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The influence of date palm mesh fibre reinforcement on flexural and fracture behaviour of a cement-based mortar

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ABSTRACT

The aim of the present paper is to investigate both flexural and fracture properties of a cement-based mortar reinforced with Date Palm Mesh (DPM) fibres. In particular, three-point bending tests on DPM fibre-reinforced specimens (with different fibre volume fractions) are performed. On the basis of the experimental results, the value of flexural strength is computed as a function of the peak load according to the UNI Recommendations, whereas the value of fracture toughness is analytically determined according to the

Modified Two-Parameter Model (MTPM) recently proposed by some of the present authors for quasi-brittle materials.

KEYWORDS: cement-based mortar; date palm mesh fibres; flexural strength; fracture toughness; Modified Two-Parameter Model.

NOMENCLATURE

a_0	notch length
B	specimen width
C_i	initial linear elastic compliance
C_u	unloading linear elastic compliance
E	elastic modulus
$K^S_{(I+II)C}$	critical mixed mode stress-intensity factor
L	specimen length
n	Date Palm Mesh fibre percentage
P_f	peak load related to load – deflection curve
$P_{\max}$	peak load related to load – CMOD curve
R_f	flexural strength
S	support span
W	specimen depth

ACRONYMS

CMOD	Crack Mouth Opening Displacement
DPM	Date Palm Mesh
MTPM	Modified Two-Parameter Model
SIF	Stress-Intensity Factor
TPM	Two-Parameter Model

1. INTRODUCTION

During last years, natural fibres (such as flax, jute, sisal, coir and bamboo fibres) have been extensively used as suitable reinforcement in cement-based composites **[1,2]**. As a matter of fact, the desirable characteristics of such fibres, represented by low environmental impact, biodegradability, low cost, low density, and good mechanical properties **[1,3,4]**, have led many researchers to analyse vegetable fibres as an alternative to conventional reinforcements, such as steel and polymeric fibres commonly employed in engineering applications **[5-7]**.

Although some building materials, such as clay bricks, have already been reinforced with vegetable fibres since ancient times, these fibres have systematically been used only for about 50 years, as potential substitutes for asbestos fibres in cement production **[1]**. Since then, natural fibres have increasingly been used as reinforcement of cement-based composites in non-structural civil applications, such as thin-sheet products for partitions, building envelopes, roofing tiles and pre-manufactured components.

Examination of the state of the art clearly shows that a significant effort has been made by the Scientific Community in order to assess the physical-chemical and mechanical properties of natural fibre reinforcements (see reviews in Refs **[8-10]**). Thanks to this large body of work, nowadays it is possible to assert that vegetable fibre reinforcements allow us to reduce both the plastic shrinkage **[11]** and the thermal conductivity **[12]**, and to improve the acoustic performance by increasing the sound absorption **[13]**. Moreover, such reinforcements are also able to provide adequate stiffness and strength to cement-based composites due to a substantial improvement of their flexural strength, fracture toughness and impact resistance **[14-16]**.

In the present paper, both flexural and fracture properties of a cement-based mortar reinforced with short vegetable fibres are investigated. Such fibres are extracted from the Date Palm Mesh (DPM), that is, the fibrous structure surrounding the trunk of the date palm. An experimental campaign is carried out on reinforced mortar specimens, by examining five different values of fibre volume fraction (that is, 2,4,6,8 and 10% by volume). In order to analyse the fibre effect on the mechanical properties, plain mortar specimens are also tested for comparison.

The above experimental campaign consists of:

(i) three-point bending tests performed on unnotched specimens to determine the flexural strength **[17]**;

(ii) three-point bending tests performed on edge-notched specimens to determine the fracture toughness **[18-20]**.

On the basis of the experimental results, the value of flexural strength is computed as a function of the peak load according to the formulation reported in Ref. **[17]**. Moreover, the value of fracture toughness, i.e. the critical Stress-Intensity Factor (SIF), is analytically determined on the basis of the experimental load against Crack Mouth Opening Displacement (CMOD) curve, according to the modified version of the Two-Parameter Model (TPM) recently proposed by some of the present authors **[21-23]**.

2. CEMENT-BASED COMPOSITES REINFORCED WITH DATE PALM FIBRES

Among vegetable fibres, those obtained from date palm (Phoenix Dactylifera, one of the most cultivated palm around the world) have been proved to be good candidates for reinforcement of cement-based composites **[24-27]**.

The date palm tree is composed by: (a) a long trunk; (b) a mesh, surrounding the trunk; (c) leaves; (d) reproductive organs; (e) fruit bunches (**Figure 1**). The mesh is characterised by a fibrous structure, which creates a natural woven mat of crossed fibres of different diameters, and is considered as a ligno-cellulosic material **[27]**.

Figure 1

The date palm is commonly found in North Africa, Middle East, India and USA (California). There are about 100 million date palm trees in the world, and each tree can grow for more than 100 years **[25]**.

In Algeria, there are more than 18.7 million trees, and the annual trimming operations produce enormous quantities of agricultural wastes, which are usually thrown away, except small quantities used for artisan products **[26]**.

Such wastes can represent an abundant source of low-cost raw material for industrial purposes. Therefore, the development of cement-based composites reinforced with this agricultural material represents an excellent solution for efficient utilization of such wastes as a renewable resource.

Some attempts to valorise Date Palm Mesh (DPM) fibres as reinforcements in cement-based composites are available in the literature **[24-27]**. For instance, Kriker et al. **[24]** examined four types of DPM fibres aiming to determine their mechanical and physical properties. More precisely, the performance of such fibres (with length equal to 15–60mm) was analysed by including them in a cement-based concrete with fibre content equal to 2-3% by volume. It was observed that, by increasing both the fibre length and the percentage, post-cracking flexural strength and toughness coefficients were improved, whereas an opposite trend was observed for both first cracking resistance and compressive strength **[24]**.

The effect of DPM fibres on the properties at both early stage and hardened stage of self-compacting concrete in hot-dry conditions has been investigated by Tioua and co-workers **[27]**. In particular, the addition of a low fraction of DPM fibres to hot-dry cured specimens was found to be effective in reducing both the early stage shrinkage and the cracking risk. Conversely, a low inclusion of DPM fibres did not significantly modify the concrete performance in the hardened state, that is, neither mechanical nor physical properties of concrete.

To the best knowledge of the present authors, no studies related to the fracture behaviour of cement-based composites reinforced with DPM fibres are available in the literature. Therefore, this paper deals with the fracture toughness of a cement-based mortar reinforced with short DPM fibres.

3. EXPERIMENTAL CAMPAIGN

3.1 Materials and mixture proportion

The DPM fibres used in the present study are obtained from Deglet-Noor date palms (Deglet-Noor date is one of the most appreciated variety in the world) from the oasis of Tolga (Biskra, Algeria).

After removing the leaves, the fibres are pulled out from the date palm trunk in a form of nearly rectangular sheets (**Figure 2(a)**). Then the mesh sheets are manually separated into single fibres and washed with fresh water. Finally, such fibres are dried at room temperature for one week and cut to the desired length, that is, 7-10 mm (**Figure 2(b)**).

Figure 2

Since the fibres here employed have the same geographical origin of those used in the experimental campaign performed by Kriker et al. **[24]**, it is reasonable to assume that the DPM fibres are characterised by similar physical properties (see **Table 1**).

Table 1

The cement-based mortar matrix consists of a limestone Portland cement (42.5 CEM II/A-LL type) and a silica sand with a grain size distribution determined according to the UNI EN 196-1:2005 European Recommendation **[17]**.

For the specimen casting, the mixture proportions adopted for both plain and reinforced cement-based mortar are cement:water:sand (by weight) = $1:0.55:3$. The ratio between water and cement is fixed after performing a workability test with the flow table according to the UNI EN 1015-3:2007 European Recommendation **[28]**. In particular, the content of water in the mixture shall be enough to produce a flow of about 110% by jolting the flow table 15 times in approximately 15 s.

The above mortar mix design is prepared according to UNI EN 196-1:2005 European Recommendation **[17]**, and the mortar mixture composition is listed in **Table 2**.

Table 2.

3.2 Specimen preparation and curing condition

Specimen preparation and curing condition are performed according to UNI EN 196-1:2005 European Recommendation **[17]**.

In the initial phase of specimen preparation, the DPM fibres are submerged in water at room temperature for 24 hours and then dried in air, before being added to the mixture. These operations are needed in order to avoid that fibres absorb an excessive amount of mixing water during the casting.

Subsequently, the DPM fibres are added in the cement-based mortar matrix, with a fibre content equal to $2, 4, 6, 8$ and 10% by volume (**Table 3**). This procedure is performed slowly in order to avoid the possible clumping of fibres.

Table 3.

Then a superplasticizer (named Concretan200l and produced by Ruredil), with a content of 1% of cement weight, is added to the mixture in order to achieve the desired self-compacting properties.

The fresh slurry is hence placed in moulds on a conventional vibrating table (the time of vibration is of 30 s for each mould). Each mould consists of a beam with prismatic shape, whose sizes depend on the test type being performed (further details can be found in the following Sub-Sections).

Finally, the specimens are cured in laboratory for 24 hours under normal climatic conditions (temperature equal to $21°$C and relative humidity of 50%) and, after demoulding, are submerged in water at room temperature for 28 days.

The reinforced mortar specimens are referenced by the notation RM_n, where n is the fibre percentage being examined (i.e. n = $2, 4, 6, 8$ and 10). Moreover, the plain cement-based mortar specimens are named with the notation PM in the following. Accordingly, six different types of specimens are obtained.

3.3 Test methods

Two mechanical properties (flexural strength and fracture toughness) of both plain and DPM fibre-reinforced mortar specimens are experimentally tested after 28 days of curing. In particular, the experimental campaign consists of:

(i) three-point bending tests performed on unnotched specimens, to determine the flexural strength;

(ii) three-point bending tests performed on notched specimens, to determine the fracture toughness.

All the tests are carried out by means of the universal testing machine Instron 8862, available at the "Testing Laboratory of Materials and Structures" of the University of Parma. The Instron 8862 testing system is a single electromechanical actuator machine for low speed static and quasi-dynamic cyclic testing, equipped by means of a load cell with capacity of 100 kN and accuracy up to 0.02%. Moreover, the Instron clip gauge, employed to measure the CMOD, is characterised by a maximum travel of 4 mm and an accuracy of ±0.05%.

The following Sub-Sections briefly summarise the specimen geometries and the test configurations related to the above tests.

3.3.1 Three-point bending tests on unnotched specimens: flexural strength

The three-point bending tests on unnotched specimens are carried out according to UNI EN 196-1:2005 European Recommendation **[17]**, which deals with the standard test method to evaluate compressive and flexural properties of cement-based mortar.

The tested specimens are characterised by the following geometrical sizes: width (B) × depth (W) × length (L) = $40\,\mathrm{mm}$ x $40\,\mathrm{mm}$ x $160\,\mathrm{mm}$, and support span (S) = $120\,\mathrm{mm}$ (**Figure 3(a)**).

Figure 3

The tests are performed under load control with a rate equal to $44\,\mathrm{Ns}^{-1}$ according to the ASTM C348-14 Standard **[29]**. More precisely, the applied load is measured by means of a load cell, whereas the deflection of the specimen is evaluated through the measurement of the head displacement. As is shown in **Figure 4(a)**, each specimen is monotonically loaded up to failure.

The flexural strength R_f can be computed according to the following equation (see Ref. **[17]**) and the experimental results in terms of peak load P_f (see a typical load against deflection curve in **Figure 4(a)**):

$$R_f = \frac{1.5 \cdot P_f \cdot S}{W^3} \tag{1}$$

where S and W are the support span and the specimen depth, respectively, both in mm.

Figure 4

3.3.2 Three-point bending tests on notched specimens: fracture toughness

The three-point bending tests on notched specimens are carried out according to the TPM **[18]** and the RILEM Recommendations **[19-20]**, which deal with the standard test method to evaluate fracture parameters of mortar and concrete.

The tested specimens present a notch in the lower part of the middle cross-section, and are characterised by the following geometrical sizes: specimen depth-width ratio = W/B = 2; support span-specimen depth ratio = S/W = 4; notch length-specimen depth ratio = a_0/W = $1/3$, and notch width <3.175 mm. In more detail, each specimen consists of a beam 15 mm x 30 mm x 160 mm ($B \times W \times L$) and, consequently, S = 120 mm and the notch length a_0 is equal to about 10 mm (**Figure 3(b)**).

The tests are performed under Crack Mouth Opening Displacement (CMOD) control, employing a clip gauge at an average rate equal to 0.1 mmh^{-1} (**Figure 5**). Moreover, the applied load is measured by means of a load cell.

Figure 5

As is shown in **Figure 4(b)**, each specimen is monotonically loaded. After the peak load $P_{\max}$ is achieved, the post-peak stage follows and, when the load is equal to about 95% of $P_{\max}$, the specimen is fully unloaded (up to a load value equal to about zero) by proceeding under load control. Finally, the specimen is reloaded up to failure under CMOD control with the same initial average rate.

On the basis of the experimental results in terms of peak load $P_{\max}$, initial (C_i) and unloading (C_u) linear elastic compliances (see a typical load against CMOD curve in **Figure 4(b)**), elastic modulus E, and fracture toughness $K_{(I+II)C}^{S}$ (i.e. the critical mixed mode SIF) are computed according to the equations related to the Modified Two-Parameter Model (MTPM), reported in Refs. **[21-23]**.

It should be highlighted that the modified version of the TPM is here employed instead of the original one since cracks are experimentally observed to generally grow under mixed mode (Mode I together with Mode II). As is shown in **Figure 6** for one specimen of each tested type, crack starting from the notch tip deflects (kinked crack) due to the inhomogeneities (i.e. aggregates and DPM fibres) embedded in the mortar matrix. As a matter of fact, fracture toughness would be overestimated by considering crack propagation under pure Mode I loading (that is, by using the TPM). Readers interested in the analytical formulation of the MTPM should refer to Ref. **[30]**.

Figure 6

4. RESULTS AND DISCUSSION

4.1 Flexural strength

By examining the experimental load-deflection curves obtained from the experimental campaign described in Sub-Section 3.3.1, it can be noticed that, by increasing the fibre percentage, the value of the peak load decreases (as is shown in **Figure 7** for plain mortar specimens and mortar specimens reinforced with 8% of DPM fibres). Such a behaviour may be induced by the increase of porosity with the fibre dosage, such an increase being due to inclusion of air during processing, limited wettability of fibres and low ability of fibres to compact **[31]**.

On the other hand, it can be observed that the use of DPM fibres improves the post-peak behaviour, and delays the failure of the reinforced specimens in comparison with the plain mortar specimens. Such a behaviour is mainly related to the fibre-bridging mechanism, which consists in the transmission of additional tensile stresses caused by the DPM fibres across the crack surfaces.

Figure 7

The obtained results are listed in **Table 5** for each tested specimen. In more detail, the measured values of peak load P_f and the results in terms of flexural strength R_f determined according to **Eq. (1)** are reported.

Table 5

It can be remarked that the best performance in terms of flexural strength is generally achieved for plain mortar specimens: the R_f value for PM specimens is, for instance, about two times greater than the corresponding value for RM_{10} specimens, that is, an increase of the DPM fibre content does not produce a beneficial effect on flexural strength.

As was observed by Boumhaout and co-workers **[32]**, such a result is mainly due to the addition of DPM fibres to the mortar matrix, which promote the creation of pores. Therefore, the porosity of the DPM fibre-reinforced specimens increases and, consequently, the compactness and the cohesion of the composite material are significantly reduced. Moreover, the decrease in flexural strength is also related to a poor bonding at the fibre-matrix interface **[33]**. Note that different chemical surface treatments (such as alkali and acid treatments) can be adopted in order to improve the fibre-matrix interfacial bonding **[25]**.

4.2 Fracture toughness

By examining the experimental load-CMOD curves coming from the experimental campaign described in Sub-Section 3.3.2, it can be observed that the use of DPM fibres generally improves the softening behaviour in comparison with that related to PM specimens. For instance, as far as the load–CMOD curves for both plain mortar and mortar reinforced with 8% of DPM fibres are concerned (**Figure 8**), a significant load-bearing capability increase in the post-peak behaviour can be noticed, even in the case of large values of CMOD. By increasing the DPM fibre percentage, this trend is much more pronounced due to the effectiveness of fibres.

Figure 8

The results deduced through the MTPM are listed in **Table 6** for each tested specimen. In more detail, the measured values of peak load $P_{\max}$ and the results determined for elastic modulus E and critical mixed mode SIF $K^S_{(I+II)C}$ are reported in such a Table.

Table 6

In agreement with other studies available in the literature **[14,34,35]**, the values of both elastic modulus and fracture toughness decrease with an increase of the DPM fibre content (**Table 6**). For instance, the effect of fibre content is evaluated in terms of elastic modulus E and critical mixed mode SIF $K^{S}_{(I+II)C}$ by interpolating the averaged experimental values of such parameters for the five different values of fibre content being examined (**Figure 8**). In particular, the following expressions are obtained:

$$E = -1885.7 \cdot n + 22474.4 \tag{2a}$$

$$K^{S}_{(I+II)C} = -0.05 \cdot n + 0.69 \tag{2b}$$

where n is the fibre percentage. Note that the single values related to E and $K^{S}_{(I+II)C}$ are also reported in **Figure 9**.

For DPM fibre content equal to 2% (RM_2 specimen type), the above equations estimate an E decrease $\cancel{E}$ equal to about 17% and a $K^{S}_{(I+II)C}$ decrease equal to about 14% with respect to the values related to PM specimens. This behaviour can be explained as follows:

(a) the lower elastic modulus of the vegetable fibres when compared with the matrix elastic modulus;

(b) the incorporation of air during the mixing phase, that increases with the amount of DPM fibres.

Figure 9

Note that the mortar specimens characterised by a low content of DPM fibres present fracture toughness values similar to those related to cement-based composites reinforced with traditional fibres. For instance, the averaged value of $K^{S}_{(I+II)C}$ related to RM_2 specimen type ($0.598\ \mathrm{MPa \cdot m^{1/2}}$)

is in agreement with that determined by Carpinteri et al. **[23]** for concrete specimens reinforced with 2.5% of polypropylene fibres ($0.658\ \mathrm{MPa}\cdot\mathrm{m}^{1/2}$).

In conclusions, although the increase of fibre content reduces the fracture properties of reinforced mortar with respect to those of plain mortar, the $K^{S}_{(I+II)C}$ values obtained for low concentration of fibres (that is, DPM fibre content equal to 2% by volume) are good enough, and enable the use of these material for non-structural and low-cost civil constructions.

5. CONCLUSIONS

The present paper concerns an experimental investigation on the flexural and fracture properties of a cement-based mortar reinforced with Date Palm Mesh (DPM) fibres. In particular, three-point bending tests on unnotched and notched specimens reinforced with DPM fibres have been performed, by examining five different percentages of fibre content: $2, 4, 6, 8$ and 10% by volume. Further, plain mortar specimens have also been experimentally tested for comparison.

The main conclusions of the present research work are hereafter summarised:

- An increase of the DPM fibre content does not produce a positive effect on both flexural strength and fracture toughness, since the best performance in terms of such parameters is achieved when plain mortar specimens are used. The decrease of the positive effect is mainly due to: (a) the lower mechanical properties of the fibres with respect to those of the mortar matrix; (b) the air incorporated during the mixing phase, that increases with the amount of fibres; (c) the poor bonding at the fibre-matrix interface;

- The addition of DPM fibres in mortar specimens generally improves both the post-peak behaviour and the ductility in comparison to plain specimens, and delays the failure of the composite material;
- Interesting fracture properties are obtained for low content of DPM fibres (that is, 2% by volume), being the fracture toughness value similar to that reported in the literature for concrete specimens reinforced with conventional fibres;
- On the basis of the results here presented, some chemical treatments of DPM fibres have to be adopted in future research works to improve both the mechanical properties of fibres and the fibre-matrix bonding and, hence, to increase the flexural and fracture properties of the cement-based composites reinforced with DPM fibres.

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Figure 4. Experimental results: (a) typical load against deflection curve for the tested unnotched mortar specimens; (b) typical load against Crack Mouth Opening Displacement (CMOD) curve for the tested notched specimens.

Figure 5. Experimental setup.

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Figure 7. Typical load-deflection curves for: (a) plain mortar specimens; (b) reinforced mortar specimens with DPM fibre content equal to 8% by volume.

Table 4. Peak load, P_f, and flexural strength, R_f, for each unnotched specimen being considered. The number of tested specimens for each type is reported in round brackets.

Figure 8. Typical load-CMOD curves for: (a) plain mortar specimens; (b) reinforced mortar specimens with DPM fibre content equal to 8% by volume.

Table 5. Peak load, $P_{\max}$, elastic modulus, E, and critical SIF, $K^S_{(I+II)C}$, for each notched specimen being considered. The number of tested specimens for each type is reported in round brackets.

Figure 9. DPM fibre content effect on: (a) elastic modulus, E; (b) critical SIF under mixed mode stress state, $K^S_{(I+II)C}$.

Figure 1.

(a) **(b)**

Figure 2.

Table 1.

Property	**Range**
Bulk density [kg/m^3]	512.2-1088.8
Absolute density [kg/m^3]	1300.0-1450.0
Natural moisture content [%]	9.5-10.5
Water absorption after 5 min under water [%]	60.1-84.1
Water absorption to saturation [%]	96.8-202.6

Table 2.

Material	**Dosage [kg/m^3]**
Cement 42.5	580
Water	320
Sand (0-2 mm)	1750
Superplasticizer	6

Table 3.

Mixture	**DPM fibre**	
	Volume fraction [%]	**In weight [kg/m^3]**
PM	-	-
RM_2	2	28
RM_4	4	56
RM_6	6	84
RM_8	8	112
RM_{10}	10	140

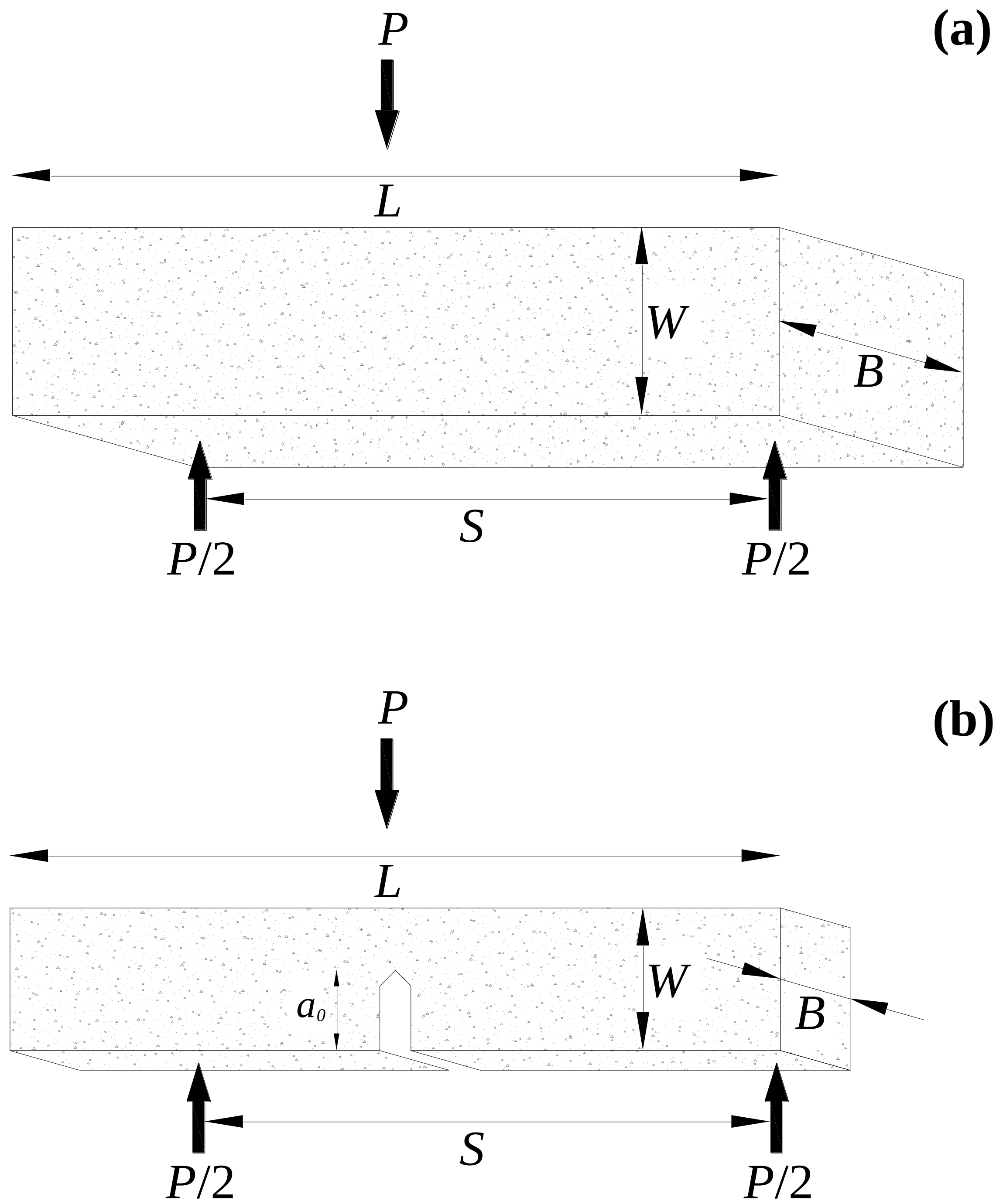
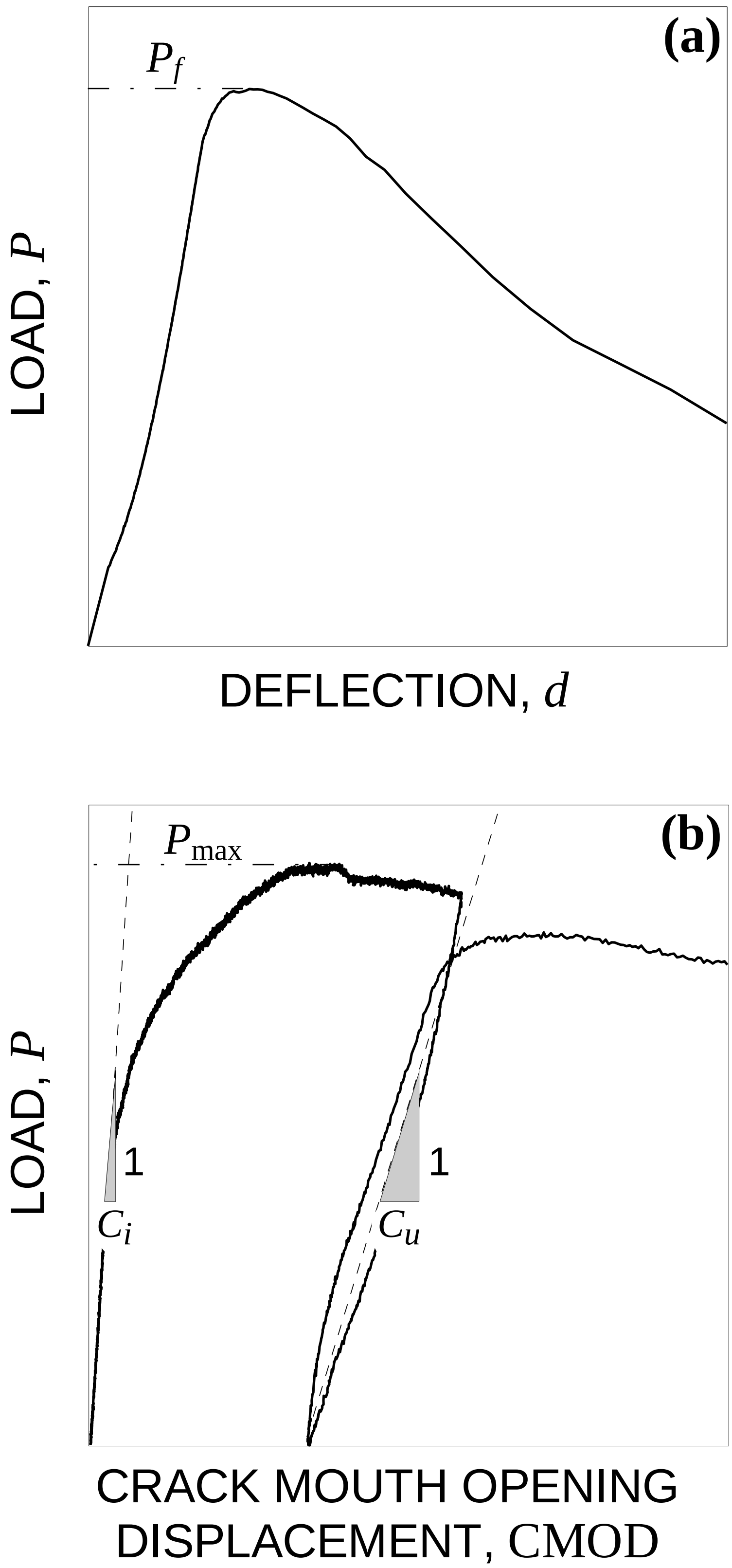


Figure 3.



(a)
P_f
LOAD, P
DEFLECTION, d
(b)
$P_{\max}$
LOAD, P
1
1
C_i
C_u
CRACK MOUTH OPENING
DISPLACEMENT, CMOD

Figure 4.

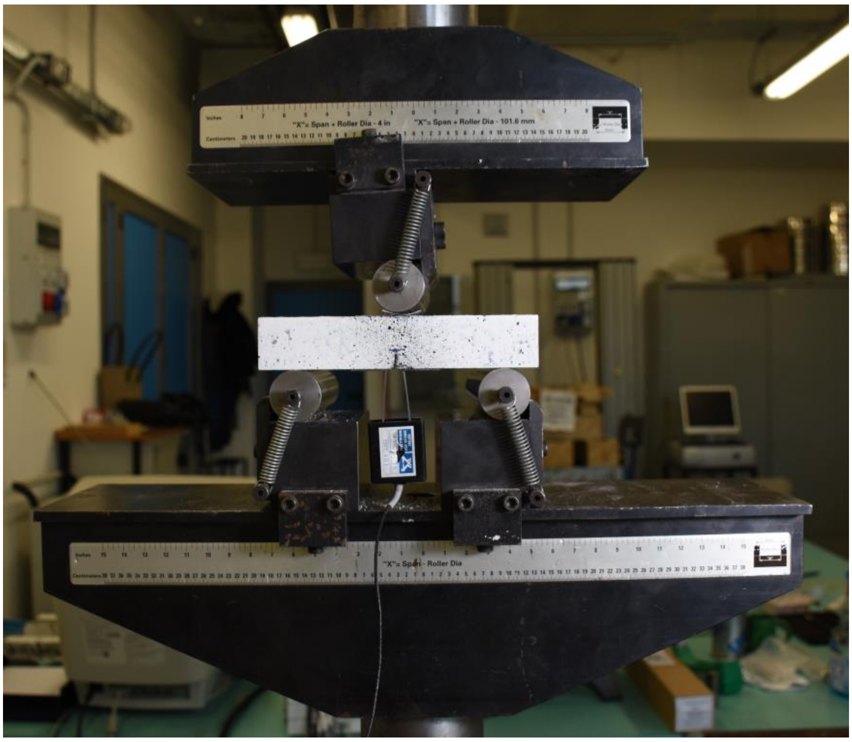

Inches
"X"= Span + Roller Dia - 4 in
"X"= Span + Roller Dia - 101.6 mm
Centimeters
"X"= Span - Roller Dia

Figure 5.

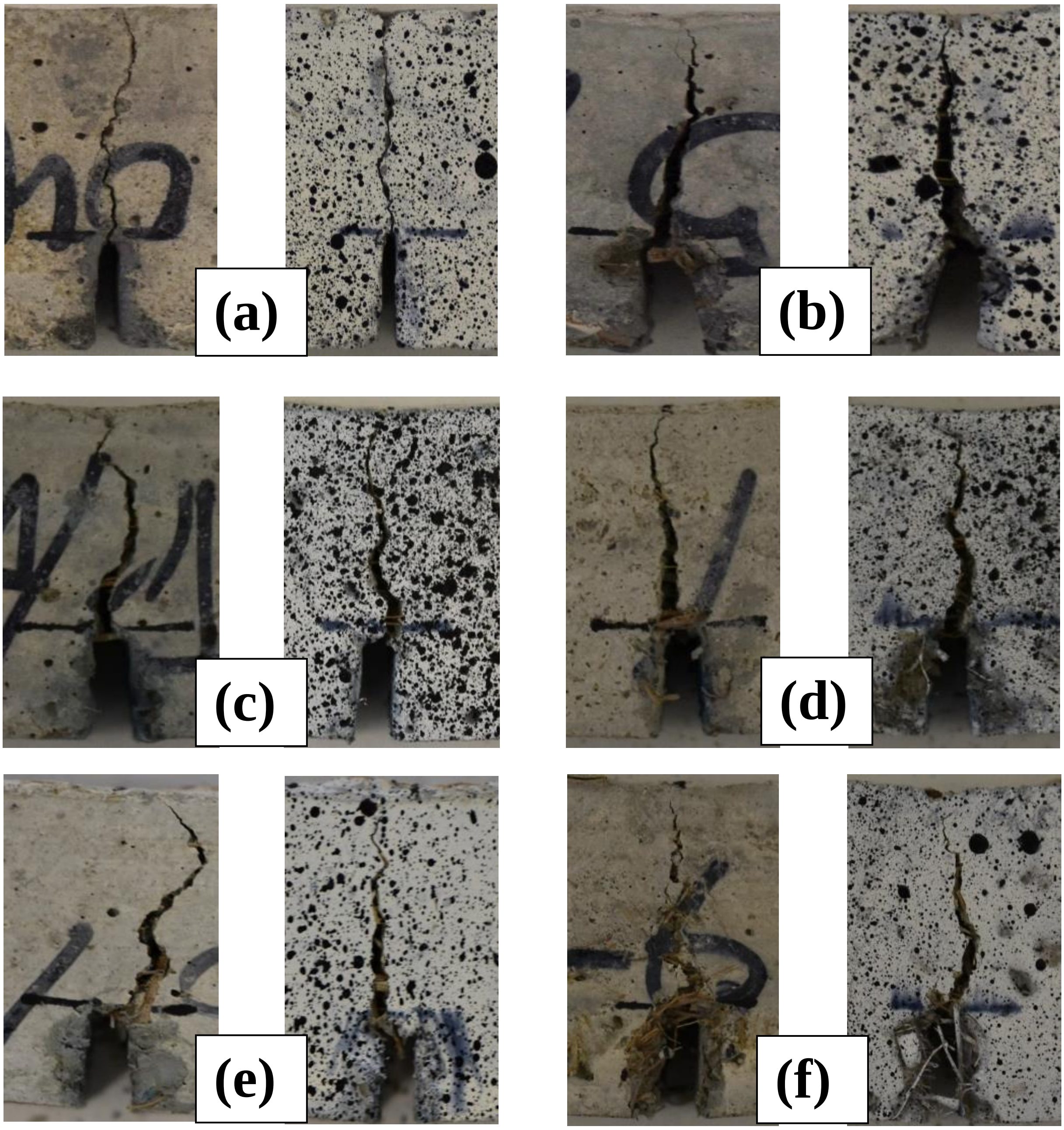
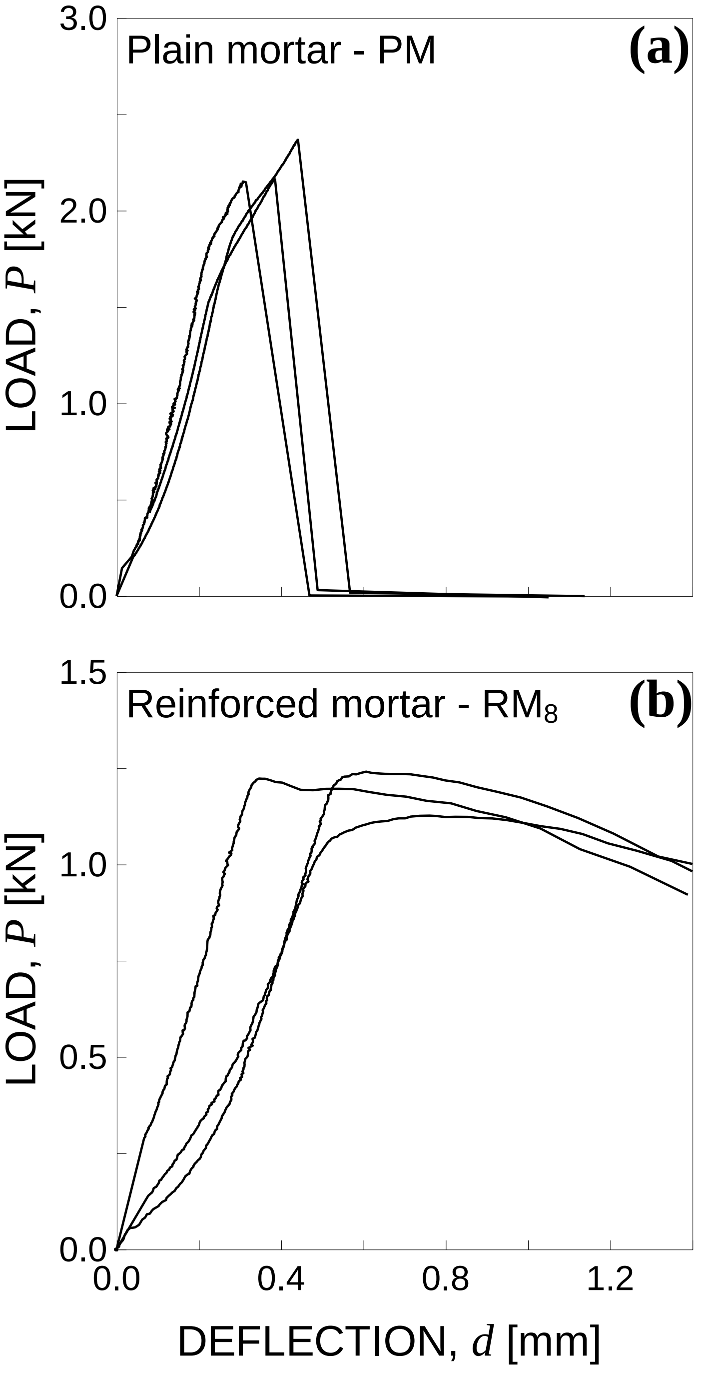


Figure 6.

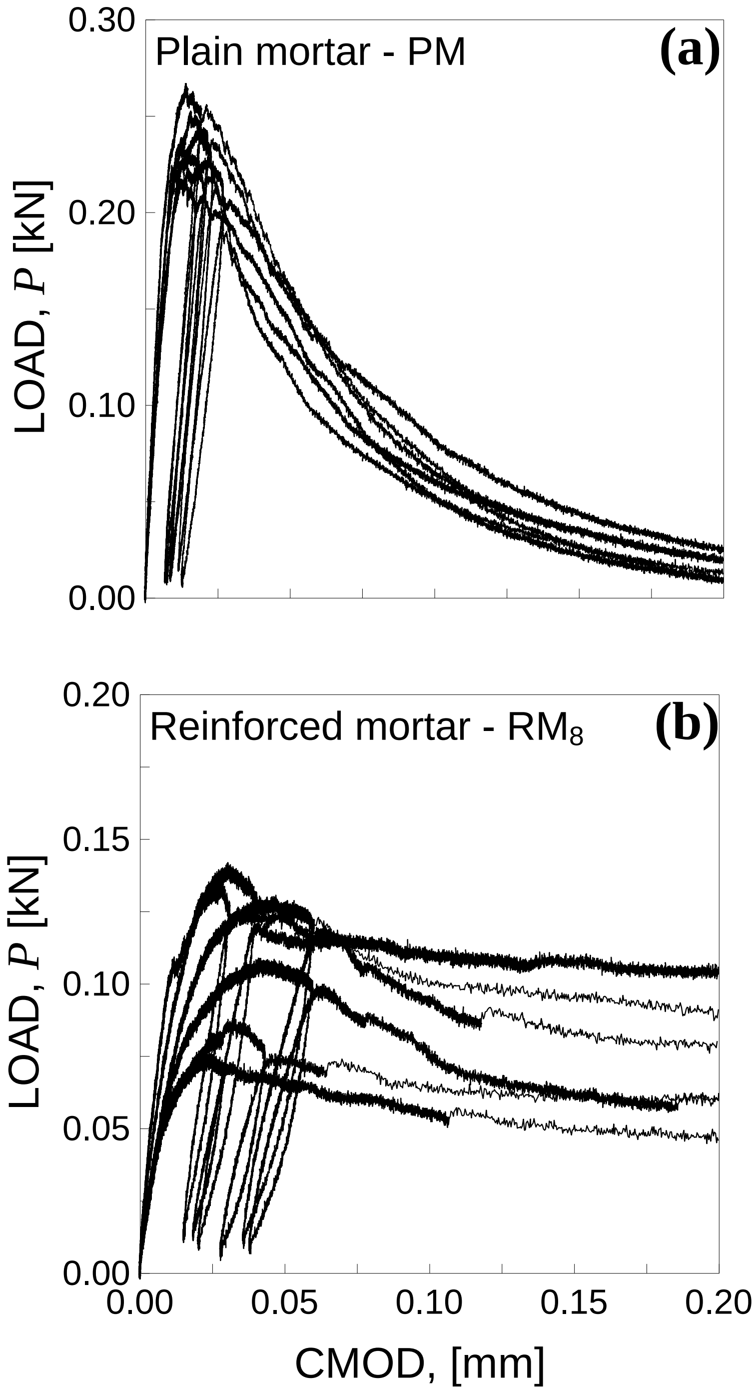


Plain mortar - PM
(a)
Reinforced mortar - RM8
(b)
LOAD, P [kN]
3.0
2.0
1.0
0.0
1.5
1.0
0.5
0.0
0.0
0.4
0.8
1.2
DEFLECTION, d [mm]

Figure 7.

Table 4.

SPECIMEN TYPE	P_f [kN]	R_f [MPa]
PM (3)	2.151	6.049
	2.367	6.657
	2.162	6.080
RM_2 (3)	2.172	6.110
	1.975	5.555
	1.902	5.350
RM_4 (3)	1.656	4.658
	1.870	5.258
	1.566	4.404
RM_6 (3)	1.294	3.640
	1.432	4.027
	1.398	3.932
RM_8 (3)	1.223	3.439
	1.126	3.168
	1.241	3.490
RM_{10} (3)	1.043	2.934
	1.197	3.368
	0.957	2.693

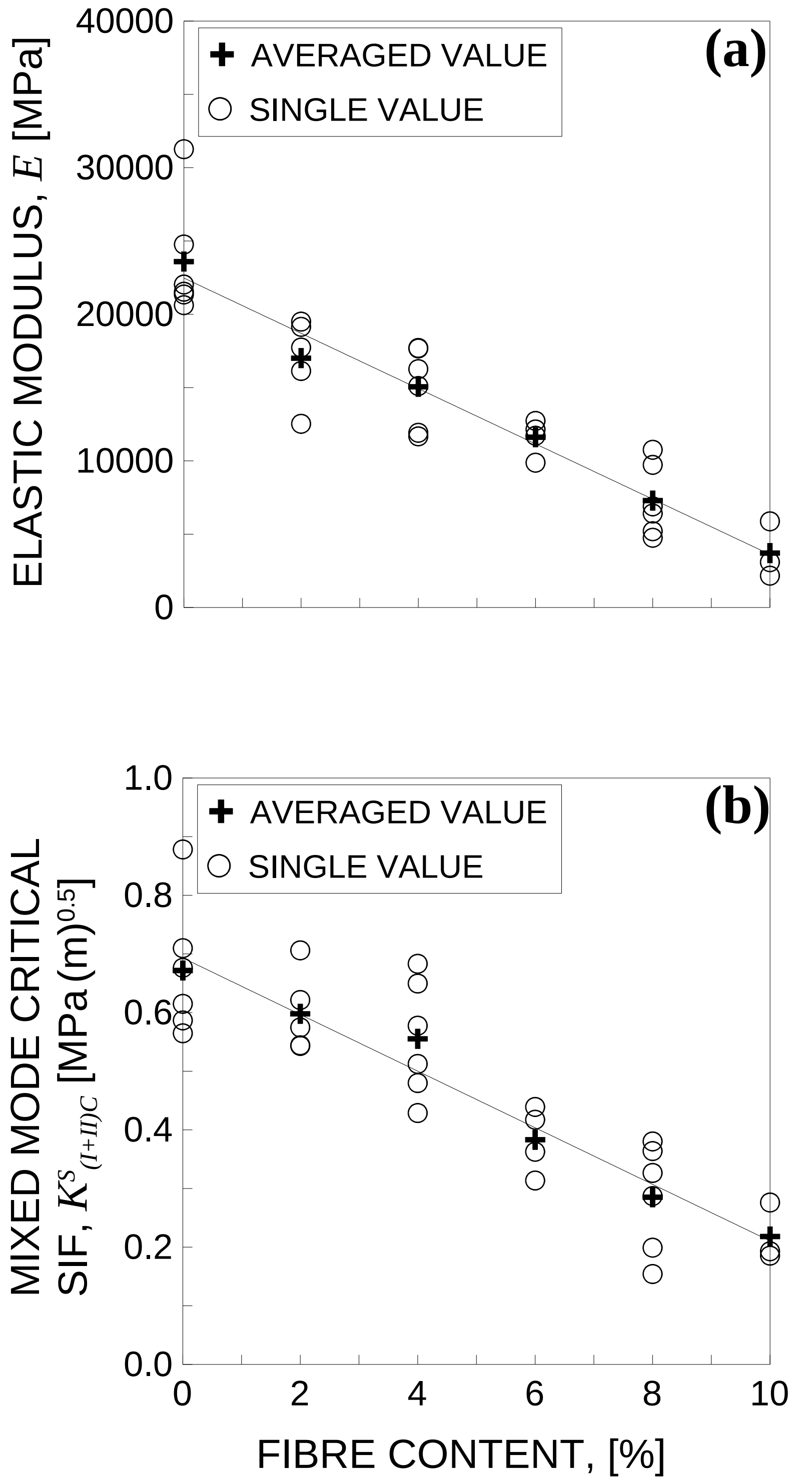


0.30
Plain mortar - PM
(a)
0.20
LOAD, P [kN]
0.10
0.00
0.20
Reinforced mortar - RM8
(b)
0.15
LOAD, P [kN]
0.10
0.05
0.00
0.00
0.05
0.10
0.15
0.20
CMOD, [mm]

Figure 8.

Table 5.

SPECIMEN TYPE	$P_{\max}$ [kN]	E [MPa]	$K^{S}_{(I+II)C}$ [MPa(m)$^{0.5}$]
PM (6)	0.249	22028.759	0.710
	0.215	24761.043	0.565
	0.240	21350.979	0.615
	0.263	21539.808	0.676
	0.227	20622.030	0.587
	0.226	31261.008	0.878
RM_2 (5)	0.230	12529.312	0.543
	0.238	19499.225	0.621
	0.221	16133.067	0.544
	0.259	19144.118	0.706
	0.187	17732.783	0.575
RM_4 (6)	0.191	17668.427	0.512
	0.209	15106.863	0.578
	0.196	11673.816	0.480
	0.222	17702.556	0.683
	0.193	16260.402	0.650
	0.166	11917.614	0.429
RM_6 (4)	0.162	12725.507	0.439
	0.087	12146.371	0.314
	0.153	9876.432	0.417
	0.109	11715.699	0.363
RM_8 (6)	0.085	5201.028	0.199
	0.106	10756.276	0.364
	0.073	4756.530	0.154
	0.133	6412.145	0.287
	0.127	6897.511	0.327
	0.139	9728.548	0.380
RM_{10} (3)	0.093	2170.236	0.193
	0.115	5876.341	0.276
	0.076	3089.028	0.185



40000
30000
20000
10000
0
ELASTIC MODULUS, E [MPa]
AVERAGED VALUE
SINGLE VALUE
(a)
1.0
0.8
0.6
0.4
0.2
0.0
MIXED MODE CRITICAL SIF, $K^{S}_{(I+II)C}$ [MPa(m)$^{0.5}$]
AVERAGED VALUE
SINGLE VALUE
(b)
0
2
4
6
8
10
FIBRE CONTENT, [%]

Figure 9.