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Repair mortars for masonry bridges.

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Abstract

Repairs to masonry bridges are often undertaken by pointing and grouting with Portland cements. As an emminently hydraulic binder, Portland cement is resistant to dissolution in aggressive environments such as those of bridges. However, most masonry bridges in Europe were built with hydraulic lime mortars, their degree of hydraulicity ranging from feeble to eminent, and due to their lime binder, added pozzolans, or the natural aggregate used for their fabrication. Artificial cements can be incompatible with masonry materials. Common problems at masonry bridges include binder dissolution, defective bond, leaching and salt damage. The objective of this paper is to assist in the design of repair mortars for masonry bridges, focusing on the importance of selecting quality materials compatible with existing fabrics. This is achieved by studying the influence of mortars on masonry structures, the properties and composition of mortars used in the construction of bridges and the problems associated with them. Analytical and experimental results are combined with today's most widely accepted conservation theory in order to set out the parameters needed for the design of compatible, quality, durable repair mortars. This paper concludes that, due to the quality of the enviroment (humid, salt-rich, with a permanently non-saturated water flow and successive soaking-drying episodes), structural mortars for masonry bridges should be hydraulic in nature. However, the paper also suggests that eminently hydraulic binders such as Portland cements are not necessary in order to ensure durability, and demonstrates that fat lime mortars strengthen with pozzolans can last for at least 2,000 years. Furthermore, this work evidences that, according to Brandi's principle of compatibility as well as recent experimental and analytical work, hydraulic lime mortars are more suitable for masonry repair than those made with artificial cements. Lime mortars are physically and chemically compatible with most carbonate and silicate rocks, materials commonly used in the construction of masonry bridges and, when correctly designed and executed, they do not induce lime leaching or salt damage. Finally, this paper provides advice on mortar preparation and states that repair mortars should be permeable and elastic, acting as a conduit for moisture in the walls thus preserving the masonry from weathering induced by moisture and salt solutions, and deforming both plastically and elastically as they absorb masonry movements. The degree of hydraulicity of the repair mortar should be settled according to the flexural and compressive strengths, capillary suction and permeability of the masonry units.

Keywords: masonry bridges, hydraulic mortar, fat lime, hydraulic lime, mechanical properties, durability.

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INTRODUCTION

The influence of mortars on masonry structures

Mortars play a significant role in masonry structures. Among other functions, they enable good adhesion between masonry units, cushioning masonry joints to absorb strains and prevent cracking, simultaneously providing some degree of tensile strength that dry masonry lacks. A mortar's composition and production technology govern the strength and durability of the masonry as studied below.

The strength of masonry largely depends on the strength of the bond between the mortar and the masonry unit, and this is determined by the mechanical properties of the mortar which in turn are dictated by its composition and production technology. The bond strength is also controlled by the moisture transport between mortar and masonry which depends on the rate of absorption of the masonry unit and the mortar water retention, which is dictated by the mortar's composition and fabrication. The correlations below evidence the influence of a mortar's quality on the properties and behavior of masonry. For example, it has been demonstrated that an increase in bond strength leads to an increase in the compressive strength of the masonry, and this improves both the flexural and shear bond strengths [1]. These authors refer to previous work by Samarasinghe et al. and Venumadhava et al. stating that the shear bond strength of masonry increases as the compressive strength of the mortar raises, and that the masonry's flexural bond strength is enhanced with an increase of mortar's strength irrespective of the type of masonry unit. The authors also refer to work by Grenley who states that flexural and tensile bond strengths of masonry as well as its compressive strength grows with the strength of the masonry units and the strength of the mortar.

The influence of mortars in the durability of masonry has also been demonstrated. For example, a mortar can induce fracturing of masonry units. Under stress, a good mortar needs to behave as an elastic material absorbing stress to recover its strain when unloaded, simultaneously suffering a certain degree of plastic deformation. Elastic deformation in the mortar occurs on the initial application of stress, and this is followed by a non-elastic behavior due to re-arrangement of mineral components, a strain that is not completely recoverable leading to plastic deformation [2]. However, strong hydraulic binders such as Portland cement tend not to absorb any movement thus transferring stresses into the adjacent masonry subsequently causing brittle failure of masonry units such as certain sedimentary rocks and clay brick [3]. Furthermore, the quality of a mortar determines the movement of moisture within the masonry, and this is an important factor in the onset of masonry weathering processes. For example, impermeable mortars increase moisture transport through masonry units thus enhancing pollutant deposition, mineral alteration, biological colonization, salt crystallization and frost damage [3]. According to the above, in order to ensure both quality and durability of masonry, mortars should be permeable and elastic, acting as a conduit for the moisture in the walls and deforming both plastically and elastically as they absorb masonry movements.

Mortars of masonry bridges

There are around 25,000 stone arch bridges in the island of Ireland, having at least one span of two metres or more [4]. Most masonry bridges in Europe were built with lime mortars of hydraulic nature. The degree of hydraulicity of these mortars ranges from feeble to eminent and is due to their lime binder, added pozzolans or the aggregate used for their fabrication.

There are two characteristic types of lime: hydraulic and non-hydraulic. They differ in the manner by which they harden and in the properties they display. Hydraulic limes harden to a greater or lesser extent due to a chemical reaction between their active clay particles, lime and water (hydraulic set). They display an additional mechanical strength due to their hydraulic set and, when compared to non-hydraulic limes, they usually posses lower permeability and flexibility and a better resistance to moisture, frost and salt attack [5-9]. Non-hydraulic limes, also known as aerial or fat limes, harden due to a reaction between their CaO and atmospheric CO_2, a mechanism known as carbonation. They possess high permeability, flexibility and plasticity, as well as a tendency to shrink in early stages of hardening, significant solubility in water and a low mechanical strength [5-9].

Both hydraulic and fat limes were used in bridge construction. The case studies below illustrate this. For example, the mortars at several Roman bridges in La Rioja, Spain, including Mantible and Viguera, were made with fat lime, and their hydraulicity is due to the addition of ceramic dust which reacted with free lime in the presence of water acting as a pozzolan, thus generating hydraulic cements similar to those formed during the hydration of Portland cements or hydraulic limes (Fig.1). In relation to the aggregate, the Romans preferred quarry sand to river sand for structural mortars in bridges. According to Vitruvious, Palladius and Faventinus [10], river sand was too weak to fabricate structural mortars. When quarry sand was not available, they recommended strengthening river sand by adding pozzolans. This can be evidenced in the aforementioned Roman bridges, where river sand and fat lime are mixed with ceramic dust in order to trigger hydraulic reaction (Fig.1).

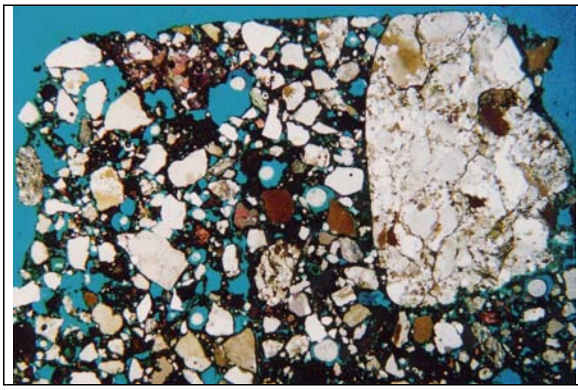

Figure 1. Structural mortar from the Roman bridge Mantible, La Rioja, Spain, including coarse and fine, predominantly siliceous river sand mixed with ceramic dust in a fat lime binder partially weathered by dissolution. 2X, polarised light.

With respect to durability, the Roman mortars studied are generally in good condition, still holding the masonry and maintaining cohesion despite being nearly 2,000 years old. Petrographic analysis evidenced that they are partially weathered due to binder loss by water dissolution, a common process of lime mortar weathering which, when the mortars are correctly made and executed, only takes place over a long time period and is due to the passage of moisture through the typically permeable fabrics of lime mortars [11]. The Roman bridges studied were made with fat lime mortars. However, in contrast, later bridge-masonry mortars were fabricated with hydraulic limes, for example those of St John's Bridge, Kilkenny, a late medieval bridge which was swept away by a massive flood in 1763. Here, the mortars were binding Irish Carboniferous limestone, and their hydraulicity arises from the binder as well as from the presence of reactive aggregate. Reactive aggregate consists mainly of microcrystalline silica (chert), however, dolomite, greywacke, shale and burned fuel are also present and were found to undergo hydraulic reaction. Fig.2.

A later example of mortars made with hydraulic lime is that of the twin arch culverts below the Grand Canal on the Griffeen river, Dublin, dated 19th century. Here, the mortars are binding Carboniferous limestone, their hydraulicity ranging from eminent to feeble and arising from both the aggregate and the binder. As in St John's Bridge, the aggregate naturally contains a reactive fraction that is contributing to the mortar's hydraulicity and consists of chert, shale and occasional greywacke. As in the case of the Roman bridges above, the mortars maintain cohesion however, they have partially weathered through binder dissolution. The binder is partially lost and appears porous and fractured, often recrystallized. Fig.3.

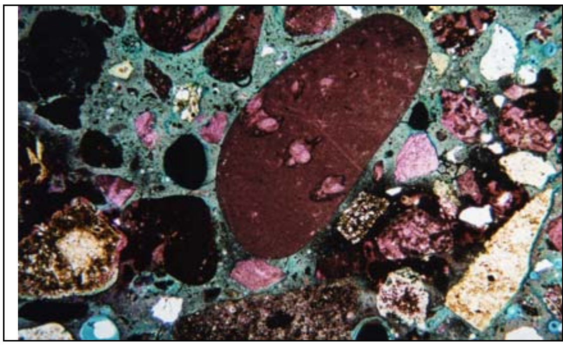

Figure 2- The pointing mortar at St John's Bridge, Kilkenny. Limestone and reactive chert aggregate in a hydraulic lime binder which remains in good condition. 2x, natural light.

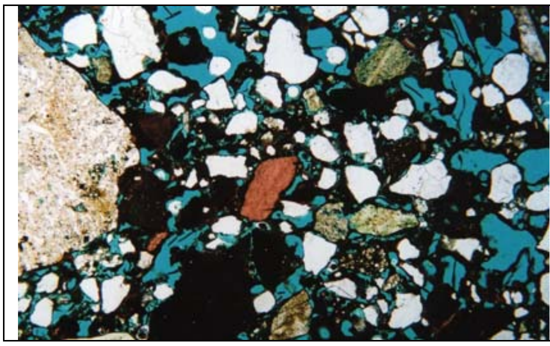

Figure 3- Hydraulic lime mortar at the Grand Canal on the Griffeen river including abundant siliceous aggregate including quartz and silicified limestone. The original porosity has increased due to partial dissolution of the lime binder. 2x, natural light.

PROBLEMS WITH MORTARS AT MASONRY BRIDGES

The environment at bridges is characterised by a high humidity and a permanently non-saturated water flow along piers and cutwaters. Furthermore, tidal bridges are often exposed to sources of sat including salt solutions and sea spray. In addition, mortar at bridges can experience successive wet-dry episodes which are much more stressful to masonry materials than a state of constant immersion. A permanently non-saturated water flow is an effective solvent, as solubility largely depends on the degree of saturation of the solvent and the solvent motion. A condition of permanent under saturation applies to the stream water at bridge masonry below water level. Due to these aggressive conditions, erosion of pointing mortars of piers and cutwaters is common often leading to the deterioration of pier cores. In general, mortar weathering is often associated to the repeated action of moisture and salt but can also be related to failures in execution or adverse environmental conditions [11]. The most relevant problems of mortars in masonry bridges are studied below.

Mortar loss by binder dissolution

As aforementioned binder loss by water dissolution, is a common process of lime mortar weathering which, when the mortars are correctly made and executed, only takes place over a long time period, and is due to the passage of moisture through the typically permeable fabrics of lime mortars. However, in masonry bridges, water percolating by gravity from the decking as well as unsaturated water flowing along piers and cutwaters can effectively dissolve mortar binders (Fig.5). Non-hydraulic lime mortars are particularly susceptible to binder dissolution. Here, the lime binder hardens by carbonation becoming calcite (calcium carbonate- Ca CO_3). Solid calcite dissolves in acidic water (e.g. containing CO_2) and is held in solution as calcium bicarbonate (Ca $(HCO_3)_2$) according to equation 1 below. This reaction is reversible, thus bicarbonate can re-precipitate back into solid carbonate in a process known as recrystallization (Fig.6).

$$Ca\,CO_3 + CO_2 + H_2O \Leftrightarrow Ca\,(HCO_3)_2 \qquad \text{(eq. 1)}$$

Carbonate recrystallization within the mortar's fabric produces secondary calcite cements which partially fill pores and coat aggregate grains (Fig.6), a process probably responsible for the maintenance of mortar cohesion despite the partial loss of binder.

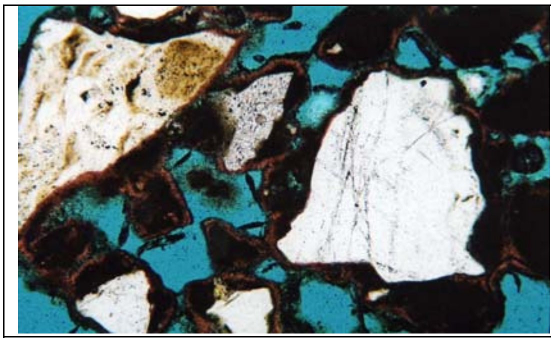

Figure 5- Mortar binder loss through calcite dissolution at the Grand Canal on the Griffeen river. 10x, natural light.2X.

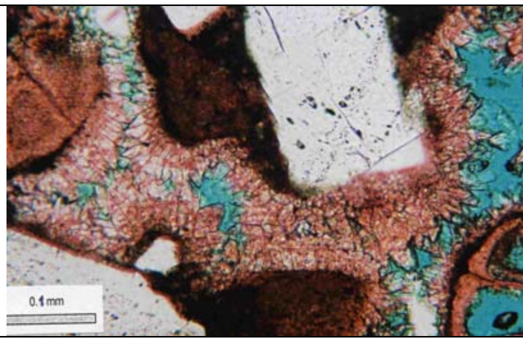

Figure 6- Recrystallization of calcite binder partially filling pores and coating aggregate grains. 20X, natural light.

Lime leaching

This phenomenon involves the formation of a hard crustification of calcite by the slow and continuous segregation of free lime from Portland cement mortars, a similar process to that leading to the formation of stalactites. When cement is gauged with lime, as moisture travels through the mortar, calcium hydroxide ($Ca\,(OH)_2$) moves towards the surface in solution as calcium bicarbonate ($Ca\,(HCO_3)_2$) according to equation 2 below.

$$Ca\,(OH)_2 + 2CO_2 + H_2O \Rightarrow Ca\,(HCO_3)_2 + H_2O \qquad \text{(eq. 2)}$$

When the bicarbonate reaches the surface, it reacts with atmospheric carbon dioxide to form calcium carbonate as a precipitate according to equation 3 below.

$$Ca\,(HCO_3)_2 \Rightarrow Ca\,CO_3 + CO_2 + H_2O \qquad \text{(eq. 3)}$$

Salt-induced damage

In the salt-rich, humid environments of bridges there are a number of salt minerals that can damage masonry materials including chlorides and sulphates. Salt-induced damage has been studied by several authors [12-14] while lime mortar sulphation arising from both atmospheric pollution and alkali-bearing Portland cement mortars has also been evidenced through petrographic analyses [15]. Salt contamination in mortars arises from rising damp, mortar aggregate, mortar binder or even certain additives. Sulphates such as gypsum may originate from atmospheric pollution, whereas chloride sources include early cement binders, ground contamination, de-icing salts or sea spray in coastal areas.

Fracturing

Fracturing in masonry structures can be either mechanically or chemically induced. The causes of fracturing have been previously studied [11], a summary of these is given below. As mentioned above, cracks are often mechanically produced in strong hydraulic binders such as Portland cement which are not flexible enough to accommodate masonry movement, thus transferring stresses into the adjacent masonry subsequently causing brittle failure of certain sedimentary rocks and clay brick. Fractures can also be chemically induced by shrinkage due to evaporation and carbonation during mortar hardening, as well as expansion by salt crystallization. Micro-fracturing also develops as a result of expansion by re-hydration of gel-like mineral components in cement based mixes. In addition, fracturing can also be due to defective mortar technology. For example, an excess of water or lime binder in a mortar will enhance shrinkage thus leading to fracturing. Furthermore, cracking can also be induced by porous, highly sorptive substrates with excessive or rapid suction which will draw water from a mortar causing the binder to fracture.

Lack of adhesion

The loss of adhesion between the mortar and the building units is usually due to water penetration. Furthermore, excessive or rapid suction from highly sorptive substrates will create a weakened mortar-masonry unit interface with risk of separation [11]. In addition, loss of adhesion between aggregate and binder can occur as a result of mineral reaction, lime shrinkage, defective mixing or incorrect proportioning.

Weathering induced by adverse environmental conditions

Harsh environmental conditions such as frost or overly strong solar radiation can cause mortar to fail. When moisture freezes in the fresh, water-saturated mortars, the expansion coupled to freezing leads to fracturing and separation from substrate. Furthermore, if moisture is driven off a wet mortar too fast due to evaporation induced by strong solar radiation, the mortar will fracture through shrinkage and water expansion.

DESIGN OF REPAIR MORTARS FOR MASONRY BRIDGES

Bridges are often repaired by pointing and grouting with artificial cements. High-performance cement grouts (e.g. Portland and microfine cement-based) are injected in deteriorated joints and cracks. Epoxy resin grouts are also used as well as high-early-strength cement incorporating silica fume [16]. However, as mentioned above, most masonry bridges in Europe were originally built with hydraulic lime mortars. Due to their nature and function, these mortars can weather and require replacement. According to Cesare Brandi´s theory of compatibility, the 20th century architect on whose work modern conservation theory and practice is largely based; existing historic materials should be replaced with their equivalent. Therefore, repair mortars for masonry bridges should be fabricated with lime. Scientific and technical studies agree with Brandi's theory. It has been demonstrated through experimental and analytical work that lime mortars are more compatible with most masonry materials than artificial cements as they are porous, permeable and flexible, they do not contain elements capable of forming salts, they develop a good bond with masonry units and their compressive strengths are suitable to withstand typical stresses in masonry structures [2, 11, 15-20].

Lime is a versatile structural binder that can be modified to suit a range of diverse uses, materials and exposures. The composition of a repair mortar must take into account the physical properties and composition of the existing masonry. Fat limes are advised for use with more ductile, porous and weathered masonry in sheltered areas while hydraulic limes (which possess an additional mechanical strength due to their hydraulic set, lower permeability and flexibility and a better resistance to weather) are advised for use with strong masonry and in aggressive environments. In Ireland, common materials used for the construction of bridges are limestone, sandstone and granite. Most of these materials can be classified as mechanically strong and impermeable, being therefore compatible with binders of medium to eminent hydraulicity. For example, the Irish Carboniferous limestone is a dense material with a low porosity (0.27-1.09 %). Its water absorption and capillary suction are comparable to those of the Leinster, Galway, Mayo and Wexford granites [2, 18]. The compressive strength of this limestone is similar to that of the aforementioned granites (102.0 -139.0 N/mm^2) and usually comparable to the typical strength of the Irish sandstones (average compressive strengths of the Drumbane, Manorhamilton and Killaloe sandstones are 70-121N/mm^2, 105 N/mm^{2}and 107-143N/mm^2 respectively [22]). The Irish sandstones are usually more permeable than Carboniferous limestones and granites (according to [average porosity values for the Drumbane, Manorhamilton and Killaloe sandstones are 1.8-6.6%; 6.2-11.6% and 1.5-8.3% respectively, and their rates of capillary absorption determined over 48 hours are 4.1, 4.9 and 1.3- 2.1 g/m^2/s^{½} respectively [22]).

The influence of the aggregate is important. Sharp aggregate as well as an aggregate with a small average particle size and superior grading (i.e. containing particles of a wide size range) increases mechanical strength and bulk density of a mortar simultaneously reducing porosity, water absorption and capillary suction thus minimising salt, moisture and frost damage [21].

Mortar properties are also significantly affected by the mortar preparation (i.e. its water content, binder proportion or degree of compaction). For example, an excess of water with mixing undermines compressive strength. Furthermore, an excess of eminently hydraulic binder will increase compressive strength simultaneously lowering flexibility and permeability while an excess of fat lime will have the opposite effect [19, 21]. Finally, when working with limes we need to follow a seasonal plan in order to avoid weathering induced by environmental conditions. Carbonation aids such as porous aggregate and setting aids such as pozzolans accelerate hardening of lime binders subsequently providing the mortar with an early strength thus becoming more resistant to weather.

CONCLUSION

This paper concludes that in the humid, salt-rich environments of bridges with permanently non-saturated water flow and successive soaking-drying episodes, structural mortars should be hydraulic. However, the paper evidences that eminently hydraulic binders are not needed in order to ensure durability, and that fat lime mortars strengthen with the addition of pozzolans can last for over 2,000 years. The analytical results in this paper demonstrate that the reportedly low durability of fat lime is a myth and that when mortars are correctly made and executed, mortar loss by binder dissolution only takes place over a long time period, and it is beneficial for the preservation of the adjacent masonry. Furthermore, recrystallization of lime binders produces secondary cements that enable the mortar to maintain cohesion.

It is important to repair masonry fabrics with adequate mortars because a mortar's composition and production technology determine the durability, compressive strength, flexural and tensile bond strengths of masonry. Mortars should be permeable and elastic, acting as a conduit for moisture in the walls thus preserving the masonry from weathering induced by moisture and salt solutions, and deforming both plastically and elastically as they absorb masonry movements. The mechanical and fluid transfer properties of the mortar should be compatible with those of the masonry. Therefore, the hydraulicity of the mortar should be settled according to the flexural and compressive strengths, capillary suction and permeability of the adjacent masonry. In Ireland, materials commonly used for bridge construction are limestone, sandstone and granite. Most of these can be classified as mechanically strong and impermeable, being therefore compatible with mortars of medium to eminent hydraulicity. Masonry bridges in Europe were built with lime mortars of hydraulic nature. In order to comply with Brandi's conservation principle of compatibility as well as recent experimental and analytical research results, lime should be preferred to artificial hydraulic cements for the fabrication of masonry repair mortars. This paper also concludes that using a sharp, fine, well-graded aggregate, carbonation aids such as porous aggregate and setting aids such as pozzolans will strengthen a lime mortar's fabric accelerating hardening thus inducing an early strength which will allow resisting adverse weather. To evaluate mortar proportions is also advised, as these will determine the final properties of the mortar. Finally, this paper suggests avoiding an excess of water with mixing and plan site works seasonally in order to prevent mortar damage.

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REFERENCES

1. Sarangapani, G., Venkatarama Reddy, B. V. and Jagadish K. S., Brick-mortar bond and masonry compressive strength, Journal of Materials in Civil Engineering, ASCE, 2005, pp. 229-237.
2. Pavía Santamaría S., Bolton J.R., Laboratory studies of the interaction between bedding/pointing mortar and building stones, International Journal for restoration of Buildings and Monuments, 1997, Vol. 3, No. 3, pp. 253-268.
3. Pavia S. and Bolton J., Stone, brick and mortar: historical use, decay and conservation of building materials in Ireland, 2002, Wordwell, Bray.
4. Cox, R. and Gould M., Ireland's Bridges, 2003, Wolfhound, Dublin.
5. Vicat, L.J., A practical and scientific treatise on calcareous Mortars and Cements, John Weale, London, 1837, reprinted by Donhead, 1997.
6. Ashurst, J., and Ashurst, N., Practical Building Conservation, Volume 3 : Mortars, Plasters and Renders', 1988, Gower Technical Press, Aldershot.
7. Gibbons, P., Historic Scotland Technical Advice Note no. 1 Preparation and use of Lime Mortars, 1995, Historic Scotland, Edinburgh.
8. Holmes, S. and Wingate, M., Building with Lime: A Practical Introduction, 2nd Edn., 1997, TDG, London.
9. BS EN 459-2, 3: 2001 Building lime. Test methods. Conformity evaluation.
10. Plommer H., Faventinus, Vitruvius and later Roman building manuals, 1973, Cambridge University Press, London.
11. Pavía S., Lime mortars for masonry repair: Analytical science and laboratory testing versus practical experience, In: Proceedings of International Seminar Theory and Practice in Conservation- a tribute to Cesare Brandi, 2006, Eds. J. Delgado Rodrigues & J. M. Mimoso. Laboratorio Nacional de Engenharia Civil, Lisboa, pp.493-500.
12. Winkler E.M., Stone: properties, durability in man's environment, 1973, Springer-Verlag. Wier N.Y.
13. Arnold, A., Determination of mineral salts from monuments, Studies in Conservation 29, 1984, p.129-138.
14. Arnold, A.; Zehnder, K., Salt weathering on monuments. In: Analytical methodologies for the investigation of damaged stones, Pavia, Italy, 1990, p.31-58.
15. Pavía S., Petrographic analyses of historic lime mortars, Research and professional reports, unpublished, 1990-2006.
16. Perret S., Khayat K.H., Gagnon E. and Rhazi J., Repair of 130-Year Old Masonry Bridge using High-Performance Cement Grout, 2002, J. Bridge Eng., ASCE, Volume 7, Issue 1, pp. 31-38.
17. Pavía S., Design of quality, durable mortar for the conservation of historic masonry fabrics, In: 6th International Congress: Global Construction, Dundee, Scotland. Dhir, Jones and Zheng Eds. Thomas Telford, London, 2005, 469-476.
18. Pavía S., Fitzgerald B. and Howard R. Evaluation of properties of magnesian lime mortar. In: Structural Studies, Repair and Maintenance of Heritage Architecture IX. Malta, Vol 83 WIT Transactions on The Built Environment. C.A. Brebbia and A. Torpiano eds., 2005, WIT Press, pp. 375-384.
19. Pavía S., Fitzgerald B. and Treacy E., An assessment of lime mortars for masonry repair**,** In: Concrete Research in Ireland Colloquium, 2005, University College Dublin, 2006, 101-108.
20. Addison J. D., The consolidation of an 18th c. masonry arch bridge on the old military road at Corgarff, Aberdeenshire, Scotland, UK. www.scotshistoryonline.co.uk/bridges.
21. Toomey B. and Pavía S., Influence of the aggregate quality on the physical properties of natural feebly-hydraulic lime mortars, 2006, In press.
22. Kissane P, Consolidation of Irish sandstone, MSc research thesis, University of Dublin, Trinity College Dublin, 2006, unpublished.