# COMPATIBLE MORTAR FOR MASONRY RESTORATIONS: DISCRETE OPTIMIZATION FOR EQUIVALENT STRENGTH & COLOUR PRESCRIPTION

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## ABSTRACT

Masonry is a smart constructive system that is used for centuries in many places around the world and is then widely encountered in many structures to be rehabilitated. The preservation requires a compatibility between parts of the masonry that will be conserved and parts of it that should be replaced because of the rehabilitation process. In most of the cases, compatibility problems are recognized concerning the formulation of mortars that will be used for repairing joints after any operations: a not sufficient compliance may have a negative impact on the durability of the intervention. In classical cases, five key parameters should be considered: the Modulus of Resistance - MOR, Modulus of Elasticity - MOE, the water (liquid and gas) permeability, the colour and the texture. On one hand, architects typically insist on aesthetical aspects as they intend not to alter the perception of treated buildings. Replicating a satisfying texture is achieved by acting on sand granularities and pointing tools. Hence, the colour problem should be approached by expensive trial and error procedures. On the other hand, engineers privilege mechanical aspects for avoiding progressive damages induced by stress concentrations. Satisfying values of MOR and MOE can be obtained by relying on published empirical recipes. Gathering both these philosophies inside practical projects is time expensive and remains currently reserved for the rehabilitation of Heritage monuments. With regard to the durability notion, it could be interesting to extend it to most of the project. The present paper describes a computer-aided framework (automatic tool) having recourse to an elitist genetic algorithm in order to establish a mortar formulation that should be, in a near future, likely to take five characteristics into account. In its preliminary shape, the integration of strength and colour aspects is treated. The global framework in which the reflexion should be posed, the optimization problem as well as the sharp manner to take each aspect into account are detailed.

KEYWORDS: masonry, compatibility, mortar, colour, strength, optimization, heritage, chromameter, cutting test

## 1 INTRODUCTION

The rehabilitation of masonry structures constitutes a key challenge for civil engineers and architects in the 21$^{st}$ century. In fact, the civil authorities have understood the ecological aspects associated with a renewed exploitation of built landscapes instead of a fevered recourse to systematic expansions. In this framework, they have decided to support wide preservation or restoration campaigns on existing buildings or monuments. This paper concerns the key problem of mortar compatibility in the rehabilitation of masonry systems. In most of interventions that may be carried out on existing masonries, the recourse to a restoration mortar will be unavoidable. After a short presentation of useful considerations, the paper describes potential risks associated with the non compatibility of restoration mortars. The focus on four fundamental characters playing a key role is proposed: the **strength** aspect important for engineers, the **colour** aspect important for architects as well as the **permeability** (associated with air and water migration) or the **rigidity** (associated with stress repartition) are treated and the usually associated pathologies are described and illustrated. For each of them, the possibility to use on-site little destructive tests for collecting values is also proposed: they will allow determining the target of the complying formulation process.

## 2 INTERVENTIONS, COMPATIBILITY AND DURABILITY

Although it is recognized to be robust, the masonry material will generally suffer the effect of ages: various phenomena are likely to alter, along the centuries, the stone or clay units as well as the mortar joints. The level of affectation will highly depend on constitutive materials (nature of stone blocks, quality of clay bricks) and on the environment in which the building has been erected. In most rehabilitation projects intending to offer a new life to existing masonry buildings, several interventions will take place that will require material to be brought (bricks or blocks replacement, bays closure, joint filling after middle pressure cleaning). Replacement masonry units are available: good state specimens may be collected on the site or elsewhere and re-used. For maintaining them together and, most of all, for ensuring a convenient load transfer (avoiding stress concentrations) between them, mortar is necessary. Unfortunately, it is by nature impossible to re-use any existing mortar, what explains the key role played by this material in the compatibility problem. Incompatibility associated with not complying mortars is acknowledged as a cause for several families of problems. A not convenient value of **strength** or **rigidity** may lead to evolving mechanical damages affecting either the mortar joint or the units (bricks/blocks edges). A not convenient **permeability** may induce durability problems associated with freeze-unfreeze phenomena. In each case, the pathologies will affect the masonry material some time after the intervention but will have a wide scale impact. Damages to the mortars are reversible: everything should be removed and the intervention should be financed again. That is far to be the case for damages affecting the stone or clay units: everything that is damaged will remain damaged. A not convenient **colour** may have an aesthetical impact on the visual perception of the building. This aspect essentially concerns Heritage buildings recognized by the civil authorities or international organisations (UNESCO) for which preservation guidelines should be strictly followed. Architects, historians and archaeologists are very sensible to this aspect and their considerations will often find an echo with people engaged in touristic management.

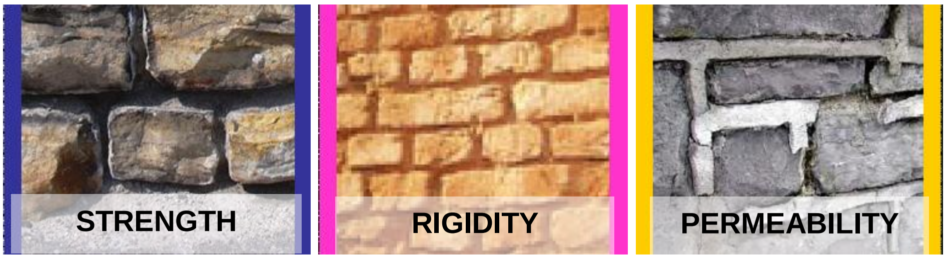


Figure 1: Potential pathologies associated with bad compatibility

## 3 QUICKLY ESTABLISHING THE ID-CARD OF A MORTAR

Achieving a convenient compatibility between the mortar that is used in the building and the one that will be used in interventions requires disposing of reliable tools for documenting the existing situation. Such tools should be likely to collect information on limited size samples. The present paper focuses on techniques used at the University of Mons (Belgium). By combining them, it is possible to get target values that should be taken into account during the prescription of a complying restoration mortar.

The **cutting test**, transposed from the petroleum industry, allows collecting a local value of the intrinsic specific energy that is correlated with the uniaxial compressive **strength** of a geo-material. The approach relies on the interpretation of a force signal that is recorded as the automatic testing device traces a groove at the surface of the material (translational cutting) or drills a hole inside the material (rotational cutting). The initial theory has been developed at the University of Minnesota (USA) and later improved at the University of Mons (Belgium). The technique as well as its strong and weak points has been widely discussed elsewhere [1] [6].

A method relying on a **luxmeter-chromameter** in order to get reference **colour** data for existing mortars has been developed at the University of Mons. The role of the “eye” is played by a luxmeter-chromameter, a measuring instrument that classically permits to determine colours of incident lights. Main advantages of it are the portability, the robustness and the low cost as it is widely used by lighting practitioners. The measures will concern the light that is reflected by the sample after that it has been impacted by the ambient light source, what confers to the luxmeter-chromameter an analogy with the human eye. In the framework of lab measurement, a black room may be used for allowing precise controls of luminosity and chromaticity for ambient light and specific diaphragms may be developed for precisely focussing on the exposed surface of limited size mortar samples. The role of the “brain” is played by a set of computer algorithms that permit to interpret the raw information outlined by the luxmeter-chromameter into digested information (CIE L*a*b*, CIE xyY, NCS, Pantone) or on-screen representations of the colour that are immediately usable by architects or engineers. A benchmarking procedure has assessed the validity of the proposed method[1].

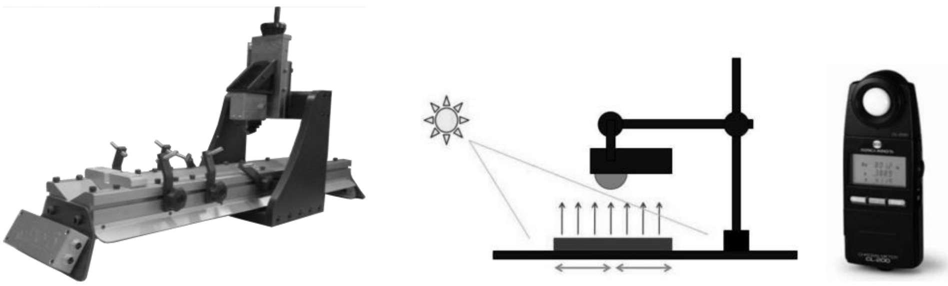

Figure 2: MOR test device (left) and colour test device (right)

As a complement, it could be mentionned that physical considerations associated with water (liquid and gas) **permeability** may namely be obtained by collecting micro-porosity data with a combination of carbon- and helium-volumeter. For mechanical considerations concerning the **rigidity**, as the sonic velocity inside a material is correlated with the dynamic (and later static) MOE, a sonic impulse device relying on exponential captors characterized by their reduced area of contact definitely allows limited size samples to be tested. Both these last approaches are commonly used at the University of Mons [1] [9] although permeability and rigidity aspects appear out of the scope of the present paper.

[1] Different colour samples have been analysed with the luxmeter-chromameter in the black room, providing xyY colorimetric coordinates. In parallel, the spectrum of each sample has been identified with a spectrophotometer and later converted into xyY coordinates, allowing a comparison.

# 4 COMPUTER-AIDED DECISION IN MORTAR FORMULATION

## 4.1 PROBLEM PRESENTATION

People engaged in rehabilitation processes have got the possibility to easily collect information concerning the mortar involved in the masonry system. This quick operation may be carried out from several places in the building, as ancient building have rarely been erected during one single phase and as material provisioning may have been variable. Aware of the main parameters that should be targeted for the restoration mortar, the problem is now to determine to what an extend it is possible, with the range of aggregates (sands of various origins) that are commercially available in a given area, by mixing them with a binder and water, to obtain a material whose properties will be closed to the targeted ones. In such a framework, the subjective trial and error approach that is usually followed by practitioners appears as time expensive and the recourse to a computational tool appears as interesting. For each aspect (MOR, colour, permeability, MOE), the problem consists in reducing the gap between the value of the proposed formulation and the targeted value obtained from existing samples. Further than such a multiple objective, several technical constraints remain as a formulation should always remain in a meaningful range (proportions refer to a mortar).

## 4.2 INTEREST OF NSGA II ALGORITHM

The multi-objective optimization with genetic algorithm concerns the solving of problems where M objective functions $f_m$ have to be minimized while admissible solutions have to verify J+K constraints $g_j$ and $h_k$. A solution x to the problem is a vector composed with n design variables $x = [x_1, x_2, \ldots, x_n]^T$ where $x_i$ has to stay inside an imposed range of values.

$$
\begin{array}{ll}
\text{min/max} \quad f_m(x), & m=1,2,\ldots,M\ ; \\
g_j(x) \geq 0 & j=1,2,\ldots,J\ ; \\
h_k(x) = 0 & k=1,2,\ldots,K\ ; \\
x_i^{(L)} \leq x_i \leq x_i^{(U)} & i=1,2,\ldots,n.
\end{array}
$$

Genetic algorithms are part of evolutionary strategies and rely on the principle of natural selection: each generation will produce too much individuals with regard to the welcoming environment, some of them will die and the survival probability depends on the adaptation of the individual. Developed some years ago, the Elitist Non-Dominated Sorting Genetic Algorithm (NSGA-II) is particularly efficient as it allows preserving the diversity inside the population. It relies on several “natural operators”.

**Evaluation** allows quantifying the adaptation of any individual with regard to the objective functions. It will be coupled with a ranking procedure that will allocate a rank to each individual depending on its dominance level and define fronts (Rank #1 for high-performance non-dominated individuals) A crowding distance is calculated for each individual of each front and will be used for increasing the diversity of the population during the sorting.

**Selection** and **replacement** allow eliminating individuals through a non-dominated sorting organized by paired evaluation. A mating pool, some kind of population with a globally higher quality, will be constituted by gathering individuals belonging to the best fronts (lower rank) and later completed by other individuals (other rank and/or higher crowding distance) in order to maintain the diversity of the population.

**Crossing-over** and **mutation** allow randomly exploring the space. Two parents from the mating pool will be imposed (probability Pc) a crossing-over by exchange between fragments of chromosomes, combined (probability Pm) with a mutation by very locally modifying the value of a gene. The local-global considerations should be taken into account in order to avoid converging towards a local optimum.

### 4.3 PRACTICAL IMPLEMENTATION INSIDE MATLAB ENVIRONMENT

For the present study, the authors propose considering an intuitive approach: so many mortar recipes are the solutions x expressed through n design variables that are the types and relative proportions of mortar constituents (type and quantity of sands, type and quantity of cement and quantity of water). Two families of design variables are required. With three discrete variables, it is possible to define one type of binder and two types of sands for a given mortar. With two bits by binder and three bits by sand, it is possible to get a choice among a library gathering 4 binder types and 8 sand types with the required properties. These discrete variables will be associated with continuous ones indicating the quantity of sand, binder and water. The initial population is created by a randomized allocation of values for each variable, giving birth to N individuals. In practice, the population of mortar recipes is likely to evolve and later converge towards an optimal mortar formulation meeting the constraints and approaching as close as possible the targets. For the selection and replacement processes, the individuals are randomly picked by pair and compared together. The best one is placed in the mating pool. A parent that will not fulfil the entirety of constraint will be rejected, except if the other one violate still more the constraints. If both individuals verify the constraints, the one with the lowest rank will be chosen. If they present the same rank, the one with higher crowding distance will be chosen. For the crossing over and mutation processes, binary (discrete) as well as real (continuous) variables may be concerned. For the evaluation process, as the present paper tries to reach a targeted value of strength as well as a targeted value of colour, the evaluation of each individual will consider two objectives: respectively minimizing the gap between the strength (colour) value of an individual and the targeted strength (colour). The constraint functions express the necessity for the sum of each sand fraction of volume to remain under 100 % and the fact that a minimum value of binder is required for being representative of a mortar. In practice, the evaluation process requires objective functions to minimize the gap between the target and each mortar associated with a set of design variables. Therefore, it is necessary to be likely, for any set of design variable (i.e. given proportion of sands, cement and water), to associate an expected value of strength or colour[2]. This clearly requires the establishment of mixing laws. For strength aspects, the authors propose to rely on the De Larrard theory while the Grassman theory will be followed for colour aspects. The following paragraphs describe related theoretical concepts and propose some experimental validation on lab mortars.

### 4.3.1 Managing the strength aspects in mortar mixing laws

The compressive strength prediction of mortars is a research field that is explored for a long time. The Féret approach has recently been improved. The method proposed by De Larrard, widely detailed elsewhere [3] [4] [5], implemented inside the BetonLab commercial software, is daily used in the building industry. Only notions that are useful in view of a transposition to the present problem will be summarized in the following paragraphs and the validity of the approach is then illustrated.

The strength of a concrete or a mortar may be predicted based on a sharp knowledge of the relative proportions of constituents, the 28-day strength of the cement and some other essentially granular-based data about concerned cement and sands (size of aggregate particle corresponding to 90% passing, volume of aggregate with size less than 80 µm). The method is articulated around two main stages. The **first stage** concerns the **sharp estimation of constituent volumes**. In fact, based on the quantity of sand, cement and water brought for the mixing is not sufficient for knowing the final volume of the mixture due to the given granular dispersion of sands and cement (porosity) and on the effect of water. A key notion namely concerns the volume of air that will be present inside the mixed material.

[2] Later, the approach could similarly be extended to permeability and/or rigidity aspects by increasing the number of objective functions).

Relying on respective contributions of sands and cement to the “serrage index” as well as on the density of the non aerated mixed material, such information may be computed. In the continuation of this sharp knowledge, the **second stage** establishes a **relation between** granular-based information associated with the **volumes of constituents and the value of 28-day compressive strength**.

$$f_c = 11{,}4\,.\,p\,.\,R_{c_{28}}.\left(\frac{V_c}{V_c + V_e + V_a}\right)^{2{,}85}.\ EMP^{-0{,}13}$$

Where p is associated with the nature of the sand, Rc28 is the 28-day strength of cement, Vc, Ve and Va are respectively the volume of cement, water and air per m³ mortar. The EMP value is the original contribution of De Larrard that allows taking into account the limitating effect of large pasta thicknesses between grains likely to influence the global strength.

Further than this presentation of theoretical notions, the following paragraph illustrates the validity of the method on some mortar compositions realized in the laboratory, cured during 28 days and then tested according to EN1015-11. Eight types of mortars have been studied.  For each of them, we have made 10 compressive strength testes and measure the mean compressive strength and the standard error.

| | | | Prediction | Lab measurement | |
|---|---|---|---|---|---|
| Type of sand | Volume of cement | Volume of sand | Strength | Strength Mean value | Strength Stand. Deviation |
| | [-] | [-] | [MPa] | [MPa] | [MPa] |
| Rhine | 1 | 4,2 | 8,8 | 8,84 | 0,46 |
| Rhine | 1 | 5,18 | 5,5 | 5,65 | 0,38 |
| Rhine | 1 | 6,21 | 3,7 | 4,28 | 0,27 |
| Rhine | 1 | 8,40 | 1,8 | 1,95 | 0,26 |
| Green | 1 | 2,80 | 11,5 | 11,69 | 0,45 |
| Green | 1 | 3,50 | 7,2 | 6,93 | 0,35 |
| Green | 1 | 4,12 | 4,7 | 4,82 | 0,24 |
| Green | 1 | 5,59 | 2,4 | 2,85 | 0,11 |

Table 1: compressive strength (prediction | measure) for various mortars

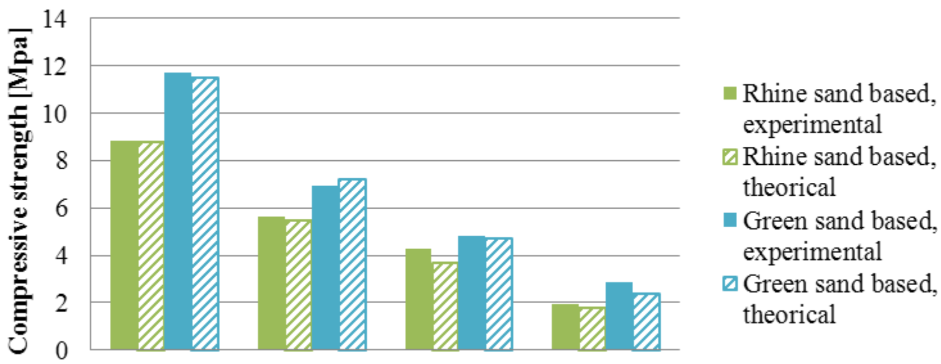


Figure 4: compressive strength (prediction | measure) for various mortars

### 4.3.2 Managing the colour aspects in mortar mixing laws

The theory of colour is governed by the superposition principle associated with the Grassmann's law expressing that any colour from the visible spectrum can be represented by an additive mixture, in given quantities, of three primary colours. Consequently, it is possible to apply the properties of additivity, associativity and multiplicity of the algebraic identities [7] [10].

The confrontation of these well-known theoretical principles with the reality of mortar mixtures in black room allowed studying, on binary and ternary mixes, the incidence of the granulometry, the water-content or even the dust pollution. Most of all, it allowed verifying the compliance with Grassmann's laws, except once specific types of refined particles (pigments) are used in a mixture[3]. For usual mortars, it is then possible to compute a 3D colour vector from the colour knowledge of base constituents (sands and cement) and their relative proportions. The prediction tool, based on the Grassmann's law, leads to satisfactory results.

Figure 5: target mortar (left), available sands (centre), obtained mix (left)

[3] A subtractive component of chromatic behaviour appears, similarly to what happens in classical painting mixes.

### 4.4 APPLICATION OF THE TOOL

For illustrating the validity of the global method proposed by the authors, a case study is proposed. It consists in establishing the recipe for a mortar that should exhibit a compressive strength of 8.29 MPa while outlining a colour expressed by the 3D vector [0,344; 0,362; 0,540] in the CIE xyY reference system. For achieving this aim, three types of sands recorded in the library of the algorithm as well as one white cement are available. The optimal formulation proposed by the algorithm is summarized in Table 2.

| | x | y | Y | Formula [% Volume ] |
|---|---|---|---|---|
| White cement | 0,325 | 0,351 | 0,860 | **13,93** |
| Rhine sand | 0,358 | 0,374 | 0,318 | **17,53** |
| Yellow sand | 0,427 | 0,423 | 0,249 | **26,75** |
| Green sand | 0,341 | 0,376 | 0,246 | **0,00** |
| Water | n.a. | n.a. | n.a. | **38,94** |
| (Air) | n.a. | n.a. | n.a. | (2,85) |

Table 2: Parameters of constituents and prescribed recipe.

## 5 CONCLUSIONS

Due to its fundamental role, the convenient formulation of mortar appears as a key for durability in rehabilitation interventions. The present paper has discussed the recourse to an elitist genetic algorithm for such a purpose. At this time, the approach is based on mixing laws integrating both the strength and the colour aspects. Concerning these laws, the recognized theoretical considerations have been experimentally validated on mortars before being used. The practical implementation of them in conjunction with the NSGA-II algorithm has been proposed and has already shown some evidence of validity. A wider-scale benchmarking campaign is in progress.

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## REFERENCES

[1] DAGRAIN F., “Présentation et application d’une méthodologie de caractérisation physico-mécanique de petits échantillons pour l’étude des matériaux du patrimoine bâti”, to be published in Archeo Sciences, revue d’archéométrie, Rennes, France (2012)

[2] DE LARRARD F., “Formulation et propriétés des bétons à très hautes performances”, Thèse de Doctorat de l’Ecole Nationale des Ponts et Chaussées, Rapport de recherche des LPC N° 149 (1988).

[3] DE LARRARD F., TONDAT P., “Sur la contribution de la topologie du squelette granulaire à la résistance en compression du béton”, Materials and Structures, RILEM, Vol. 26 (1993), pp. 505-516.

[4] DE LARRARD F., SEDRAN T., ANGOT D., “Prévision de la compacité des mélanges granulaires par le modèle de suspension solide. I : Fondements théoriques et calibration du modèle”, Bulletin de Liaison des Laboratoires des Ponts et Chaussées, N° 194, (1994), pp. 59-70.

[5] DE LARRARD F., SEDRAN T., ANGOT D., “Prévision de la compacité des mélanges granulaires par le modèle de suspension solide. II : Validations et Cas des mélanges confinés”, Bulletin de Liaison des Laboratoires des Ponts et Chaussées, N° 194, (1994), pp. 71-86.

[6] DETOURNAY E., DEFOURNY P., A phenomelogical model for the drilling action of drag bits, International Journal of Rock Mechanics and Mining Sciences. Vol 29, n°1 (1992) pp. 13-23.

[7] KOWALISKI P., “Vision et mesure de la couleur”, $2^{nd}$ updated edition, Masson, Paris (1990)

[8] LEOSKOOL L., “Caractérisation colorimétrique des mélanges binaires et ternaires : outils de mesures et de representation en vue d’une application aux mortiers de restauration”, Master thesis under the direction of Pr. Van Parys L. and Pr. Renglet M., Department of civil engineering and structural mechanics, UMONS, Mons (2011).

[9] VAN PARYS L., DAGRAIN F., LEOSKOOL L., “The recourse to cutting-based tomography for quantifying the surface strengthening of altered stones”, International Conference Durable Structures: from construction to rehabilitation, Lisbon (2012)

[10] TROUVE A., “La mesure de la couleur : principes, technique et produits du marché”, AFNOR-CETIM, France (1991)