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Mix-Design and Application of Hydraulic Grouts for Masonry Strengthening

Springer

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Preface

1. It is commonly admitted that grouting of existing masonry building elements has a merit to completely respect the initial form of the element to be repaired or strengthened, while improving its resistance and integrity. In the specific case of cultural heritage structures, the respect of the "monumentic" value of the form is of particular interest. That is why, grouting is accepted also in fissured monolithic architectural members, as well as in detached and cracked mosaics or frescoes or surface decoration jointing mortars and plasters; hence the broader significance of this method of structural intervention of existing masonry structures.

   This book has a clearly practical scope: to assist the person in charge to design and apply such grout mixes. It is however important to note that masonry grouting is a rather delicate method of structural intervention. Strength improvement is achieved only if grouts of appropriate properties reach the fine discontinuities (voids and microcracks) of the main mass of masonry; simple filling of large voids and cracks is not sufficient. That is why in several cases, masonry grouting was reported to be ineffective, due to grout mixes:

   - unable to *penetrate* into finer discontinuities, or
   - *not fluid* enough, or
   - excessively bled or segregated (i.e., deprived of *stability of the grout*).

   That is why, grout-mix-design cannot be carried out by means of rough empirical rules: The number of intervening parameters and their nature do not allow such a solution. Consequently, in order to serve its practical scope, this book should describe in detail the aforementioned performances of a correct grout, in relationship with the internal structure of the masonry. The extent of such descriptions, however, and the necessary scientific handling of the related analysis should not be considered as an unnecessary sophistication; on the contrary, it is presented in a way to help a better understanding of the related phenomena, thus contributing to the best application of this strengthening method.

By its scope, the book is addressed to a rather large audience, such as:

- Structural engineers
- Material engineers
- Chemists
- Architects
- Construction contractors
- Students in the respective disciplines
- Archaeologists specializing in restoration of monuments may also find an interest in reading a good part of this book.

2. The book attempts to contribute toward to a holistic methodology for the mix-design and application of hydraulic grouts,

   - taking into account their injectability (as well as their strength and durability),
   - considering the conditions of the masonry to be repaired or strengthened, and
   - having in mind the targeted properties of masonry after its grouting.

   To this end, the comprehensive concept of injectability is first analyzed as the resultant of three grout performances:

   - Penetrability, the capacity of the grout to pass through the effective finest width of discontinuities (voids, microcracks, interfaces, joints),
   - Fluidity, the capacity of the grout to overcome lateral frictions and to flow up to lengths larger than the distance of consecutive grout tubes,
   - Stability, the capacity of the grout to avoid harmful bleeding and segregation along its flow or when in its final place.

   Regarding the conditions of the existing masonry, a practical expression of the permeability of its mass is introduced, by means of the concept of nominal width (W_{nom}) of its fine discontinuities affecting its compressive strength.
   The required strength of the grout is roughly estimated by means of calibrated empirical formulae, based on the targeted after grouting strength of the masonry.
   Finally, durability issues are discussed, depending on both environmental conditions and chemical properties of the constitutive materials of the masonry.
   Based on these concepts, the book describes decision-making methods, resulting in the quantitative composition of the appropriate grout. Due to the multi-parametric nature of the problem, it is obvious to refer also to several preliminary tests, in order to face the inevitable uncertainties accompanying the entire procedure. However, the rationality of the followed methodology insures the rapid convergence of the whole procedure.
   The book is concluded with a long chapter, offering practical recommendations for the execution of grouting, together with indispensable quality assurance procedures.

3. A short presentation of the contents of this volume may assist the reader in understanding various aspects of the conceptual design and execution of grouting, as well as in better organizing the reading of the book.

Chapter 1 is an *Introduction* assisting the reader in understanding basic issues of the grouting technology. First, the categories (simple, binary, ternary) of grouts are presented in combination with examples of their use. Subsequently, the main performances required from a hydraulic grout are enumerated; thus, the corresponding design parameters of a grout mix become clear. A design procedure is then described, with reference to the relevant parts of the book, where the reader will find detailed assistance. Finally, it is reminded that an experimental verification of the performances of the "trial mix" has to be carried out in laboratory, and in all cases in situ, during pilot grout preparation and application.

Chapter 2 deals with the first component of injectability, i.e., the *penetrability* of the grains of the grout through the effective finest width W_{nom} of masonry discontinuities (voids, microcracks, interfaces, joints). As it is known, grouting is intended to fill voids, fissures, and open joints of the masonry as a system, producing a "dendrite" (a three-dimensional skeleton), directly contributing to the strength of the masonry as a whole. However, to do so, the grout should be able to pass through the "narrowest" possible width of such discontinuities, in order to reach the maximum possible internal volume of masonry and open joints, avoiding most of possible blockages. In the specific case of three-leaf masonries, the most decisive result of the grouting is expected to be the strengthening of the bond along the interfaces between the external layers and the infill; the rather small voids, as well as pre-existing fissures along these interfaces, have to be penetrated.

In this chapter, the penetrability of hydraulic grouts is discussed, and relationships between (i) two characteristic diameters of the grains of the solid phase of the grout and (ii) the nominal minimum width of fissures and voids of the structure to be injected are proposed. Furthermore, the beneficial role of replacing part of the cement or hydraulic lime with ultrafine materials in order to improve penetrability is presented, and related criteria are proposed. Extensive experimental verifications of the proposed quantitative models are finally offered.

Chapter 3 refers to *fluidity,* i.e., the second component of injectability of the grout: The grout should be able to easily flow along the sinuous paths of internal interconnected discontinuities, up to a distance larger than the distance between consecutive grout tubes. To this end, appropriate water-to-solid ratio (W/S), superplasticizer content (SP), and mixing technique should be selected. A new practical (but scientifically significant) fluidity measurement is proposed (the fluidity factor test—FFT); thus, a "fluidity factor" is defined. It is proved that the follow-up of this factor as a function of the water-to-solid ratio may reveal fundamental characteristics of the grout composition under design.

The influence of the mixing method and superplasticizer on grout's fluidity is also experimentally studied. The chapter concludes with a case study to highlight the practical use of the proposed test.

Chapter 4 deals with the final component of grout's injectability, i.e., the *stability* of the suspension against excessive bleeding and segregation. The grout should keep its homogeneity up to its setting, as much as possible. When the bleeding remains lower than a certain limit, the grout can be used; otherwise, the grout may be unable to flow in and adhere to the internal surfaces of the discontinuities. Similarly, because of inadequate internal cohesion, larger solid particles of the grout may quickly settle, resulting in segregation phenomena, i.e., creation of a non-homogeneous layered structure of the mix. Excessive bleeding and segregation may produce blockage of the flow and sudden dangerous increase of the pressure.

The most prevailing parameters shaping stability characteristics are water content and percentage of ultrafine materials. After a brief literature survey, an oversimplified predictive model of bleeding is firstly proposed and then its validity is confirmed using the results of an experimental study. The role of superplasticizers is also discussed. In both cases, with and without superplasticizer, semi-empirical formulae are proposed, that are useful for the design of a grout composition. Finally, the chapter presents experimental results demonstrating the role of water and superplasticizer content in the appearance of segregation; some empirical formulae are also proposed for the estimation of the critical water content initiating segregation.

Chapter 5 describes the categories of possible internal discontinuities of masonry; it is because of such discontinuities (pores, local interface detachments, local slidings, cracks) that masonry strength may be reduced. The filling of these discontinuities by means of an appropriate grout may increase masonry strength, provided that the grout was able to penetrate the body of masonry, to reach most of these discontinuities and flow along each of them. In order to decide the necessary "penetrability" capacity of the grout, a rough evaluation of a *critical value "*W_{nom}*"* of the opening of these discontinuities of masonry is needed.

This chapter examines several possibilities of quantification of such a representative opening value for several categories of masonry. Finally, an easy to apply practical approach of "opening classes" is proposed, and relevant examples are given. Thus, for each specific case, the selection of grout solids' grading is facilitated, in order to satisfy penetrability requirements established in Chap. 2.

Chapter 6 deals with grout-mix-design issues related to the targeted *strength* of the masonry to be grouted. Only two parameters enter the discussion: targeted $f_{wc,s}$-value and corresponding required $f_{gr,c}$-value. The chapter explores how a range of required $f_{gr,c}$-values suffices to be related to a targeted $f_{wc,s}$-value. This loose correlation is due to the fact that grout-to-stone bond properties are shaping the final structural behaviour of grouted masonry. Thus, tensile rather than compressive strength of the grout is the relevant parameter. Besides, dehydration of grout entering the masonry takes place; consequently, some additional rules regarding mix-composition are respectively derived.

Finally, several empirical relationships are offered predicting masonry compressive strength before and after grouting. Obviously, among the grout compositions resulting in $f_{gr,c}$-values within the required strength range, those mixes will be retained respecting the other required performances.

The chapter ends with a long Appendix presenting detailed strength results (both tensile and compressive) for several grout compositions, described in the literature.

Chapter 7 is related to *durability* issues. Physical effects are considered first, referring to the consequences of water introduced in masonry by the grouting (freezing and dissolution of soluble phases). Subsequently, chemical effects are considered, such as sulfate reactions, alkali–silica reactions, and possible chlorides' attack and leaching. The chapter ends with a brief presentation of the literature results of durability tests and with a guide for the selection of binders vs. durability.

Chapter 8 refers to some inevitable *contradictory* requirements of a grout, especially related to ultrafines' content (penetrability against fluidity), superplasticizer's content (fluidity against stability), type and content of binders to achieve sufficient bonding with masonry materials, without however imparting to the masonry disproportionally high stiffness (strength against ductility) and without jeopardizing durability (strength against durability) or level of grouting pressure to avoid local rupture of very low masonry strength.

Optimization of grout performances is needed in most cases. To this end, a simple first procedure is proposed following a step-by-step selection of mix-design parameters (Sect. 8.2). First, the type of binder is selected, based on strength and durability demands. An appropriate percentage of fines is then selected, based mainly on penetrability criteria, in combination with strength and durability aspects as well. Using experimental results already presented in Chaps. 2–6, diagrams combining penetrability, fluidity, stability, and strength characteristics vs. W/S ratio are traced. Thus, a "usable" area of water content appears; its compatibility with the required grout strength range will be checked. Normally, several satisfactory solutions are thus found. Otherwise, the necessary correcting measures are discussed in the chapter for each specific case, mainly by means of increased percentages of fines and addition of superplasticizers. This way, the rationality of the proposed methodology is understood. Thus, the designer is in better position to handle the final design of the grout, by means of a better knowledge of the interplay of the intervening numerous parameters.

In Chap. 9, the scientific approach followed in this book finds its justification: The rational and detailed examination of all properties of a grout offers now the possibility to follow a practical step-by-step procedure of mix-design, permitting to handle numerous parameters in a logical sequence. Thus, Chap. 9 contains more practical guidelines for the mix-design of grouts used in masonry strengthening. The guided use of *Tables* and *empirical formulae* presented in Chaps. 2–7 greatly facilitates the selection of (i) the type of binders and the final grading of the solids, (ii) the minimum acceptable fluidity factor, depending on the finest discontinuity width class (W_{nom}), (iii) the zero-bleeding and the critical-bleeding (W/S) expressions (with or without superplasticizers), as a function of the calculated average specific surface S_A of the solid phase*, and* (iv) the limit value W/S against segregation. Subsequently, a practical procedure for the selection of the final (W/S) ratio of the mix is described, respecting all the aforementioned limits. Corresponding remedy measures are presented in case such a complete respect is not feasible. Moreover, for masonries of minor historical importance and with representative $W_{nom} \geq 0.25$ mm, a Table is offered, containing approximate compositions of grouts for four different required grout strength ranges. Experimental verification of the required grout performances will be in any case necessary.

Chapter 10 presents a set of recommendations for the *execution* of grouting, regarding grout tubes installation, description of equipment needed, in situ preparation of the grout, and in situ control of injectability characteristics, as well as in-time evolution of grout's strength. Moreover, methods of in situ checking of injection procedure are presented, together with a description of the data that should be recorded during grouting operations and their evaluation.

The chapter concludes with the assessment of the efficiency of grouting; overall quality management is finally described, together with a detailed presentation of laboratory and in situ nondestructive control tests.

A final observation may be needed here.

To a not yet experienced reader, the described procedure for the design of a correct grout may seem too long. But it should not be forgotten that the final product aimed at by the design, depends on 6 parameters: penetrability, fluidity, bleeding, segregation, strength, and durability—some of them being contradictory to each other, and thus needing optimization. Mathematically *thinking*, it is expected that the solution of a system of 6 equations with 6 variables is not a short procedure; besides, after appropriate modifications, the system should be solved several times, in order for an overall optimum solution to be achieved. With this analogy, the proposed relatively long procedure for grout design may be better justified. Without such a disciplined method, the design may become chaotic.

Obviously, experienced designers will continue employing their own design method; but it is believed that, even experienced designers, may better recognize the nature of some phenomena, thanks to the preceding analysis.

In conclusion, this book may be considered both as a *rational synthesis* and as a *practical guide.*

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Contents

1 Introduction 1
1.1 The Significance of the Subject 1
1.2 Categories of Grouts for Masonries 2
1.3 Basic Data Influencing the Design of a Masonry Grout 4
1.4 Main Performances of a Hydraulic Grout 4
1.5 Design Procedure 5
1.6 Practical Guidance for In-Situ Grouting Application Methodology 7
References 7

2 Penetrability 13
2.1 Introduction 13
2.2 Literature Survey 15
2.2.1 Significance of Penetrability and Relevant Tests for Its Control 15
2.2.2 Maximum Grain Size Criterion 20
2.2.3 Criterion for the Grading of the Coarser Grains 22
2.2.4 Means to Improve Penetrability 24
2.3 Simplified Model and Additional Experimental Data 26
2.4 Calibration 30
2.5 Practical Means to Improve Penetrability of Hydraulic Grouts 35
2.5.1 A Simple Analytical Model 35
2.5.2 Experimental Verification 37
2.6 Conclusions Regarding the Penetrability Grading Criteria for the Grout's Solid Phase 38
2.7 Estimation of a W_{nom}-value 39
References 40

3 Fluidity . . . 45
3.1 Introduction . . . 45
3.2 Literature Survey . . . 46
3.2.1 Significance of Fluidity . . . 46
3.2.2 Relevant Tests for the Control of Fluidity (The Flow Cone Test) . . . 47
3.2.3 Fluidity Factor Test (FFT) . . . 53
3.3 Further Significance of the Concept of Fluidity Factor—Acceptable Lower Fluidity Factor Values . . . 58
3.4 Effects of Mixing Method on Fluidity . . . 62
3.5 Effect of Superplasticizers . . . 64
3.6 A Case Study of Practical Use of the Fluidity Factor . . . 66
3.7 Conclusions . . . 67
References . . . 68

4 Stability . . . 73
4.1 Introduction . . . 73
4.2 Literature Survey . . . 75
4.2.1 Main Parameters Influencing Stability . . . 75
4.2.2 Main Tests to Measure Stability . . . 77
4.3 An Oversimplified Predictive Model of Bleeding . . . 85
4.4 Experimental Investigation on Bleeding . . . 88
4.4.1 Bleeding of Grouts Without Added Superplasticizer . . . 88
4.4.2 The Role of Superplasticizers . . . 95
4.5 Segregation . . . 102
4.5.1 In-Time Modification of Grading of an Unstable Grout . . . 102
4.5.2 In-Space Differentiation of Grading . . . 104
4.5.3 A Simple Analytical Model . . . 104
4.5.4 Practical Criterion of Segregability . . . 106
4.5.5 Cohesiveness Index . . . 108
4.6 Conclusions . . . 110
References . . . 111

5 Guidelines for the Estimation of W_{nom} . . . 115
5.1 Introduction . . . 115
5.2 Information on Existing Internal Discontinuities . . . 119
5.3 Quantification Attempts . . . 123
5.4 Practical Approach . . . 124
References . . . 127

6 Strength-Related Data of Grouts . . . 129
6.1 Introduction . . . 129
6.2 In Situ Modifications of the Grout After the Injection . . . 130
6.2.1 Dehydration of Grouting Entering the Masonry . . . 130

6.2.2 Measures Against the Dehydration . . . 131
6.3 Grout Strength Versus Masonry Strength Required . . . 131
6.3.1 Introduction . . . 131
6.3.2 Estimation of the Strength of Existing Stone-Masonry Before and After Grouting . . . 132
6.4 Expected Strengths of Grouts . . . 137
6.4.1 Introduction . . . 137
6.4.2 The Main Parameters Influencing the Strength of the Grout . . . 137
6.4.3 Experimental Checking . . . 139
6.4.4 Indicative Strength Values of Grouts . . . 140
6.5 Grout-to-Stone Bond Properties . . . 147
6.6 Selection of a Required $f_{gr,c}$-range, for Targeted f_{wc}-values . . . 151
6.7 Shrinkage . . . 155
Appendix: Data Regarding Grouts Compressive and Tensile Strength in Function of the Water to Solids Ratio . . . 156
References . . . 171

7 Durability . . . 177
7.1 Introduction . . . 177
7.2 Physical Effects . . . 177
7.2.1 Water Introduced During Grouting . . . 178
7.2.2 Fluctuation of Moisture . . . 179
7.3 Chemical Effects . . . 179
7.3.1 Sulphate Reactions . . . 179
7.3.2 Alkali-Silica Reaction (ASR) . . . 181
7.3.3 Chlorides . . . 181
7.3.4 Leaching . . . 182
7.4 Brief Presentation of Main Literature Results on Grout's Durability Testing . . . 183
7.5 Guidance for the Grout Design Versus Durability . . . 184
References . . . 188

8 Optimisation of Grout Performances . . . 191
8.1 Introduction . . . 191
8.2 The Interaction Between Design-Parameters . . . 193
8.3 Increase of Fines to Improve Compatibility Between Stability and Fluidity . . . 195
8.4 Increase of Fines to Improve Stability Itself . . . 197
8.5 Modifications to Obtain a Minimum Tensile Strength . . . 199
8.6 Addition of Superplasticizer . . . 200
8.7 Conclusion . . . 202
References . . . 202

9 Practical Guidelines for the Mix Design of Grouts in Masonry Strengthening . . . 205
9.1 Selection of Binders . . . 206
9.2 Selection of a W_{nom}-value . . . 206
9.3 Checking the “Fineness” of the Binders’ Mixture . . . 206
9.4 Additional Ultrafine Materials . . . 207
9.5 Expected Fluidity Factor and Minimum Water-to-Solids Ratio . . . 208
9.6 Maximum Water-to-Solids Ratio to Ensure Stability . . . 209
9.7 Experimental Examination of the Candidate Composition . . . 210
9.8 Early Critical Bleeding . . . 214
9.9 Strength Evaluation . . . 215
9.10 Possible Simplification . . . 215
9.11 Worksite Conditions . . . 215
References . . . 219

10 Practical Recommendations for the Execution of Grouting . . . 221
10.1 Introduction . . . 221
10.2 Preparation of Masonry and Installation of Injection Tubes . . . 222
10.2.1 Masonry Survey . . . 222
10.2.2 Cleaning of Loose Material and Sealing of Cracks and Voids . . . 223
10.2.3 Drilling the Holes—Grid of Injection Tubes . . . 225
10.2.4 Cleaning of Drilled Holes . . . 229
10.2.5 Installation of Injection Tubes . . . 231
10.2.6 Installation of Fine Injection Tubes in Specific Cases . . . 235
10.3 Main Characteristics of In Situ Grouting Equipment . . . 237
10.3.1 Mixer . . . 237
10.3.2 Agitator . . . 240
10.3.3 Grouting Pump . . . 240
10.3.4 Grout Pipe Lines . . . 241
10.3.5 Grout Recorder . . . 242
10.4 Preparation of Grout and Execution of Injections . . . 242
10.4.1 Mixing Procedure . . . 242
10.4.2 Injection Procedure . . . 243
10.4.3 Finishing of the Masonry Injected Face . . . 247
10.5 On-Worksite Checking of the Prescribed Grout Design Data . . . 250
10.5.1 Pilot Production of Grout in the Worksite . . . 250
10.5.2 Pilot Masonry Application of Grouting . . . 252
10.6 Quality Control of the Grout and of the Injection Procedure During the Execution of Works . . . 253
10.6.1 Visual Inspection . . . 253
10.6.2 Checking Grout Characteristics . . . 254
10.7 Final Report of the Execution of Injections . . . 261

10.8 Assessment of the Grouting Effectiveness After the Completion of the Works 264
10.8.1 Core Taking 265
10.8.2 Endoscopy 265
10.8.3 Sonic/Ultrasonic Methods 267
10.8.4 Radar Technique 272
10.8.5 Other Non-destructive Methods 275
10.8.6 Structural Dynamic Measurements 277
References 278

Notations

A	Area of the cross section of the nozzle
b	Normalized bleeding value or bleeding capacity
B	Height of bleed water
C	Cement
c	Grout-to-stone cohesion (grout-to-stone shear bond strength under zero normal stress)
C_v	Cement volume
C.I.	Cohesiveness index
d	Diameter of grains
d_v	Diameter of monogranular ultrafine material
d_{ch}	The equivalent diameter of the "channel" (the void)
d_{85}	Diameter of the grains of a granular material (of the solid phase of a grout), corresponding to 85% passing
d_{99}	Diameter of the grains of a granular material (of the solid phase of a grout), corresponding to 99% passing
d_{100}	"Maximum" diameter of the grains of a granular material (of the solid phase of a grout)
D_{15}	Diameter of the grains of a soil or other granular medium to be injected, corresponding to 15% passing
DSF	Densified silica fume
f_{bc}	Compressive strength of blocks
$f_{gr,c}$	Compressive strength of grout
$f_{gr,t}$	Tensile strength of grout
$f_{gr,s}$	Shear resistance of the grout
$f_{gr,b,t}$	Grout-to-stone tensile bond strength
$f_{gr,b,s}$	Grout-to-stone shear bond strength
f_{mc}	Compressive strength of mortar
$f_{wc,requ.}$	The required compressive strength of the masonry after strengthening
$\mathrm{f}_{\mathrm{wc},0}$	Estimated compressive strength of masonry before intervention
$\mathrm{f}_{\mathrm{wc},\mathrm{s}}$	Estimated compressive strength of masonry, after strengthening
$f_{wc,e}$	Compressive strength of the external masonry leaf

$f_{wc,i}$	Compressive strength of the infill
$f_{wc,i,s}$	Compressive strength of the infill after grouting
f_0	A reduction of masonry strength due to the inhomogeneity of construction, depending on non-orthogonality of blocks
f	Fines (ultrafines)
f_m	Mass percentage of fines (ultrafines)
f_{mp}	Minimal mass percentage of ultrafines to replace a part of the basic binder, in order to ensure penetrability
f_v	Volume percentage of ultrafines
f_{vp}	Minimal volume percentage of ultrafines to replace a part of the basic binder, in order to ensure penetrability
FFT	Fluidity factor test
F_l	Fluidity factor
max F_l	Maximum possible fluidity factor value (for a given composition of solids) under stable conditions
min F_l	Minimum value of fluidity factor for a grout (with appropriate grain penetrability) to be injectable through a sand column with nominal lower value of widths of voids equal to "W_{nom}"
G_{gr} and G_w	Weight of the injected grout and initial weight of the single leaf wall, respectively
h_0	Height of the initial specimen of the grout at starting time t_0
h_w	Height of bleed water at prescribed intervals
H	Normalized height of bleeding
HT	High turbulence mixing
IE	Instability estimator
$\mathrm{IE}_{\mathrm{crit}}$	Lowest acceptable level of instability
k	Permeability coefficient
k_{i}-variables	Expressing the planeity of blocks' sides (k_1); the filling of joints by mortar (k_2); and the visible cracks and on mortar and block/mortar detachments (k_3)
k_0	Ratio of the volume of mortar to the volume of masonry (one-leaf masonry)
ℓ	Total length of the grouted "channel"
L	Lime
n	Numerical factor larger than unity, to compare W_{nom} and d_{85} (Chap. 2)
n	"Equivalent number" of solid cubes, with an average width of "d"
n	Ratio of the volume of grout embodied to the masonry, normalized to the total volume of the mortar (Chap. 6)
NHL	Natural hydraulic lime
P	Pozzolan
P_{max}	Maximum grouting pressure
Q	Volume of the grout (to pass through the nozzle of a Marsh cone)
r_{32}	Volume percentage of initial cement "retained" on 32 μm
R_{32}	Volume percentage of blend material retained on 32 μm

$\mathrm{S_A}$	Calculated average specific surface of a blended material
$\mathrm{S_b}$	Specific surface Blaine
SP	Superplasticizer percentage
SF	Silica fume
SE	Santorini earth
$\mathrm{S_v}$	Solid volume
S	Solid mass
$\mathrm{s_u}$	Critical slip leading to maximum shear bond resistance
t_f	Flow time through the nozzle of a Marsh cone
$\mathrm{t_{500ml,\ d\,=\,4.75}}$	Flow time of 500 ml out of 1000 inserted in the Marsh cone with a 4.75 mm nozzle diameter
$\mathrm{t_0}$	Thickness of intergranular adsorbed water
$\mathrm{T_{36}}$	The time the grout takes to reach the top of the sand column (of a height of 36 cm)
US	Ultrasound dispersion mixing
UF	Ultrafines
V	The velocity of flow
V_0	Variable expressing the “permeability” of the building mortar and the infill material of masonry
$\mathrm{V_c}$	Volume of cement
V_{ext}	Volume of the external leaves of masonry
$\mathrm{V_m}$	The volume of mortar
V_w	Volume of bleed water
$\mathrm{V_i}$	The volume of the initial infill material within the entire masonry
$\mathrm{V_{i,\ gr}}$	Intial volume of the grout at the begining of bleeding test
$\mathrm{V_w}$	The volume of the entire masonry wall
W	Water mass
W_i	Water to solids ratio
$\mathrm{W_v}$	Water volume
W/C	Water-to-cement ratio by mass
W/S	Water-to-solid ratio by mass
$\mathrm{W_v/S_v}$	Water-to-solid ratio by volume
$\mathrm{W_{nom}}$	Nominal lower value of the aperture of fissures or orifices to be injected
W_i*-values*	Values of the aperture of fissures or orifices to be injected
$\left(\frac{W}{S}\right)_{0,\,bl}$	The minimum water-to-solid ratio able to initiate bleeding
$\left(\frac{W}{S}\right)_{0,\ bl,\ SP}$	The minimum water-to-solid ratio able to initiate bleeding, in the case the grout contains superplasticizer
$\left(\frac{W}{S}\right)_{0,\ f}$	The minimum water-to-solid ratio able to initiate flow
$\left(\frac{W}{S}\right)_{bl,\ cr}$	Water-to-solid ratio leading to 5% bleeding
$\left(\frac{W}{S}\right)_{bl,\ cr,\ SP}$	Water-to-solid ratio leading to 5% bleeding, in the case the grout contains superplasticizer
$\left(\frac{W}{S}\right)_{sand.-col.}$	Water-to-solid ratio for which the grout starts to be able to be injectable in the sand column

$\left(\frac{W}{S}\right)_{segr.}$	Water-to-solid ratio for which the grout starts to exhibit segregation
$\left(\frac{W}{S}\right)_{u,\ f}$	An ultimate value of water-to-solid ratio, which practically results in the maximum possible fluidity factor (for a particular composition of solids) without instability effects
z	An Instability estimator (IE)-related quasi-constant
α	Rate factor
β	Coefficient reflecting the substrate type (Chap. 6)
$\alpha,\ \beta,\ \gamma,\ \delta$	Rheology-related constants, depending on the roughness of the walls and the form of the cross section of the channel, as well as on rheological properties of the grout (Chap. 3)
δ	Constant
$\delta = t_e/t_i$	Ratio of the respective thickness of external leaf and infill (in case that the external leaves have the same thickness)
$\delta_{e1} = t_{e1}/t_i$	Ratio of the respective thickness of external leaf “1” and infill
$\delta_{e2} = t_{e2}/t_i$	Ratio of the respective thickness of external leaf “2” and infill
ΔH	Bleeding capacity (settlement per unit original height)
Δf_0	Reduction of the masonry inhomogeneity factor (counteracting the severity of the initial f_0-value included in the expression of $f_{wc,\ 0}$)
Δf_m	Additional quantity of fines
Δw	Additional quantity of water
Δp	Pressure loss along a length “ℓ”
ζ	Constant
η	Plastic viscosity
λ	Correction factor
λ	Mortar-to-stone bond factor
λ_1, λ_2	Numerical factors
λ_3	A constant, reflecting the lowest acceptable level of instability IE_{crit}
λ_e, λ_i	Correction factors in order to take into account the interaction between the external leaves and the infill
λ_i-variables	In function to the type of the wall (one-leaf, two-leaf, or three-leaf)
μ	Water equivalence constant of superplasticizer
μ_{max}	Maximum friction coefficient
μ_{res}	Residual friction coefficient
ξ	A factor expressing the adverse effect of thick mortar joints
ρ_{ms}	Average density of the solids
ρ_w	Water density
ρ_{mf}	Average density of fines
ρ_b	Density of the basic binder
σ	Normal stress acting on a sheared interface
τ_0	Yield stress of a fluid
ω	Equivalent W/S, accounting for SP