Methodology to evaluate the cracking susceptibility of mortars. Selection criteria of rendering and repointing mortars for ancient buildings[1]

Author: VEIGA, M. Rosário, Civil Engineer (Ph. D)
Laboratório Nacional de Engenharia Civil (LNEC), Lisboa, Portugal

1. INTRODUCTION

The selection of renovation mortars for rendering and repointing of ancient buildings must be based on criteria that guarantee the verification of **functional** and **aesthetic compatibility** with the remaining old materials and the whole of the construction.

Functional compatibility of masonry mortars means, in the first place, **not to damage the old masonry** and, secondly, **to be able to protect it against external actions** such as moisture, climatic actions, impact forces and chemical attack. In third place, it also means **durability**, because there is no real protection if durability is very low.

Water is one of the most powerful destruction agents for old masonry. In fact, freeze-thaw phenomena, dissolution and transportation of salts and slow dissolution of constituents are very aggressive to porous materials.

Masonry in general, and old masonry in particular, has low resistance to tensile stresses. Nevertheless, some usual phenomena produce tensile stresses in render and repointing mortars, that can also be transmitted to old masonry: render shrinkage restrained by adherence to the background and thermal and hygrothermal volume variations of mortars are among those causes.

So, some of the main characteristics of compatible renovation mortars are:

- Water protection capability
- Low cracking susceptibility
- Low stresses developed during restrained shrinkage and thermal and hygrothermal variations

CEN European standards are being developed to establish test methods for masonry mortars [1]. However, there are no standardised test methods to characterise in a satisfactory, scientific way those most relevant aspects of mortars performance.

Test methods to verify those properties are being developed and extensively tested at LNEC [2 to 5].

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The evaluation of cracking susceptibility has considerable complexity, because it depends on several factors that change in time: the evolution of shrinkage; the ratio between elasticity modulus and tensile resistance; finally, it also depends on the capacity of the mortar to dissipate stresses by relaxation [2, 6].

In this paper a test method is described to evaluate the cracking susceptibility of rendering and repointing mortars and to determine the stresses developed during restrained shrinkage and other restrained deformations. The adequability of the method is analysed by applying it to a variety of rendering and repointing mortars. The utility of the method to assess mortars for conservation interventions is verified by applying it to some mortars generally considered adequate for that kind of work.

The test method also gives us complementary data, such as tensile resistance, rupture energy, elasticity modulus and relaxation capacity. It is also possible to determine free shrinkage with the same apparatus and identical specimens.

2. DESCRIPTION OF THE METHODOLOGY

2.1 - Equipment

To perform these tests a special equipment was prepared: an apparatus was designed and constructed at LNEC [6], basically constituted by a rigid structure and two “heads” that work as a mould; the inferior head is fixed to the structure and the superior one has a free longitudinal movement, stopped by a force transducer linked to a screw; when shrinkage acts, the screw stops the displacement and the force is transmitted to the transducer; the remaining small displacements are also measured by a displacement transducer of the LVDT (linearly variable displacement transducer) type, in order to be taken into account; five more similar apparatus were then constructed in a factory; a data logger with a special software prepared also at LNEC is able to read, register and save the data measured by the six force transducers and the six LVDT .

2.2 – Restrained shrinkage test

The experimental model used consisted on blocking the shrinkage deformation, since the mortar moulding until a relative stabilisation took place, in unidimensional specimens (fig. 1), prepared in a way as similar as possible with the usual application method for renders, and measure the forces Fr(t) generated for the predefined test periods.

The specimens were moulded inside the apparatus in horizontal position (fig. 2 to 4) and 18 hours later they were turned to vertical (fig. 5). At the age of 18 h all of them showed to be resistant enough to be able to maintain the vertical position.

Force/time curves curves were plotted from the restrained shrinkage tests.

Figs 1-3 (see separate page)

Fig. 1 – Scheme of the experimental model

Fig. 2 – Apparatus prepared for moulding of a specimen for restrained shrinkage test

Fig. 3 - Moulding of a specimen for restrained shrinkage test

Figs 4-5 (see separate page)

Fig. 4 – First phase of a test with the whole of six apparatus

Fig. 5 – Second phase of a test (vertical position)

2.3 – Tensile test

At the ages of 7 days (cement mortars) or of 28 days (lime mortars), a tensile test was performed on the specimens submitted to restrained shrinkage, by slowly turning the screw (fig. 6). Force/displacement curves were plotted from the tensile tests.

2.4 – Free shrinkage test

The equipment is also used to perform free shrinkage tests (fig. 7), by moulding identical specimens in the apparatus adapted to that kind of test and measuring and registering the displacements [2, 7].

2.5 – Classification of cracking susceptibility

Based on the data obtained at restrained shrinkage and tensile tests two criteria were chosen to define cracking susceptibility classes.

The first criterion is quantified by the **Safety coefficient to the opening of the first crack**: $\mathbf{S = Rt(t)/Fr(t)}$

(Rt – Tensile resistance; Fr – Measured force)

The first crack opens if $\mathbf{S<1}$ at any moment t during the test

The second criterion is energy related and it is quantified by the **Resistance coefficient to cracking evolution:** $\mathbf{R=G/F_{rmáx}}$

(G – Rupture tensile energy; Fr – Measured force)

The larger is R, the larger is the energy needed to the evolution of the micro-cracking - produced after the non-verification of the 1st criterion – until the instability point is attained; so the less probable is that evolution.

The classification established after analysing the results obtained initially for 16 mortars, in several different curing conditions, applied on two different backgrounds (an absorbent one and a non-absorbent one) [2] is described at table 1.

Fig. 6-7 (see separate page)

Fig. 6 – Crack after a tensile test

Fig. 7 – Apparatus prepared for free shrinkage test

Table 1 - Classification of cracking susceptibility based on coefficients *S*/*R*

CLASS	**S**	**R** (mm)
1 (Low cracking susceptibility) *	S ≥ 1	R ≥ 1
2 (Medium cracking susceptibility) *	S ≥ 1	0,6 ≤ R <1
3 (High cracking susceptibility) **	S <1	R < 0,6

* It must verify both conditions

** It must verify one of the conditions

3. MATERIALS AND CONDITIONS

To verify its adequability to assess the cracking susceptibility, the method was tested in a variety of mortars used as renders in Portugal, including cement mortars, lime-cement mortars, lime mortars, hydraulic lime mortars, mortars reinforced with fibres and nets, a mortar modified with acrylic resin and industrial renders.

The mixing water quantities and the sand types used also were diversified, and its influence was evaluated.

The designations adopted and the compositions chosen are synthesised at table 2, where the mortars tested with a view to conservation interventions appear in shading lines.

The mixing water dosages for renders made on site were selected according to the workability verified by the application on a brick of a type often used in wall construction in Portugal: for each render, several water dosages were tried and the driest one with a good enough workability was chosen; then the water dosage used was fixed for the considered render. *C4w* render was the exception, because it was designed to study the water quantity influence: the adopted water quantity was the largest quantity possible for application, using the same methodology (application on a brick).

For industrial renders and for the render modified with a resin, all of them patented renders, the water quantity adopted was the established by the producer.

Table 2 - Tested renders

TYPE	RENDER	COMPOSITION		
		Volumetric dosage	Constituents	Factor to study
Comparison render	C4	1:4	cement:river sand (1) w/b=1,15	all
Cement Renders made on site	C3	1:3	cement:river sand w/b=0,84 (2)	dosage of cement
	C4y	1: 4 (2+2)	cement:sand (river sand + Corroios yellow sand (3)); w/b=1,09	sand nature
	C4w	1:4	cement:river sand w/b=1,30	mixing water quantity
Cement matrixes reinforced with dispersed fibres	FV	1:4+0,3% fv(4)	cement:river sand:alkali - resistant glass fibre; w/b = 1,15	use of dispersed fibres
	FPP	1:4+1% fpp(4)	cement:river sand:fibrillated polipropylene fibre w/b=0,97	
Cement matrixes reinforced with fibre nets	N1	1:4	cement:river sand w/b=1,15 glass fibre net (N1, N2); polypropylene net (N3)	use of nets
	N2			
	N3			
Render modified with a resin	CR	(5)	-	use of resin
Industrial cement renders	IC1	(5)	-	Industrial cement compositions
	IC2			
	IC3			
	IC4			
	IC5			
	IC6			
Lime based renders made on site	HL	1:4	hydraulic lime:river sand; w/b = 1,67	binder nature and sand nature
	C-L	1:1:6	cement:lime:river sand w/b = 1,32	
	C-Lclay	1:3: (11+1)	cement:lime: (river sand+clay) w/b = 1,42	
	L	1:3	lime: river sand w/b = 2,27	
	Lclay	1: (2,8+0,2)	lime: (river sand+clay) w/b = 2,09	
Industrial lime renders	IL	(5)	Lime mortar	Industrial lime compositions
	IHL	(5)	Lime and hydraulic lime mortar	

(1) - silicious sand extracted from Tagus river, predominantly coarse, very used in the Lisbon area for renders and plasters

(2) - w/b - ponderal ratio water/binder

(3) - pit sand with coarse and fine grains, with some clay, extracted near Lisbon and often used in Lisbon area for renders and plasters

(4) - 0,3% fv - volumetric dosage of fibre, related to the total volume of fresh mortar

(5) – Patented renders

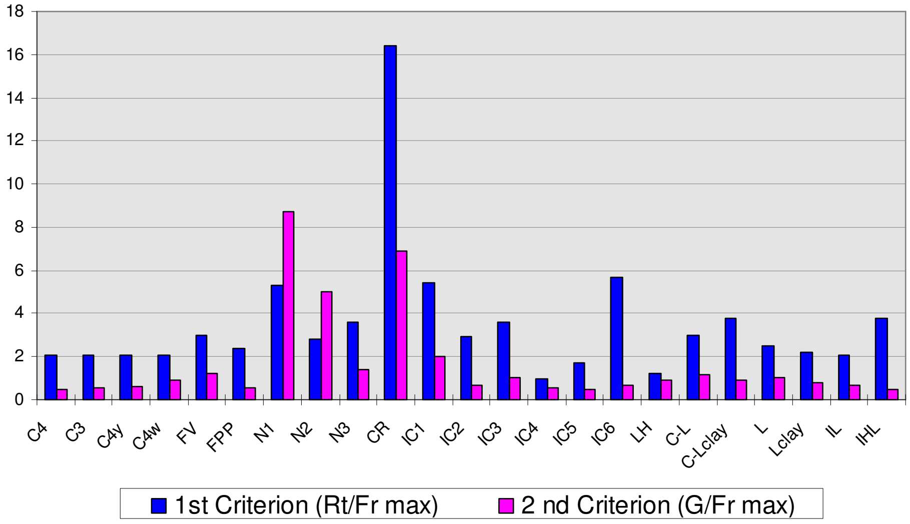
3 - RESULTS

The samples of the 23 tested mortars were cured and maintained, since moulding until the end of the test, at standard conditions characterised by 23ºC of temperature and 50% relative humidity.

All mortars were submitted to restrained shrinkage till the age of 7 days (cement mortars) or 28 days (lime mortars) and then to a tensile test (fig. 2 to 4).

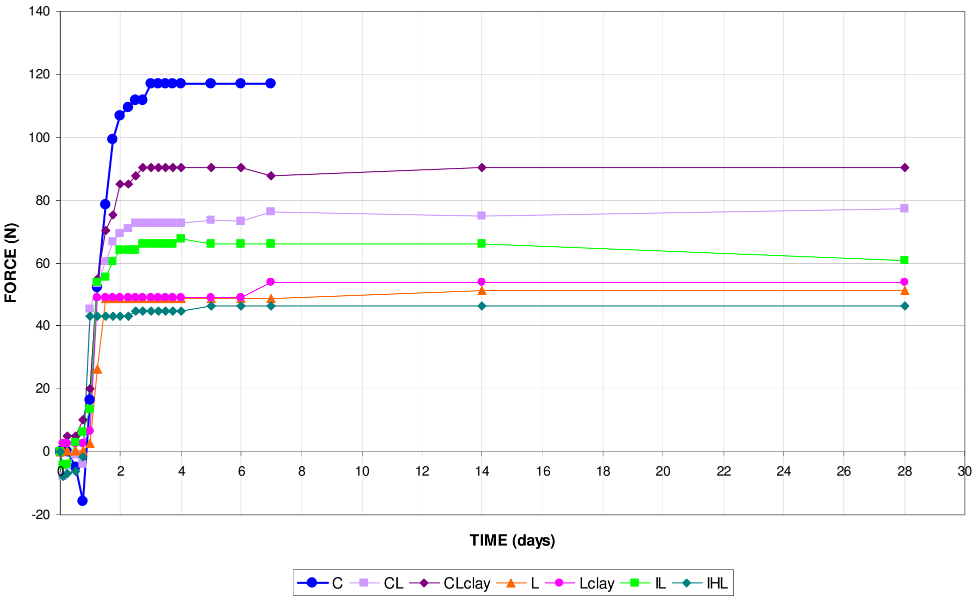
Table 3 synthesises the main characteristics determined related to cracking susceptibility classification.

Results of both cracking susceptibility criteria - *S* and *R* – are synthesised at graphic 1.

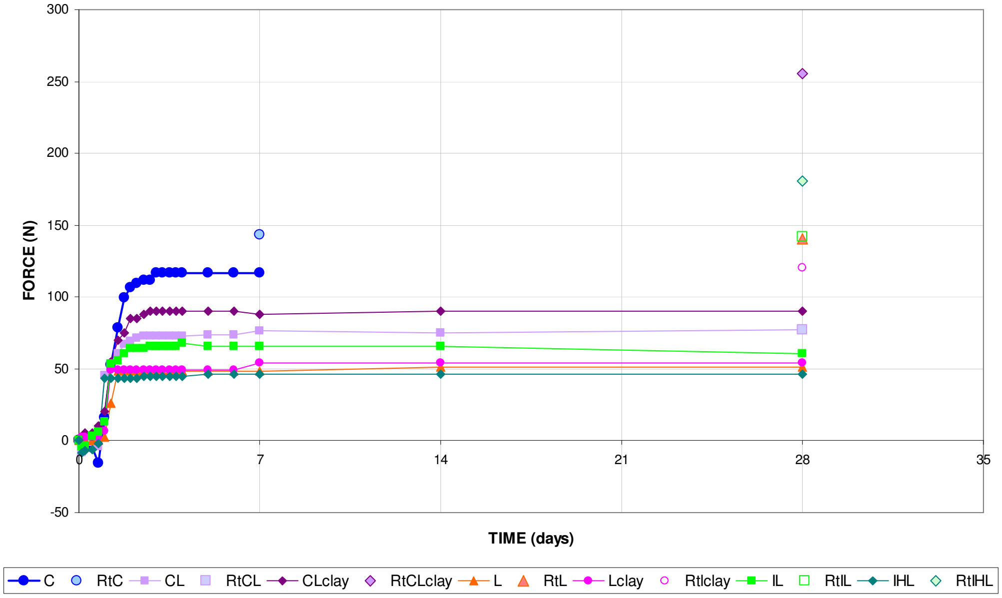


Graphic 1 – Comparison of cracking susceptibility criteria for all the studied mortars

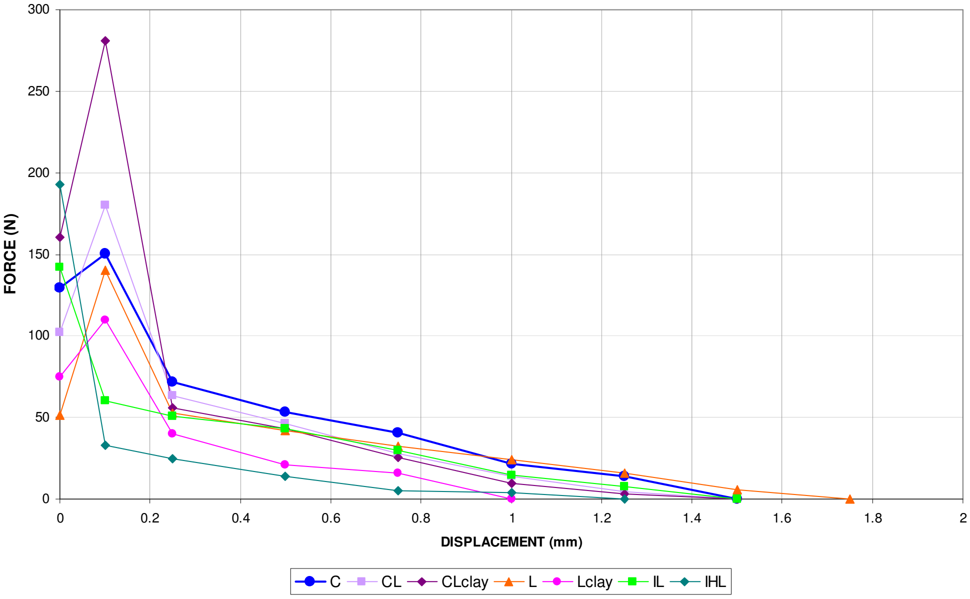
Graphics 2 to 4 show average curves (from six samples) obtained for the group of mortars tested for conservation, compared with mortar C4, in a restrained shrinkage test and in a tensile test.



Graphic 2 - Restrained shrinkage average forces of mortars C4 (S=2,1); C-L (S=3,0); C-Lclay (S=3,8); L (S=2,5); Lclay (S=2,2); IL (S=2,1); IHL (S=3,8)



Graphic 3 - Restrained shrinkage average forces and tensile resistances of mortars C4 (S=2,1); C-L (S=3,0); C-Lclay (S=3,8); L (S=2,5); Lclay (S=2,2); IL (S=2,1); IHL (S=3,8)



Graphic 4 - Force-displacement average curves for tensile test of mortars C4 (R=0,51); C-L (R=1,18); C-Lclay (R=0,89); L (R=1,01); Lclay (R=0,81); IL (R=0,68); IHL (R=0,50)

Table 3

MORTAR	n_{cs} *	MAXIMAL FORCE Frmáx (N)	TENSILE RESISTANCE Rt (N)	RUPTURE ENERGY G (N.mm)	S (Rt/Frmáx)	R (G/Frmáx) (mm)	CLASSIFICATION FOR CRACKING SUSCEPTIBILITY **(S/R CRITERIA)**
C4	3	136	292	70	2,1	0,51	HIGH
C3	2	193	403	106	2,1	0,55	HIGH
C4y	2	133	285	84	2,1	0,63	MODERATE
C4w	2	128	314	118	2,1	0,92	MODERATE
FV	0	98	292	118	3,0	1,20	LOW
FPP	0	109	266	59	2,4	0,54	HIGH
N1	0	81	429	709	5,3	8,75	LOW
N2	0	151	417	752	2,8	4,98	LOW
N3	0	110	398	157	3,6	1,43	LOW
CR	0	83	1361	570	16,4	6,87	LOW
IC1	0	61	328	123	5,4	2,02	LOW
IC2	0	117	342	82	2,9	0,70	MODERATE
IC3	2	95	341	99	3,6	1,04	LOW
IC4	6	97	93	55**	1,0	0,57**	HIGH
IC5	4	140	248	69	1,7	0,51	HIGH
IC6	0	118	677	80	5,7	0,68	MODERATE
HL	2	59	69	55	1,2	0,93	MODERATE
C-L	1	49	145	58	3,0	1,18	LOW
C-Lclay	0	72	272	62	3,8	0,89	MODERATE
L	0	58	143	58	2,5	1,01	LOW
Lclay	0	53	120	44	2,2	0,81	MODERATE
IL	0	68	142	46	2,1	0,68	MODERATE
ILH	0	54	193	27	3,8	0,50	HIGH

* - number of cracked specimens

** - all the specimens cracked, however their rupture energy is greater than zero, due to a residual resistance to crack propagation

4. DISCUSSION OF RESULTS

The results synthesised on the graphics 1 to 3 and on table 3 allow for some conclusions concerning the influence of composition factors on the cracking performance of rendering and repointing mortars:

- The binder nature is very significant for cracking susceptibility of mortars and it also influences strongly the maximum force induced in the mortar by restrained shrinkage. In fact, cement mortars seem to have higher susceptibility to cracking than lime or lime-cement mortars, mainly because of a lower ductility, traduced by a lower S coefficient.

- The cement dosage doesn't seem to influence very much the cracking susceptibility but it affects directly the force level induced by restrained shrinkage.

- The water/binder ratio doesn't appear to be very significant to cracking susceptibility or to force level. In fact, a larger amount of water produces a higher shrinkage, but the relaxation also gets higher.

- The type of sand has some influence, but the compositions studied are not enough to draw conclusions. However, comparing C-L and C-Lclay it seems that some clay content may reduce a little the R coefficient, meaning the mortar becomes more fragile.

- The use of dispersed fibres and fibre nets improve very much the cracking susceptibility of mortars, because of a large gain in ductility and the phenomenon of multiple cracking verified, but they don't change the level of forces induced in the mortar by restrained shrinkage.

- The addition of an acrylic resin seems to be very effective, producing a ***low susceptibility*** to cracking mortar, with a low level of forces induced.

- Some industrial cement mortars can have better performance concerning cracking resistance, compared to made on site mortars, but this is not a general rule, as it depends on their formulation. In fact, this kind of products can have diversified characteristics, and allow for variable cracking resistance and induced forces.

- The industrial lime mortars tested show ***moderate susceptibility*** to cracking and low induced forces.

It is important to take notice that, besides the composition factors studied in this paper, also climatic and application factors strongly influence cracking resistance and forces induced in mortars. In fact, the ambient temperature and humidity and the curing methods used influence the drying process and the shrinkage; the same happens with the absorption characteristics of the background; in the same way, the number of coats, the drying period between coats and the method of application condition the mortar performance and the parameters related to cracking susceptibility here defined [2, 8].

5. CONCLUSIONS

Considering the results obtained, it is possible to conclude that, **from the point of view of cracking resistance and stresses transmissible to the background**, the most favourable mortars for rendering and repointing of ancient buildings are pure lime mortars made on site. Lime-cement mortars and hydraulic lime mortars seem to be also possible options, in some conditions. Industrial lime mortars can be appropriate too, but their performance characteristics must be verified case by case.

The study is going on to establish limits for the parameters obtained in these tests, taking into account the relevant work factors. In any case, it seems sensible to prevent the use of high susceptibility mortars, and of mortars which had more than one specimen cracked in the test. The maximum force Fr_{max} admissible must depend on the type of background, namely its resistance.

It must be emphasised that this is one of the performance aspects that must be considered when recommending mortars for masonry conservation. In fact, low cracking susceptibility guarantees better protection of the masonry against water and better durability and low forces induced by restrained shrinkage or by restrained volume variations due to hygrothermal effects prevent a high level of stresses induced in the old masonry and other old materials in contact.

However, there are several other aspects of equal importance to consider, as it is referred in 1, before an option can be made on the mortars to specify for a conservation intervention.

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