7251, ASTM D1435, and ASTM D3359) should it make to compare the properties of new formulations to the original materials.

*Product testing:* For ultimate approval for use on roadways, the National Transportation Product Evaluation Program (NTPEP) carries out full-scale tests. These are primarily field tests focusing on weathering and vehicle collision.

### Sound Barrier Wall

Sound barriers are structures along roadways used to mitigate noise from passing traffic, especially in residential areas (Figure 5). They are large installations designed for long service life. Performance characteristics of sound walls include sound transmission loss, structural requirements, weathering durability, and aesthetic acceptance (Land 2004). However in many cases they do not need to meet stringent collision requirements because they are generally offset from the road.



**Fig. 5.** A sound barrier wall

#### *Step 1: Isolating components*

There are many possible designs for sound barriers involving a wide range of materials such as precast concrete panels, masonry blocks, wood, and plastics. All are made of many components. The material and style are chosen based on performance as well as aesthetic qualities, and are commonly decided on with input from local government and citizens (VDOT 2008). The design most appropriate for application of

wood plastic composites with low-grade biomass content seems to be the modular post and plank system. These typically comprise of steel H profile posts anchored in concrete foundation and series of horizontal planks forming the wall in the spaces between the posts. Of these three elements, only the planks are obvious candidates for material replacement, although there are existing designs where wood plastic composites are also used for short posts (Polyplank 2010).

#### *Step 2: Current materials*

There are several designs of post and plank type sound walls on the market today. For this exercise a Carsonite design based a hollow, extruded plastic profiles filled with a sound-absorptive material was selected (Carsonite 2010; HLH 2010; SFS 2007).

#### *Step 3: Processing constrains*

Extrusion is a common processing mode for many WPC products (Klyosov 2007); hence the direct addition of woody biomass filler may be possible without major changes to the manufacturing process. Currently there are a few manufacturers of WPC sound barrier walls, including Polyplank AB from Sweden (Polyplank 2010). Adapting this product to include low-grade forest slash filler would address the needs of biomass utilization and increasing the sustainability of highway related products, as presented in this paper.

#### *Step 4: Analyze Effect on Critical Material and Product Properties*

The critical properties of a sound wall are sound absorption and reflectivity, the resistance to weathering and visual characteristics, structural loading including dead and live loads, and impact requirements. The Oregon Department of Transportation Noise Manual mandates that a sound wall must obtain substantial noise reduction, defined as minimum decrease of 5 dB (decibels) (ODOT 2007). Depending on the design, not all the components of a sound wall should need to meet these requirements, even though the sound wall as a whole does. For example, the sound absorption/reflectance of the posts is a secondary concern to their structural performance, while an opposite would be true for the planking system of the sound barrier.

*Small coupon testing:* Small-scale testing should be focused on weathering and the acoustics of the material, although the tests may require coupons of different scale. Material specimens may be examined using standard tests such as ASTM E90, ASTM D7251, and ASTM D1435. The stiffness and mass of a material directly influences its sound characteristics. Wood fillers will likely have a direct effect on the product's acoustic properties. Consideration should also be given to using woody biomass as the sound absorptive batting within the extruded profile. However some jurisdictions do have fire resistance requirements, which need to be taken into account. While small-scale impact tests can be used to predict impact behavior of the structure, medium to full-scale element tests may be needed for actual crash tests.

*Product testing:* NTPEP or local departments of transportation require full-scale tests of the complete sections of sound wall assemblies. These are primarily field tests focusing on weathering and sound transmission loss of the sound wall.

### **Cost-Benefits Evaluation**

There are many potential benefits of material substitution leading to partial replacement of currently used materials with WPCs filled with low-grade woody biomass. These benefits may include, but are not limited to direct cost savings and material property improvement. The environmental impact of material substitution will depend on the amount, or ratio of woody biomass incorporated in to materials that preserve the critical functionality of the product. In particular, if only very small percentages of woody biomass filler can be used to maintain desired mechanical characteristics, the cost of process adjustment must be weighed carefully against the potential benefits. However, even a moderate biomass content should translate into substantial volumes of sequestered biomass and saved plastic in products manufactured in large volumes. Additional benefits may be realized if recycled plastics are used for matrix. Further, the effect of the new formulation on the manufacturing equipment (cost of processing material of higher viscosity, wearing of parts and components, etc.) requires consideration.

Small-scale of wood-plastic processing operations and variety of products involved makes it a feasible business option for enterprises in rural communities close to the raw material source. Locating the manufacturing in rural communities in forested areas could reduce the cost of transportation of raw materials and therefore substantially affect the economic balance of the operation. Other synergistic effects have been discussed in previous sections.

The assessment of environmental benefit must also rely on a thorough investigation of life cycle inventory data of materials currently in use, and composite materials employing low-grade woody biomass.

### **CONCLUSIONS**

1. A conceptual framework for systematic assessment of the potential for replacing or partially substituting materials used currently in highway related hardware, with sustainable woody biomass-based composites has been developed.
2. The purpose of the procedure is to guide the decision making process on feasibility of material substitution in individual products and components. The procedure involves five steps in which the effects of material substitution on the manufacturing process, material properties, product design, and functionality as well as the costs and benefits of the substitution are carefully considered.
3. The cost-benefit analysis and sustainability of the material substitution in highway products is measured not exclusively in terms of direct savings on their ticket price, but is assessed in the context of benefits to the environment, local economies, and communities.
4. The flow of the procedure has been demonstrated on three highway-related products: raised pavement markers (Botts' dots), tubular markers, and sound barrier walls. The actual analysis leading to qualification or disqualification of the substitution in each of these products exceeds the scope of this paper.

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