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Date palm spikelet in mortar: Testing and modelling to reveal the mechanical performance

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HIGHLIGHTS

- Acceptable performance of modified mortars with moderate date palm spikelet content.
- Load transfer at interface is a key limiting factor for better mechanical performance.
- Finite element computation provides quantification of load transfer.
- Exact topography of spikelet is needed to proper evaluation of mechanical performance.
- Limited benefits of carbon nanotubes but prime role of spikelet chemical treatment.

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ABSTRACT

Date palm residues capabilities in civil engineering are evaluated by combining numerical and experimental approaches. Date palm spikelet originated from Elghers variety is added to mortar as a raw material or after chemical modification. Evaluation of reinforcement effect is performed using mechanical testing. Finite element modelling is considered to predict the interfacial behaviour and mechanical performance under various structural and mechanical hypotheses. Experimental results show limited effect of untreated spikelet on mortar performance for volume reinforcement of 1%. Larger contents result in severe degradation of mechanical performance compared to reference mortar. The addition of carbon nanotubes improves slightly the performance. Chemical treatment using both NaOH and CaO results in reinforced effect of spikelet. Numerical predictions show limited load transfer across the matrix/untreated spikelet interface and large interface stiffness for those formulations including small spikelet, CNT and chemical treatment.

1. Introduction

The present context of global food demand imposes new challenges for bridging environmental impact reduction and increasing agricultural activity [1,2]. Risk assessment analysis shows that agricultural activity is a threat to biodiversity [3]. Both agricultural intensification and expansion are responsible for an increasing CO_2 emission, higher pollution rate and water resource degradation [1]. Multiple scenarios are advanced to conciliate food security and environmental impact of agriculture leading to concepts such as sustainable intensification and green revolution [2,4]. Solutions leading to higher yield production, waste reduction and diet shift are in hand to achieve sustainable intensification [1,4]. In all these scenarios, recycling of agricultural residues does not come as a foreground measure [5,6]. Behind the scene, several contributors work on injecting the agricultural wastes in material engineering applications. Indirect environmental effect is sought through the development of bio-based materials to create added value for agricultural waste and compete with oil-based synthetic polymers [7,8]. Speculation on better impact for waste to energy versus waste to material depends on different criteria. From the material engineering perspective, development of eco-friendly materials needs to tip different scales such as satisfactory technological

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properties vs. variability, durability vs. degradability, green value vs. chemical modification, etc.

Many examples of scientific achievements for material valorisation of agricultural waste can be found in the literature [9–12]. Among available waste resources, date production generates significant amount of waste, which is considered for both energy and material production.

Following recent statistics provided by the Algerian government and other sources [13], Algeria is the seventh ranked country exporting dates with annual production of about 700,000 tons and more than 18 million trees covering an area of more than 150,000 ha. This agricultural activity generates 200,000 tons of waste, which can have various usages. Date palm residues, as a biomass energy resource, are investigated by several scientists [14,15]. These studies aim at relating reactivity, and thermal behaviour of these residues to their caloric value as biofuels. The use of date palm fibres in system filtration is attempted for wastewater treatment [16]. The recent literature refers to various attempts to use data palm residues as reinforcement in polymeric composites. In these applications, chemical treatment or physical grinding are associated to the design chain to obtain better interfacial adhesion and higher dispersion rate of the natural filler in the polymeric matrix [10,17,18].

In building sector, thermal insulation capabilities of different parts of the date palm are exploited to design heat insulation panels [19,20]. Abdel-Rahman reports one of the first attempts to use stalk as a reinforcement in structural concrete [21]. More recent contributions focus on durability analysis of date palm residues in cementitious materials [22]. Indeed, structural integrity of building structures, which is supposed to be guaranteed for several years, can be affected by the natural tendency of date palm residue for degradation.

Mechanical performance and durability of cementitious materials modified by the presence of date palm fibres depends on several factors such as the processing, geometry and microstructure of fibre in addition to the interfacial adhesion between the matrix and the fibre. The multiplicity of these factors requires a large number of experiments to handle each factor individually and possibly to show factor-interdependence. Numerical approaches based on finite element computation reached a high level of maturity, which makes them able to address these difficulties. It is possible now to develop finite element models that incorporate the exact microstructure of the cementitious material and perform durability analysis with the help of simple hypotheses [23].

In order to resolve the lack of predictive analysis in recent literature on the subject, this study aims at providing a combined numerical and experimental study to evaluate the mechanical performance of mortar modified by palm date spikelet. Our concern is to quantify the exact nature of the palm fibre effect: Is it a filler or reinforcement? Also, another purpose of this study is the quantification of the interfacial effect, which seems to be only qualitatively put forward without appropriate mechanical justification.

2. Experimental layout

All mortar formulations are based on the cement grade CEM II/B-M (S-LL) 32.5 R CP1 NF EN 197-1. This cement contains clinker, slag and other mineral additions. In addition, dry siliceous natural sand calibrated to 0/2 mm (norm EN 196-1) is used in the formulation of the cementitious matrix.

Palm date spikelet is used as filler to the cement in the formulation of modified mortars. It corresponds to branches, where the perianth, also called calyx or cap, connects the fruit to the spikelet. In the concerned literature, some authors refer, for simplicity, to the spikelet as stem. The spikelet is obtained from the palm variety Elghers (*Phoenix dactylifera* L.) originated from Biskra, Algeria. It should be noted that this spikelet compares fairly with the empty fruit bunches, which is a by-product of the oil palm trees from the *Palmaceae* family. In this work, date palm spikelet is cut in regular length (Ls) of either 2 or 15.8 cm (Fig. 1a). This natural filler is used as a raw material with and without chemical treatment (Table 1). The two types of chemical treatments correspond to impregnation in NaOH and CaO solutions (Fig. 2). Prior treatment, spikelet elements are washed and dried. Then, these are placed in a solution of either 10% NaOH or 10% CaO for 24 h. The spikelet elements are again washed and dried at 60 °C for 6 h. Due to the variability of the spikelet geometry, a study of its topography is conducted to quantify the dispersion of the lateral dimension and surface state. The average diameter of the spikelet cross-section is labelled Ds. Fig. 1b–c illustrate the overall arrangement of the date spikelet using optical imaging. The longitudinal view (Fig. 1b) shows a smooth epidermis outer surface of the internode. The inner part of the spikelet is partially visible, and the axial arrangement of the cell tissues is distinguishable. A close look at the transverse view (Fig. 1c) shows clear details of the fibrovascular bundles located under the outer epidermis. These bundles are themselves composed of various differentiated cell types that are not visible here.

Both 2D and 3D structural analysis are accounted based on standard optical imaging and laser scanning. 3D surface topography measurements are carried out using 3D scanner coupled with VxElements software from CREAFORME Company. Triangulation principle is used to obtain surface meshing of the spikelet with a total point number of 43769 and minimum spacing between measured points of 50 µm. Quantifiers of the spikelet geometry are extracted from image analysis using series of protocols under public domain Imagej software [24] (Fig. 1d). Among the quantities of interest, we mention the spikelet diameter, lateral and longitudinal shape factors, average roughness and maximum roughness.

Tensile testing of the date palm spikelet is conducted to reveal the reinforcement effect of the natural material (Fig. 3). Testing is performed using both texture analyser from AMTEK group and MTS 50 KN machine. More than 20 spikelet samples are tested with both apparatus. For the first equipment, a load cell capacity of 250 N is used with an accuracy of 0.5%. The maximum displacement is adjusted to 20 mm whereas the displacement rate is fixed to 0.5 mm/min. The distance between the grips is 160 mm. Spikelet fixture is ensured by means of screws to avoid sliding during loading. For the second testing apparatus, wedge tensile grips are used. The distance between the grips is adjusted to 200 mm. The same displacement rate is imposed and testing is conducted up to failure.

Several levels of reinforcement are attempted by positioning a certain number of spikelet Ns, where Ns = 2, 4 and 16. This corresponds to a volume content labelled as fs. The large spikelet elements are combined with the smallest number (Ns < 16). These are positioned at mid-height with a regular spacing in the mould (Table 1). For the remaining condition (Ns = 16), the smaller spikelet elements are randomly oriented in the mould (Table 1). The mould has a regular parallelipipedic shape (of $4 \times 4 \times 16$ cm^3).

Among the other additives to the cementitious matrix, Carbon NanoTubes (CNT) are used to increase the strength of the modified mortar. CNT is delivered by Arkema Company in the form of a liquid solution with CNT concentration of about 2 wt%. For those formulations requiring the addition of CNT, a concentration of 0.01% is included in the mixing water (Table 1).

Eleven different possibilities of formulations are studied (Table 1) including a reference mortar (without any addition) S00, modified mortar with varied number and orientation of date palm spikelet, presence or absence of CNT and spikelet chemical treatment.