Tire-Based Anti-Seismic Fibers to Increase the Ductility of Traditional Hydraulic Lime Concrete

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Keywords: Earthquake-Resistant Fibers, Traditional Lime Concrete, Tire Recycling, Rubber, Ductility

Abstract: Fibers have been widely used in construction since antiquity to reinforce raw earth or lime-based mortar. They prevent the propagation of micro-cracks and improve cohesion and shear strength. High-elasticity and plasticity fibers also enhance the material's capacity to absorb energy. The aim of this paper is to investigate the possibility of improving the seismic behavior of traditional buildings through the incorporation of fibers extracted from waste tires known for their high ductility. The objective is to recycle this non-biodegradable waste and utilize its mechanical characteristics to enhance the seismic performance of traditional buildings. Rubber fibers were incorporated at a rate of 1.5% and 3% on a comparative traditional hydraulic lime concrete. Ductility parameters are estimated from the analysis of stress-strain diagrams obtained by applying uniaxial compression tests in accordance with French standards NF P94-420, and NF P94-425. The results show a significant improvement in the traditional hydraulic lime concrete ductility after the addition of fibers made from tire waste. This method will enable the recycling of tire waste, environmental protection, and enhanced seismic performance of traditional structures. The aspects to be addressed for the development of research fields on earthquake-resistant fiber technology were also formulated.

Nomenclature

Rh	Relative humidity
T	Temperature
ε_e	Elastic limit
ε_f	Fracture strain / maximum strain at rupture
ε_u	Strain at maximum stress
ρ	Hardened density
σ_f	Stress rupture strength
σ_u	Ultimate strength
μe	Micro-Deformation ($10^{-6}\ \Delta L/L$)

Abbreviations

CRC	Crumbled Rubber Concrete
ERFT	Earthquake-Resistant Fiber Technology

NF	French Standard
ISO	International Organization for Standardization
NSAS	National School of Applied Sciences
EN	European Standard
USC	Stress-Strain Curve
UCS	Unconfined Compressive Stress

1. Introduction

One billion old tires are generated each year, only 5% of which are recycled in the sector of civil engineering, with the remainder being disposed of in landfills [1]. The energy dissipation, ductility, and damping rate of CRC concretes have been clearly improved in previous investigations on the addition of rubber crumb, while the compressive strength has decreased [2], [3]. These properties are frequently advised for structures that are vulnerable to seismic shocks, particularly for traditional structures made of geo- and bio-sourced materials, for which it is extremely challenging to increase stiffness and strength or to create conventional seismic-resistant solutions by incorporating steels.

Before it can be implemented, recycling tire waste in the traditional building industry requires rigorous technical and economic research. If we exclude efforts to improve seismic behavior using glass and carbon fiber reinforcements [4]or the technique of confining walls with wire mesh or polypropylene mesh strips [5], there aren't many viable and effective alternatives for the development of seismic solutions for traditional buildings. Faced with this reality, it would be very useful to take stock of the idea of developing earthquake-resistant fibers based on the concept of hybrid construction technology [6]capable of improving the anti-seismic behavior of traditional constructions by recycling waste materials, in particular tires.

It is proving very difficult to give traditional materials (stone or raw earth) sufficient rigidity and strength to limit deformation without reinforcement, even with stabilization by binders such as cement [6]. Studies on the stabilization of raw earth with binders have shown that there is only a small increase in strength compared to the percentage of binders added [7], so it is important to make sure that the structure has the ductility needed to absorb seismic energy through inelastic deformation and resist without collapsing. The two advantages of this method are the ecological benefit of recycling plastic and tire trash and the technological advantage of providing conventional building materials the ductility to absorb seismic vibrations.

Historical evidence clearly demonstrates how traditional structures built with masonry lime-based mortar resist earthquakes well, such as Hagia Sophia. This is because lime mortar's presence gives masonry its ductility, which enables the structure to absorb seismic energy[8]. In a similar vein, more research on the mobilization of ductility and form is required to enhance the anti-seismic performance of traditional structures.

Studies on the use of tires in concrete have concentrated on using crumb rubber-based aggregates in place of some common aggregates. In contrast, in our study we used fibrous shaped rubber incorporated into hydraulic lime concretes from Marrakech, with the aim of assessing their impact on improving the ductility of lime concrete. Rubber fibers were incorporated at a rate of 1.5% and 3% on a comparative lime concrete. The results of stress-strain diagram analysis obtained by applying uni-axial compression tests for the various specimens prepared show an increase in ductility depending on the ratio of added fibers. The term "earthquake-resistant fiber technology" will be used going forward to describe this technology.

2. Materials and experimental methods

2.1 Materials selection and characteristics

We used Marrakech hydraulic lime for this investigation, which is produced through the traditional firing of marly limestone from the Marrakech region. This process generates a high percentage of unfired marly limestone, which is combined with the silicoclastic fraction to form the aggregates of the mixture [9]. The average density of the used lime is 2,46. Particle size analysis was carried out in accordance with French standard NF P94-056 [10]for the fraction of soil greater than 80 µm, followed by a sedimentation test for fines in accordance with French Standard NF P94-057 [11] (figure 1):

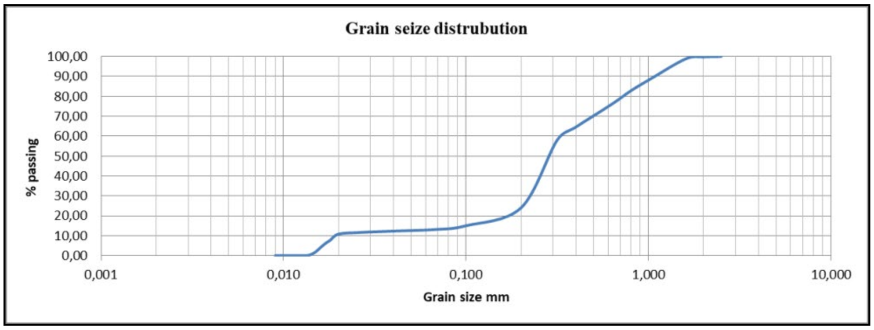

Figure 1 : Grain size distribution of the used Marrakech hydraulic lime

It is common knowledge that 24% of grains have a weighted diameter of less than 200 µm, this portion makes up the binding phase of the mixture [12]. As a result, the combination has a weight ratio of one component binder to three parts aggregate. This is the proportion historically used to formulate the hydraulic lime-based mortar used in old lime concrete constructions [13]. For our study, we will use this mix without any correction for the incorporation of other aggregates, as the main objective is to evaluate the impact of the incorporation of rubber-based fibers on the ductility and not on the strength or compactness of the mix.

Employed tires are sliced into fibrous shape in order to obtain the rubber fibers that were employed in this investigation (Figure 2). The extraction of fibers from used tires is motivated by the desire to recycle this type of waste in the construction industry, with all its attendant ecological benefits as well as for their high mechanical ductility, which can improve the seismic behavior of materials through improved damping and energy dissipation rates. The mechanical properties of the fibers (figure 2) were determined by stress-strain diagram analysis carried out on tire components in accordance with ISO 527, which describes methods for testing the tensile strength of plastics and other resinous materials.

Figure 2 : Fibers extracted from tire waste

The physical and mechanical characteristics of tire-based fibers are listed in Table 1.

Table 1 : Physical and mechanical characteristics of tire-based fibers

Parameters	Values
Density	1.342
Diameter (mm)	3 à 6
Length (cm)	3 à 5
Young's modulus (GPa)	8.561
Rupture stress σ_f (MPa)	2.06
Rupture strain ε_f (%)	69.60

A ratio of 0.3% to 0.45% is used by Imanzadeh [14]to assess the ductility of earth concrete forced by flax fibers. Studies carried out on the improvement of mechanical and technical performance through the incorporation of different types of fibers such as polypropylene, glass and Basalt fibers have adopted a ratio of between 0.20 and 2% by volume [15]. Weidong [16]used a ratio of 1.2 and 3% by weight to study the properties of asphalt mixtures modified with recycled tire rubber. For our study, we adopted a ratio of 1.5% and 3% by volume on a control mix of lime concrete from Marrakech. Following the example of studies carried out on hydraulic lime mortar, we have adopted a Water/Lime ratio equal to 0.60[15].

2.2 Test methods

2.2.1 Specimen preparation

After determining the physical properties and proportions of the materials used to formulate lime concrete, samples of fiber-reinforced lime concrete were prepared for characterization in the hardened state. The NSAS laboratory served as the location for the mixture preparation. To obtain a homogeneous mixture with evenly distributed fibers, we used a laboratory blender with a capacity of 5l. First, we mixed the Marrakech hydraulic lime with the earthquake-resistant fibers to homogenize the mixture, then we added water successively according to the predefined dosage. Samples were taken in accordance with standard EN 12350-1 [17]. Cylindrical specimens were filled in three layers, hand-tightened with a pitting bar. Each layer of concrete was subjected to 25 blows to eliminate air bubbles. Demolding was carried out after 24 h. The specimens were then numbered, dated and stored for 90 days under controlled laboratory conditions (T=22± 3 and Rh= 65% ± 5) until the day of testing, the optimum conditions for ideal carbonation [18].

2.2.2 Composite characterization tests in the hardened state

Density measurement in the hardened state was carried out in accordance with EN 12390-7 [19], It is obtained by dividing the mass of the specimens by its volume. Ductility parameters are estimated from the analysis of stress-strain diagrams obtained by applying uniaxial compression tests in accordance with French standards NF P94-420, and NF P94-425, [20], [21]on previously prepared samples. The experimental set-up includes a press with a maximum loading capacity of 110 kN and a displacement transducer with an accuracy of ±0.05 mm. The displacement speed chosen for the experiment is 0.1 mm/min[14]. The machine applies an increasing compression force centered on the specimen until it breaks. The machine is connected to a computer, which processes the results obtained in the form of reports, curves and tables (Figure 3).

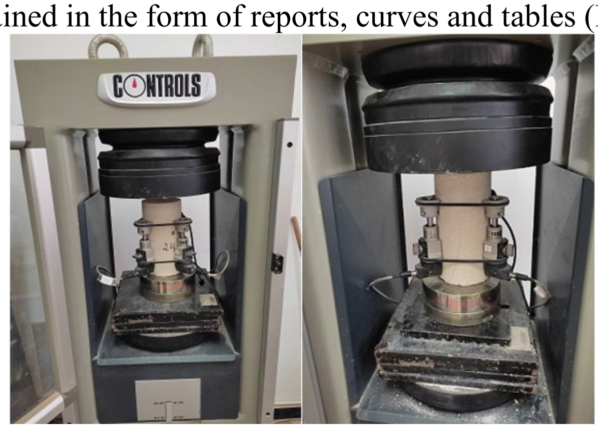

Figure 3 : Device for determining the stress-strain diagram of samples with extensometers

The concrete press allows measurement of longitudinal displacements using longitudinal strain transducers (extensometers), as shown in figure 4. The stress-strain curve is then plotted to study of the mechanical behavior of the lime concrete in question, especially in the plastic zone considered in this study.

Figure 4 : Longitudinal displacement measuring device (extensometers)

To characterize the ductility of lime concrete, from the stress-strain diagram we will determine strain at maximum stress ε_u , maximum strain at rupture ε_f . A qualitative approach is adopted to conclude on the evolution of the strain-hardening zone; the choice of this approach is justified by the difficulty of accurately determining the elastic limit strain ε_e by the obtained results for this study.

3. Results and discussion

The stress-strain diagrams of the four specimens of traditional lime concrete with 0% fiber incorporated were plotted in Figure 5, and the results were grouped together in Table 2. The stresses at rupture obtained were low, varying between 0.68 and 0.93 MPa, with an average value of 0.795 MPa. This is essentially due to the sandy nature of the aggregates, but also to the traditional procedure followed in the production of traditional hydraulic lime, which results in ineffective quality control of the final product. As a result, traditional lime concrete has to be reinforced with cement when used as mortar or concrete, a course of action that the ecological community does not advise. Hence the interest in using conventional hydraulic limes, not yet available on the Moroccan market, with a rigorous mix design. It should be noted that methods for formulating hydraulic lime concrete are not widely developed in the literature, compared with portland cement-based concrete[9]. Maximum strains obtained ranged from 681 to 1798.8 10^{-6}, with an average absolute value of 1257.35 10^{-6}. These relatively low values correspond well to the low values of stresses at fracture. It should be noted that the device used did not record deformations corresponding to stresses of less than 0.5 MPa, so we cannot draw any dismaying conclusions about the elastic characteristics of the hydraulic lime concretes used.

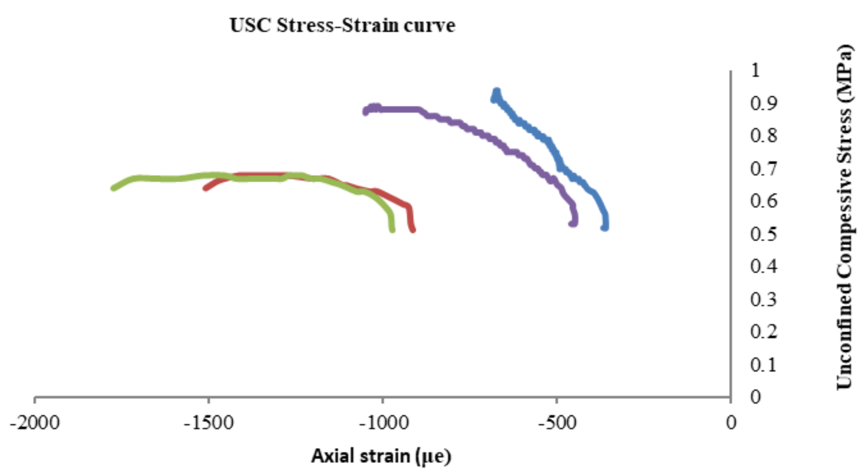

Figure 5 : Summarizing stress-strain diagrams for specimens with 0% rubber fibers

Table 2 : mechanical characteristics of the specimens with 0 % volume content of rubber fibers

	P (g/cm³)	Ultimate strenght σ_u (Mpa)	Fracture stress σ_f (MPa)	Strain at maximum stress ε_u (µe)	Ultimate strain ε_f (µe)
Spicemen 1	1.217	0.93	0.88	-671	-681
Spicemen 2	1.143	0.89	0.82	-1017	-1033
Spicemen 3	1.110	0.68	0.64	-1129.60	-1798.80
Spicemen 4	1.108	0.68	0.60	-1278.80	-1516.60
Average values	1.144	0.795	0.735	-1024.100	-1257.350

The stress-strain diagrams of the four specimens of traditional lime concrete with 1.5% fiber incorporated were plotted in Figure 6, and the results were grouped together in Table 3. The stresses at rupture obtained were low, ranging from 0.77 to 0.92 MPa, with an average value of 0.812 MPa. It can be seen that the incorporation of fibers had no significant impact on the evolution of stress at fracture, since the difference between the mean values for the two cases is of the order of 0.017 MPa. In contrast, there was a significant change in the maximum deformations obtained, with the average value between the two cases rising from 1257.35 to 2041.78 10^{-6}, confirming the basic hypothesis concerning the effect of tire-based fibers on the evolution of the ductility of the composite material as a function of the percentage of fibers added. The same observations were noted for the evolution of strain at maximum stress ε_u, which rose from 1024.1 10^{-6} in absolute value to 1635.88 10^{-6}, with a clear evolution of the necking zone in particular and the plastic zone in general of fiber-reinforced lime concrete curve.

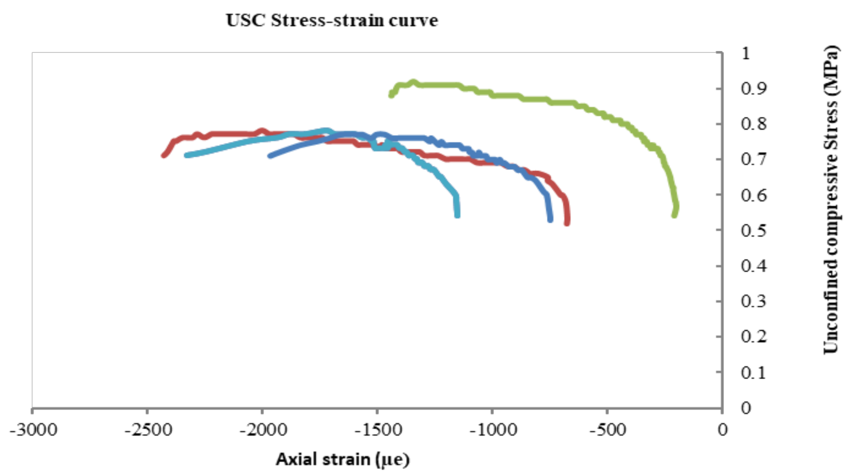

Figure 6 : Summarizing stress-strain diagrams for specimens with 1.5% rubber fibers

Table 3 : mechanical characteristics of the specimens with 1.5 % volume content of rubber fibers

	ρ (g/cm³)	Ultimate strenght σ_u (Mpa)	Fracture stress σ_f (MPa)	Strain at maximum stress ε_u(µe)	Ultimate strain ε_f (µe)
Spicemen 5	1.166	0.77	0.71	-1469	-1965
Spicemen 6	1.109	0.78	0.71	-1724.9	-2329.6
Spicemen 7	1.127	0.92	0.88	-1346.1	-1441.8
Spicemen 8	1.139	0.78	0.71	-2003.5	-2430.7
Average values	1.135	0.812	0.752	-1635.880	-2041.780

The stress-strain diagrams of the four specimens of traditional lime concrete with 3% fiber incorporated were plotted in Figure 7, and the results were summarized in Table 4. Obtained ultimate stresses were low, varying between 0.66 and 1.13 MPa with an average value of 0.82 MPa. It can be seen that the incorporation of fibers had no significant impact on the evolution of stress at fracture, since the difference between the mean values for the three cases did not exceed 0.025MPa as the maximum value. The significant difference between the maximum compressive strength of the different specimens at 3% fiber incorporation, which rose from 0.66Mpa for specimens 11 and 12 to 1.13MPa for specimen 9, can be interpreted by the effect of fiber length on their homogeneous distribution in the mix, so a low strength is a sign of poor fiber distribution in the mix that has impacted strength. In order to avoid this phenomenon, we recommend using fibers with an average length of 2 cm. With the mean value rising from 2041.78 10^{-6} for specimens at 1.5% to 4784.9 10^{-6} in absolute value for specimens at 3%, there was a clear increase in the ultimate strain values obtained as a function of the percentage of fibers incorporated, further validating the basic hypothesis regarding the impact of tire-based fibers on material ductility. Similar observations were noted for the evolution of strain at maximum stress ε_u, which rose from 1635.88 10^{-6} in absolute value to 2937.475 10^{-6}, with a clear evolution of the necking zone in particular and the plastic zone in general of the fiber-reinforced lime concrete strain-stress curve. It is clear that the values of characteristic deformations and ductility will continue to increase as the mechanical characteristics of concretes, the fibers used and their incorporation rate increase [22].

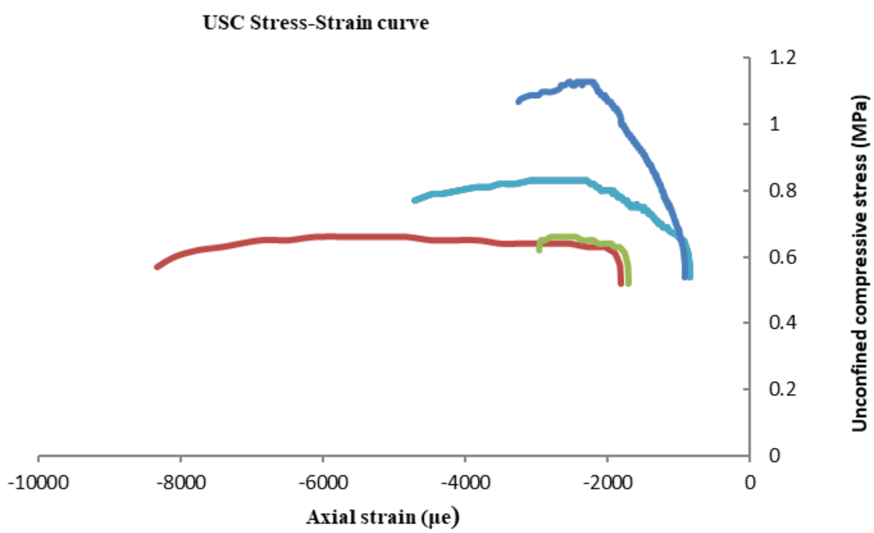

Figure 7 : Summarizing stress-strain diagrams for specimens with 3% rubber fibers

Table 4 : mechanical characteristics of the specimens with 3 % volume content of rubber fibers

	ρ (g/cm3)	Ultimate strenght σ_u (Mpa)	Fracture stress σ_f (MPa)	Strain at maximum stress ε_u(µe)	Ultimate strain ε_f (µe)
Spicemen 9	1.133	1.13	1.07	-2196.8	-3252.4
Spicemen 10	1.179	0.83	0.77	-2288.4	-4712.9
Spicemen 11	1.149	0.66	0.57	-2444	-2665
Spicemen 12	1.109	0.66	0.53	-4820.7	-8509.3
Average values	1.142	0.820	0.735	-2937.475	-4784.900

Table 5 provides an overview of the outcomes discovered. As can be seen, the density of the fiberized lime concrete was not significantly affected by the fibers' incorporation. This is essentially due to the very close values of the density of the hardened lime concrete, which is of the order of 1.144, and that of the rubber fibers used, which is of the order of 1.342. The same is true of the tensile stresses, with a very modest improvement that can be explained by the fact that the tensile strength of fibers (2.06 MPa) is higher than that of traditional lime concrete (0.735 MPa). On the positive side, the incorporation of tire-based fibers has been shown to improve the ductility of the composite material. Indeed, the average value of $\Delta_{\varepsilon_u \varepsilon_f}$ characterizing the necking zone increased from 233.255 10^{-6} for lime concrete with 0% of fibers incorporated to 1847.425 10^{-6} for 3% of fibers incorporated. A qualitative analysis of the resulting curves leads to the same conclusion regarding elastic limit and strain-hardening zone, confirming the hypothesis that the addition of tire-based fibers improves ductility. The same hypothesis has been supported by earlier research on the recycling of tire crumbs into cement with a significant reduction in compression resistance [23]. This is due to the significant difference between the mechanical characteristics of cement-based concrete and rubber.

Table 5 : Summary table of obtained results with different rates of rubber fibers incorporation by volume

	ρ (g/cm3)	**Ultimate strenght σ_u (Mpa)**	**Fracture stress σ_f (MPa)**	**Strain at maximum stress ε_u(µe)**	**Ultimate strain ε_f (µe)**	**Necking Zone $\Delta_{\varepsilon_u \varepsilon_f}$**
0% rubber fibers	1.144	0.795	0.735	-1024.1	-1257.35	233.250
1.5%rubber fibers	1.135	0.8125	0.7525	-1635.88	-2041.78	405.900
3% rubber fibers	1.142	0.820	0.735	-2937.475	-4784.900	1847.425

While biobased fibers have the same advantage of increasing the ductility of traditional lime- or earth-based concretes [24], rubber-based fibers offer a number of additional advantages: they are less affected by moisture, which is an intrinsic characteristic of hygroscopic materials such as hydraulic lime concrete, even though in-depth studies are needed on the effects of lixiviation on the construction and its environment. Similarly, tire recycling reduces the environmental impact of waste and creates economic value and employment [25]. One of the techniques used for seismic reinforcement of traditional buildings is reinforcement with boundary wooden elements [26]. Even this technique can prevent the total collapse of the building and delay the onset of collapse, it just ensures limited structural continuity, not forgetting the difficulty of installation and the extra cost involved in incorporating wood. For the technique of confining walls with wire mesh or polypropylene netting strip [5], it just strengthens the wall as a whole without any effective improvement in the mechanical characteristics of strength, rigidity and ductility of the materials. With earthquake-resistant fiber technology, we can improve the mechanical characteristics of traditional concretes, especially ductility and tensile strength, and consequently improve the structure locally and globally. In addition, this technique proves more suitable for improving the anti-seismic behavior of constructions based on monolithic structure technology, a construction technique recently patented in Morocco which is based on the casting of a single structure with a well-defined shape regenerated from an arched portal frame [27].

Conclusions and recommendations

The present study analyzes the effects of fiber incorporation on improving the ductility of traditional hydraulic lime concrete. Following the example of studies carried out in the literature on the effects of fiber incorporation on ductility improvement, it has also been demonstrated in our study that the incorporation of rubber-based fibers considerably improves this property of the composite. In this study, the incorporation of tire-based fibers (at a rate of 3%) increases significantly the material's ductility. Seismic fiber technology has a number of advantages: it recycles tire waste, protects the environment and improves the seismic behavior of traditional buildings. If this technology is to be successfully implemented, a number of aspects need to be addressed in future studies on the subject, including:

- Verify the outcomes of the full-scale vibration table test.
- Expand research on tire-based fibers in order to comprehend the impact of forms and dimensions on the development of the mechanical properties of lime concretes made from tire fibers.
- Extend studies on earthquake-resistant fibers to other forms of traditional materials such as rammed earth, widely used in Morocco.
- Develop multi-scale numerical models capable of accurately simulating the behavior of earthquake-resistant fiber-based concretes.
- Produce standards relating specifically to seismic-resistant fiber technology in traditional construction.

Consent For Publication

Not applicable

Funding

None

Conflict of Interest

The authors declare no conflict of interest, financial or otherwise.

Acknowledgements

The authors would like to thank the universities for allowing to conduct this research.

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