Expedient *in situ* test techniques for predictive maintenance of rendered façades

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Abstract

The practice of predictive maintenance (through periodic inspections) depends on the efficiency of *in situ* evaluations of the in-service performance of the constructive solutions, which in turn depends on a set of logical procedures inherent to a performance-based methodology and a correct diagnosis.

In situ tests are a precious auxiliary tool for visual inspections, since they allow the detection of gross diagnosis mistakes, reduce the subjectivity of visual inspections and enable a more accurate assessment of the real maintenance needs. These tests have limitations, however, and depend on the technique used (often the limited precision of a technique only allows a qualitative analysis) and the experience of the practitioners. *In situ* tests for rendered façades include a variety of tests and techniques, most of them not standardised, and therefore a coherent and global classification is sometimes difficult to establish.

In this paper a methodology for choosing the most adequate *in situ* techniques to diagnose in-service performance of rendered façades is proposed. The subjects of this analysis were current and expedient techniques, used in several inspections performed in

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different renders, within the PhD research work of the first author. These techniques are classified and also characterised in terms of the data collected (parameters measured), their contribution to understanding in-service performance (analysis of relevant properties), the degradation state (anomalies and their causes) and their relation to maintenance needs. Finally, they are compared and rated using various criteria and evaluated in terms of their adequacy for *in situ* assessment.

Keywords:

in situ tests, predictive maintenance, façades, rendering, expedient techniques

INTRODUCTION

Maintenance is becoming increasingly more decisive for buildings' management and an important contribution to global expenses throughout their life cycle. For example, for an undertaking with a service life of 50 years, expenses related to the design and execution stages represent around 20–25 per cent of global costs, while the service and maintenance stage is responsible for 75–80 per cent of these costs (Perret, 1995).

Maintenance is defined in ISO 15686–1 (ISO, 2000) as a combination of all the technical and administrative actions that allow the building and its elements to perform during its service life the functions they were designed for. There are various ways of approaching buildings' maintenance depending on knowledge of the behaviour of the component to be studied:

- Preventive maintenance (often termed planned maintenance): the items included in this category are those works which are planned to take place at predefined, regular intervals in order to keep the component in good performance (Riley and Cotgrave, 2005); this type of maintenance reduces the number of non-planned works and allows the estimation of overall costs.
- Predictive maintenance (or conditioned-based maintenance) by performing inspection planning: the predictions involved in this type of maintenance show an important capacity for growth in accuracy (Palmer, 1999); for some time it has been a useful tool for reducing life cycle costs and finding more efficient ways of using maintenance budgets (Hertlein, 1999); it is an appropriate maintenance strategy for elements whose condition and performance can be suitably monitored (Morcous and Lounis, 2005).
- Reactive maintenance: associated with the correction of unexpected anomalies, almost always of an urgent nature, leading to unavoidable extra costs; thus, it is important to standardise technical procedures that allow the minimisation of the drawbacks of this type of maintenance (Flores, 2002).

The preventive and predictive maintenance strategies can be integrated in proactive maintenance, preventing problems before they occur

(Palmer, 1999) and minimising cost throughout a building's service life. Therefore, the performance of periodic inspections during the service stage (predictive maintenance) increases the capacity to detect ('when' and 'where') the need for interventions, reducing the number of unforeseen anomalies (Flores-Colen and de Brito, 2004) and allowing a growing knowledge of the in-service behaviour of construction elements, their residual service life and premature degradation agents (BCIS, 2001).

In this context, the practice of predictive maintenance depends on the efficiency of *in situ* assessment of the in-service performance of the various construction elements, which must account for a set of logical procedures inherent both to a performance-based methodology, to be implemented after the design stage, and to a correct diagnosis at the service stage.

For façade rendering, the performance-based methodology includes the definition and quantification (by the designers, backed by the manufacturers) of the rendering properties relevant to proper in-service performance, taking into account the functions they must fulfil to ensure a good performance of the façades: watertightness and protection of the walls, finishing of the surfaces, durability faced with the outer actions, and adequacy to use (Veiga, 2005). A correct diagnosis must define the problem, collect the available data, characterise the existing anomalies and their probable causes, evaluate the in-service performance (fulfilment of the functions established at design), check whether the users' demands are being fulfilled and, finally, define the corrective, preventive or monitoring actions. In Figure 1, a methodology is proposed to support rendered façade diagnosis and to choose intervention strategies, based on various other existing methodologies (referred to in Flores-Colen et al., 2006), related to service life estimation, diagnosis improvement (through observation and *in situ* techniques) and backing criteria for the selection of maintenance actions.

In situ assessment of in-service performance is a complex activity, usually restricted to a visual appraisal of an element's degradation, which may lead to a deficient diagnosis and consequent performance of inadequate interventions. The usual absence of records of intervention (historic to the building) aggravates this situation through an accumulation of errors. The main reasons justifying the complexity of this type of assessment can be identified as follows.

- Design solutions are prescriptive and not performance-based by nature.
- Technical data provided by manufacturers most of the time is insufficient (or descriptive by nature); even when the minimum requirements of EN998–1 are specified, properties stated are not enough to evaluate the global behaviour of outer rendering (Veiga, 2005).
- *In situ* inspections are mostly visual and only rarely are other auxiliary diagnosis techniques (*in situ* or in laboratory) used.
- Most of the buildings do not possess access means, thus limiting the inspection to the ground floor, causing the need for auxiliary means of access or entering the building.

Figure 1: Flowchart of a diagnosis methodology for rendered façades, adapted from Flores-Colen et al., 2005

- Insufficient available data (eg outdated final drawings and ignorance of both the characteristics of materials applied and previous interventions).

IN SITU TEST TECHNIQUES FOR INSPECTION SUPPORT

Inspections and *in situ* test techniques

The frequency of inspections during the service life of buildings differs in various countries and is related to several factors (economic, cultural and social, among others). For example, Bureau Veritas (Bureau Veritas, 1993) recommends localised inspections every three to five years to check anomalies and in-service performance, and global inspections every 10 to 15 years to examine eventual functional liabilities and factual ageing of all the elements. BS 8210 (BSI, 1986) recommends systematic inspections as follows:

- Continuous, regular observation by the building user as part of the occupancy of the building;
- Annual visual inspection of the main elements under supervision of suitably qualified personnel;
- Full inspection of the building fabric by suitably qualified personnel at least every five years.

In Portugal, legislation about to be approved (General Code for Edifications, RGE) refers that current periodic inspections must be performed every 15 months after issue of the dwelling licence and that they are intended to detect anomalies and originate the actions listed in the building's Manual of Inspection and Maintenance (MIME). Buildings without a MIME must be subjected to an expert inspection at least once every eight years.

Inspections normally occur through visual observation of the building's elements. They allow the qualitative characterisation of anomalies, the evaluation of their eventual causes and the assessment of in-service conditions, complementing the documentation obtained previously (claims report, design elements and inspection reports, among others).

In situ tests are a precious auxiliary tool for visual inspections and allow a more accurate characterisation of:

- Existing degradation mechanisms of the walls (eg staining, efflorescence, dampness and cracking);
- Changes of the rendering properties directly related to its performance (eg mechanical strength and water absorption coefficient);
- *In situ* conditions (eg environmental parameters);
- Type of materials applied, by laboratory testing specimens collected *in situ* (eg characterising the mortar formulation and its binder content).

Therefore, carrying out these tests reduces the subjectivity of visual inspections (which are very dependent on the background and experience of the inspector) and assesses with greater precision the real maintenance needs. Testing also allows the detection of small changes that may be associated with pre-pathology symptoms (phenomena preceding easily detectable anomalies) (Flores, 2002; Calejo, 1996).

These tests have several shortcomings, however, possibly leading to an increase in the inspection duration and to results that are confusing and hard to interpret (especially when available data concerning the materials applied are scarce or nil). They have limitations and, depending on the technique used, the limited precision only allows a qualitative analysis.

According to ISO 15686–2 (ISO, 2001):

‘Standardized techniques are usually recommended just because they are standardized. However, apart from generally being phenomenological and very simple (too simple in certain cases), many of the standardized inspection techniques suffer from the fact that they rely upon subjective judgements of the practitioners. This makes comparisons between studies from different practitioners less reliable, which in fact counteracts the purpose of standardization. Accordingly, there is a need for further development in this field and the standardization of existing, more sophisticated techniques.

Currently, there are only a few (usually expensive) *in situ* test techniques that allow reliable data of a quantitative nature about any degradation level (Branco and de Brito, 2005). Nevertheless, the combined use of various techniques facilitates the interpretation of the results and minimises the limitations referred. Therefore, even with some shortcomings, these tests allow the detection of gross diagnosis mistakes (Silva, 2004) and, in some cases, spare the use of laboratory analyses (time-consuming and increasing the inspection’s costs) (Branco and de Brito, 2005). It is also preferable to use them in conjunction with visual observation instead of relying solely on the latter.

CLASSIFICATION AND CHARACTERISATION OF EXPEDIENT *IN SITU* TECHNIQUES

In situ tests include a variety of techniques associated with the determination of various characteristics, raising some difficulties in putting together a coherent and global classification (Branco and de Brito, 2005). There are different classifications for *in situ* test techniques. According to the literature (Branco and de Brito, 2005; Silva, 2004; Campanella, 2003), they may be classified in terms of the:

- degree of destruction caused in the surfaces they are applied to (destructive, semi-destructive and non-destructive);
- existence or non-existence of an artificial intervention (passive, also named non-invasive, and active, also named invasive);
- principle they are based on (mechanical, electrical, magnetic, electromagnetic, ultrasonic, radioactive, sensorial, thermic, chemical, electrochemical, among others);
- type of results obtained (properties to be evaluated);
- type of technology used (low or high-tech);
- main objectives (eg strength, durability and geometry);
- elements they are applied to (eg cladding, background or both);
- activities where they intervene (eg quality control, building inspection, code conformity check-up, among others).

The adequate choice of technique is very important since it significantly influences the costs and time schedule involved, the type of equipment to carry *in situ*, the data to collect, the know-how needed, the type of human resources (number of people involved and their technical background) and the activities needed before (eg acquisition of the temporary means of access) and after (eg repairs to restore the initial conditions) the test.

To facilitate the choice of the best *in situ* technique to assess the in-service performance of renderings in outer walls a methodology is proposed based on the experience acquired in inspections of building façades, within the PhD research work of the first author, and a specialised technical bibliography (on existing procedures).

The techniques that are subject to analysis in this paper (Table 1) are current techniques to support inspection (Hollis and Gibson, 1991) used in several inspections performed in different renders: pull-off (T1) (RILEM, 2004), pendulum hammer (T2) (RILEM, 1997), *Martinet-Baronie* device (T3) (RILEM, 1982), ultrasounds (T4) (ASTM, 2002a), infrared thermometer (T5), infrared radiation pyrometer (T6),

Table 1: Identification of the expedite *in situ* test techniques under analysis

Technique T1	Technique T2	Technique T3	Technique T4

Technique T5	Technique T6	Technique T7	Technique T8

Technique T9	Technique T10	Technique T11	Technique T12

Technique T13	Technique T14	Technique T15	Technique T16

thermohygrometer (T7), *Karsten* tube (T8) (RILEM, 1980), colorimetric strips (T9), field kit (T10), pH/conductivity/overall salt content measurement (T11), humidimeter (T12), binoculars (T13), cracks gauge (T14), optical microscope (T15) and colorimeter (T16) (ASTM, 2002b).

The previous techniques were divided according to the principle they are based on and then characterised in terms of data collected (measured parameters), their contribution to understanding the in-service performance (in terms of the properties that may be analysed with the technique), the anomalies and their relationship with the maintenance needs. The flowcharts presented in Figures 2–5 systemise the previous data.

The characterisation of each technique using flowcharts allowed the conclusion that these techniques can help in the diagnosis of current anomalies in rendered façades: cracking, loss of adherence, loss of cohesion, staining, dirt, biological colonisation and efflorescence, among others. Generally these techniques did not provide a direct correlation with the performance requirements for rendering considered in EN 998 (CEN, 2003) or other technical documents (see Table 2); most of these criteria result from laboratory tests. The pull-off technique (T1 — determination of the adherence tension to the background) is the only one of those analysed that allows a direct correlation with the minimum requirements of EN 998 (see Figure 2).

Maintenance needs therefore can be identified in a qualitative manner. In order to improve the diagnosis during inspections and in-service performance assessment, additional requirements must be defined for

Legend: RA (adherence strength), DS (surface hardness), RS (surface strength), RI (impact strength), MED (dynamic modulus of elasticity).

Figure 2: Mechanical and ultrasonic techniques for rendered façades — measured parameters, performance properties, type of anomalies and eventual maintenance needs

Figure 3: Thermic and hydrodynamic techniques for rendered façades — measured parameters, performance properties, type of anomalies and eventual maintenance needs

these expedient techniques which must be correlated with performance requirements mentioned in standards, complementing the existing procedures (eg RILEM or ASTM documents). This aspect is still the subject of on-going research.

Figure 4: Chemical and electrical techniques for rendered façades — measured parameters, performance properties, type of anomalies and eventual maintenance needs

Legend: AA (water absorption), RH (resistance to humidity), RM (mechanical strength), RQ (resistance to chemical reactions), RA (resistance to climatic actions).

Figure 5: Sensorial (including optics) techniques for rendered façades — measured parameters, performance properties, type of anomalies and eventual maintenance needs

COMPARISON OF EXPEDIENT *IN SITU* TEST TECHNIQUES

The comparison of the various techniques must take into account their adequacy for *in situ* assessment to be performed in each case. Accordingly, the techniques mentioned above were compared based on criteria already defined in previous studies for *in situ* techniques applied to concrete bridges (Branco and de Brito, 2005) and to the diagnosis of staining of rendered walls (Flores-Colen et al., 2006).

In Table 3 limits for each criterion are proposed to clarify the comparative analysis and facilitate the choice between techniques (the ones within this analysis or others that may be used in the future); the following weights are considered (Branco and de Brito, 2005): $P = 2$ (the technique fulfils the criterion), $P = 1$ (the technique does not fully comply) and $P = 0$ (no compliance with the criterion).

The adequacy coefficient for each technique was obtained through the sum of the various criteria according to equation 1 (the bigger the sum the more adequate the technique to be used *in situ*):

$$\text{Coefficient}_{\text{adequacy}} = A + B + C + D + E + F + G + H + I + J + K \quad (1)$$

where:

- A: low equipment acquisition costs
- B: easy and swift use of the equipment
- C: significant volume of useful data

Table 2: Hardened rendering properties, acceptance criteria and methods of assessment from literature review (Flores-Colen et al, 2005)

Properties	Specification and acceptance criteria	Specifications Doc. reference	Tests methods Doc. reference
Compressive strength (R_c)	Categories: CSI ($R_c = 0.4$ to 2.5 N/mm ²), CSII ($R_c = 1.5$ to 5 N/mm ²), CSIII ($R_c = 3.5$ to 7.5 N/mm ²), CSIV ($R_c \geq 6$ N/mm ²)	EN 998-1	EN 1015-11 EN 196-1
Flexural strength (R_f)	$R_f \geq 1.5$ to 2 N/mm ² (wall with high exposure to impact loads)	Cahiers 2413, 2401 LNEC 289/95	Cahier 2669-4 EN 196-1 DIN 18555 EN 1015-11 EN 1015-18
Capillary water absorption (C)	Categories: W1 to W2 $C \leq 0.4$ or ≤ 0.2 kg/m ² .min ^{0.5} $C \leq 2$ to 4 g/dm ² .min ^{0.5} $C = 1$ to 2.5 or < 1.5 g/dm ² .min ^{0.5} (wall with high exposure to rain)	EN 998-1 Cahiers 2401, 2477, 2413	Cahier 2669-4 NF B10-502
Water permeability (W_p)	≤ 1 ml/cm ² after 48 h	EN 998-1 CSTB (1992) Cahier 2401	EN 1015-21
Dynamic elastic modulus (E_d)	$E_d \leq 7500$ to 14000 N/mm ² $E_d \geq 5000$ to 10000 N/mm ² (wall with high exposure to impact loads) $E_d \leq 10\,000$ N/mm ²	Cahiers 2401, 2413, 2477 LNEC 289/95	Cahier 2669-4 NF B10-502
Stresses induced by shrinkage (restrained)	Classification (cracking susceptibility): little ($S \geq 1$ and $R \geq 1$) or medium ($S \geq 1$ and $0.6 \leq R < 1$), where S (safety coefficient to the opening of the first crack), R (resistance coefficient to cracking evolution)	Veiga (1997)	Veiga (1997) DIN 52450
Water vapour permeability	Water vapour permeability coefficient $\mu \leq$ declared value Thickness of air layer of equivalent diffusion to 0.1 m of render $S_d \geq 0.15$ m	EN 998-1 Cahier 2401 LNEC 289/95	EN 1015-19 DIN 18555-Part I
Adhesion on substrates	≥ 0.3 MPa or cohesive fracture pattern (at least in 80% of the area)	EN 998-1 CSTB (1992) Cahier 2401	EN 1015-12 LNEC 289/95
Durability	No visible degradation after weathering cycles tests, checking compatibility of one coat rendering with substrates (adhesion and water permeability)	LNEC 289/95 EN 998-1	EN 1015-21

D: easy interpretation of the results

E: none or little degree of destruction

F: portable equipment

G: no energy source needed *in situ*

H: no need for specialised workmanship or technicians with specific training

I: reliable results

Table 3: Description of the values adopted for each criterion

Criterion	Description of the values adopted		
	2	1	0
A	if $A \leq 500$ €	if $500 \text{ €} < A \leq 2500 \text{ €}$	if $A > 2500 \text{ €}$
B	if it is easy and swift to use, i.e. maximum duration of up to 1 h	if it does not comply with one of the conditions	if it does not comply with any of the conditions
C	if it provides data on performance and degradation	if data provided is limited to one of the fields mentioned	if data is very often insufficient on both fields mentioned
D	if measurements made are rapid to analyze	if measurements require some time to analyze	if measurements made need other tests for a better interpretation
E	non-destructive technique	semi-destructive technique needing slight repair afterwards	destructive technique needing repair
F	equipment easy to carry, both in terms of dimension and mass	if it does not comply with one of the conditions	if it does not comply with any of the conditions
G	if it does not need energy or is self-sufficient	if it needs an energy source <i>in situ</i>	if it does not comply with the criterion
H	if there is no need for specific training of any of the inspectors	if at least one of the inspectors needs specific training	if it does not comply with the criterion
I	quantitative analysis	qualitative analysis	analysis depending on other results
J	if it fully complies with the criterion	if in some cases it requires the collection of <i>in situ</i> specimens for laboratorial tests	if collecting <i>in situ</i> specimens is always mandatory
K	if it fully complies with the criterion	if means of access are needed but they are relatively easy to carry to the site	if it does not comply with any of the conditions

J: no laboratory work needed

K: no means of access needed

Finally, the expedient *in situ* test techniques identified in Table 1 are compared in Table 4 taking into account the adequacy factors obtained through the use of the values for each criterion (Table 3). These criteria analyse the techniques as well as the additional works before, during and after the test.

Table 4 leads to the conclusion that most techniques under analysis show a good adequacy for *in situ* assessment and are rapid to use (expedient techniques). Generally, however, they do not allow a direct assessment of the performance (criterion C in Tables 3 and 4), are more prone to the characterisation of degradation and depend in excess on auxiliary means of access. The pull-off technique has the lowest adequacy factor (10 out of a possible 22) due to the low values of factors B (the preparation procedures, the time to cure the resin, the test execution and the repairs can take more than one day), E (high degree of destruction),

Table 4: Comparison between *in situ* test techniques (list non-exhaustive) applied to outer rendering, using weight factors and determining the adequacy to *in situ* assessment of the techniques

<i>In situ</i> test technique	Comparison criteria											Adequacy factor
	A	B	C	D	E	F	G	H	I	J	K	
T1	1	0	2	2	0	0	0	1	2	2	0	10
T2	1	2	1	0	2	2	2	2	1	2	1	16
T3	0	1	2	2	1	1	2	2	2	2	0	15
T4	0	2	1	0	2	2	1	2	2	2	1	15
T5	2	2	0	2	2	2	2	2	0	2	1	17
T6	1	2	1	2	2	2	2	2	2	2	1	19
T7	1	2	0	2	2	2	2	2	2	2	2	19
T8	2	2	1	2	2	2	2	2	1	2	1	19
T9	2	2	1	2	1	2	2	2	1	1	1	17
T10	1	1	1	2	1	2	2	2	2	1	1	16
T11	1	2	1	2	1	2	2	2	2	1	1	17
T12	1	2	1	1	2	2	2	2	1	1	1	16
T13	2	2	1	1	2	2	2	2	1	2	2	19
T14	2	2	1	2	2	2	2	2	2	2	1	20
T15	1	2	1	2	2	2	2	2	2	2	1	19
T16	0	2	2	2	2	2	2	2	2	2	1	19

F (the equipment that was used is not easy to carry, even though there are other lighter pieces of equipment on the market), G (an energy source is necessary to create the test core) and K (means of access are necessary). This technique is nevertheless recommended especially for claddings instead of other more complex test techniques (not analysed within this study), because it allows a direct correlation with the minimum requirements of EN 998 (CEN, 2003).

Therefore, it is important that the inspector decides what is more relevant for the analysis in each case, knowing the limitations of the available techniques. The adequacy factors of these techniques, or of others not referred to in this paper, can be adapted by the inspector by modifying the weight of each criteria according to its importance to the analysis (eg in certain cases the absence of means of access to the building is very limiting to the choice of *in situ* techniques).

CONCLUSIONS

It is always better to perform *in situ* tests in conjunction with a visual inspection instead of resorting only to the visualisation of the problem. The simultaneous use of various test techniques facilitates the interpretation of the results and minimises some of the shortcomings of this type of test (confusing and hard-to-interpret results and subjective judgments by the inspectors).

In this paper a methodology to support the choice of various *in situ* test techniques was proposed, by analysing 16 expedient techniques currently used in the diagnosis of rendered façades: pull-off, pendulum hammer, *Martinet-Baronie* device, ultrasounds, infrared thermometer, infrared radiation pyrometer, thermohygrometer, *Karsten* tube, colorimetric strips, field kit, pH/conductivity/overall salt content measurement, humidimeter, binoculars, cracks gauge, optical microscope and colorimeter.

This methodology included the classification of the techniques under analysis according to the principle they are based on: mechanical, ultrasonic, thermic, hydrodynamic, chemical, electrical or sensorial. It also included the characterisation of the techniques in terms of data collected, in-service performance assessment, anomaly detection and estimation of maintenance needs. It was concluded that these expedient techniques analysed presented a large spectrum in terms of the parameters mentioned and therefore, to a great extent, their selection depends on the inspector's main objectives. In order to give rational tools for this selection, a set of criteria was presented with which the techniques were rated. It was concluded that this rating, even though helpful, may exclude techniques which for some purposes are indispensable (eg the pull-off test). This rating could be improved either by using different weights for each criterion or by making some criteria eliminatory in certain cases.

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