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A bio-wicking system to dehydrate road embankment

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ABSTRACT

Water within pavement layers is a major cause of pavement deteriorations. A small moisture content increment will result in significant reduction in both base course and subgrade resilient behavior and increment in permanent deformation. Conventional drainage systems can drain gravitational water, but not capillary water. An economically feasible, energy saving, and environmentally friendly alternative is required to deal with the excess water induced distresses. Both lab and field tests have proven the effectiveness of a newly developed geotextile with wicking fibers in dealing with such problems as frost heave, thaw weakening, and moisture content induced differential settlement. However, the geotextile is exposed to the open air at the road slope in the original design, raising several potential application concerns, such as ultraviolet degradation, mechanical failure, malfunction due to high suction in the air, and clogging issues.

This paper aims at studying the possibility of using a bio-wicking system to address the potential concerns and further reduce the moisture content of base course material for the long run. Two types of tests, elemental-level and full-scale tests, were performed to evaluate the moisture migration in a typical aggregate with 14.5% of fines. Test results indicated that the bio-wicking system successfully addresses the concerns in the original design and is a more effective drainage system to dehydrate a base course compared with the original design.

1. Introduction

Water within pavement layers is a major cause of pavement deteriorations (Cedergren, 1994). A recent NCHRP (National Cooperative Highway Research Program) study estimated that excess water reduced the life expectancy of pavement systems by more than half (Christopher and McGuffey, 1997). Government transportation engineers in cold regions have credited a minimum of half of road maintenance expenditures to the effects of freezing and thawing (Henry and Holtz, 2001). When a road is built, both the base course and subgrade are compacted at their optimum moisture contents to achieve the best performance. After construction, aggregates inside the pavement structure tend to reach equilibrium with the ambient environment. The surface aggregate can be quickly air dried since the suction (negative pore water pressure) in the air can be as high as 14 MPa (Fredlund and Rahardjo, 1993). Under such a high suction level, the hydraulic conductivity for the surface aggregate will be very small (nearly impermeable) under unsaturated conditions (Brooks and Corey, 1964) and the water exchange between the aggregates and the ambient environment will be impeded. On the other hand, the moisture content within the pavement structure will gradually increase due to capillary action, precipitation infiltration, and water condensation. Numerous studies (Barksdale, 1972; Haynes and Yoder, 1963; Li et al., 2011) have indicated that the pavement performance can be significantly influenced by a small increment in the moisture content. Conventional drainage systems rely on gravity to drain water out of pavement systems (AASHTO, 1993; ARA, 2004; Henry and Stormont, 2002), which cannot drain capillary water or prevent the above scenarios from happening. Beskow (1991) found that conventional drainage systems are not wholly effective at reducing water-related problems in partially saturated soils. However, a pavement is under unsaturated conditions during most of the time in its service life. Consequently, no matter how well the road is constructed, it will inevitably experience distresses with time due to the increasing moisture content.

Even though numerous techniques have been developed to mitigate pavement damages caused by excess water, current engineering practices indicate that improvements are still expected in a more cost-effective way. In general, the state-of-practice can be

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divided into three categories: edge drain, open-graded base courses (permeable base), and the use of geotextiles for drainage purposes (Ariza and Birgisson, 2002). Pavement edge drains are designed to collect and remove water within and under the pavement structure (Ridgeway, 1982). Edge drains must have the necessary hydraulic capacity to handle the discharged water without getting clogged. Therefore, the applications of edge drains are limited to relatively clean base materials (FHWA, 1994). Another treatment is to use open-graded base course (OGBC) in the pavement structure (Fassman and Blackbourn, 2010; Lin et al., 2014). The high permeability of the OGBC allows water to freely flow to the road edge. However, not all places can find such good construction materials and the cost of producing and/or hauling may be unaffordable. Firstly, OGBC are mainly composed of crushed stone with limited fines (FHWA, 1994). The manufacturing of OGBC requires a large amount of energy during the excavation, screening, and sizing processes. According to the DOE (Department of Energy) (DOE, 2002), 33,775 kJ of energy are required to mine and process one ton of aggregate. This is not an environmentally friendly and sustainable way of producing large quantity of construction materials and the price for OGBC is more expensive than conventional base course. Schmitt et al. (2010) reported that the initial construction cost of asphalt-treated OGBC was 27% higher than that for dense-graded base course (without OGBC). Secondly, such a high-quality material is not available near all construction sites and the cost for hauling may be not affordable. For example, the geological survey of the greater Fairbanks Area, Alaska (Mulligan, 2004) indicated that most of the landscape is covered with finer sediments and organic material of varying thickness for about 2 m, and permafrost covers one-third to one-half of the survey area (1043 km^2). Even though the specification (Jeffers, 2017) requires the fine content (soil particles passing No. 200 sieve (sieve opening of 0.075 mm)) for D-1 base course to be lower than 6%, it is not economically feasible to get such material within a reachable distance considering the large quantity required. Therefore, OGBC is a neither environmentally friendly nor universally reachable construction material. In addition, geotextiles and geocomposites are also frequently used as capillary barriers (Doré and Zubeck, 2009) to prevent water from rising to the base course. Although the geotextiles and geocomposites impede the capillary water intrusion, they also result in excess water accumulation near the barrier. Numerous researchers have reported that capillary barriers will lead to an increase in water content of the overlying soil (Clough and French, 1982; Richardson, 1997; Zornberg et al., 2010). In summary, none of the treatments can effectively solve the problem. Improvements are still expected to reduce or eliminate the impact of moisture accumulation in a more effective, energy saving, environmentally friendly, and sustainable way.

A newly developed geotextile with wicking fibers (hereafter will be denoted as the “wicking fabric”) has the capability to solve this issue. The geotextile is a dual functional product: the high modulus polypropylene yarns (black) for reinforcement purpose and the special hydrophilic and hygroscopic wicking fibers (white) for drainage purpose, as shown in Fig. 1a. The key to this type of specially designed fiber material is its high wettability (to maintain saturation under unsaturated conditions) and high unsaturated hydraulic conductivity (to laterally transport water). The cross section has a high shape factor and great numbers of channels per fiber (specific area is 3650 cm^2/g) (Tencate, 2015), which gives the wicking fabric great potential for maximizing capillary action and water transport under unsaturated conditions. Most importantly, it can maintain saturation under low relative humidity (RH) conditions. The original drainage design is also presented in Fig. 1a. By installing a layer of the wicking fabric horizontally, both gravitational and capillary water in the pavement structure can be absorbed from the base course, transported along the wicking fabric to the shoulder, and eventually vaporized into the surrounding atmosphere. In this way, the wicking fabric serves as a “pipe” and the atmosphere serves as a “natural pump”, which can work 24 h a day and 365 days a year to dehydrate the roadway. When the water is removed and the base course is kept relatively dry, the pavement performance will be significantly improved. By doing so, one can use low-quality materials to achieve the same performance, or use the same materials to achieve a better performance. This design has the potential to become an economically feasible, environmentally friendly, and sustainable alternative to deal with excess water induced pavement deteriorations. Moreover, this concept has been validated by several field applications (Azevedo and Zornberg, 2013; Delgado, 2015; Lin et al., 2017; Zhang and Belmont, 2011). For example, the wicking fabric has been used to prevent frost heave and subsequent thaw weakening issues at the Dalton Highway Beaver Slide, Alaska (Zhang and Presler, 2012). After 7.5 years of field observation, the wicking fabric has successfully eliminated the frost heave issue. In addition, the applications of the wicking fabric also extended to the treatment of differential settlement in expansive subgrades (Delgado, 2015). The monitored results indicated that the wicking fabric was effective in uniformly distributing moisture of the pavement subgrade.

However, the original design (Fig. 1a) may have some potential concerns. In the original design, the wicking fabric was exposed at the roadside so that water can be vaporized to the ambient environment. This design may cause issues when considering the long-term performance of the wicking fabric during the pavement's service life (usually 20–30 years). Such potential concerns are: (1) the wicking fabric may degrade over time due to sunlight exposure; (2) routine grass mowing maintenance may cause mechanical damage to the wicking fabric; (3) the wicking fabric may lose function under high suction conditions due to air intrusion into the drainage channels; and (4) clogging and salt concentration may influence the drainage efficiency of the wicking fabric.

This paper aims at further improving the original design by investigating the possibility of a bio-wicking system to address the above concerns. The proposed drainage design of the bio-wicking system is shown in Fig. 1b. The wicking fabric is buried at a certain depth below the topsoil at the road shoulder. The road shoulder is then hydroseeded to establish vegetation so that evapotranspiration will occur at the grass leaves, instead of directly evaporating from the wicking fabric. The vegetation works as a “pump” to vaporize the water while the wicking fabric serves as a pipe that maintains saturation under unsaturated conditions. By doing so, the wicking fabric will not become overly dried since vegetation wilts at a suction of 1500 kPa (Kramer and Boyer, 1995). This bio-wicking system also maintains the benefits of wicking fabric while simplifying maintenance. By adding a layer of vegetation protection, the wicking fabric will be protected from direct UV (Ultraviolet) deterioration and mechanical failure. The objectives of this paper are to (1) compare the drainage efficiency of the original design and the proposed bio-wicking system; (2) evaluate the long-term performance of the bio-wicking system; and (3) explore the working mechanism of the bio-wicking system.

2. Test materials and test methodologies

Two types of tests were performed to evaluate the short-term and the long-term drainage efficiency of the bio-wicking system. The elemental level test lasted for 19 days and aimed at comparing the drainage efficiency of the conventional drainage system (no wicking fabric and no vegetation), the original design (with wicking