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Physical and mechanical behaviour of a fibre-reinforced rubber membrane with self-healing purposes via microwave heating

J. Norambuena-Contreras [a,b,*], V. Gutierrez Aguilar [a], I. Gonzalez-Torre [a]

[a] Department of Civil and Environmental Engineering, University of Bío-Bío, 4081112 Concepción, Chile
[b] Centro de Investigación de Polímeros Avanzados (CIPA), Beltrán Mathieu 224, piso 2, Concepción, Chile

HIGHLIGHTS

- Fibres distribution and mechanical behaviour of membrane were analysed.
- Influence of different environmental conditions on membrane was evaluated.
- Steel wool fibres presented a good distribution into the rubber-based membrane.
- Because mixing process long fibres used may produce clusters in the membranes.
- Fibres do not contribute to improve the mechanical behaviour of the membranes.

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ABSTRACT

Recycled rubber powder from shredded End of Life Tyres (ELTs) has been used for the development of a new elastomeric membrane with self-healing purposes via microwave heating. Nevertheless, due to the environmental exposure of this rubber-based material, the environmental conditions may contribute to premature deterioration of membranes, reducing their mechanical strength and durability over time. To improve it, steel wool fibres can be incorporated in the rubber-based matrix. Metallic fibres in composite materials are known for enhancing its strength and fatigue characteristics while increasing ductility. These fibres can also be used for self-healing purposes via heating process. Hence, the addition of fibres may influence the properties of the new membrane, although it is not clear how this influence works. For these reasons, fibres distribution and mechanical behaviour of fibre-reinforced rubber membrane under the influence of different environmental conditions have been studied. With these purposes, four different membranes, with the same rubber powder gradation, but with four different percentages of steel wool fibres, have been considered. In addition, the influence of fibres on preconditioned test samples under three different environmental conditions: water-saturated, cold and ageing, have been evaluated via tensile strength test. Finally, fibre distribution results showed that steel wool fibres presented a good distribution into the rubber-based membrane. However, due to the mixing process long fibres used may produce clusters in the central area of membranes, while short fibres disperse very well in the contour of the membrane. Additionally, it was found that steel wool fibres do not significantly contribute to improve the tensile mechanical properties of the membranes evaluated under different environmental conditions.

1. Introduction

The increasing number of vehicles in industrialised and developing countries generates millions of waste tyres every year. Based on current statistics, each year about 1.4 billion tyres are sold worldwide until they can be considered as End of Life Tyres (ELTs) [1]. ELTs are one of the largest and most problematic wastes, due to the volume produced and their durability on time. In the case of Chile, according to a diagnosis made in 2009 by the Clean Production Council (CPL) and the Chilean tyre Industry Chamber (CINC), around 3 million ELTs are generated per year, which amount to 42,000 tonnes of wastes [2]. So, the inadequate disposal of tyres may constitute a potential threat to human health and it can also potentially increase environmental risks. As a result, landfills are currently reducing the acceptance of tyres with the aim of minimising the health and environmental risks into tyres storage. Hence, environmental awareness has led researchers to seek alternative usage of waste tyres. By this way, waste tyres and its

* Corresponding author at: Department of Civil and Environmental Engineering, University of Bío-Bío, 4081112 Concepción, Chile.
E-mail address: jnorambuena@ubiobio.cl (J. Norambuena-Contreras).

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derivatives such as rubber powder and rigid steel metal fibres, have become natural candidates for the development of new civil engineering materials with improved properties [1–6]. For example, rubber from waste tyres has been used for a variety of civil engineering applications such as scrap tyres in road construction [3], reinforced-concrete with scrap tyre rubber [4], use of waste tyre rubber in asphalt and Portland cement concrete [5], amongst others. Additionally, recycled rubber powder in different sizes has been used in the development of new asphalt mixtures and cement-based materials, flooring for playgrounds and sports stadiums, as shock absorbing mats, paving blocks, and roofing materials [6]. However, authors have not found in literature applications of the use of rubber powder in the manufacture of new polymeric membranes with energy purposes, such as: smart membranes for walls acoustic insulation or roofs waterproofing, and reinforced-membranes with self-healing properties. In this context, polymer membranes with different objectives have been developed in engineering. For example, Polyvinylidene Fluoride (PVDF) membranes [7] have applications such as water treatment, membrane distillation, gas separation, pollutants removal, bioethanol recovery, support for preparing composite membranes, among others uses [8]. However, due to the environmental exposure of these materials, the environmental conditions may contribute to premature deterioration of membranes, reducing their mechanical strength, functionality and durability over time. Therefore, with the aim of improving the mechanical behaviour of new rubber membrane against environmental damages and prolonging their rehabilitation, steel wool fibres can be incorporated to rubber-based matrix [9]. Metallic fibres in composite materials are known for enhancing its strength and fatigue characteristics while increasing ductility [10]. Especially, when the fibres have high tensile strength relative to matrix material, they may improve the cohesive, tensile strength and fracture resistance of the composite material [11–13]. In consequence, fibre-reinforced rubber membranes may have a good resistance to ageing, moisture damage and cracking. Additionally, metallic fibres into composite materials can also be used in order to modify their thermal and electrical conductivities [14]. However, the final use of a new fibre-reinforced rubber membrane is with self-healing purposes via microwave heating [15]. Nowadays, microwave technology is considered as a promising technique to promote self-healing of new composite materials with metallic fibres [16]. This is because those metallic fibres can be used to increase the heating rates of the composite materials, according this paper, which metallic fibres can absorb more heat energy than the rubber-based matrix. Therefore, with the help of a microwave heating device, it is possible to heat the metallic fibres locally and through heat diffusion, heat the rubber powder matrix and heal the membrane cracks.

This study has been prepared in the frame of a research about the development of a new rubber-based elastomeric membrane with self-healing purposes via microwave heating. In this way, electrically conductive steel wool fibres have been incorporated in the rubber powder-based matrix. However, the addition of fibres may influence the properties of the new reinforced membrane, although it is not clear how this influence works. For these reasons, the fibres distribution and mechanical behaviour of the new fibre-reinforced rubber membrane have been studied. To reach these objectives, four different membranes with the same rubber powder gradation but with four different percentages of steel wool fibres have been studied.

2. Materials and methods

2.1. Materials

Recycled rubber powder with density of 1.189 g/cm^3 was used in this research. The rubber powder size gradation is shown in Table 1. Basically, the rubber powder was characterised in four different sizes, such as: 0.425 mm, 0.25 mm, 0.18 mm and less than 0.18 mm. Fig. 1 shows a grain size distribution of the recycled rubber powder used in this study. Additionally, steel wool fibres mechanically cut were added to the rubber based matrix, see Fig. 2. The material used in the steel wool was low-carbon steel, with density 7.180 g/cm^3. These fibres have an approximate average diameter of 0.15 mm with an average aspect ratio of 45, and initial lengths ranged from 3 to 10 mm, which means that both short and long fibres were added to the rubber powder-based matrix. Finally, 4 different percentages of fibres were used: 0%, 0.5%, 1% and 2%, by total volume of rubber powder (see Table 1). In total, 4 different types of rubber membranes were prepared: 1 reference membrane without steel wool fibres and 3 membranes with different percentages of fibres, always maintaining the same mass of rubber powder, but changing the mass of fibres added.

2.2. Test specimens preparation

Materials were manually mixed into a metallic bowl at a mixing speed of 80 rpm. Two mixture batches of rubber and steel wool fibre were prepared for each one of the 4 membranes. The amount of raw material in each mixture was added according to weight proportions shown in Table 1. Raw materials were added to the bowl in the following order: first the rubber powder, and second the fibres. Thus, all the materials were mixed during approximately 2 min. First rubber membrane batches, membrane type 1 in Table 1, with dimensions 350 × 350 × 3 mm were used to cut standard tensile samples (see Fig. 3(a)). Additionally, second rubber membrane batches, membrane type 2 in Table 1, with dimensions 170 × 190 × 10 mm were used to evaluate the fibres distribution into the membranes (see Fig. 3(b)). Both membranes were manufactured by using a pneumatic laboratory static compaction plate at a temperature of 180 °C. For this, each mix of rubber powder and fibres previously mixed was placed within a steel frame with the same dimensions of the above defined membranes. Then, the mix of rubber powder and fibres was uniformly distributed within the frame avoiding the zones with more density. And after that, mix of rubber powder and fibres uniformly distributed within the frame was located between two hot compaction plates with dimensions 600 × 600 mm. Before the compaction started, a separator plate was placed around this setup frame in order to avoid direct contact between the raw materials and the compaction hot plate. The compaction was carried out according to pressure–time function that is shown in Fig. 4. After the compaction, all membranes were removed from pneumatic laboratory compactor and were put under a prismatic mass of 45 kg during an approximate time of 1800 s, until they reached the room temperature. Thus, a total of 16 membranes type 1 and 4 membranes type 2 were manufactured according to methodology described above. Moreover, an average number of 20 standard tensile samples were randomly cut from each membrane type 1 (see Fig. 3(c)), and then they were preconditioned in four different ways before tensile testing, according to the following configuration:

- Dry: Tensile test samples were conditioned in a temperature-controlled room at a temperature of 20 °C during 24 h.
- Water-saturated: Firstly, tensile test samples were vacuum-saturated. Secondly, they were submerged in a 40 °C water bath for 120 h.
- Cold: Tensile test samples were conditioned in a temperature-controlled freezer at a temperature of −30 °C during 24 h.
- Ageing: Tensile test samples were placed in an oven for 240 h at a temperature of 85 °C.

2.3. Bulk density and air voids content of the test samples

In order to evaluate the physical properties of the rubber powder-based membranes with and without steel wool fibres, bulk density and air voids content on all tensile test samples have been determined. Bulk density has been calculated as the

Table 1
Composition of the rubber powder-based membranes with steel wool fibres.

Sieve size (mm)	Rubber powder mass % retained	Cumulative rubber powder mass % retained	Membrane 1 Rubber powder mass (g)	Membrane 2 Rubber powder mass (g)
0.425	10.8	10.8	47	41
0.25	63.6	74.4	278	244
0.18	21.0	95.3	92	80
<0.18	4.7	100.0	20	18
Steel wool fibres (% vol. of rubber powder)	Length range (mm)	Average diameter (mm)	Steel wool fibre mass (g)	Steel wool fibre mass (g)
0.5% fibres	3.2–9.8 (short & long fibres)	0.157	13	12
1% fibres			26	23
2% fibres			53	46