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Characterization of permeable pavement materials based on recycled rubber and chitosan

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HIGHLIGHTS

- Composite materials for use as permeable pavers were prepared from chitosan and tire crumb.
- Compressive strength and hydraulic conductivity similar to conventional permeable pavers was achieved.
- Sorption capacity of dissolved zinc from water was as high as 0.63 mg per gram of chitosan.
- Unlike other permeable pavements, properties were not strongly dependent on binder content.
- Material properties and morphology were dominated by the concentration of chitosan solution used.

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ABSTRACT

A variety of composite permeable pavement materials were prepared from crumb rubber embedded in a matrix of the biopolymer chitosan, which is a waste product of the seafood industry. We have characterized the hydraulic conductivity, mechanical properties, and the capability of these materials to remove particulate and dissolved pollutants (including zinc) from water. The dependence of material properties on process parameters such as binding polymer content differs from what is typical of binder-based permeable pavement, due to the mechanism by which chitosan is introduced, and in many cases the stability of the composite material increases with decreased binding polymer content.

1. Introduction

One of the most important areas of focus where water quality is concerned is management of stormwater and runoff. As development increases and natural vegetative groundcover is replaced by pavement and roofing, rainfall that would have otherwise been absorbed and slowly released by plants and soil is concentrated into fast-moving streams in pipes and gutters, dramatically increasing its ability to erode soil, carry pollutants and overflow into other water management systems such as wastewater systems. In addition to increasing the fraction of impermeable space, development is typically associated with increased soil vulnerability – removing the vegetative groundcover for development makes soil susceptible to erosion. Developing countries and regions responding to disaster are similarly vulnerable to pollutants carried by stormwater, and when existing stormwater systems are overtaxed or destroyed, a major health risk is caused by uncontrolled flood water mixing with sewage. A simple solution to these problems involves increasing the capacity of developed areas to infiltrate rainwater rather than conveying it over impermeable surfaces to rivers, lakes and streams.

Permeable or porous pavement is a family of passive technologies that address the problem of runoff by providing pathways for water to infiltrate down through walkways, parking lots and roads [1–3]. Rainwater may be directed over an expanse of permeable pavement, which (if large enough) can allow all of the runoff to infiltrate down into groundwater. This reduces the buildup of ice in cold conditions, and may achieve physical filtration and pollutant removal [4,5], but its most important role is to reduce the impact on other stormwater conveyance systems by reducing the volume of runoff and its capacity for erosion.

Two major categories of permeable pavement that include a large fraction of aggregate materials are (1) permeable cement or

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asphalt and (2) resin- or elastomer-bound pavement. Materials falling into the former category are typically prepared by omitting or limiting a void-filling component of what would normally be impermeable concrete or asphalt [1,6] (Fig. 1) and those falling into the latter category are made by bonding granular and/or aggregate material within a polymeric matrix that inherently leaves spaces [7]. Cement- or asphalt-based permeable pavement is usually heavy and capable of supporting similar compression as their impermeable counterparts [6]. Binder-based permeable pavers are light, often flexible and are more likely found in walkways than driveways because of their lesser resistance to compression.

Crumb rubber is a common filler material for both types of permeable paver [7,8], as it is low in cost and can often impart elasticity and resilience that is desirable in walkways. Crumb rubber is generally made from waste car and truck tires that have failed or have exceeded their usable lifetime [9]. More than 300 million waste tires accumulate each year in the USA and the majority of the approximately 80% that are reused are used as fuel. Less than 5% of the tire is typically eroded from the surface before the tread depth becomes insufficient to ensure safe use and the tire is discarded. Because the rubber used in tires is chemically crosslinked, it cannot be reformed into new rubber without significant energy input that generally makes such recycling uneconomical. Tires brought to a tire recycling facility are cryogenically or mechanically crumbled and ground, and the steel belting and fiber is removed magnetically and through the flow of air, respectively. The remaining crumb rubber is sized for the appropriate application and most often there is no washing or cleaning step involved in the preparation of the final crumb product. Primary applications for tire crumb include filler, athletic and equestrian running surfaces, road resurfacing [6,10,11], playing surfaces [12] and garden mulch. In some of these applications, significant cleaning of the rubber is required after it has been purchased from the tire recycling facility, because of the contaminants present in tires-most notably organic compounds and heavy metals such as zinc, lead and cadmium [12,13]. These metals eventually leach from untreated crumb rubber into water, and similarly pose a threat to water along roadways, where the tread has been abraded off in the form of tiny, high-surface area particles that eventually get swept from the road into ditches and other stormwater conveyances.

Because of the environmental impact of tire waste, significant interest exists in developing new applications for crumb rubber. While most existing applications treat tire crumb as a commodity filling material, some researchers have pursued more exotic applications that might increase its value and indirectly motivate more progressive approaches to tire recycling. Crumb rubber has been used as an experimental filter media [14–16] that becomes more compressed with increased depth in the filter, leading to decreasing pore sizes ideal for physical filtration (where large particles are stopped first, smaller particles make their way further into the filter and ultimate filter clogging involves a full filter, rather than one blocked by a small amount of material at the top). Crumb rubber has also been considered as an absorbent of the very heavy metals and other contaminants it is known to contribute to surface water.

In this paper we present results describing the preparation of stormwater filter materials suitable for permeable pavement from crumb rubber that is untreated following collection from the tire recycling facility. The binding material we have used to hold the matrix of rubber particles together is the biopolymer chitosan, which is derived from chitin. Chitin is the second-most abundant polysaccharide found on Earth, and plays a structural role in most invertebrate exoskeletons. Chitosan can degrade in a landfill (with suitable temperatures, moisture and enzyme content) and correspondingly is a candidate material for many single-use packaging applications that promises to relieve stress on overfilling landfills. Chitosan is a waste product of the seafood industry and, like tire rubber, it is underutilized because of difficulties associated with its processing. Unlike common thermoplastics, the high degree of inter- and intra-molecular bonding in chitosan prevents it from melting, and only solution-based processing methods are available. Dilute solutions of chitosan (dissolved in weakly acidic, aqueous solutions) can be dried to form films, coatings and membranes but chitosan is rarely used in a structural capacity (in spite of this being one of its roles as a biomolecule in nature). Instead, chitosan currently finds application in specialty products requiring antimicrobial properties, biocompatibility (chitosan can be formed into implants that resist rejection from the body) and fat-binding capacity: chitosan can be eaten but not digested, and it can bind to fats and prevent their digestion. Because of hydroxyl and amine side groups on the chitosan monomer, it is reactive and readily binds with metals [17].

In developed countries, rubber and chitosan are both industrial waste products for which much-needed recycling technologies may be encouraged by higher value applications. We have used largely untreated rubber and chitosan as it is available from large-quantity manufacturers to demonstrate that this type of technology can be made available not only to the developed world where stormwater is increasingly of concern, but also to developing nations and areas recovering from disaster. Cleanliness of water is of primary concern in such areas, and it is our hope that because both chitosan and rubber are easily available and because the processing techniques described below are simple and inexpensive this type of technology may find use in such areas where water quality and pollution are of more critical concern.

2. Materials and methods

We have prepared a variety of candidate permeable paving materials by mixing crumb rubber and weakly acidic aqueous chitosan solutions, using various solution concentrations and ratios of solution to rubber. A subset of these samples were exposed to sodium tripolyphosphate solution to achieve chemical crosslinking (but without the toxic consequences of typical crosslinkers such as glutaraldehyde), as some form of crosslinking of chitosan is necessary to prevent dissolution should

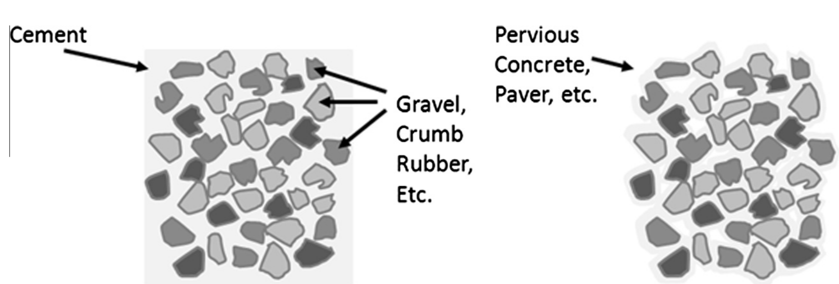

Fig. 1. Schematic representation of cement-based permeable pavement, which differs from conventional concrete (left) in that the cement content is reduced, leaving a continuous network of pores between aggregate materials (right).