Masonry – sustainable, contemporary and durable

Anachronism, bold statement or visionary outlook?

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Abstract:
Looking around us, we notice the durability of masonry structures.
A well-build masonry structure assures a long term sustainable solution by its durability, adaptability and maintain-ability.
However, building practice has changed in the last decennia. Building speed and technology have been major drivers in the main stream construction industry during the last 50 years.
In Europe the common market has been created leading to a unified market needing common definitions. Unified product standards have been developed, engineering guidelines being written, this all in order to strive to a market where products can freely circulate.
In the sector of restoration of cultural heritage, scientists and conservators have been seeking towards products matching with the longevity requirements of preservation of historic buildings which have been standing out there for hundreds of years.
In the last years, we see that the mainstream construction industry also took the step towards sustainability and durability, so those words have become more than buzz words.

In today's masonry practice, several issues can be observed.
Masonry is becoming more and more brittle, stress sensible and slender therefore questioning its traditional image of solid, durable and sustainable building material.

Looking into the masonry structures which have proven durability by survival, a lot of lessons can be learned for future practice.
Nowadays only it is evidenced that the complex stress state in the mortar explains the ductile behavior of masonry with lime based mortars. These mortars give an appropriate answer being deformable and elastic. They introduce a reliable adhesion mortar-brick leading to ductile masonry with high flexural strength.

Inspired by these observations, the actual article discusses the background of this evolution and seeks towards a future of durable, sustainable masonry.

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Background:
Throughout the years, we have observed an undesirable tendency on behalf of mortar quality. Especially since the development of the EN standards in the early 2000's this has been remarkable in countries where traditional, experienced based, recipe mortars were used.

The switch from these experienced based, recipe mortars towards performance, compressive strength based, mortars has been detrimental to the other aspects like the durability and long term behavior of the mortars and the masonry.

A tendency can be observed to sub optimize single properties e.g. compressive strength. The explanation is probably to be found in the fact that the choices made to define performance of mortars are over focusing on easy tests coming from other building technologies. These are barely or not taking into account the relevant parameters. The evaluation focuses on short term performance testing of the solitary mortar and not on the mortar as part of a system and its long term behavior.
Different authors are looking into improvement of masonry behavior to keep the architectural freedom which is today increasingly limited by framework documents such as Eurocode 6 Masonry structures or Eurocode 8 Earthquake resistance.

For the items expansion joints, bond strength, etc, the mortar characteristics play an important role in masonry performance.

In the conservation sector, the proof of the historical heritage and research made in the restoration sector puts into evidence the beneficial contribution lime can have towards today's issues such as durability, sustainability and global masonry behavior.

In the following sections different steps are analyzed to come to the conclusion:

1. identify existing knowledge
2. put the knowledge gaps in to evidence
3. define the potential paths forward to fill the gaps and have mortar relevant parameters taken into account in future standardization making the link between product-application and engineering standards.

The existing knowledge:
In a bibliographic study which was performed in 2009[7], the relevant parameters for different stakeholders were analyzed: The masons, the designer and the owner.
The evaluation looked into the characteristics of masonry in fresh state (relevant to the mason – contractor), in young hardened state (28 days – relevant to the designer) and to the durability aspects (relevant to the end user and owner).

[7] Bibliographic study on mortars – DTI 2009 – commissioned by Eula – available on request

The mortar in fresh state: build-ability, the attention point for the mason
Looking in to the relevant parameters for the mason, it appeared that the users of the fresh mortar are mainly interested in a product which is easy to handle, easy to mix, easy to use, controllable and preferably cheap.
The mason is seeking for the workability of the mortar and its ability to retain water. Speeding up the process of mortar production, the proven solution of matured lime putties (saturated hydrated lime) as a rheology agent has been abandoned for the main stream mortars. The cheapest and fastest solution which has been found to obtain the workability of the mortar has been the entrainment of air by organic admixtures.

The natural air content of mortars based on purely mineral binders is found around 3 to 5%. In mainstream mortars as much as 20 – 25% of air is possible to obtain the required workability. The loss in compressive strength is then compensated by overdosing the hydraulic content leading to a high air containing but low porosity skeleton with detrimental effects on the bound strength mortar-brick.

The speed of the actions on the jobsite, including the time spend to mix the mortar, is not compatible with binders with high finesse and high specific surface which by nature need more energy (more surface to be wetted). The risk of not applying enough energy on the mortar is a late stiffening of the mortar in the mortar tub.
Making a good mortar is assuring the build-ability of the edifice. This means adjusting the different components in the mortar to the specificity of the brick while maintaining good workability (water retention, speed of mixing, the right amount of water) and short term durability (exposure to water, rain, frost, sun at young age).

The strength of hydraulic bound mortars is that they will very quickly have a certain strength which makes them withstand aggressions at young age. The workability requirements can be obtained using organic admixtures.
The back fire is the big sensibility on the dosage of the chemistry (including in appropriate mixing energy) and the durability on the long term. Special attention is needed in design (expansion joints, maintenance, and exposure to rain) and execution (exposure to rain and frost).

The strength of air binder containing mortars is that they will show good workability and water retention on the short term and on the long term they will deliver exceptional durability, however on the short term (first months) they can show lower compressive strength and resistance to frost. Special attention is needed in design (exposure to rain) and execution (exposure to rain and frost).

The mortar in young hardened state: the engineer-designer seeking strength
When we make the analysis on the relevant parameters for the designer, first thing which comes up is the mechanical behavior of the masonry, key for the engineer who has to approach the stability under vertical and horizontal loading.
Vertical loads cover weight, load and other static loads as rain and snow. For horizontal loading, the engineer looks into wind and seismic. Other issue to be dealt with in horizontal loadings is the horizontal displacement of the structure.

The functionalities of the mortar which focus upon having an influence on the mechanical behavior of the masonry are the compressive and flexural strength of the mortar.
These all lead to the capacity of the masonry to carry the vertical loads. Research and standards to some extend take into account the fact that the important parameter in masonry strength is the strength of the masonry unit and only to a very limited extend the compressive strength of the mortar.

For the horizontal loads, which are in general the most delicate ones, flexural strength and flexural bond strength are determining factors. Especially, given the improving insulation degrees of the walls, the wall leafs become more and more slender which is increasing the importance of the two mentioned parameters.
The practice as described in the fresh phase of adding large amounts of air into the mortars to obtain the workability is killing the performance of the mortar-brick couple towards flexural strength. In pure hydraulic bound mixtures, the flexural strength of the masonry is divided by 10-20 if the air content is increased by a factor 5 from 3 to 15% of air content. Above that, one can question if flexural strength can be measured in a reliable way (values > 0,1 MPa) and is functional.
If future masonry is to be engineered with these low values, it quickly becomes impracticable (to much shear walls), inconvenient (no openings) and is replaced by other building materials such as concrete or steel. Masonry will be used as filling material without any load bearing function.

Under horizontal loads, we need also to approach the horizontal movement due to volume variations of the products. In any building material volume variation is present induced by shrinkage, creep, thermal and moisture variations and imposed action.
If one passes over the intrinsic characteristics of high elastic mortars to accommodate the stresses build up before the wall breaks (vertical and diagonal cracks), expansion joints have to be build in on very short distances or walls need to be armed to withstand these forces.
The values which are today foreseen in the engineering rules, Eurocode 6, are very conservative and based on the low elasticity of hydraulic bound mortars. In high hydraulic containing mortars, it will be the mortar which will determine the behavior of the wall. If a fundamental part of the binder is air bound, setting will occur before hardening and less stresses will be build in an. The elasticity of the mortars is increased and the behavior of the wall will be determined by the masonry unit.

The mortar in hardened state: the major attention points for the architect and owner are aesthetics and durability

Talking about the movement facilities, joints us into the esthetic considerations of masonry which are the relevant part for the architect and owner.

Aesthetics is determined by physical behavior in time of the masonry. The relevant parameter for the physical behavior over the life time of masonry will be the vapor permeability and porosity.

Whatever one does, water will always be a fundamental part of the life of a building material. At young age, either water is introduced for the construction or the new build edifice is exposed to rain during construction. Afterwards, rain and ground water need to be dealt with. Trying to make masonry impermeable is an admirable ambition but, unless we create a plastic sealing, regrettably impracticable for mineral construction materials.

The movements, because of the volumetric variations or because of the stress state, will always occur. Whatever one does, water will be there.

The only solution is to have a breathable structure dealing with humidity:

- If it is not dealt with in the right way, it will lixiviate chemical substances from the building materials in the drying direction leading to discolored walls (efflorescence).
- If it is not dealt with in the right way, it will provide a humid environment for fungi and mould.
- If it is not dealt with in the right way, it will capture water in the structure which will expand when frost- thaw will occur

Identifying the gaps:

The major research and engineering issues in the 20th century have been focusing on concrete and steel. Already since Eiffel a competition has developed between today's two mainstream building materials.

In the research on building materials after WW II, masonry has been somehow orphanaged and concrete and steel have been attracting the main resources and efforts. Especially for the mineral bound interfaces, the research on concrete has been a huge source of knowledge. The tests which have been developed to make the quality control on Portland cement (by measuring the hydraulic capacity by compressive strength) have proven to be a highly repeatable and reproducible test. Moreover, the fact that this test is giving, for hydraulic bound mixtures and hydraulic conditions, a highly reliable result after 28 days (or 4x7 days – perfectly fitting in today's work organization) in a perfectly easy controllable environment (20°C, 95-100% of Relative Humidity has made it the reference.

In the wake of the test on compressive strength, the other affiliated test methods such as spread by the shocking table to determine water content have found their entrance in the world of modern laboratories.

Because of their easiness to apply and reproducibility, these tests have been adapted by the industry of mineral based materials.

In concrete, one can plead the relevance for the test; concrete is less impermeable and maintains high water content inside. There is no carbon dioxide uptake and exothermal

reaction of cement is delivering a coherent temperature. Carbon dioxide uptake is even undesirable in concrete since it will lead to depassivate of the steel reinforcement and loss of performance of reinforced concrete.
The complete opposite is applicable to mortars. Products such as renders, plasters and masonry mortars are exposed in rather thin layers. They are placed in a more complex environment leading to other conservation conditions, therefore to other strengthening kinetics.

Mortars are put on or in between bricks. They are exposed to a more dynamic environment. The brick is exercising a sucking on the mortar (1) reducing its water content “rapidly”, (2) sucking water-binder solution into the brick which is ensuring the adhesion brick-mortar.
The reduced water content of the mortar is then facilitating the entrance of air and carbon dioxide in the mortar. The cycles of watering and drying is accelerating the stiffening and strengthening of the mortars.
The hardening of a mortar is a refined combination of the hydration of the hydraulic phase combined with the carbonation of the air binder phases.
When we use mortar prisms of 40x40x160 mm, the dimensions of the samples are very well fitting with an operational execution of the test but show little resemblance with the real dimension of the mortar in the masonry. The samples are stored in a 95% relative humidity condition and are hardly representing the real state and real conditioning of a mortar used as render or as masonry mortar.
We need to go back to the formulas and accept that binders of different origin exist: hydraulic and air binders where hydraulic will react with and under water where air binders will react with and during exposure with air.

The measurement of spread (slump) on a shaking table is used to have a certain reference regarding workability. One determines the water content of the mortar seeking for a certain spread. This test is based on gravity and behavior under dynamic load. However, the test does not take into account the difference in density, particle size and specific surface between different binders at the aimed spread is defined independently of the difference of rheological behavior of such materials.
Workability assessment through the actual spread/slump test is without any doubt a good method to assess workability of pure sand-hydraulic based mortars on which the standard has been calibrated but need to be reassessed for materials with different rheology as air binder based materials.

The easy reliable testing of compressive strength under hydraulic conditions is a short cut which is making a simplification of the relevant parameters for masonry strength. The relevant parameters in the masonry system leading to strong masonry are (1) the flexural strength influenced by the material characteristics and (2) the adhesion/bound between the different elements in the wall.

These simplified testing used to make the quality control according to the actual standards do not reflect the differences in binding kinetics in the different systems. It

does not reflect the difference in mechanical behavior of mortars when subjected to the stresses they are carrying into the mortar/brick or block composite.
It explains why highly hydraulic bound mixtures are preferred over systems with other binding characteristics. Regrettably, when one overlooks the binding specifics, the specific of masonry behavior are badly projected and the potential of masonry under estimated.
One can even be stronger in its statements stating that the today's standards are detrimental to masonry and mortars.

Potential paths forward towards durable and sustainable masonry:
Composition plays a major role in the durability of masonry and its mortars.
The composition and the mixing define the workability of mortars. Workability will influence the filling of the joint and their permeability. In direct relation with the curing (drying and hardening), the composition will influence the porosity and will define a compatible pore system. The pore system will influence water transfer and the water permeability which will influence the frost resistance.
The bond interface will heavily depend on the composition of the mortar and it is related to the mechanical properties of the mortar. These mortar properties influence the mechanical properties of the masonry and in particular the deformation. All these features will influence the behavior of the masonry wall to its exposure to weather, to differential settlements and to earthquakes.

In order to assess the functioning of the masonry system, the structure needs a holistic approach. The tests on the individual building bricks are incomplete and the testing on solitary mortar is irrelevant for determining the behavior of the system. The combination mortar and substrate needs to be investigated together and the reciprocal influence should be taken introduced. . To properly estimate the properties of each component in the masonry testing procedures should take into account the real boundary conditions to which they are subjected.

In order to be able to model the behavior, all aspects in the life of the young mortar namely the workability of the mortar, the porosity of the system, the unit mortar interface, the mechanical interaction between mortar and unit (tri-axial behavior), shrinkage versus hardening, the chemical reactions involved and the wetting and drying (as cycles including leaching and self-healing) need to be addressed.

Proof of durable and sustainable masonry can be found al around in our historical city centres. "Send the people to Pompei" is probably a convincing visit but is loosing weight in a scientific community in front of piles of research results.
For historic building the argument is won on the basis of compatibility and authenticity. Since lots of information for practitioners are available to use traditional recipe mortars, there are no excuses not to use lime-based materials in conservation.
However the link to modern contemporary materials is not so easy to make.

In the actual, fast moving world, the appearing contradiction of long term durability and perception of short term failure (e.g.. Freeze thaw, differential movements between mortar and substrate, differences in the strength of mortar and substrate and micro cracking caused by shrinkage in strong mortars) is an issue which needs attention.
A good definition of durability is certainly necessary and has to take into account the total life cycle of an edifice. It is not only a matter of material parameters but also of the building practice. Durability needs to be challenged in is broadest form namely that of a Life Cycle including the time between repair of a structure.

Bringing the relevant parameters into standardization

In order to get a long term future for masonry, the masonry has to be characterized by its real behavior. As explained, today's modeling is based on basic assumptions in relation with simplified testing. Calculation methods are based on compressive strength where as masonry strength is determined by is tri-axial behavior and its flexural bond strength. Regrettably, this approach is missing in EC6. Some first ideas about future evolution are present in some of the former national standards and in some of the national annexes of EC6 (e.g. Germany) which give examples on the formula (k, α, β) for the different type of masonries.

A fundamental job needs to be done to identify and quantify the different parameters that explain the performance of walls: compressive strength, the tensile strength of units, flexural strength, elastic modulus, flexural bond strength and bond strength due to water retention of the mortar.

On basis of the research and the understanding of the fundamental material behavior, a failure model for mortars in masonry which takes into account realistic and real behavior in complex stress states can be developed and verified.

A corner stone will be to develop reliable, reproducible and repeatable tests (e.g. bond/flex) which are technically and commercially realistic and that reflect the actual failure modes of the mortar in the joint and in the masonry;

In order to evolve in an appreciation of the long term performance and have a reliable evaluation of the sustainability of masonry, durability tests (e.g. freeze-thaw; water penetration) need to be considered which reflect performance in the masonry system under realistic conservation procedures instead of on idealized hydraulic environment.

Conclusion:

Under today's preoccupancy on behalf of energy efficiency, sustainability and durability, masonry is facing crucial challenges.
At the same time, the Eurocodes are introducing unified engineering rules all over Europe for the design of masonry and for the evaluation of its resistance to seismic loading.

In order to cope with these challenges, masonry understanding has to be reassessed in its fundamental behavior. The failure mode of masonry in compression needs to be investigated in view of the relation between the tensile strength of units and mortar towards the bond in the interface between units and mortar.
The relevant product parameters such as bond need to be taken into account for factory production control by the means of a reliable simple test.

Practice shows the need for the development of simple (but still realistic!) product property tests supplying data to be used in the modeling of the strength of masonry in compression.

To the benefit of the modeling, the characterization of the masonry samples has to reflect as closely as possible the real strengthening kinetics of the system. It has to cover as well the contribution from the hydraulic phases as those from air binders.
This all needs to start by stating on a workability test method reflecting individual mortar behavior. Maturing conditions need to go beyond the quality testing for idealized hydraulic performance and need to have realist humidity and timing.
Giving the interaction and the importance of the conditioning environment on durability and product characterization, a holistic approach needs to look at the complete system in stead of the individual elements such as brick and mortar separately.

Even if we can develop the best short term durability test to simulate the performance of our products, human long term – real size - experiments with masonry, as we can see in traditional lasting constructions, have fostered experiences which should be used in modern technique.

If a realistic modeling taking into account the actual behavior of the entire system is developed and appropriate products are used, the future build-ability of masonry will be assured.

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Publications to which the participants have contributed are listed in the bibliography.
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