Polymer Testing 54 (2016) 67–77

Contents lists available at ScienceDirect

Polymer Testing

journal homepage: www.elsevier.com/locate/polytest

Material behaviour

Nanomechanical properties of polymeric fibres used in geosynthetics

J. Norambuena-Contreras [a], I. Gonzalez-Torre [a,*], J.F. Vivanco [b], W. Gacitúa [c]

[a] LabMat-UBB, Department of Civil and Environmental Engineering, University of Bío-Bío, Concepción, Chile
[b] Facultad de Ingeniería y Ciencias, Universidad Adolfo Ibáñez, Viña del Mar, Chile
[c] Departamento de Ingeniería en Maderas, Universidad del Bío-Bío, Concepción, Chile

ARTICLE INFO

Article history:
Received 18 May 2016
Accepted 28 June 2016
Available online 29 June 2016

Keywords:
Polymeric fibres
Geosynthetics
Nanomechanical properties
Nanoindentation
Damage evaluation

ABSTRACT

Geosynthetics are composite materials manufactured using different types of polymeric fibres, usually employed as anti-reflective cracking systems in asphalt pavements. Materials that compose geosynthetics can be damaged due to mechanical and thermal effects produced during the installation process under hot mix asphalts. In this paper, different polymeric fibres extracted from geosynthetics have been evaluated using nanoindentation tests. The main objective was to evaluate the effect of installation process (dynamic compaction and thermal damage) on the mechanical behaviour of individual polymeric fibres at nano-scale. To do this, elastic modulus (E) and hardness (H) of three different polymeric fibres commonly used in geosynthetics (polypropylene, polyester and polyvinyl-alcohol), in two testing directions and under two different states have been studied. Main conclusions of this work are that mechanical properties of geosynthetics individual fibres can change after installation, producing changes in the behaviour of geosynthetics at macro-scale with consequences in the pavement functionality, and that these changes are different depending on the material that composed the fibres.

1. Introduction

Geosynthetics are composite materials manufactured using different types of synthetic fibres (e.g. polypropylene, polyester, polyvinyl-alcohol, etc.). One of the main applications of synthetic fibres in civil engineering is to reinforce asphalt pavements, whether in a randomly inclusion form or as oriented fibres like geosynthetics [1]. Geosynthetics used as anti-reflective cracking systems are usually placed on cracked pavements before the spread and compaction process of a Hot Mix Asphalt (HMA) overlay layer [2]. Thus, materials that compose geosynthetics can be damaged during the installation process of HMAs due to two reasons: (1) mechanical effect produced by the extension and compaction of the asphalt mixture and (2) thermal effect due to high temperatures of the mixture (about 150 °C). During recent years, some studies have been carried out with the aim of evaluating behaviour variations produced in geosynthetics due to installation ([3–7]) or due to contact with bituminous products ([8–11]). From these studies, it was concluded that mechanical behaviour of geosynthetics was modified after installing under HMAs or by contacting bituminous products, mainly due to damage. Although, those studies were all carried out at macro and micro scales, it is still not clear what variables have more influence on the deterioration of geosynthetics and on the reduction of their several mechanical properties [7].

Recently, the utilization of the nanoindentation technique has increased for the design and evaluation of mechanical properties of engineering materials, including polymers and polymer-composites ([12–15]). Moreover, several researches have used this technique to study variations in the behaviour of materials after aggressive processes ([16,17]). The main advantages of nanoindentation are its excellent sensitivity and ability to obtain mechanical properties from a small local deformation, which is extremely valuable for systems that are only available with limited dimensions, such as individual fibres of geosynthetics [15]. This technique consists of driving a rigid indenter tip with a well-described geometry into a material's surface while high-resolution load and displacement data are simultaneously recorded. Nanoindentation tests include a loading-hold-unloading cycle characterized by a load-displacement curve. Elastic contact considerations are usually adopted to analyse load-displacement curves, so material properties such as elastic modulus (E) and hardness (H) can be calculated assuming linear elastic behaviour at the onset of unloading [18]. Despite the advantages, direct measurements of nano-mechanical properties of polymeric fibres

* Corresponding author.
E-mail address: irene.gonzaleztorre@gmail.com (I. Gonzalez-Torre).

http://dx.doi.org/10.1016/j.polymertesting.2016.06.024
0142-9418/

extracted from geosynthetics used as anti-reflective cracking systems have not been found in the literature.

For all these reasons, the main objective of the current work is to study the effect of damage at nano-structural level produced on three different polymeric fibres from geosynthetics (polypropylene, polyester and polyvinyl-alcohol) commonly used as reinforcement in asphalt pavement designs. With this purpose, nanoindentation tests have been carried out in order to characterize mechanical behaviour of individual fibres that compose geosynthetics before and after induced damage. These data are important to understand the underlying properties of a class of widely used polymeric fibres in asphalt pavements. In addition, these data can be further used as input parameters into various computational techniques such as Finite Element Analysis (FEA) commonly used in structural design.

2. Materials and methods

2.1. Description of geosynthetics and polymeric fibres

Three different geosynthetics commonly used as anti-reflective cracking systems in asphalt pavements were used in this study. They were made of different polymers and can be described as: a polypropylene non-woven geotextile (G1), a polyester geogrid with bituminous coating bonded to a polypropylene non-woven light geotextile (G2) and a polyvinyl-alcohol geogrid with bituminous coating bonded to a polypropylene non-woven light geotextile (G3). Table 1 presents their main physical and thermal properties. Moreover, Fig. 1 shows a theoretical scheme of their morphological structure. Individual fibres were extracted from the structural elements of the geosynthetics. Hence, polypropylene fibres were extracted from geotextile G1 (see Fig. 1(a)), and polyester and polyvinyl-alcohol fibres were extracted from the resistant fibres strings of G2 and G3, respectively (see Fig. 1(b)). The main characteristics of the studied fibres along with their theoretical elastic modulus and Poisson's ratio are shown in Table 2.

2.2. Installation damage procedure

With the aim of simulating the effect produced on geosynthetics by their installation under HMA, they were submitted to a combined thermal and mechanical damage based on damage procedure developed by Gonzalez-Torre et al. [3]. Geosynthetics were placed between two layers of semi dense HMA, with the aim of simulating the real installation process. To do this, geosynthetics were placed on an HMA layer using an asphalt emulsion as tack coat. The semi dense HMA used was type IV-A-12, according to Chilean specifications [19]. The asphalt mixture had a density of 2.357 g/cm^3 and air void content of 5.5%. Asphalt emulsion type CRS-2 according to Chilean specifications [20] was used (see amount of emulsion in Table 1). The damage procedure consisted of the dynamic compaction of a 40 mm deep prismatic semi dense HMA layer at 150 °C on the geosynthetics by using an asphalt slab roller compactor, according to EN 12697–33:2003 + A1:2007 [21], reaching 98% of the Marshall density. In this context, dynamic compaction of HMA simulates both the mechanical part of damage and the high temperature at which HMA is compacted (150 °C). After that, in order to extract the geosynthetic from inside the asphalt mixture, asphalt specimens were heated at a temperature of 110 °C for 2 h. According to the geosynthetic's maximum working temperature provided by the manufacturers (see Table 1), 110 °C should not produce any further damage. Therefore, the two HMA layers were easily separated and the geosynthetic extracted without applying high force. Finally, individual fibres were manually extracted from the damaged geosynthetics without applying any treatment.

2.3. Test specimens preparation

The extracted fibres were embedded in epoxy resin with the aim of giving them good mechanical support and alignment for testing, as shown in Fig. 2. Fibres were oriented in two different directions in the specimens, cross and longitudinal, with the purpose of analysing the possible anisotropy. Thus, nanoindentation tests were carried out in cross and longitudinal directions, as shown in Fig. 2(a) and (b), respectively.

After preparing the specimens, they were cut to ensure that oriented fibres were visible in the indentation surface (see cut plane in Fig. 2). Then, the indentation surface was improved with a rotary microtome (Leica RM2265) by conducting thin cuts with a thickness of 500 nm using a glass knife followed by a diamond knife. This was done with the purpose of obtaining flat and uniform surfaces which ensure high quality of the nano-mechanical analysis. Finally, a total of 12 samples per group were used for nanoindentation testing.

2.4. Morphological and thermal characterization of polymeric fibres

Surface aspects of the polymeric fibres obtained from geosynthetics were studied by using an optical microscope (Leica EZ4-HD) and a scanning electron microscope (JEOL JSM-6610/LV). Fibres were examined before and after the damage procedure with the aim of visually quantifying the damage produced. Additionally, thermal behaviour characterization of the fibres was conducted by thermo-gravimetrical analysis (TGA) by using a TGA equipment Q50 V20.10 Build 36. Tests were performed operating at a heating rate of 20 °C/min under nitrogen atmosphere, and TGA profiles were recorded in a temperature range of 0–600 °C. The weight of the sample used in each test was about 5–10 mg in all cases.

2.5. Nanomechanical characterization of fibres

A Hysitron TI900 Triboindenter (Hysitron Inc., Eden Prairie, MN, USA) equipped with a diamond Berkovich probe was used to perform the indentation tests. The indentation area was located in the centre of each fibre and identified using the instrument's optical microscope (see Fig. 3(a)). In-situ images were obtained with the Berkovich probe acting as a Scanning Probe Microscope (SPM) by raster scanning the probe across the sample surface before and immediately after each indentation test (see indentation footprints in Fig. 3(b)). A series of 16 partial unload indentation tests, with locations selected using in-situ SPM imaging, were performed in load-controlled feedback mode on each sample. All tests were

Table 1
Physical and thermal properties of geosynthetics.

Geosynthetic	Unit weight (kg/m^2)	Grid size (mm × mm)	Thickness (mm)	Working maximum temperature (°C)	Residual bitumen content (kg/m^2)
G1	140	n/a	1.2	165	1.10
G2	270	40 × 40	1.9	190	0.35
G3	160	40 × 40	1.5	190	0.35

n/a: not applicable.