Sustainability Assessment of Protein-Soil Composite Materials for Limited Resource Environments

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ABSTRACT: This article presents the sustainability assessment of a novel biocomposite material that is under investigation by NASA for use in construction in limited resource environments. The composite consists of soil particles solidified by a protein binding agent. Preliminary compressive strength data suggests the biocomposite could be used for numerous construction applications. To assess the biocomposite's potential for use in sustainable construction, a comparative process-based life cycle assessment between biocomposite and concrete pavers was performed to analyze the life cycle primary energy and IMPACT 2002+ points of both types of pavers. Results show that the concrete pavers outperform the biocomposite pavers in initial impact. However, biocomposite pavers can be more favorable when binder reclamation and reuse scenarios are taken into account at end-of-life. Based on these results, recommendations include switching to a mixture of lower grade proteins to reduce the biocomposite impact as well as further laboratory investigations into recycling scenarios.

KEYWORDS: Biocomposite, sustainability, protein, concrete

1 INTRODUCTION

Materials production is a major source of global greenhouse gas emissions. As one example, cement production is very energy intensive and accounts for 5% of global anthropogenic CO_2 emissions [1,2], along with significant levels of SO_2, NO_x, particulate matter and other pollutants [3,4,5]. Moreover, the mining, manufacturing, and transportation of other concrete components (i.e., sand, aggregates, supplementary cementitious materials, admixtures) creates additional burdens in the form of CO_2 emissions, SO_2 emissions, NO_x emissions, particulate matter releases, and other impacts [6]. Following this pattern, the production flows for many materials that form the foundation of our modern economy (i.e., cement, silicon, steel) are energy-intensive, consume raw materials in an inefficient manner, and are emissions-intensive in nature.

Separate from the large industrial flows associated with cement, steel, aluminum, and other anthropogenic materials production are large ecological flows associated with biological materials production. In many instances throughout nature, species have evolved to produce biological composites that are structurally substitutable with industrial composites. For instance, structural composites comprised of a mineral particle phase bound by a biological "glue" phase are common in many natural systems. Examples of these biocomposite materials (or biominerals) include nacreous shells, conch, marine worm teeth, animal teeth, and bone. These complex materials, which have developed over millions of years of evolution, have been successfully shown to be a functional basis for the development of new, engineered biocomposites that can serve as a "more sustainable" replacement for traditional engineered composite materials [7].

Natural biocomposites have outstanding mechanical properties when compared to many engineered composites. Against intuition, biocomposite materials are often stronger and tougher than their individual organic and non-organic constituents might suggest [8,9,10,11]. It has been widely concluded that the unique microstructure of these materials, like nacre and bone, is critical to their outstanding mechanical performance. For example, interlocking platelets bound together with thin layers of protein form the dense microstructure of naturally occurring nacre [11].

Naturally-produced biocomposites, like nacre, defy our engineering intuition and appear to be excellent templates for microstructural design of other biocomposites. In the case of nacre, the material synthesis requires a highly complex series of steps that are finely coordinated by the living organism. Nacre growth

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begins with the secretion of proteins that mediate the initial precipitation of $CaCO_3$ as calcite, followed by a phase transition from calcite to aragonite. There are at least seven distinct proteins involved in the process. As steady state is reached, nacre deposition occurs through the successive arrest of biomineralization by means of a protein-mediated mechanism. This is followed by the subsequent reinitiation of biomineralization on the new surface layer [12]. Protein phase transformations are also believed to occur by surface dissolution of protein precursors, which mediate the free energy of activation of protein interconversion at the interface to form the bond between aragonite and protein [7]. The replication of all of these detailed phases of a biosynthetic pathway is often thermodynamically or economically inefficient, and in some cases industrially impossible. In order to follow all of the steps of the natural biosynthesis process for nacre, a colony of biomineralizing organisms would need to be maintained, at substantial cost, material intensity, and energetic intensity [12]. Working with biologically produced polyhydroxyalkanoate composites, Rostkowski *et al.* found that the energy and materials required for microbial reproduction during biocomposite synthesis was on the order of energy within the material produced (or energy required for production) [13].

In light of such large energy requirements, biocomposite materials can have both potential benefits and costs in large-scale applications. Benefits may include renewably sourced raw material feedstocks, biodegradation at end-of-life, and low levels of toxicity to humans and ecosystems. Costs may come from larger energy and nutrient inputs needed to nourish a colony of bioproducing organisms, larger material waste flows at end-of-life, and limited strength, stiffness, or durability of biocomposites, thus resulting in greater life cycle material consumption [14,15].

This article investigates the sustainability profile of a novel biocomposite material that is under investigation for use in construction in limited resource environments. Specifically, these composites are being developed in collaboration with NASA for construction of human habitats on long-duration space exploration missions to the moon and Mars. However, terrestrial applications of these biocomposites are the focus of this article. The composite consists of inorganic basalt particles solidified by a protein binding agent. In the following sections the composite material and its production are described, a process-based life cycle assessment of the composite material for use in a terrestrial construction application is detailed, and a discussion focuses on potential improvements to the material and its processing. Conclusions regarding the sustainability of these biocomposites are ultimately drawn for the case of terrestrial construction.

2 PROTEIN-BOUND INORGANIC PARTICLE BIOCOMPOSITES

2.1 Biocomposite Constituents and Processing

Protein-bound inorganic particle biocomposites are a newly developed, multiphase composite containing biological polymers (protein) and minerals. These biocomposites are a three-phase composite with a protein, mineral, and protein interface phase. There is also a void fraction with the composite. The protein phase accounts for 5–10% of composite mass. Bovine serum albumin (BSA), used as a protein binder for these investigations, is a widely studied protein found in the blood of bovines and is responsible for the transport of lipids and metallic ions. BSA is characterized as a globular protein with a mass of 66 kDa and has been fully gene sequenced [16]. The BSA used was purchased from Sigma Aldrich Co. LLC, St. Louis, Missouri, USA (Product ID A-4378, CAS Number 9048-46-8) and comes as a lyophilized powder with a molecular weight of 66 kDa and purity greater than 97% BSA (as determined by agarose gel electrophoresis).

The mineral phase of biological polymer composite makes up 70% to 95% of the material mass. In laboratory prototypes, the basaltic mineral phase has a chemical makeup of primarily silica oxides (45.7%), aluminum oxides (16.2%), ferrous oxides (12.4%) and calcium oxides (10%) with smaller fractions of other constituent oxides [17]. The particles have a size gradation between 5 microns and 2 mm with an average particle size of approximately 100 microns [18]. The mineral phase, trade name "JSC-1A," was purchased from Orbital Technologies Corporation, Madison, Wisconsin, USA.

Biocomposite synthesis was done using vacuum assisted resin infusion methods (VARIM). The use of VARIM for production of biocomposites is described in more detail in Roedel *et al.* [19]. VARIM is commonly used in the polymer composites industry to infuse polymer resins into woven sheets of glass reinforcing fibers to create complex shapes and large structures (e.g., yacht hulls). A vacuum infusion frame was designed and fabricated for biocomposite synthesis. The infusion began with filling the frame with oven-dry inorganic mineral phase and preparing a highly concentrated BSA solution for infusion. A 150 mL solution of BSA in deionized water was used with a concentration of 300 g/L.

Figure 1 Biocomposite specimen bound with bovine serum albumin (BSA) protein. (Specimen shown is a 25 mm × 25 mm × 25 mm cube.)

Infusion was carried out by connecting the frame to a vacuum source (pressure of −635 mmHg) at 20°C and drawing the protein solution into the packed particle structure. This allowed the protein solution to be pulled into the inorganic mineral structure and saturate the void space. Following completion of the infusion, signaled by a visible flow of BSA solution through the frame, the inlets were clamped to prevent further infusion of solution through the rig. The biocomposite was left under vacuum until all excess solution was removed and to allow for initial desiccation. The biocomposite was then fully desiccated under ambient laboratory conditions. The desiccated biocomposite is shown in Figure 1.

2.2 Biocomposite Mechanical Properties and Microstructure

A detailed review of biocomposite mechanical testing procedures can be found in Roedel *et al.* [19]. Biocomposite specimens were cut into prismatic test specimens for mechanical testing. Cutting was done with a Ryobi 3/4 HP 7 inch (17.8 cm) wet tile saw fitted with a 17.8 cm diamond tipped rotary blade. Prismatic test specimen dimensions for compression testing were 5.3 cm × 1.25 cm × 1.25 cm. The prism dimensions were chosen to allow for material crushing failure prior to buckling failure of the specimen during compression testing.

Compression tests were carried out using a digitally controlled pneumatic MTS 858 tabletop system with a 13300N load cell. Prismatic specimens were loaded vertically along their long axis until failure. The rate of deformation was set to 1 mm/min, adopted from ASTM C469, with data collected at 20Hz. A total of 52 compression tests were carried out on biocomposite samples. These biocomposites have an average elastic modulus of 1.2 GPa, with a coefficient of variation of 25%, and an average compressive strength of 12.5 MPa, also with a coefficient of variation of 25%.

Following mechanical testing, scanning electron microscope (SEM) imaging of BSA biocomposites synthesized using VARIM techniques was carried out. This imaging, performed on uncoated specimens using a Hitachi S-4800 II Field Emission SEM instrument confirms the formation of interfacial microstructures at the protein-mineral interface. At the submicron level, these structures form ligament-type ties that extend between adjacent inorganic particles. This is shown in Figure 2 at magnifications ranging from 3.8×10^4 to 7.5×10^5. Figure 2(a) shows the BSA biocomposite at magnification of 3.8×10^4 with angular mineral particles surrounded by BSA protein structures. Figure 2 (b) is the same material at higher magnification (1.5×10^5) in which BSA protein "ligaments" can be seen as spires reaching between adjacent mineral particles. Figure 2(c) is a further magnification of the biocomposite material (7.5×10^5) in which a 50 nm long BSA protein ligament can be seen bridging between mineral particles coated in protein.

As described by Roedel *et al.*, failure of the biological polymer phase governs the compressive response of the composite [19]. Up to compressive strains of approximately 1%, the material response follows a linear elastic regime. This elastic response is then followed by nonlinear softening. The onset of the nonlinear region is likely due to both pore collapse, a phenomenon discussed in detail by Wong and Baud [20], and the growth and coalescence of cracks to the macroscopic scale until a brittle failure is observed at compressive strains of greater than 1.5%. The images in Figure 2, in particular Figure 2(c), provide evidence that the failure of biological polymer phases governs the mechanical response of the composite through a failure mechanism in the protein binder.

3 LIFE CYCLE ASSESSMENT OF BIOCOMPOSITE MATERIALS

3.1 Goal and Scope

The goal of this assessment is to compare the life cycle environmental and economic impacts associated with the production, use, and end-of-life management of prefabricated paving units produced from biocomposites to those produced from conventional concrete. Such pavers are commonly used in sidewalks and patio applications and are subjected primarily to

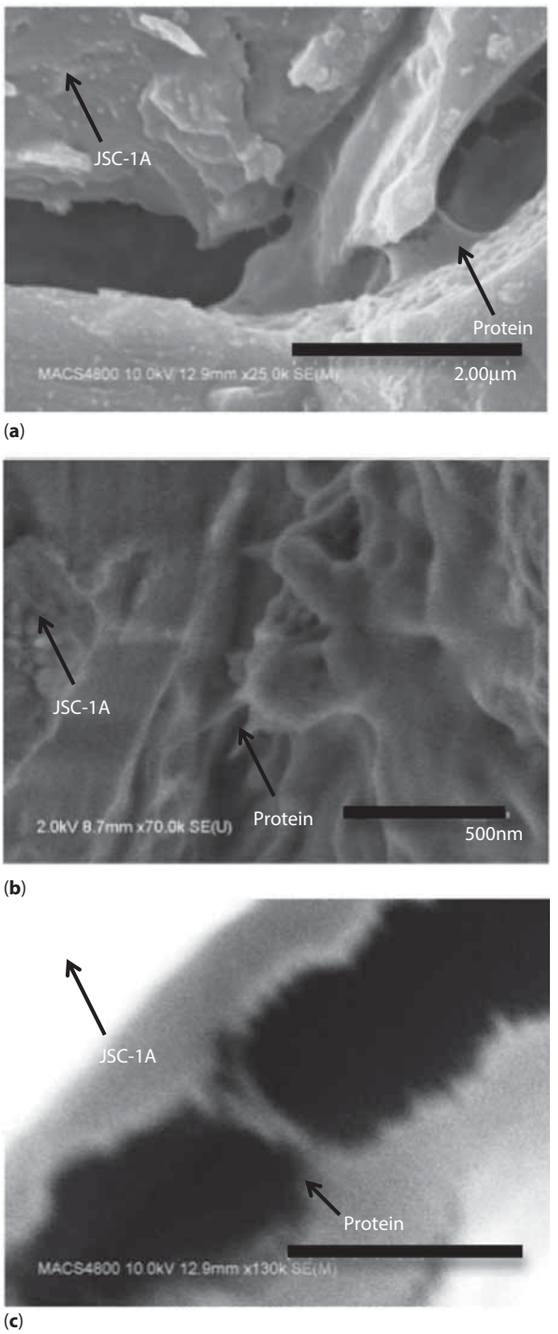

Figure 2 Scanning electron micrographs of biocomposite showing BSA protein ligament structure between mineral particles. (a) BSA biocomposite at magnification of 3.8×10^4. Bar = 2 microns. (b) Enlarged image at magnification of 1.5×10^5. Bar = 500 nm. (c) Enlarged image at magnification of 7.5×10^5 of material shown at left. A BSA protein ligament bridging mineral particles coated in protein with microstructure is clearly visible. Bar = 100 nm.

pedestrian loads. However, the ultimate design case considered is for emergency vehicle traffic with equivalent single axel loads of 80 kN [21,22]. The functional unit chosen was 10,000 paving units that measure 300 mm × 300 mm × 38 mm and are placed on a granular sub-base. The assessment is done for a 20-year analysis period. For each of the two paving systems, the scope of the assessment included raw material acquisition, material processing, paver prefabrication, use, recycling, and end-of-life management of the pavers. Transportation between all phases was also included. The sub-base, being common and equivalent among all systems, was excluded from the scope of the analysis.

In addition to the comparison between biocomposite pavers and concrete pavers, a second comparison between biocomposite proteins was also conducted. As discussed in the previous section, scientific grade BSA was used to make laboratory specimens for mechanical testing and microstructure analysis. Unfortunately, processes used to purify bovine blood plasma are energy intensive [23]. Thus, a variant of BSA protein binder was also investigated that is comprised of dried bovine plasma, with trade name AP920. Within AP920, BSA is one of the primary components in addition to other proteins, fat, and minerals. Since AP920 requires less energy to produce than scientific grade BSA, it was seen as a viable alternative for biocomposite binding. Preliminary studies have shown that AP920 bound biocomposite materials have compressive strength similar to biocomposites bound with pure BSA, preserving the functional unit of comparison [19].

The process flow diagrams for both the biocomposite paver life cycle and the concrete paver life cycle are shown in Figures 3 and 4, respectively. For the biocomposite, the primary raw materials include water used for production of protein solution, basaltic mineral mining and production, and bovine blood production. Following mining, the basalt raw material is jet milled to produce a particle size distribution suitable for production. To produce pure BSA, bovine blood is put through an albumin purification process that includes centrifugation, removal of immunoglobulin antibodies (IgG), heat shock, filtering purification, and lyophilization. The production of AP920 requires only centrifugation and spray drying to separate the plasma fraction of bovine blood. These constituent materials are placed into a paver form and mixed using vacuum infusion methods. Following initial infusion and desiccation, the paver is compacted under 15 MPa pressure to ensure proper compaction of the mineral phase. The pavers are then desiccated in air and thereby develop strength through the formation of protein-

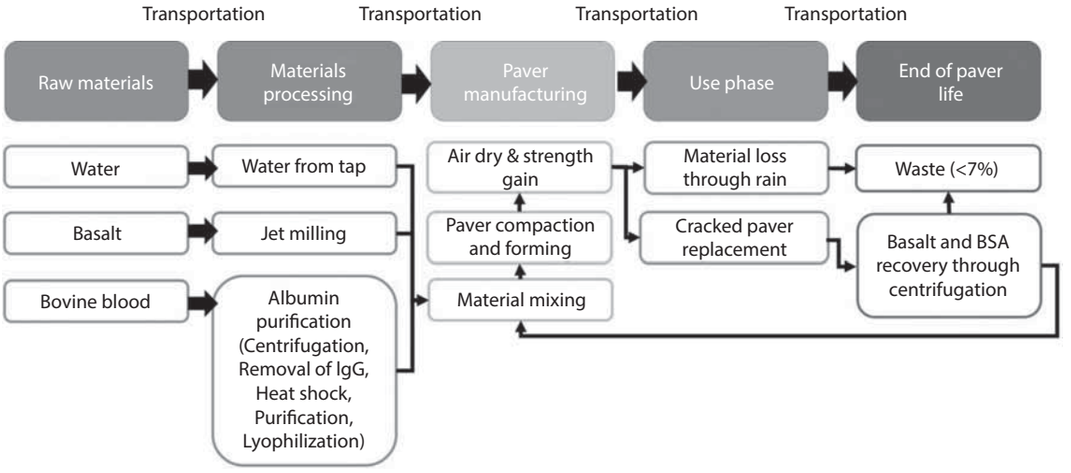

Figure 3 Life cycle process flow diagram for BSA bound biocomposite pavers. (BSA and AP920 differ in the amount of albuimn purification that is done to remove impurities from bovine plasma.)

binding ligaments, similar to those shown in Figure 2 (c).

The use phase of biocomposite materials is unique in that due to the use of protein-based binders, which are water soluble, some material degradation and loss is expected during service life. This degradation, and associated maintenance or replacement of pavers, is accounted for in the use phase model during the 20-year analysis period. Additionally, some pavers will undoubtedly crack when overloaded during use. These pavers will also need to be replaced during the 20-year analysis period. Finally, the end of life includes some generation of landfill waste, while the majority of the biocomposite paver is recovered and can be recycled through centrifugation.

As seen in Figure 4, the production of concrete pavers is conventional in nature in that it begins with the basic components of cement and concrete, and uses conventional concrete mixing, placing, and compaction equipment to produce the pavers. These pavers are then moist cured to prevent shrinkage cracking during hydration. Unlike the biocomposite pavers, which are susceptible to degradation during use, the concrete pavers only require replacement when overloaded and cracked during extreme use. The end-of-life management of the concrete pavers is similar to the biocomposite pavers in that a small fraction of the overall mass is sent to landfill, while the majority is crushed and recycled.

While not explicitly called out in Figures 3 and 4 for simplicity and clarity, each of the life cycle phases described above for biocomposite and concrete paver production requires process energy, process materials, process emissions (i.e., airborne particulates), and complex transportation logistics. These inputs and outflows from the life cycle process flow are included in the final analysis.

3.2 Life Cycle Inventory Modeling

Life cycle inventories for commodity products, including industrial deionized water, basalt mineral sources,

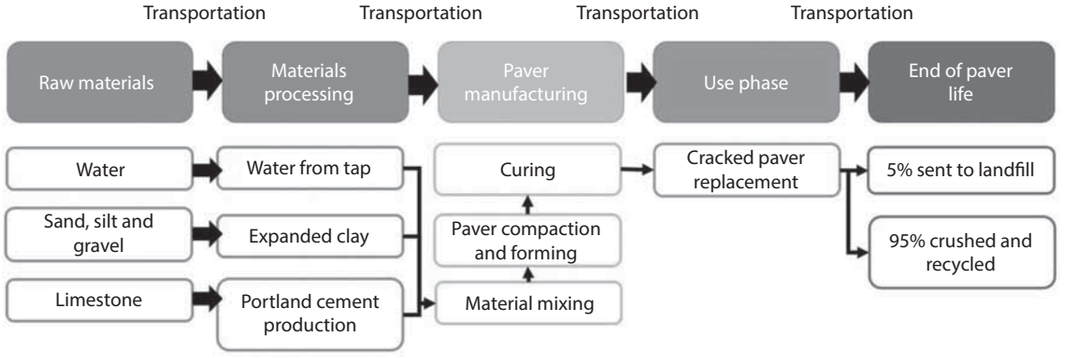

Figure 4 Life cycle process flow diagram for concrete pavers.

sand, gravel, cement, energy (i.e., electricity, natural gas), and transportation were taken from the EcoInvent database [24]. A major effort in this work was the creation of a life cycle inventory for the production of BSA and AP920 protein binders for the biocomposite materials. Bovine blood is a waste product of slaughterhouses, and therefore has low economic value. Using economic allocation of all slaughterhouse products, bovine blood constitutes approximately 1% of total slaughterhouse products [25]. Thus, the only impacts associated with bovine blood production are impacts stemming from its collection and management as a beef coproduct. At the slaughterhouse, the blood is centrifuged and the plasma is shipped by truck to a purification facility. Bovine blood is a commodity market within the United States, and thus the supply contract for a purification facility is awarded to the lowest bidder annually. To determine the average transportation distance of bovine blood plasma, the locations of slaughterhouses cleared by the US Animal and Plant Health Inspection Service (APHIS) to accept imported cattle nationally was used [26]. The distances from the slaughterhouses to the purification plant were determined from plant geocoordinates using Equations 1 through 3 [27].

$$D = \sqrt{(K_1 \Delta\phi)^2 + (K_2 \Delta\lambda)^2} \tag{1}$$

$$K_1 = 111.13209 - 0.56605\cos(2\phi_m) + 0.00120\cos(4\phi_m) \tag{2}$$

$$K_2 = 111.41513\cos(\phi_m) - 0.09455\cos(3\phi_m) + 0.00012\cos(5\phi_m) \tag{3}$$

where, D is the distance in kilometers, $\Delta\phi$ is the change in latitude, $\Delta\lambda$ is the change in longitude, and ϕ_m is the mean latitude. To account for the indirect routes provided by roadway infrastructure, these distances were increased by a factor of $\sqrt{2}$, a conservative assumption given the maximum increase in plane geometry.

To determine the volume of bovine blood required to produce both BSA and AP920, the method proposed by Reynolds to calculate the volume of blood and plasma in non-lactating cows was used [28]. Plasma density and protein percentages were taken from Opoku *et al.* [29] and Duarte *et al.* [30]. This resulted in a fraction of protein of 28 g/L and 68 g/L for BSA and AP920 respectively.

The processing of bovine blood required modeling of centrifuge and dry spraying processes. Centrifuging is necessary to separate hematocrits from plasma in whole blood. The centrifuge model was based on Zonelink's GQ150A animal blood centrifuge, which has a capacity of 3000 kg/hr and a power rating of 3kW. The spray drying mdoel was based on Yibu's LPG-150 Spray Drier, which has an evaporation capacity of 300 kg/hr and a power rating of 99 kW. Bovine blood is primarily composed of hematocrits and plasma, both of which can be sold as feed to pigs [28]. As such, the waste stream for centrifuged hematocrits is not within the scope of this assessment.

Since durability of the biocomposite was expected to be a key driver in this life cycle assessment, the use phase was modeled by calculating the fraction of pavers that would need to be replaced due to structural failure over the 20-year analysis period. Given the similar mechanical strengths of both concrete and biocomposite paver materials, failure and replacement of individual pavers due to structural overload was assumed equal, with 20% of the total number of pavers requiring replacement over the 20-year analysis period for both materials.

Of greater concern is the potential for biocomposite pavers to degrade over time due to the water solubility of the protein binder. Preliminary studies have shown that exposure to moisture does not lead to degradation of biocomposite mechanical properties, but submersion in water for critical periods of time can begin to degrade the binder [19]. Based on the sorptivity of biocomposite pavers, an extreme rainfall event of 50 mm in one hour, accounting for infiltration and no runoff, would sufficiently damage the biocomposite pavers to require replacment. Using rainfall data from the US National Oceanic and Atmospheric Administration, the return period of a 50 mm rain event with a duration of one hour or longer was determined [31]. Using this return period, the analysis period of 20 years, and modeling rainfall occurance as a Poisson process, the expected probability of this rainfall event occurring during the 20-year analysis period was calculated using Equation 4.

$$P_{recurrence} = 1 - e^{\left(\frac{-Y}{R}\right)} \tag{4}$$

where, $P_{recurrence}$ is the probability of recurrence during the analysis period, Y is the length of the analysis period, and R is the return period. For instance, a return period of 1000 years would equate to a 2% probability of occurrence during a 20-year analysis period. Were such an event to happen, 100% of the biocomposite pavers are assumed to be removed and put into end-of-life management.

In addition to moisture exposure, the service life of biocomposite pavers may also be limited by other physical or chemical deterioration mechanisms. Such deterioration mechanisms include exposure to ultraviolet (UV) light, aggressive chemical attacks, or animal/biological attack. To date, no published studies have been carried out looking at these additional

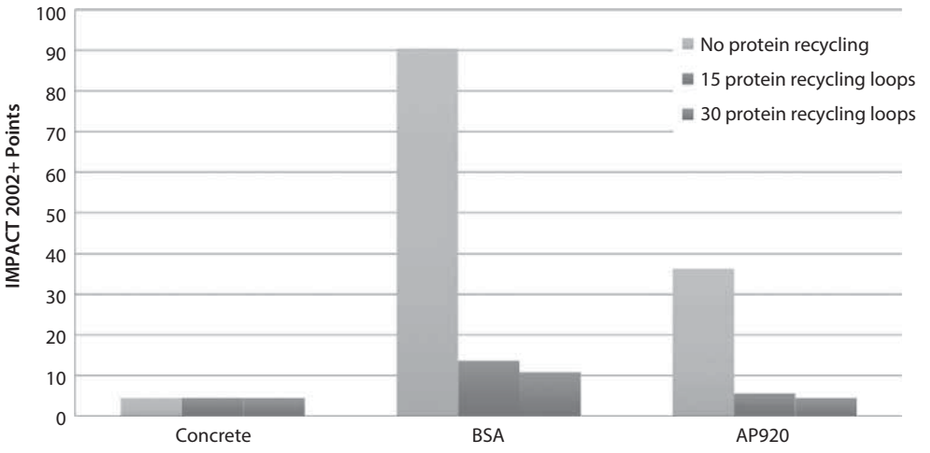

Figure 5 Life cycle IMPACT 2002+ single score points for conventional concrete pavers, biocomposite pavers produced with scientific grade BSA protein, and biocomposite pavers produced with AP920 protein. Results are shown for no protein recycling, along with 15 protein recycling loops, and 30 protein recycling loops.

deterioration mechanisms of the biocomposite materials studied in this paper. As such, future experimental and analytical research should focus on the multi-physics deterioration mechanisms that could lead to more rapid material degradation and end of service life.

At the end of life, 95% of the concrete paver mass is recycled, modeled as rock crushing. The potential for paver overload and cracking is accounted for by increasing the number of pavers fabricated and recycled over the 20-year analysis period by 20%. This is based on a 1% replacement per year due to overload cracking or discoloration. Similarly, 95% of the biocomposite paver is recycled by mass. When accounting for overload failure and possible water degradation, a 40% increase in the number of pavers over the 20-year analysis period is required. At end-of-life the biocomposite pavers are crushed, dissolved, and centrifuged to reclaim the protein binder.

3.3 Life Cycle Impact Assessment

Life cycle impact assessment was carried out for all three of the paver types (concrete, biocomposite using BSA, biocomposite using AP920) using the IMPACT 2002+ life cycle impact assessment methodology. This method was chosen due to its robustness, completeness, and relevance to current standards. Figure 5 shows the single point IMPACT 2002+ score total for three different paver materials considered in this study. Based on a one-time use over a 20-year analysis period, the concrete paver has a life cycle impact score of 4.47 points, the BSA biocomposite paver has an impact score of 90.5 points, and the AP920 biocomposite has an impact score of 36.3 points.

The larger impact associated with BSA biocomposite pavers and AP920 biocomposite pavers is due to larger human health and ecosystem quality impacts associated with bovine blood management and purification. Primary energy consumption throughout the life cycles of each of the three systems follow the same trend with concrete, BSA, and AP920 pavers showing life cycle primary energy consumptions of 130GJ, 2400GJ, and 500GJ, respectively, for the 10,000 paver functional unit of analysis. Also of note is the very high impact associated with the multi-step purification process associated with the production of scientific BSA protein. The impacts associated with the additional purification processes of removal of immunoglobulin antibodies (IgG), heat shock, filtering purification, and lyophilization, account for the large difference in IMPACT 2002+ points (52.4 points) and life cycle primary energy (1900GJ) between the biocomposite pavers produced with BSA and AP920.

A distinct benefit of the biocomposite pavers over the conventional concrete pavers is the potential for reclamation and reuse of the binder at end-of-life. Cement, the binder in the concrete pavers, cannot be reclaimed and reused after it hydrates. As such, recycling of the concrete pavers only includes the sand and aggregates. The production of new pavers using recycled paver aggregates still requires the use of energy-intensive and emissions-intensive cement. Protein binders, however, can be used if effectively separated from the recycling stream and rehydrated. Figure 5 shows the drop in life cycle IMPACT 2002+ points following 15 and 30 protein binder reuses. This drop is due to the comparatively low impact processes of protein binder recovery and rehydration as compared to BSA and AP920 production originating from slaughterhouses. While the reuse of scientific BSA will

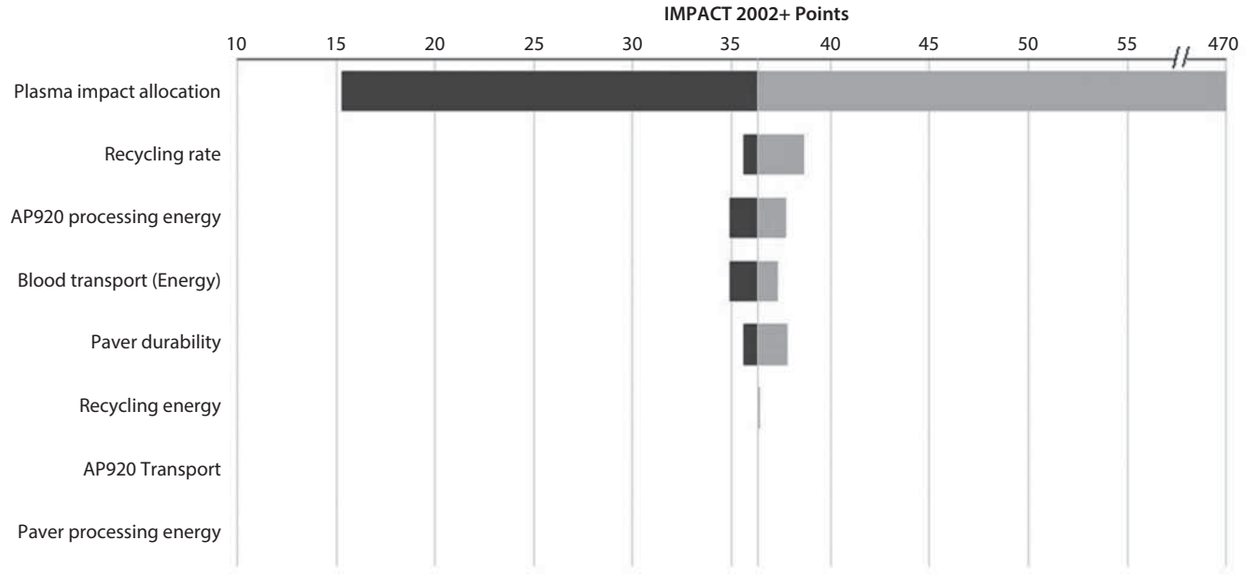

Figure 6 Sensitivity of life cycle IMPACT 2002+ single score points for biocomposite pavers produced with virgin AP920 protein.

never result in lower life cycle IMPACT 2002+ points, the crossover point for biocomposite pavers produced with AP920 is 29 reuses of the protein binder.

3.4 Sensitivity Analysis

A sensitity analysis was carried out for all three of the paver types studied. For brevity, only the sensitivity analysis of the biocomposite pavers made with AP920 is discussed in this article. Given that this is the biocomposite paver alternative that could be competitive with concrete, when considering reclamation and recycling at end-of-life, the uncertainty assocaited with the biocomposite pavers produced with AP920 is of greatest interest.

The AP920 biocomposite paver life cycle model inputs that were varied include: (1) the plasma impact

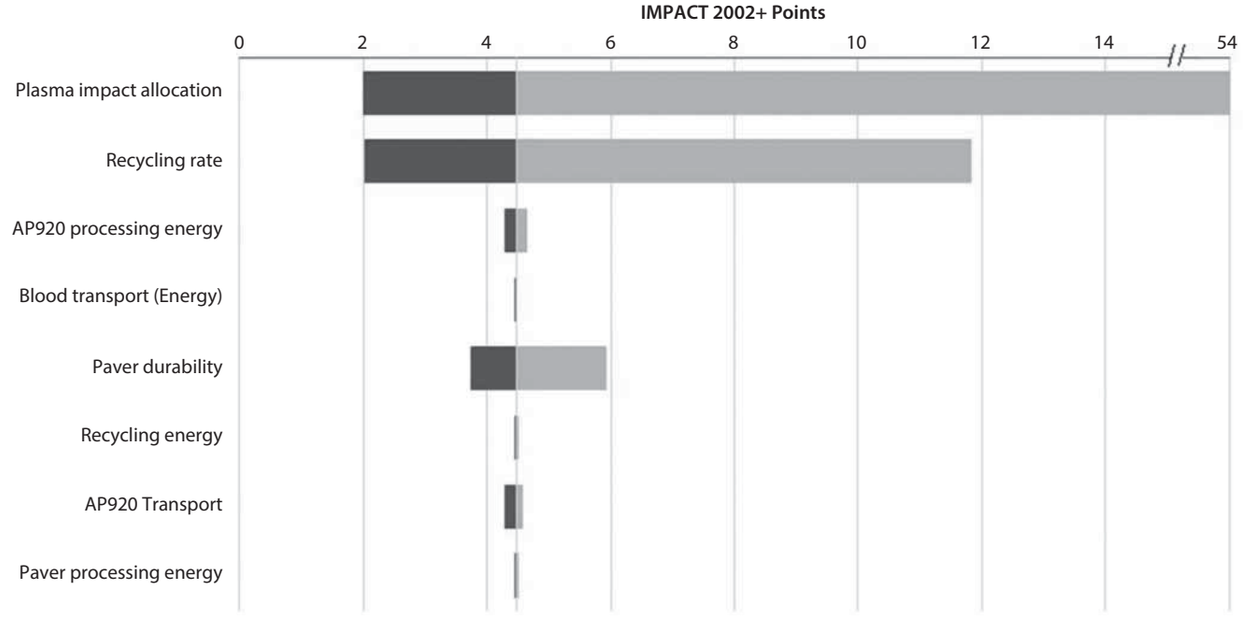

Figure 7 Sensitivity of life cycle IMPACT 2002+ single score points for biocomposite pavers produced with reclaimed and recycled AP920 protein after 30 reclamation cycles.

allocation, (2) paver recycling rate, (3) AP920 processing energy requirement, (4) blood transport distance and weight, (5) paver durability, (6) recyling energy requirement, (7) AP920 transport distance, and (8) the paver manufacture processing energy. The allocation of beef coproduct impacts to the plasma portion of bovine blood was done on a mass basis. This allocation was varied from 100% of beef coproduct impacts being attributed to the blood plasma down to 25% of the mass basis allocation being attributed to the plasma. The recycling rate of the AP920 biocomposite pavers was varied from a rate of 100% to a rate of 80%. The AP920 processing energy was varied from 75% to 125% of the baseline AP920 LCI discussed in Section 3.2. The blood transport weight was varied from transporting 100% of bovine whole blood to the purification facility to 62% of bovine whole blood (the fraction of wet plasma in bovine blood). The blood transport distance varied between an arithmetic mean of distances computed for APHIS cleared slaughterhouses using Equations 1 through 3 and a geometric mean of distances computed for APHIS cleared slaughterhouses. The paver durability varied between a return period of 500 years and 2000 years for a 50 mm rain event with a one hour duration. The AP920 processing energy was varied from 75% to 125% of the baseline AP920 LCI discussed in Section 3.2. The AP920 transportation distance was varied between the transportation distance from each of the two plasma purification sites considered. The paver manufacture processing energy was varied from 75% to 125% of the baseline AP920 LCI discussed in Section 3.2.

The baseline IMPACT 2002+ single score for biocomposite pavers produced using AP920 was 36.3 points (Figure 5). The sensitivity of the single impact score to the variables described above is shown in Figure 6. As seen, the impact of the pavers is highly sensitive to the allocation of beef coproducts to the plasma portion of bovine blood. As mentioned previously, the baseline allocation was done on a economic basis. However, given the economic value of the hematocritc fraction of the blood as pig feed, there is reason for selection of an allocation method which would result in significantly lower impacts of beef coproducts being attribued to the plasma fraction of the bovine blood. Conversely, if impacts associated with the whole blood fraction are attributed to the sourcing of AP920, the IMPACT 2002+ single score is over 12 time higher than the baseline analysis. (Note the discontinuous y-axis in Figure 6.)

Apart from the allocation method chosen for beef coproduct impacts, there is low sensitivity to the set of model variables investigated. In order from most sentisitve to least sensitive, these other modeling variables are paver recycling rate, AP920 processing energy requirement, blood transport distance and weight, and paver durability. The life cycle model was found to be insensitive to variations in recyling energy requirement, AP920 transport distance, and paver manufacture processing energy.

Similar to the sensitivity analysis performed for the production of biocomposite pavers using virgin AP920, a sensitivity anaysis was also performed for biocomposite pavers produced using reclaimed and recycled AP920. As seen in Figure 5, after 30 reclamation cycles the IMPACT 2002+ single score impact drops as low as 4.5 points for the biocomposite pavers produced using reclaimed and recycled AP920. Varying the same inputs as described previously, the sensitivity analysis results are shown in Figure 7.

As seen in Figure 7, the model remains sensitive to the allocation method chosen for beef coproduct impacts. But unlike the sensitivity analysis for biocomposite pavers produced using virgin AP920, the model is also sensitive to the recycling rate of the pavers and, to a lesser extent, the durability of the pavers. In fact, at the lower bound of these sensitivity results, the biocomposite pavers produced using reclaimed AP920 have an IMPACT 2002+ single point score of approximately 2.0. This is lower than the 4.5 points associated with conventional concrete pavers.

4 INTERPRETATION AND DISCUSSION

A number of improvements to the life cycle assessment model, and the biocomposite pavers themselves, can be suggested based on the results presented in Section 3. From an engineering perspective, additional mechanical characterization and fatigue characterization is needed to support the assumption of substitutable performance between conventional concrete pavers and biocomposite pavers. Additionally, durability characterization of biocomposite pavers produced with either scientific grade BSA or AP920 is needed. If the pavers' resistance to deluge is lower than modeled in this study, it is recommended that an energy-efficient method of rainproofing the biocomposite pavers be adopted. The surface application of a hydrophobic agent would meet this recommendation. However, in order to remain preferrable to a conventional concrete paver, it is essential that the hydrophobic agent not jeopardize the opportunity to reclaim and recycle the protein binder at end-of-life.

Since the majority of the uncertaity, and much of the impact, associated with the biocomposite pavers comes from the bovine source of the protein (i.e., uncertainty associated with allocation of beef coproduct impacts), the production of binder proteins from a

non-bovine, or even non-mamalian, source is also recommended. This could be accomplished through the adoption of proteins sourced from plants or microorganisms that are designed to produce globular proteins that can effectively bind inorganic particles. Such work is currently being explored by the authors and other collaborators through the application of synthetic biology tools [32].

Based on the results shown in Figure 5, and the sensitivity analysis shown in Figures 6 and 7, it is recommended that concrete pavers continue to be used in most construction applications, such as sidewalks and patios. However, the results showed that significant reductions can be made in the IMPACT 2002+ single point profile of biocomposite pavers by switching the protein binder from scientific grade BSA to less refined, and therefore less energy intensive, AP920. When effectively reclaimed and recycled, and considering the degradation of proteins during each recycling loop, the biocomposite pavers produced with AP920 remain unlikely to have a life cycle IMPACT 2002+ single point profile equal to or lower than conventional concrete pavers.

5 CONCLUSIONS

This article presented the environmental sustainability assessment of a novel biocomposite material that is under investigation by NASA for use in construction in limited resource environments. The composite consists of basaltic soil particles solidified by a bovine-based protein binder. The compressive elastic modulus and ultimate strength of these composites are 1.2 GPa and 12.5 MPa, respectively. These mechanical properties indicate that this biocomposite could be used for numerous low-grade construction applications, including sidewalk and patio paver applications.

To assess the biocomposite's potential for use in more sustainable construction applications, a comparative process-based life cycle assessment between biocomposite and concrete pavers was performed. The scope of the assessment of 10,000 pavers over a 20-year analysis period ran from raw material acquisition to end-of-life management and recycling. The life cycle primary energy and IMPACT 2002+ single point score of both types of pavers was assessed. Results show that the concrete pavers outperform the biocomposite pavers in initial impact. However, biocomposite pavers can be increasingly favorable when binder reclamation and reuse scenarios are taken into account in end-of-life.

A major finding of this study was the importance of limiting protein purification processes for the biocomposite binder. Initially, the use of scientific grade bovine serum albumin (BSA) as a protein binder caused the life cycle environmental impact of the biocomposite pavers to be over 20 times higher than the conventional concrete pavers. Based on this finding, a less pure protein binder, AP920, was investigated which is also derived from bovine blood. This change to a lower grade binder reduced the life cycle biocomposite paver impact profile by 60%. Sensitivity ananlysis showed that with additional improvements in allocation methods or supply chain, biocomposite pavers produced with AP920 binder may be more environmentally comparable to conventional concrete pavers over a decades-long life cycle.

Significant future work is planned by the authors to build upon the findings presented in this paper. This work includes ongoing mechanical characterization of biocomposite materials, fatigue characterization of biocomposite materials, and durability characterization of biocomposite materials in ultraviolet exposures or after exposure to animal/biological degradation. Additional experimental investigations of other globular proteins are planned to assess their binding capacity, including proteins produced from plants or microorganisms. Additional research is also ongoing in the development of micromechanical models to numerically predict the mechanical and durability properties of biocomposite materials.

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