Experience feedback of repair techniques for wharves in the tidal area: the MAREO project

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EXPERIENCE FEEDBACK OF REPAIR TECHNIQUES FOR WHARVES IN THE TIDAL AREA: THE MAREO PROJECT

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ABSTRACT

Ageing of concrete structures located in coastal environments is very actual challenge since a lot of them have been built from 30 to 50 years ago. Three main challenges are faced by companies and owners: diagnosis, reassessment and repair. The paper focuses on the last one and more precisely, on the repair of concrete beams of wharves in the tidal area. In fact, this zone is the point of confluence of a modeling challenge (non saturate conditions), a repair technique application (repair during the low level tide) and a real stake (most of the beams of concrete wharves located in this area).

1 INTRODUCTION

Concerning repair of concrete for marine structures, european standards offer the basis in terms of requirements in predefined and standardized conditions. However, repair of wharves is performed in harsh conditions: access, humidity, position of the operator for instance. These conditions move the real works away from the standardized ones. By accounting for these requirements, the repair technique consists in: (1) to rebuild the concrete cover and in some cases (2) to use protective coating for some beams. We focus here on the first point. The aim of Mareo project (French project of competitiveness group for civil engineering) is to compare several repair techniques carried out in the most difficult area for repair: the tidal zone. The project focuses on four criteria: initial performance, sustainability, durability, cost.

This paper focuses on the experience feedback of three repair techniques carried out in real conditions of works. The comparative study is carried out on twelve beams that were part of the structural system of a port built in 1927 at Lorient, France and demolished in 2006. The comparative test consists in to subject the repaired beams to controlled tidal cycles during the following years.

Since the study is principally addressed to compare the repair techniques independently of products it is preferable to use products of similar composition. This requirement is also important to calibrate the future destructive and non-destructive tests. The selected repair techniques should be applicable to large-scale projects; therefore the local “patch” repairs are beyond the scope of the study.

The choice of the repair techniques/products should consider that the structural components to be repaired are located in the splash and tidal zones (e.g., beams and piles of quays). The selected techniques were: wet shotcrete, dry shotcrete, formed concrete and manual repair.

This paper focuses on three criteria to compare these techniques: sustainability (including water consummation, transport of materials, …), cost, efficiency.

2 MAIN STAKES OF REPAIR OF WHARVES IN FRANCE

Social and economical stakes: Why this project?

564 various types of ports can be found along the French coastline, 60% of which were built before 1955 (see Figure 1). Various techniques have been used during the last century. Boero *et al* (2009) have shown that the most current one in France in the seventies and eighties was the on pile supported wharf made on steel piles and a concrete platform supported by concrete beams. Figure 2 presents the distribution, in linear kilometres, of the construction techniques used for the berthing and mooring’s structures. They are

classified from right to left in order of chronological appearance but, after the six first ones, techniques coexist.
The great majority of the structures are masonry, followed by concrete blocks, reinforced-concrete caissons, steel piles supported wharves, steel sheet piles seawalls and diaphragm walls. This figure illustrates the inventiveness of engineers confronted with the challenges of designing maritime structures; however it also means that owners are faced with delicate management decisions with regards to the principles of mechanical functioning and multiple failure modes.

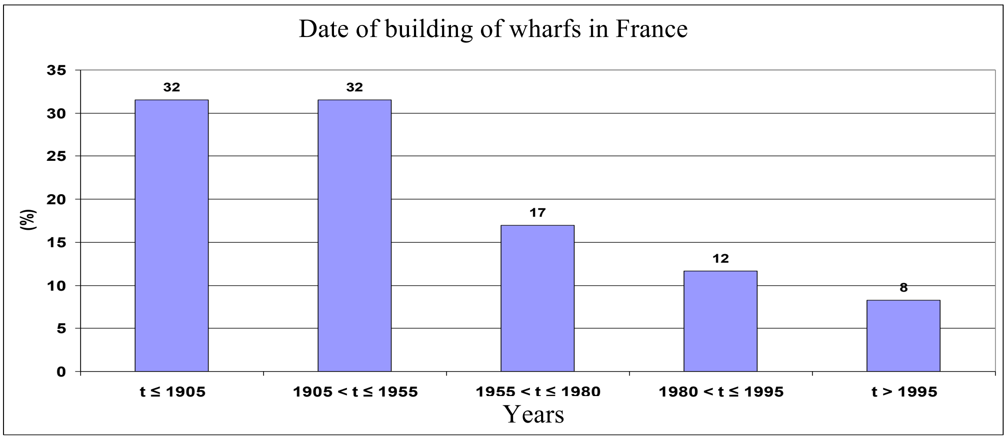

Figure 1. Date of building of wharves in France (Source: project GEROM (OXAND-GeM) 2005-2008).

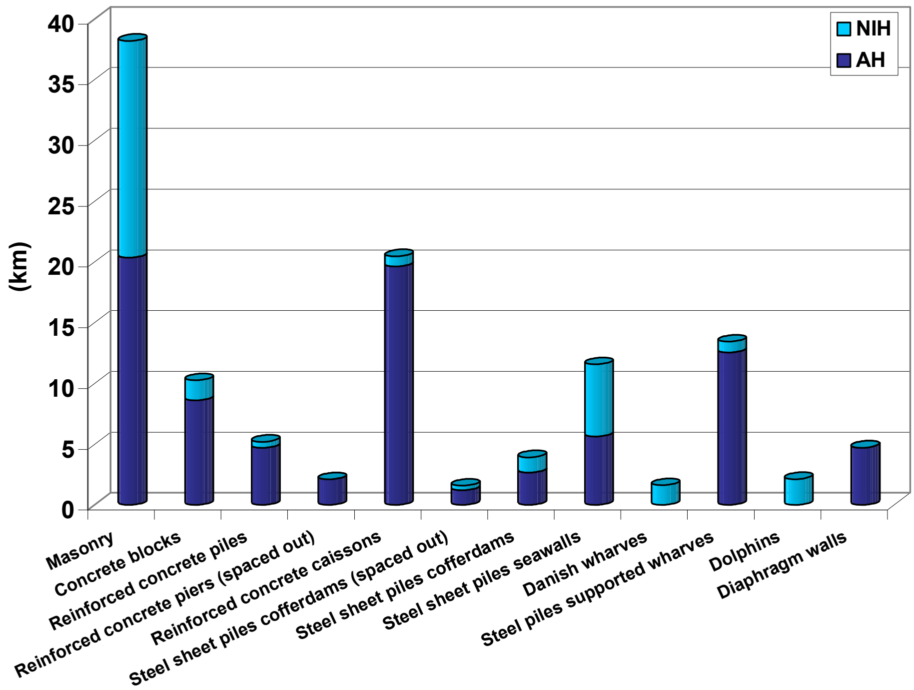

Figure 2. Distribution of construction techniques of berthing and mooring structures in Autonomous Harbours (AH) and National Interest Harbours (NIH) according to Boero *et al.* 2009.

In this context, the patrimony to maintain is larger than the patrimony to build. Environmental considerations have raised important questions regarding the new developments and decommissioning of existing infrastructure. Maintenance planning optimization is therefore a major challenge, with multiple constraints imposed by tourism, economical and environmental considerations.
Infrastructure owners must optimizing actions even if the choice of multiple technical solutions is complex, due to the lack of accurate and reliable knowledge on the performance of these techniques and their evolution with time.
Taking these considerations as its basis, the MAREO project (2008-2010, French project supported by PGCO (West Competitiveness Pole for Civil Engineering), French Government, and French west district ‘Pays de la Loire’) has been developed with objectives to:

- Compare the efficiency of repair techniques on concrete structures in coastal regions, within the global context of reassessment of repaired structures. The project therefore relies on global methodologies for risk analysis and assessment.
- Identify and quantify uncertainties and hazard sources in assessing the performance functions.

The partners are: French laboratories (GEM, LCPC, IFREMER, CERIB, LMDC, CETE de l'Ouest), companies (SEMEN-TP, ETPO, ARCADIS-ESG), risk analysis societies (OXAND), owners (CG44 et PANSN (associated members)), and international laboratories (Trinity College of Dublin (IRELAND)).

Scientific stakes:

The research is performed at several levels:
- Identify performance indicators of structures with a view to prescribing condition based criteria.
- Investigate exhaustively evaluation chains, direct or indirect, of these indicators and compare them in terms of risk analysis. This implies particularly to consider modeling uncertainties and to propose other models based on non-deterministic approaches (for example probabilistic: physical or analytical response surfaces) and to identify uncertainties on performance indicators or influential factors and thereby to characterize the so-called intrinsic hazards.
- Outline experimental devices and protocols, in laboratory or on site (pilot building sites), with controlled conditions of measurement; identify failure mechanisms.
- Suggest computational methods coming from previous works for re-engineering. Develop a methodology for semi-probabilistic analysis through pilot studies (20 x 80 years old beams repaired and tested, repaired structures from harbors (PANSN) and general council (CG44), repaired beam with composite sticking).

Economical expectation from the project results:

Currently the rehabilitation market represents half of the building trade activity and a significant percentage of public works. Companies consider that as in the building trade, the rehabilitation activity will develop in the public works field and may reach a volume near that of new works.
Owners of structures are waiting for validated methodologies, service societies require tested models and services and contractors need guidance on optimized techniques.

3 SELECTION OF MATERIALS IN THE MAREO PROJECT

Since the study is principally addressed to compare the repair techniques independently of products it is preferable to use products of similar composition. This requirement is also important to calibrate the destructive and non-destructive tests.
The selected repair techniques should be applicable to large-scale projects; therefore the local "patch" repairs are beyond the scope of the study.
The choice of the repair techniques/products should consider that the structural components to be repaired are located in the splash and tidal zones (e.g., beams and piles of quays). That means that work conditions are very difficult: in some cases the repair should be applied in 6 hours with a very quick efficiency.

French standards:

The series "special products for hydraulic concrete constructions" encompasses the French standards in this field. These standards deal the following issues:
- P18-821: Hydraulic binder based leveling and sealing products.
- P18-822: Synthetic resin based leveling and sealing products.
- P18-840: Synthetic resin or hydraulic binder based products or products systems intended for hardened concrete surface repairs.
- P18-870: Synthetic resin or hydraulic binder products or products systems for structural bonding between two concrete elements.
- P18-880: Products based on synthetic resins or binders for injections into concrete structures.
- GA P18-902: Application guide - Products and systems for the protection and repair of concrete structures - Recommendations for the selection of surface protection systems for concrete intended for the works of civil engineering.

European standards:

From 1st January 2009 the French standards concerning to products and methods to protect and to repair reinforced structures will be substituted by the European standard EN 1504 called “Products and systems for the protection and repair of concrete structures – Definitions, requirements, quality control and evaluation of conformity”. This standard is divided into ten parts:

- Part 1: Definitions.
- Part 2: Surface protection systems for concrete.
- Part 3: Structural and non-structural repair.
- Part 4: Structural bonding.
- Part 5: Concrete injection.
- Part 6: Anchoring of reinforcing steel bar.
- Part 7: Reinforcement corrosion protection.
- Part 8: Quality control and evaluation of conformity.
- Part 9: General principles for the use of products and systems.
- Part 10: Site application of products and systems and quality control of the works.

Selection within the MAREO project:

By accounting for the requirements described in before paragraphs, the repair technique consists in: (1) to rebuild the concrete cover and (2) to use protective coating for some beams. For all the beams, the contaminated concrete was removed using high-velocity water jets (hydrodemolition). Figure 3 shows a beam after hydrodemolition and the different techniques used to rebuild and increase the cover (from 3 cm to 5cm). The selected techniques were: wet shotcrete, dry shotcrete, formed concrete and manual repair.

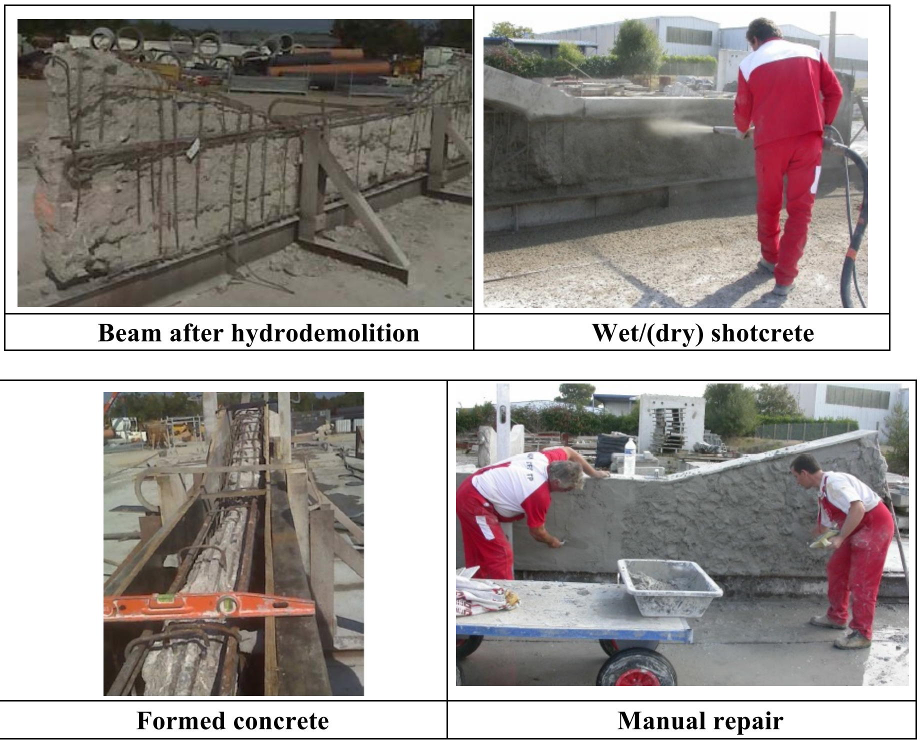

Figure 3. Adopted repair techniques during MAREO project.

4 SELECTION OF SPECIMENTS AND EXPOSURE CONDITIONS

When considering natural exposures like marine environment ones must select with care the specimens and the testing protocol. First it was decided to perform both accelerated and non-accelerated tests. For non accelerated tests, a controlled tide (pure sinusoid) has been obtained in an external basin at IFREMER (Brest city) and a pure natural exposure is considered in the Nantes Harbour. Accelerated tests

are made in the CERIB laboratory by immersion of 2 to 3 centimeters depth of a slab during 6 hours and a drying with a ventilator during 18 hours. Thus 4 types of specimens are considered.
- slabs (40cm x 40cm x 12cm) for accelerated tests. Their dimension allows performing all Non Destructive Tests (NDT);
- slabs (50cm x 50cm x 15cm) for mechanical and physical characterization and calibration of NDT tools;
- concrete beams placed in basins, in controlled tide;
- real wharf in natural conditions.

Concerning concrete beams (Figure 4 and 5, table 1), they were part of the structural system of a port built in 1927 at Lorient, France and demolished in 2006. Figures 1 and 2 present the beams before repair and indicates their designation. The comparative test consists in to subject the repaired beams to controlled tidal cycles during the following years. Twelve beams have been repaired: small beams Po have the size: 20x30*150 and large ones, 60*30*470.

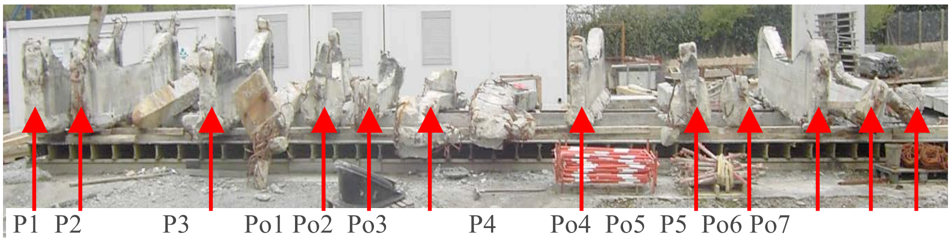

Figure 4. Beams after 80 years of exposure.

Figure 5. Scheme of beam P1 before repair.

Table 1. Beams and corresponding repair techniques

Beam	Repair technique
P1	Formed concrete
P2	Wet shotcrete
P3	Dry shotcrete
P4	Manual repair
P5 (reference sample)	Without repair
Po1a	Wet shotcrete
Po1b	Wet shotcrete

5 FIRSTS RESULTS

The study case concerns the Agri-foodstuffs terminal of the port of Nantes Saint-Nazaire, a structure subjected to chloride-induced corrosion. The Autonomous Port of Nantes Saint-Nazaire is the government agency managing the harbor activities of this structure. This agency observed a generalized problem of corrosion affecting mainly the RC beams and decided to perform a large-scale repair (Rosquoet et al., 2006).

This terminal is part of the port of Nantes Saint-Nazaire (fourth largest port in France) which is linked to 400 ports worldwide. With a maximal draught of 14 m, the Agri-foodstuffs terminal plans to receive big tonnage ships as container carriers (50,000 Ton). The Port of Nantes Saint-Nazaire is the French market leader for cattle feed imports with nearly 60% market share. There are four berths at the Agri-foodstu s terminal, which also handles fertilizers, peat, cement and other miscellaneous industrial bulk products. This wharf was built in 1971 and is located at the west of France (Montoir de Bretagne) in the estuary of the Loire River.

Assumptions for random variables and stochastic processes

Let us now compare the techniques within an optimization framework in the context of sustainable maintenance. A computational comprehensive model of chloride ingress in un-saturated environment has been developed and is presented in Bastisdas *et al.* 2010. Table 2 gives the description of random variables and the probabilistic model based on the review of publications (Saetta *et al.*, 1993) and the first results of the MAREO project (Villain *et al.*, 2010). The environment – temperature, humidity and environmental chloride concentration - is modeled as a stochastic process. Trajectories are plotted on figure 6 (see Bastisdas *et al.* 2010 for details): they are based on classical assumptions along european Atlantic coasts. The stochastic process of chloride ingress is simulated and coefficients of Markov Matrix are assessed. The corrosion is initiated and repair is performed if, respectively the thresholds C_{th} = 2.56 kg/m3 with COV[C_{th}]=0.20 and C_{rep} = 1.2 kg/m3 are exceeded. Note that imperfect inspection is modeled too but is not discussed in the paper (see Bonnet *et al.*, 2007).

Table 2. Random variables for modeling chloride ingress

Variable	Units	Distribution	Mean	COV
$D_{c,ref}$ (original material)	m^2/s	log-normal	3.0×10^{-11}	0.2
$D_{c,ref}$ (formed concrete)	m^2/s	log-normal	4.5×10^{-11}	0.2
$D_{c,ref}$ (wet shotcrete)	m^2/s	log-normal	2.0×10^{-11}	0.2
$D_{c,ref}$ (dry shotcrete)	m^2/s	log-normal	1.8×10^{-11}	0.1
U_c	kJ/mol	beta on [32;44.6]	41.8	0.1
m		beta on [0;1]	0.15	0.3
$D_{h,ref}$	m^2/s	log-normal	3×10^{-10}	0.2
α_0		beta on [0.025;0.1]	0.05	0.2
n		beta on [6;16]	11	0.1
λ	W/(m°C)	beta on [1.4;3.6]	2.5	0.2
c_q	J/(kg°C)	beta on [840;1170]	1000	0.1
ρ_c	kg/m^3	Normal	2400	0.2

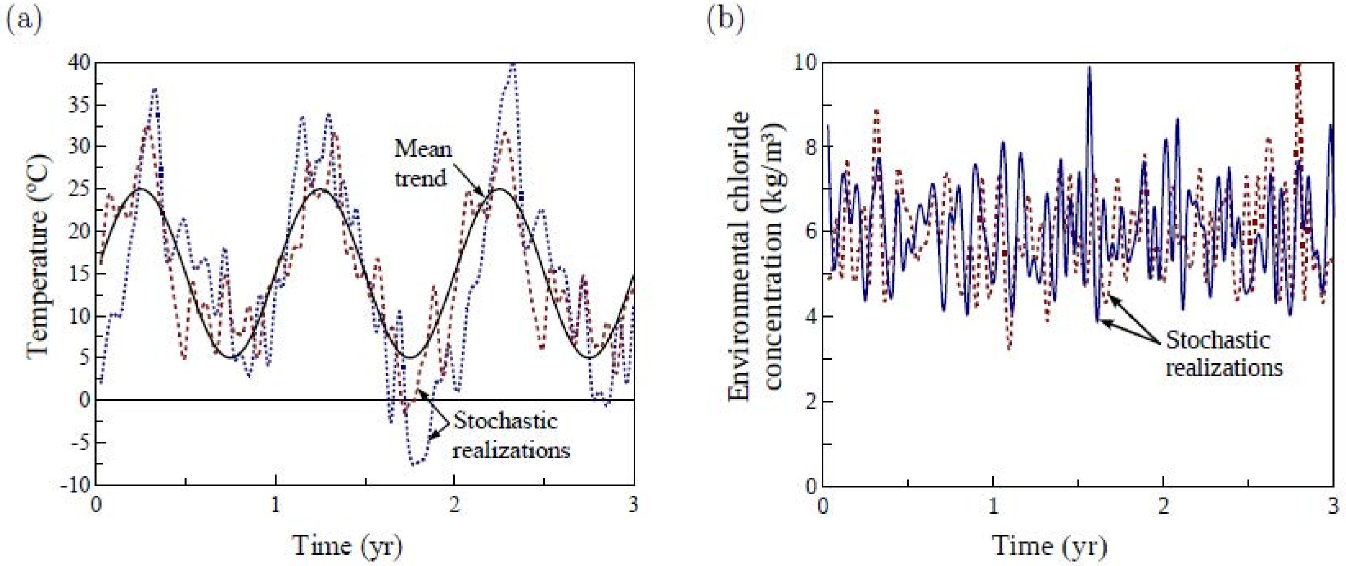

Figure 6. Stochastic inputs of: (a) weather (temperature, humidity), (b) environmental chloride concentration.

Assumptions for costs and wastes

Assumptions concerning costs of works and relative costs (coefficients applied on C_0) are given on table 3.

Table 3. Computed agency costs and coefficients for cost models

Item	Wet shotcrete €	Dry shotcrete €	Formed concrete €
Hydrodemolition	1500	1500	1500
Recovery, treatment and disposal of waste	172	172	172
Materials	1309	828	250
Labor	685	418	192
Equipments	183	210	94
Total	3848	3128	2208

Parameter	Repair technique		
	Formed concrete	Dry shotcrete	Wet shotcrete
Initial cost of construction, C_0	1000	1000	1000
Inspection coefficient, k_I	0.005	0.005	0.005
Repair coefficient, k_R	0.15	0.21	0.26
Failure coefficient, k_F	0.30	0.42	0.52

Parameters used for CO2 emission computation are given in table 4 and waste generation lies on the expert judgment: dry shotcrete requires a higher quantity of material (30% of waste generation) increasing the emissions of transportation and production.

Table 4. Assumptions for CO_2 emission

Variable	Value
Capacity of the transportation vehicle, V_t (m^3)	8
Volume of concrete to repair, V_r (m^3)	65.7
Expansion factor, γ	1.3
Distance of provisioning of repair materials, L_m (km)	100
Distance of disposal of waste, L_d (km)	150
Distance of provisioning of equipments, L_e (km)	100
CO_2 emissions of the transportation vehicle, ν_t (kg CO_2 per km)	1.7
CO_2 emissions for production of cement, ν_p (kg CO_2/ kg of repair material)	0.83
Content of cement per m^3 of concrete, c_c (kg/m^3)	400

Results of optimization

The multi-objective index (MOI) is used for research of the optimal maintenance strategy (Lounis, 2006). The procedure using Markov chains is presented in Sheils *et al.*, 2009. The assessment of the MOI assumes that the agency's policy gives weighting factors of 0.5 for costs (w_C), 0.25 for waste (w_W)and 0.25 for CO_2 emissions (w_E). We focus here on one result mainly: the over-cost due to the accounting of environmental criterion. For that the cost factor varies between 0.2 and 1 and the factors for CO_2 and waste are equal and such that the sum equals 1. The cost weighting factor $w_C = 1$ implies that the decision is controlled only by costs. In this case, environmental constrains are not considered, and then, the overcharges are zero. On the contrary, for $w_C = 0$, the overcharges lead to a constant value determined at a larger inspection interval where the repair rate is minimum (i.e., Figure 7). For the range of cost weighting factors presented in Figure 7, the maximum overcharges vary from 10% to 12% depending on the characteristics of each the repair technique. If the agency decides to give equal importance to economical and environmental criteria (i.e., $w_C = 0.50$, $w_W = 0.25$ and $w_E = 0.25$) the overcharges are lower than 6% for all the cases. This means that including environmental constrains in decision making does not generates larger overcharges.

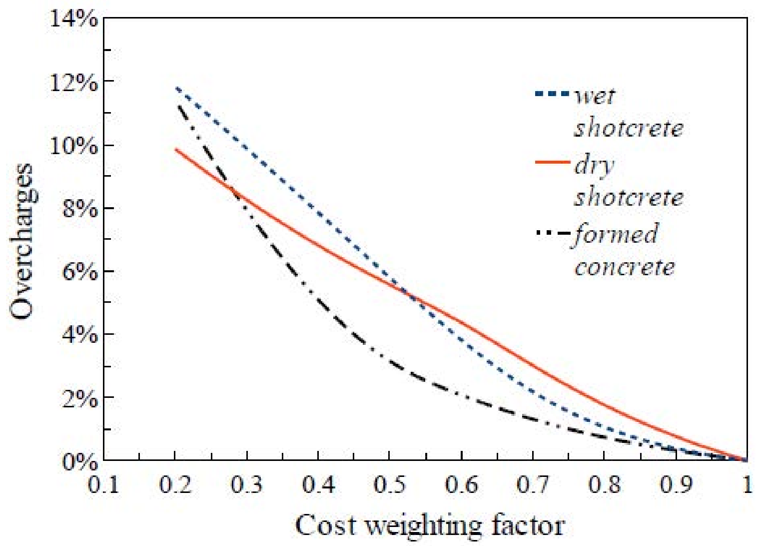

Figure 7. Overcharges produced when environmental criteria are considered.

CONCLUSIONS

The analysis of repair efficiency for concrete beams in unsaturated conditions is still a challenge. MAREO project suggest improvements in three main axis:

- the stochastic modeling of material properties and environmental conditions;
- new data for repair techniques efficiency;
- optimisation accounting for sustainable criterion.

The paper provides both the methodology and results concerning this project. Moreover the method is shown to be efficient when comparing repair techniques when environmental constrains are accounting for. It is shown that, within an optimal policy, these constrains lead to an over-cost less than 6% whatever the repair technique.

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