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Fracture behaviour of a fibre reinforced earthen material under static and impact flexural loading

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HIGHLIGHTS

- We studied the effect of hemp fibres on the mechanical performance of an earthen material.
- The samples were subjected to static and impact bending.
- Hemp fibres greatly increase the fracture resistance and the energy absorption capacity.
- Both unreinforced and reinforced materials show a strong sensitivity to the rate of loading.
- The post-cracking performance is improved by increasing the fibre fraction and length.

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ABSTRACT

The study investigates the enhancements in the load carrying capacity, crack resistance and energy absorption properties provided by the addition of hemp fibres in an earthen material. Notched earthen samples reinforced with two fibre contents (2% and 3% in weight) and three fibre lengths (10, 20, and 30 mm) were manufactured and tested under static and impact bending to investigate and compare the influence of the reinforcement on the fracture resistance of the soil material at low and high strain rates. The results of the experimental analyses show that the incorporation of fibres greatly improves the peak load, the post-crack strength, the ductility and the energy dissipation of soil under both static and impact bending. The mechanical response of both unreinforced and reinforced samples is significantly affected by the rate of loading, with samples exhibiting higher values of strength and absorbed energy under impact than under static bending. For both static and impact loading, the post-crack response of the material at large deformations is clearly improved by increasing the fibre content and, at the same fibre content, by increasing the fibre length.

1. Introduction

Earth is the most widely utilised natural construction material in the world and unfired earth is by large the prevalent material used for dwelling structures in many hot, arid or temperate regions, with estimates indicating that 30–50% of the world's population live in houses made of unbaked earth-based materials [1,2]. Earth construction methods are varied, including techniques such as rammed earth, cob, wattle and daub, brick masonry, with soil or mud bricks (adobes) being probably the most common methods of earth construction worldwide [3,4].

The use of earth as a construction material is a natural solution in developing countries, since the raw materials, typically soil and sand, are abundant and locally available, and can be processed with simple technologies, without requiring expensive tools or specialised manufacturing skills. Even though the majority of earthen architecture is located in less developed countries, the past decade has witnessed a growing interest in the use of earthen building materials in industrialised countries; this renewed interest has been prompted not only by specific requirements for conservation and rehabilitation of *architectural heritage* sites [5], but also by increasing demands for more sustainable and energy-efficient materials and techniques for the building and construction industry [6]. In this respect, as compared to conventional building materials, earth-based materials provide significant reductions in environmental impact, because of the low toxicity and high recyclability properties, the minimal transportation costs

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(as a consequence of the local availability of raw materials), and the high energy efficiency and ecological compatibility of the manufacturing processes. [6,7]. As an example, it has been estimated that building a square metre of masonry with compressed earth blocks consumes about 15 times less energy than a square metre of fired bricks [8]. Similarly, a recent case study [9] revealed that the embodied energy of a three-storey rammed earth building was about one third than that of an analogous building made of conventional clay fired bricks and between one ninth and one fourth of that of a reinforced concrete framed structure building.

Further benefits of earthen building materials are related to their excellent performances in terms of heat storage capacity, thermal inertia and hygrothermal behaviour, which ensure low fluctuations in indoor air temperature and relative humidity [10]. Good acoustic attenuation and fire resistance capabilities are additional advantages of this class of materials [11].

However, there are still many challenges that have to be addressed before the potential of earth materials may be fully exploited for modern buildings in industrialised or economically developed countries. In addition to the high labour costs and the lack of standards and codes for characterisation and design, the use of earth in construction has been restricted by limitations inherent to the material, which suffers from drying shrinkage and high susceptibility to water erosion, as well as from low tensile and flexural strength, poor ductility and limited fracture resistance [2–4].

The low tensile strength and the brittle behaviour are probably the major issues for structural use of earth-based materials, particularly for buildings and constructions exposed to seismic hazard [12,13]. Vegetal or animal fibres, such as straw, flax, jute, sisal and wool [1,2,14–16], have been often used in the past to improve the mechanical and deformation properties of the soil material for specific applications. While a number of investigations have been conducted to study the effect of reinforcing fibres on the compression behaviour of earthen materials [14,17–20], fewer studies are available on the influence of fibres on the response of the materials under flexural or tensile loadings [20–33].

Bouhicha and coworkers [21] examined the flexural response of prismatic earth samples reinforced with chopped barley straw, using fibre/soil ratios up to 3.5% in weight and fibre lengths ranging between 10 and 60 mm. It was found that the flexural strength increased with fibre fraction and with fibre length, and that higher deflections were achieved at failure in reinforced specimens. The flexural response of different types of clay soils stabilised with polypropylene or wool fibres was investigated in [22–24]. The analyses indicate that the fibrous reinforcement reduces the shrinkage and improves the flexural strength of the soil samples, even though the potential benefits achievable by the addition of fibres depend on both the class of soil and the type of fibres. Similarly, significant increases in strength and deformation at failure were observed in unbaked soil samples subjected to bending loads when reinforced with sisal [25], kenaf [26,27], or banana fibres [28].

Danso and co-workers conducted splitting tensile tests to examine the tensile strength of soil blocks stabilised with different fibres and observed that the samples failed gradually, with multiple fine cracks and substantial deformation at final failure [29]. Improvements in ductility were also reported for soil–cement samples enhanced with flax [30] or sisal fibres [31].

Little attention has been up to now specifically devoted to the characterisation of the toughness and energy absorption properties of fibre reinforced earthen materials. Unnotched and notched earth blocks samples reinforced with straw fibres and subjected to three point bending were investigated in [32] to examine the resistance to crack propagation of the material with increasing crack openings. The improvements in flexural strength and post-fracture performance achievable by wool fibres in notched earthen samples were examined by the authors in a previous study [33]. It was found that the addition of fibres greatly improves the flexural strength and the energy absorption of the samples after first cracking, and that longer fibres provide better toughness and residual strength properties at large deflections.

To date, to the authors' knowledge, no studies have been conducted to investigate the effect of fibrous reinforcement on the fracture resistance and energy absorption capabilities of earth-based materials under dynamic loading conditions. The poor strength and the brittleness of soil materials make earth constructions particularly vulnerable to the high levels of seismic forces that develop during earthquakes. For this reason, accurate analyses and reliable characterisations of the contribution of the fibres to the enhancement of the fracture resistance and deformation capacity of earth-based materials under high strain rates are strongly required for safe utilisation of these materials in earthquake-prone regions. As a note of caution, it should be however pointed out that while the deformation capacity of the earthen material is critical in controlling the earthquake response of layered or rammed earth constructions, other constructive aspects, such as the quality of joints between earthen blocks and the lack of horizontal reinforcement, play a primary role in the seismic behaviour of adobe or block constructions [34].

This study investigates the improvements in strength, crack resistance, post-cracking performance and energy absorbing capability achievable under static and dynamic (impact) loading conditions by the addition of hemp fibres in an unbaked soil material. Notched samples reinforced with different fibre contents and fibre lenghts were tested in a three point bending configuration under both quasi-static and low-velocity impact loading conditions. The results obtained during the experimental analyses are illustrated and discussed in the paper to compare the mechanical response and the damage resistance of the various materials at low and high strain rates.

2. Materials and experimental methods

2.1. Materials

The soil used in this study was extracted from quaternary sediments in the area of the Tirso River, near Oristano (Sardinia, Italy). The particle-size distribution of the soil, illustrated in the graph of Fig. 1, was characterised by sieve and hydrometer analyses carried out in accordance with ASTM standard D422 [35]. The liquid and plastic limits of the soil are respectively 29% and 17%, and the soil may be classified as CL (Lean Clay), i.e. inorganic clay with low plasticity and low liquid limit, in the Unified Soil Classification System (USCS) [36]. X-ray diffraction (XRD) revealed the quartz as the dominant component, in association with other minerals such as plagioclase and illite.

Natural bast fibres collected from the phloem (or bast) of the hemp plant were selected to reinforce the soil material. Hemp fibres are cellulosic in nature and consist of bundles of elementary, single-cell, fibres bonded together by pectin [37]. Technical hemp fibres with an average diameter of 0.2 mm and an average tensile strength of 320 MPa were used in the study.

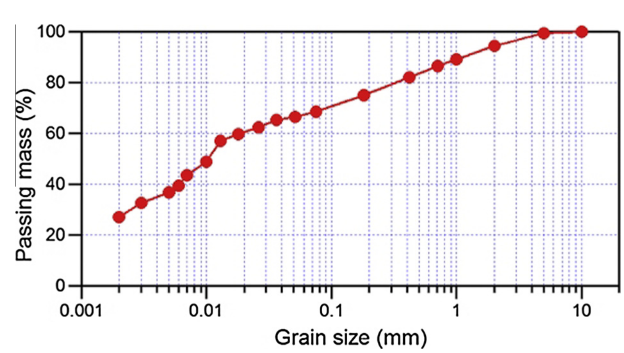

Fig. 1. Particle-size distribution of the soil.