

Mechanical and hygric properties of natural hydraulic lime (NHL) mortars with pozzolans

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ABSTRACT: Currently, hydraulic limes are used as binders to strengthen and repair traditional and historic masonry. For hundreds of years, pozzolans have been used in combination with lime binders to improve the properties and durability of masonry mortars and concrete. This paper studies flexural and compressive strength, porosity, water absorption and capillary suction of natural hydraulic lime (NHL5) mortars prepared with two pozzolanic additions (ground granulated blastfurnace slag –GGBS- and rice husk ash-RHA). Portland limestone dust was used as a filler. The mixing, curing, binder/aggregate ratio and flow were kept constant in order to attribute variation of mortar properties to the type of additive. Two pozzolan/lime percentages were used (10% and 20%). The results indicate that at age of 28 days, the partial replacement of NHL5 by 20 % GGBS (i) greatly increased compressive and flexural strength by 125% and 67% respectively compared to a control mortar (without additive); and (ii) decreased porosity, water absorption and capillary suction by 46%, 44% and 66% respectively when compared to a control mortar.

1 INTRODUCTION

Natural hydraulic limes have been used as a binder for building since antiquity. They are produced by burning limestone which naturally contains impurities mainly in the form of silica and alumina. Nowadays, these limes are used for new building and repairs to existing masonry. They are often chosen as a compatible materials to repair traditional and historic masonry. They are sometimes preferred to hydrated lime because of their hydraulic set leads to an earlier strength development, a lower shrinkage and greater durability. In the past, hydraulic limes were locally produced and used wherever impure limestone was available. The use of hydraulic lime binders decreased with the development of cements in the early nineteenth century, however, hydraulic limes are regaining popularity as a sustainable alternative to Portland cement. Their environmental credentials are based on their lower production energy consumption and the reabsorption of the CO₂ emitted during burning.

Pozzolans are materials with an amorphous siliceous or siliceous and aluminous content that react with calcium hydroxide in the presence of water to form cementitious hydrates (calcium silicate and calcium silicate aluminate hydrates). In many ancient civilizations, pozzolans were used to enhance the properties of lime mortars and concrete and many structures still remain as a testament to the durability of lime–pozzolan mortars and concrete. Today, pozzolans are often used to enhance the properties and increase the durability of Portland cement (PC) concrete and other Portland cement composites. Most pozzolans commercially used today are often industrial or agricultural byproducts, therefore, as wastes, their use in construction drops energy consumption and CO₂ emissions and is a better alternative to landfill disposal.

Evidence of the use of pozzolans has been found in the Neolithic period (7000 BC) in Galilee (Caijun 2001 referring to Malinowski et al.), the Minoan civilization (2700 to 1450 BC) (Carr 1995) and Ancient Greece (1500 BC) (Moropoulou et al. 2004 referring to Jiang and Roy). The Roman Empire is however most associated with the use of pozzolans. According to historic records and current research (Hicky Morgan (1914) Hooper and Ash (1939) Davey (1961) Plommer (1973) Boynton (1980) Pavia and Caro (2008) the Romans often used both natural (volcanic ash) and artificial pozzolans (brick and tile dust) to render pure lime hydraulic.

According to the European lime standard EN 459-1 (Schiffner 2011) there are three strength classes of natural hydraulic lime: NHL2, NHL3.5 and NHL5; where the numbers refer to the minimum compressive strength (MPa) at 28 days. According to this standard, when pozzolanic or hydraulic materials such as PC are incorporated as additives (up to 20%) the letter Z follows the lime designation e.g. NHL5-Z. NHL is obtained by burning limestones with a high content of clay (6.5–20%) below the sintering temperature (1250°C). This results in the formation of mainly clinkers that hydrate and raise strength slower than those in Portland cement (dicalcium silicate-belite- C_2S) and a significant amount of available lime ($\geq 15\%$ by mass for NHL5). As a result, NHL mortars harden through a dual mechanism (a more or less fast hydration and slow carbonation).

In the last decades, practical research in the conservation of historic buildings has linked the use of hydraulic lime mortars with pozzolans to an ease of application, compatibility with substrates and durability. For example, (Maravelaki-Kalaitzaki, Bakolas et al. 2005) used NHL3-Z lime mortar to restore historic bioclastic limestone masonry in Chania Crete, Greece. The authors recorded no failure, cracks or release of soluble salts after three years. Proprietary hydraulic lime mortars were used in the restoration of the renaissance façade of the Courts Office in Bruges in 2000 (Naeyer 2000). These were reported to retain workability being easy to apply and remaining plastic for longer periods so that masons could rework and reset their repairs. In the restoration of the Cathedral at Kirkjubøur in the Faroe Islands (Larsen, von Konow et al. 2007) different hydraulic lime mortars were tested in the laboratory and on site to determine resistance against weathering. The authors concluded that only a hydraulic lime mortars (NHL5-Z and NHL3.5) would be durable in the exposed environment of the islands. Allanbrook and Normandin (2007) used NHL mortars to repair the limestone of the Fifth Avenue facade of the Metropolitan Museum of Art in New York City. They reported that the mortars were inherently compatible with limestone because of their mineral composition and found that the NHL mortar can reach the strength typically achieved by type N mortar (an ASTM C270-07 mix widely used by craftsmen and specified by architects after 1931, consisting of hydrated lime, portland cement and sand).

Laboratory research has also reported NHL mortars as highly workable materials of low shrinkage, that can develop a good bond with masonry units and display high deformability and water vapor permeability and are resistant to salt and frost damage (Lanas et al. 2004, Hanley and Pavia 2008, Ball et al. 2011, Grilo et al. 2014). Other authors have improved the mechanical properties of NHL mortars using fibres: Chan and Bindiganavile (2010) used polypropylene micro-fibres in NHL2 mortars to impart post-peak stress carrying capacity in compression, flexure and shear; and increase their flexural toughness. However, despite a considerable amount of literature devoted to the cement/pozzolan composites, there is a paucity on research publications on NHL mortars with pozzolans. Former authors have investigated their mechanical strength Grist et al. (2013) and Grilo et al. (2014 b). This paper contributes to the understanding of the properties of NHL mortars with pozzolans by measuring the mechanical

and hygric properties of NHL5 mortars with additives including Ground Granulated Blastfurnace Slag (GGBS), rice husk ash (RHA) and Portland stone dust (PSD) in an effort to improve the characteristics and the performance of NHL mortars. In this study, the pozzolans and PSD were used as partial replacements for the NHL binder.

Pozzolans GGBS and RHA have been successfully used with Portland cement for decades to enhance properties and durability of PC concrete. Their reactivity and impact on the properties of hydrated lime pastes have also been investigated. Walker and Pavía (2010, 2011) demonstrated that, out of 9 pozzolans, GGBS and RHA were amongst the most reactive due to their high amorphousness; and that GGBS (and metakaolin) produced the highest strength followed by the high-silica pozzolans RHA and microsilica (with a strength 68% lower). The results concluded that strength produced depends on the amount of lime combined by the pozzolan which is determined by the pozzolan's reactivity (in turn governed by the pozzolan's amorphousness); the type of hydrates formed and the physical filler effect induced by the pozzolan.

Pozzolans react with lime ($\text{Ca}(\text{OH})_2$ -portlandite) forming hydrates similar to those found upon hydration of PC and hydraulic limes. In this research, the NHL5 binder contributes a significant amount of free lime (≥ 15 according to EN459-1) to the pozzolanic reaction.

According to Massaza (2007) pozzolanic reaction is slow however, when combined in the right ratio, pozzolans increase the ultimate strength of lime composites: the compressive strength at 2 years can be as high as 3 times the 28-day strength. Pozzolanic reaction has always been reported as slow in literature however, according to Pavía et al. (2014), in RHA-lime mortars, pozzolanic reaction had already began at 1 day of curing, and pozzolanic hydrates were clearly present after 24 h, progressively increasing in size and amount (at 3 and 7 days) and linking to each other forming continuous networks throughout the paste after 14 days.

2 MATERIALS AND METHODS

2.1 Materials

A natural hydraulic lime (NHL5) complying with EN 459-1 is the binder in all mortars studied. Two pozzolans and stone dust were used as additives including Ground Granulated Blastfurnace Slag (GGBS), Rice Husk Ash (RHA) and Portland stone dust (PSD). The physical properties and chemical composition of the pozzolans are included in Tables 1 and 2. The RHA studied has a high specific surface area ($13.70 \text{ m}^2/\text{g}$), significantly superior to GGBS and comparable to hydrated lime ($16.08 \text{ m}^2/\text{g}$).

The chemical composition was analysed with XRF, their mineral composition and amorphousness with XRD and their particle size and specific surface area with laser and gas adsorption respectively. Details can be found in Walker and Pavía 2010 and 2011. The PSD consists mainly of calcite (CaCO_3), with traces of silica in the form of quartz (SiO_2). A siliceous sand similar in grading and composition to the European CEN standard sand was used as aggregate. The composition and water demand of the mortars studied are shown in Table 3. The mortars were mixed to a constant initial flow of $165 \pm 5 \text{ mm}$ (measured with a flow table in accordance with EN 459-2), with a binder:aggregate ratio of 1:3 by weight, in order to attribute variation of mortar properties to the type of additive. Two additive-binder replacements (10 and 20%-by weight) were investigated.

Table 1- Chemical, mineral composition and amorphousness of the pozzolans (Walker and Pavía 2011). – not detected.

Pozzolan	SiO ₂	Al ₂ O ₃	CaO	Fe ₂ O ₃	SO ₃	MnO	K ₂ O	MgO	Amorphousness rate (1-5)	Mineralogical composition
GGBS	34.14	13.85	39.27	0.41	2.43	0.25	0.26	8.63	(5) Totally	no crystalline fraction
RHA	93.84	1.93	0.68	0.29	-	0.12	1.38	0.45	(4) Mostly	quartz and cristobalite

Table 2. Physical properties of the pozzolans. *Approx. 90% of particles.

Pozzolan	Specific surface area (m ² /g)	Particle size (µm)*
GGBS	2.65	1.0-11
RHA	13.7	2.5-14

Table 3. Composition and water content of mortars investigated.

	NHL5 (%)	GGBS (%)	RHA (%)	PSD (%)	W/B
Control	100	0	0	0	0.65
G1	90	10	0	0	0.65
G2	80	20	0	0	0.66
R1	90	0	10	0	0.73
R2	80	0	20	0	0.75
D1	90	0	0	10	0.60
D2	80	0	0	20	0.58

2.2 Sample preparation and curing

The lime, additives (if applicable) and aggregate were dry mixed for 2 min. Water was then added and mixed for 2 min at low speed and finally at high speed for 1 min. As aforementioned, water was added to achieve a flow diameter of 165±5 mm. The mortars were moulded and compacted on a vibration table for 5 seconds according to EN 459-2. They were initially covered with damp hessian to prevent shrinkage cracking, removed from the moulds after 3 days and cured for 25 days at approximately 90% humidity and 20 ± 2°C temperature. Each property measured is the arithmetic mean of three specimens.

2.3 Mechanical strength and hygric properties

The compressive (F_c) and flexural strength (F_f) were measured according to EN 1015-11(1999). The flexural test was performed on 40x40x160 mm mortar prisms using a Zwick testing machine at rates of loading of 1mm/min. Compression strength tests were carried out on the half prisms using a loading rate of 1 mm/min.

The porosity and bulk density of the mortars was tested according to RILEM recommendations (RILEM 1980). The water absorption was measured according to UNE . Capillary suction was measured according to EN 1925 (1999). In this test, the dry samples were immersed to a depth of 3 ± 1 mm. They were removed and weighed at specific time intervals of

1, 3, 5, 15, 30 and 60 minutes and the coefficient of water absorption by capillarity then calculated according to EN 1925 (1999).

2.4 Scanning electron microscope analysis of the mortar microstructure and the products of hydration/ pozzolanic reaction.

The microstructure of the hardened mortar and the products of hydration and the pozzolanic reaction were studied with a scanning electron microscope (SEM). The analytical system employed was a Zeiss DSM-950 SEM equipped with a backscattered electron detector and a LINK-QX 2000 energy dispersive X-ray analysis attachment (EDX). Spectra were taken with a voltage of 20 kV through a beryllium window.

3 RESULTS AND DISCUSSION

3.1 Mechanical properties

The compressive and flexural strength of the mortars are shown in Table 4. The low coefficient of variation (COV) indicates that the results are consistent. As it can be seen from this table, replacement of NHL5 by GGBS, RHA and PSD enhances compressive and flexural strength at 28 days. This agrees with the results obtained by (Grist et al. 2013) and (Işıkdağ and Topçu 2013).

Table 4. Compressive (F_c) and flexural (F_f) strength of mortars at 28 days.

	F_c (Mpa)	COV%	F_f (Mpa)	COV%
100% NHL5 (control)	9.53	1.86	0.97	1.88
10% GGBS (G1)	9.99	7.50	2.03	0.98
20% GGBS (G2)	21.52	2.76	1.59	4.72
10% RHA (R1)	12.02	2.94	1.49	0.94
20% RHA (R2)	14.17	2.87	1.70	2.93
10% PSD (D1)	13.11	7.50	1.34	5.83
20% PSD (D2)	11.88	2.76	0.96	4.52

The strength increase by the pozzolans is probably due to the presence of additional pozzolanic cements. As it can be seen from figure 2, the NHL5 binder shows significant portlandite after 90 days of curing while the NHL5:GGBS mortar shows no portlandite and abundant needle-shaped and low-crystallinity hydrates. This indicates that the free lime (Ca(OH)_2 -portlandite) released on hydration of the NHL5 clinkers has been consumed by the GGBS to produce cementing hydrates that have strengthen the mortar microstructure.

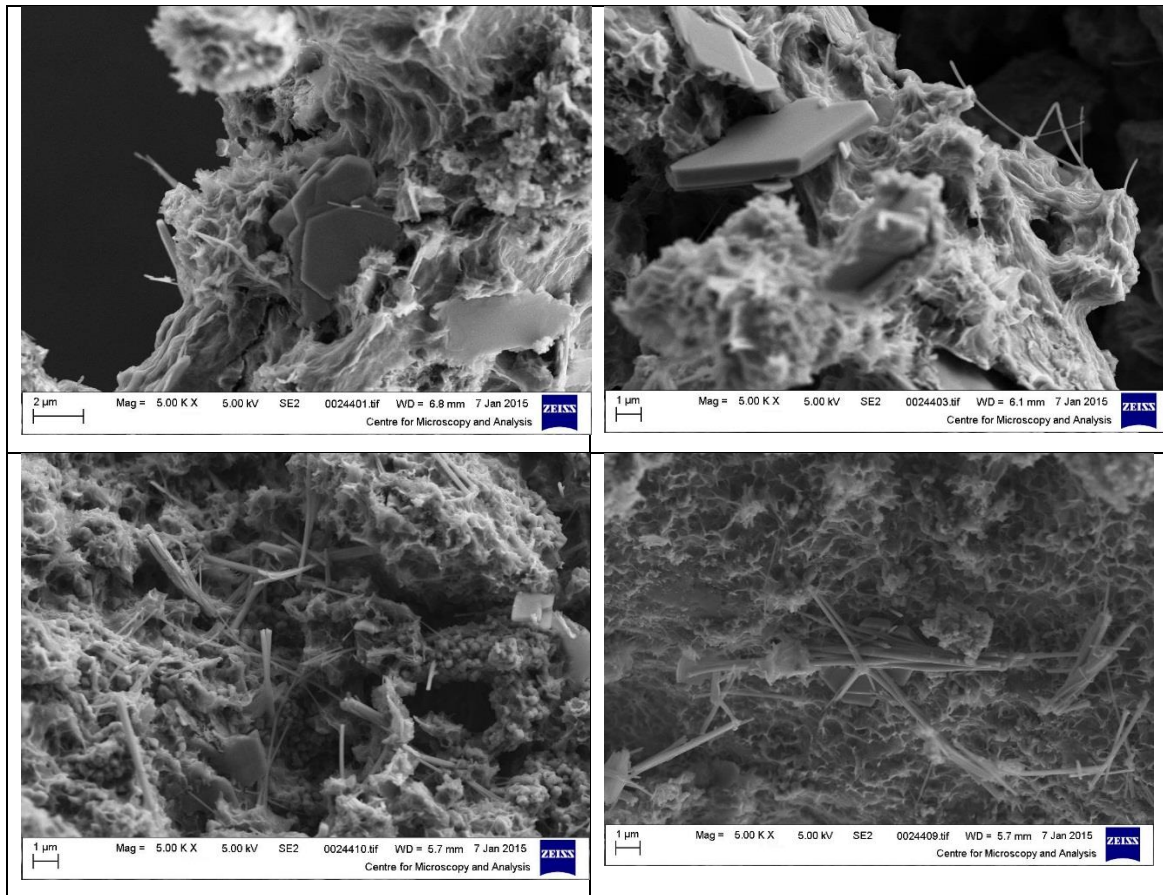
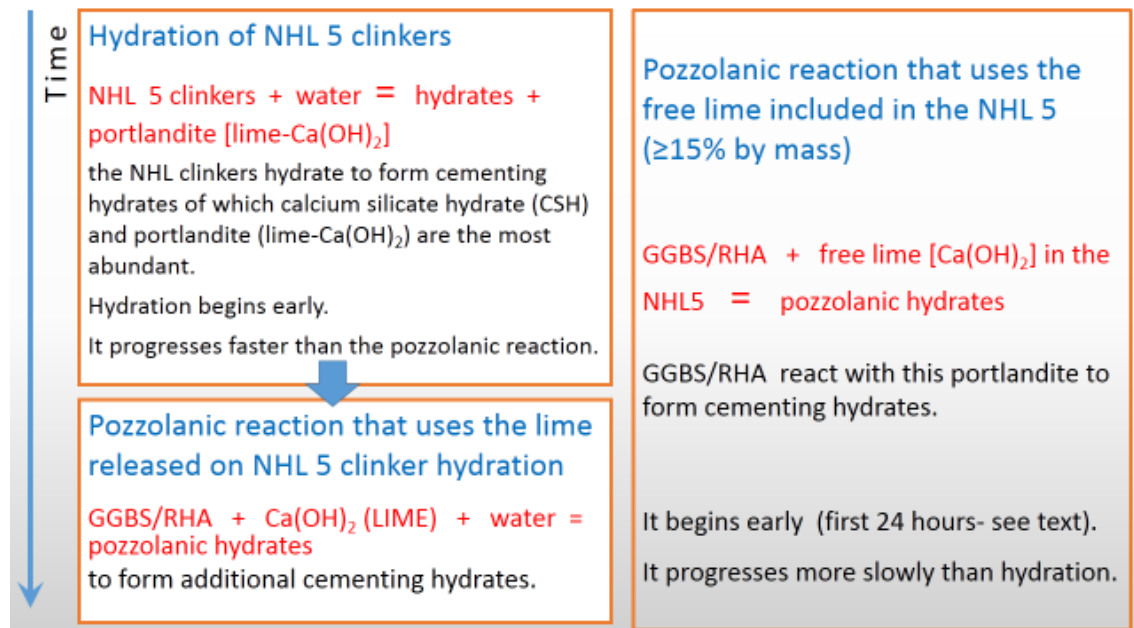


Figure 2. SEM micrographs of NHL5 mortar (top images) and NHL5:GGBS mortar (bottom images) at 90 days. The NHL5 mortar includes some carbonated lime, rare needle-shape hydrates and abundant hexagonal plates of portlandite whereas the NHL5:GGBS mortar shows abundant needle-shaped hydrates and no portlandite.

In NHL-pozzolan mortars there are several simultaneous processes contributing to setting and strength development. These are summarized in Figure 3. The hydration of the NHL5 clinkers begins early and occurs simultaneously to the pozzolanic reaction where GGBS and RHA react with the free lime (Ca(OH)_2 -portlandite) in the NHL5 (as aforementioned, the NHL5 binder contributes a significant amount of free lime to the system: $\geq 15\%$ by mass). Pozzolanic reaction is often reported in the literature as beginning late and progressing slowly however, in RHA-lime pastes, pozzolanic hydrates were recorded after 24 hours, increasing in size and amount at 3 and 7 days and linking to each other, forming continuous networks throughout the paste after 14 days (Pavía et al. 2014).

The hydration of the NHL5 clinkers progresses more or less fast forming early cementing hydrates and releasing additional free lime (Ca(OH)_2 -portlandite) which also reacts with the GGBS and RHA pozzolans in the presence of water to form additional cements.

Figure 3- Simultaneous processes in NHL 5 – pozzolan system.



The 20% GGBS mortar achieved the highest compressive strength, with an approximately 125% increase when compared to the control mortar. This result was expected as GGBS is not a true pozzolan but contains clinkers that quickly hydrate. However, the amount of clinker is very low (under the 5% X-ray diffraction detection limit as no crystalline fraction was detected by XRD-Table 1). The results agree with former authors reporting that GGBS (and metakaolin) pozzolans produced the highest strength followed by high-silica pozzolans such as RHA with a 68% reduction (Walker and Pavía 2010, 2011). The RHA mortar results agree with Pavía et al. 2014 who reported that rising RHA content significantly increases compressive and flexural strengths of hydrated lime (CL90s) mortars: the 1:3 (CL90s:RHA) mortars were over 37 times stronger in compression and nearly 5 times stronger in flexion than the control lime mortars.

The GGBS and RHA specimens increased both flexural and compressive strength with increasing replacement level: the compressive and flexural strength of the 20%RHA mortars are 48 and 7.5% higher (respectively) than those of the control mortar, whereas the 10%RHA mix is only 24% higher in compression and 5% higher in flexion than the control mortar. A 10% increase in GGBS replacement level doubles the strength of the mortars whereas a 10% increase in RHA only raises the compressive strength slightly (from 12 to 14 MPa). The superior strength triggered by the GGBS can be attributed to the presence of clinkers.

In contrast, it was noted that the rate of strength increase in PSD mortars is higher at low-level replacements: the 10% PSD mortar showed 56 and 37 % increase in compressive and flexural strength respectively, while the 20% PSD mix increased 24 % in compressive strength and did not increase flexural strength when compared to the control mortar.

These findings agree with (Menéndez et al. 2003) who reported that in cement mortar the compressive strength slightly decreases with increasing limestone replacement level up to 20%. They found that the replacement of cement by 20% limestone powder slightly reduces the strength by about 4%, at 28 days, compared to cement mortar with 10% limestone powder. The results also agree with (Courard and Michel 2014) who concluded that the compressive strength of cement mortar decreases by increasing the ratio of limestone filler. According to the previous

publications (Menéndez, Bonavetti et al. 2003), (Péra, Husson et al. 1999) and (Bonavetti, Rahhal et al. 2001), the addition of limestone powder to cement mortar completes the fine fraction in the particle size distribution curve of cement without an increment on water demand that improves the packing density, blocks the capillary pores and increases the strength of the composites. This finding was also noted in NHL/PDS mortars, as listed in Tables 3 and 4 the replacement of NHL 5 by 10 and 20 % PSD slightly decreases the water demand by 7 and 10% respectively and increases strength compared to the control mortar. Furthermore, they reported that the limestone dust constitutes nucleation sites of calcium hydroxide crystals at early hydration ages accelerating the hydration of clinker particles. As a result, it increases the early strength, but it does not have pozzolanic properties and it does not produce CSH.

3.2 *Hygric properties*

SEE COSGROVE

(The porosity, water absorption and suction of NHL5 mortar found by (Cosgrove and Pavía, 2009) are slightly higher than the current results, may be because they used higher flow (185mm), while in this work the flow was 165 mm).

The hygric properties of lime mortars are of great importance as they significantly impact the performance of the materials in relation to water, frost, salt and chemical weathering which determine durability. According to the results, Table 3, the porosity of the RHA mixes and the control mortar are similar to the porosity of historic hydraulic lime mortars documented by (Moropoulou, Bakolas et al. 2005). **GIVE A RANGE OF POROSITIES REPORTED BY THESE AUTHORS.**

(They obtained the porosity values from tests performed on a large number of historic composites sampled from ancient structures in the Mediterranean Basin, they reported that the porosity values of historic hydraulic lime mortars are between 18-40%).

However, the GGBS and filler mortars have slightly lower porosities. Furthermore, the porosity of the control mortar agrees with the porosity recorded by (Gulotta, Goidanich et al. 2013)

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(They found that the porosity of NHL 5 mortar, with standard quartz–siliceous sand at B/A ratio of 1:3 by weight, is 21.42 %)

The results showed that the porosity of lime/GGBS mortars was significantly lower than that of the control mortar. Around 46 and 33% decrease was observed for mixes G2 and G1 respectively. The result agrees with the observation made by (Griffin 2004), who reported that the addition of GGBS to non-hydraulic lime putty decreases the porosity by about 25% compared to control mortar.

According to (Siddique and Bennacer 2012) the addition of GGBS to lime in mortar results on an interface with smaller gel pores and fewer larger capillary pores; a finer pore structure that lowers porosity and enhances durability.

Replacement of NHL5 by 10 and 20 % PSD reduced the porosity by about 16 % compared to the control mortar. **This decrease can be on account of the filler effect of PSD that enhances the density of the lime matrix reduces the mortar porosity.**

On the otherside, the addition RHA had no significant effect on the porosity. Although, RHA and GGBS have a similar particle size, RHA has a greater surface and significantly higher water demand. As reported by (Papayianni and Stefanidou 2006), the water/binder ratio is the most important factor influencing the porosity. This may explain why RHA mortars have higher porosity than GGBS mortars. It is generally accepted that the strength increasing by decreasing the porosity, and that was evident from GGBS and PDS results. However, according to results in table 2 it seems that strength is also dependent on the pozzolanic reactivity and hence the RHA despite having a higher porosity on account of the high water/binder ratio also have a higher strength, which agrees with the same results of (Papayianni and Stefanidou 2006) (Walker and Pavía 2010).

Similar trend was observed for the water absorption (table 3), as it strongly related to the porosity of the mortar. According to the results in table 3, about 19% decrease was observed for mixes D1 and D2, more than 49% decrease for mix G2. Further more, mix R1, which contained 10 wt.% RHA possesses a slightly higher absorption than the control mix. While mix R2 nearly achieved similar results as the control mortar.

DOES SUCTION FOLLOW THE SAME TREND?

(It follows the same trend in GGBS and PSD mixes, but did not follow the trend in RHA mixes. Where CS in R1 is lower than the control mortar. However, the porosity and water absorption for R1 is slightly higher than the control mortar)

The coefficient of capillary suction (CS) is related to the size and amount of pores and their degree of interconnection. As it can be seen from the results in Table 3, the control mortar and D2 have the greatest CS and their values are similar to the value of the mortar that designed by (Maravelaki-Kalaitzaki, Bakolas et al. 2005) to repair historic Bioclastic limestone. The 20%GGBS mortar shows the lowest suction with a 64% decrease with respect to the control mortar. Followed by mixes G1 and R2, that achieved about 49 and 41% decrease in CS with respect to the control specimen. This decrease indicates that hydrates filling pores in lime/pozzolan mortars reduce capillary action.

Table 3. Hygric properties of mortars at 28 days

	Porosity (%)	COV%	Water absorption (%)	COV%	Capillary suction (kg/m ² .min ^{0.5})	COV%
100% NHL5 (control)	20.07	2.49	10.65	2.71	1.198	2.95
10% GGBS (G1)	13.36	2.48	6.82	2.64	0.659	1.59
20% GGBS (G2)	10.65	1.7	5.35	1.74	0.423	4.21
10% RHA (R1)	20.75	0.5	11.12	0.74	0.929	3.47
20% RHA (R2)	19.78	1.23	10.62	1.41	0.697	0.33
10% PSD (D1)	16.37	3.04	8.53	3.26	0.924	6.75
20% PSD (D2)	16.85	3.40	8.74	5.57	1.058	3.49

3.3 Conclusion

- Portland stone dust has a reasonable contribution to improve the strength and reduce the porosity, water absorption and suction of the mortar but it has a fixed ratio and percentages. Further, investigations are needed to discover a proper way of using the dust without affecting the strength of the mortar.
- The replacement of lime by 20% GGBS greatly improved compressive and flexural strength at 28 days. Furthermore, it significantly reduces porosity, water absorption and capillary suction at 28 days.
- The replacement of lime by RHA, improves the compressive and flexural strength at 28 days. Although the addition of RHA slightly decreases capillary suction, it did not contribute in decreasing either porosity or water absorption.

References

In the text, place the authors' last names without initials and the date of publication in parentheses, e.g. Demir et al (2014) or Michels et al. (2013). At the end of the paper, list all references in alphabetical order, in a separate "References" section. The references should be typed using the References style (10 pt font, second and further lines indented by 4.0 mm). If several works by the same author are cited, entries should be chronological.

- Caijun S (2001) Studies on several factors affecting hydration and properties of lime-pozzolan cements. *J Mater Civ Eng* 13(6):441–445
- Carr JG (1995) An investigation on the effect of brick dust on lime-based mortars. Masters dissertation, University of Pennsylvania
- Moropoulou A, Carmak A, Labropoulos KC, Van Grieken R, Torfs K (2004) Accelerated microstructural evolution of a calcium-silicate-hydrate (C-S-H) phase in pozzolanic pastes using fine siliceous sources: Comparison with historic pozzolanic mortars. *Cem Concr Res* 34(1):1–6
- Hicky Morgan M (1914) *Vitruvius: the ten books on architecture*. Harvard University Press, Cambridge
- Hooper WD, Ash HB (1939) *Marcus Porcius Cato and Marcus Terentius Varro, De Re Rustica*. William Heinemann Ltd, Harvard University Press, London
- Plommer H (1973) *Faventinus, Vitruvius and later roman building manuals*. Cambridge University Press, London
- Pavía S, Caro S (2008) An investigation of Roman mortar technology through the petrographic analysis of archaeological material. *Constr Build Mater* 22(8):1807–1811
- Davey, N. (1961). *A history of building materials*, Phoenix House, London.
- Griffin, I. (2004). "Pozzolanas as Additives for Grouts." *STUDIES IN CONSERVATION* 49: 23-34.
- Boynton, R. S. (1980). *Chemistry and technology of lime and limestone* (2nd ed.), John Wiley & Sons, Inc., New York.
- Schiffner, H. 2011 EN459- the new European standard for building lime. ZKG International. Number 5, pages 76-89
- Lanas, J., J. L. Perez Bernald, M. A. Bello and J. I. Alvarez Galindo (2004). "Mechanical properties of natural hydraulic lime-based mortars." *Cement and Concrete Research* 34: 2191-2201.

- Hanley, R. and S. Pavía (2008). "A study of the workability of natural hydraulic lime mortars and its influence on strength." Materials and Structures **41**: 373-381.
- Ball, R. J., A. El-Turki and G. C. Allen (2011). "Influence of carbonation on the load dependent deformation of hydraulic lime mortars." Materials Science and Engineering: A **528**(7-8): 3193-3199.
- Grilo, J., P. Faria, R. Veiga, A. Santos Silva, V. Silva and A. Velosa (2014) a. "New natural hydraulic lime mortars – Physical and microstructural properties in different curing conditions." Construction and Building Materials **54**: 378-384.
- Grilo, J., A. Santos Silva, P. Faria, A. Gameiro, R. Veiga and A. Velosa (2014) b. "Mechanical and mineralogical properties of natural hydraulic lime-metakaolin mortars in different curing conditions." Construction and Building Materials **51**: 287-294.
- S. Pavía, R. Hanley (2010) Flexural bond strength of natural hydraulic lime mortar and clay brick. *Materials and Structures*, 43 , (7), 2010, 913 - 926
- Grist, E. R., K. A. Paine, A. Heath, J. Norman and H. Pinder (2013). "Compressive strength development of binary and ternary lime–pozzolan mortars." Materials & Design **52**: 514-523.
- Muhit, I. B., M. T. Raihan and M. Nuruzzaman (2014). "Determination of mortar strength using stone dust as a partially replaced material for cement and sand." Advances in Concrete Construction **2**(4): 249-259.
- EN 459-1 (2010) Building lime. Part 1: Definitions, specifications and conforming criteria. European Committee for Standardisation CEN, Brussels
- UNE 67-027-84. Determinacion de la absorcion de agua. Ladrillos
- EN 1015-11 (1999) Methods of test for mortar for masonry. Determination of flexural and compressive strength of hardened mortar.
- EN 1925 (1999) Natural stone test methods. Determination of water absorption coefficient by capillarity.
- RILEM (1980). "Recommended tests to measure the deterioration of stone and assess the effectiveness of treatment methods." Materials and Structures **13**: 175– 253
- Walker, R. and S. Pavía (2010). "Effect of pozzolan properties on the properties of building composites. In: BCRI Bridge Infrastructure Concrete Res Ireland, Ní Nualláin, Walsh, West, Cannon, Caprani, McCabe Univ. of Cork, 457-468.
- Walker, R. and S. Pavía (2011). Physical properties and reactivity of pozzolans, and their influence on the properties of lime–pozzolan pastes. Materials and Structures **44**: 1139–1150.
- Işıkdağ, B. and İ. B. Topçu (2013). "The effect of ground granulated blast-furnace slag on properties of Horasan mortar." Construction and Building Materials **40**: 448-454.
- Chan and Bindiganavile (2010)
- S. Pavía, R. Walker, P. Veale, A. Wood (2014) Impact of the properties and reactivity of rice husk ash (RHA) on lime mortar properties, *Journal of Materials in Civil Engineering*, ASCE, 2014. DOI: 10.1061/(ASCE)MT.1943-5533.0000967
- Maravelaki-Kalaitzaki, P., A. Bakolas, I. Karatasios and V. Kilikoglou (2005). "Hydraulic lime mortars for the restoration of historic masonry in Crete." Cement and Concrete Research **35**(8): 1577-1586.
- Allanbrook, T. and K. C. Normandin (2007). "The Restoration of the Fifth Avenue Facades of the Metropolitan Museum of Art. APT BULLETIN-FREDERICKSBURG VA- 38.4: 45."
- Larsen, P. K., T. von Konow and S. Johansson (2007). "The restoration of the cathedral at Kirkjubøur in the Faroe Islands." Non-Destructive Evaluation of the Penetrability and Thickness

of the Concrete Cover-State-of-the-Art Report of RILEM Technical Committee 189-NEC: 653-660.

Naeyer, A. (2000). *New Materials for Safeguarding Cultural Heritage*. Architectural Preservation, University Ghent, Hogeschool Antwerpen, Plantinkaai 22/1, B-2000 Antwerpen, Belgium

Massazza, F. (2007), 'Pozzolana and pozzolanic cements', in: *Hewlett P.C. Ed. Lea's chemistry of cement and concrete*, Elsevier, UK, 471-602.

Siddique, R. and R. Bennacer (2012). "Use of iron and steel industry by-product (GGBS) in cement paste and mortar." Resources, Conservation and Recycling **69**: 29-34.

"EN 459-1 (2001) Building lime. Part 1: Definitions, specifications and conforming criteria. European Committee for Standardisation CEN, Brussels."

"UNE 67-027-84. Determinacion de la absorcion de agua. Ladrillos."

(1999). "BS EN 1015-11, Methods of test for mortar for masonry. Determination of flexural and compressive strength of hardened mortar."

(1999). "BS EN 1925, Natural stone test methods. Determination of water absorption coefficient by capillarity."

Allanbrook, T. and K. C. Normandin (2007). "The Restoration of the Fifth Avenue Facades of the Metropolitan Museum of Art. APT BULLETIN-FREDERICKSBURG VA- 38.4: 45."

Ball, R. J., A. El-Turki and G. C. Allen (2011). "Influence of carbonation on the load dependent deformation of hydraulic lime mortars." Materials Science and Engineering: A **528**(7-8): 3193-3199.

Bonavetti, V. L., V. F. Rahhal and E. F. Irassar (2001). "Studies on the carboaluminate formation in limestone filler-blended cements." Cement and Concrete Research **31**(6): 853-859.

Courard, L. and F. Michel (2014). "Limestone fillers cement based composites: Effects of blast furnace slags on fresh and hardened properties." Construction and Building Materials **51**(0): 439-445.

[ASTM C270-07 Standard Specification for Mortar for Unit Masonry, Proportion Specification](#)

Griffin, I. (2004). "Pozzolanas as Additives for Grouts." STUDIES IN CONSERVATION **49**: 23-34.

Grilo, J., A. Santos Silva, P. Faria, A. Gameiro, R. Veiga and A. Velosa (2014). "Mechanical and mineralogical properties of natural hydraulic lime-metakaolin mortars in different curing conditions." Construction and Building Materials **51**: 287-294.

Grist, E. R., K. A. Paine, A. Heath, J. Norman and H. Pinder (2013). "Compressive strength development of binary and ternary lime–pozzolan mortars." Materials & Design **52**: 514-523.

- Gulotta, D., S. Goidanich, C. Tedeschi, T. G. Nijland and L. Toniolo (2013). "Commercial NHL-containing mortars for the preservation of historical architecture. Part 1: Compositional and mechanical characterisation." Construction and Building Materials **38**(0): 31-42.
- Hanley, R. and S. Pavía (2008). "A study of the workability of natural hydraulic lime mortars and its influence on strength." Materials and Structures **41**: 373-381.
- Işıkdağ, B. and İ. B. Topçu (2013). "The effect of ground granulated blast-furnace slag on properties of Horasan mortar." Construction and Building Materials **40**: 448-454.
- Lanasa, J., J. L. Pe´rez Bernalb, M. A. Bellob and J. I. Alvarez Galindo (2004). "Mechanical properties of natural hydraulic lime-based mortars." Cement and Concrete Research **34**: 2191-2201.
- Larsen, P. K., T. von Konow and S. Johansson (2007). "The restoration of the cathedral at Kirkjubøur in the Faroe Islands." Non-Destructive Evaluation of the Penetrability and Thickness of the Concrete Cover-State-of-the-Art Report of RILEM Technical Committee 189-NEC: 653-660.
- Maravelaki-Kalaitzaki, P., A. Bakolas, I. Karatasios and V. Kilikoglou (2005). "Hydraulic lime mortars for the restoration of historic masonry in Crete." Cement and Concrete Research **35**(8): 1577-1586.
- Menéndez, G., V. Bonavetti and E. F. Irassar (2003). "Strength development of ternary blended cement with limestone filler and blast-furnace slag." Cement and Concrete Composites **25**(1): 61-67.
- Moropoulou, A., A. Bakolas and S. Anagnostopoulou (2005). "Composite materials in ancient structures." Cement and Concrete Composites(27): 295–300.
- Naeyer, A. d. (2000). *New Materials for Safeguarding Cultural Heritage*. Architectural Preservation, University Ghent, Hogeschool Antwerpen, Plantinkaai 22/1, B-2000 Antwerpen, Belgium
- Papayianni, I. and M. Stefanidou (2006). "Strength–porosity relationships in lime–pozzolan mortars." Construction and Building Materials **20**(9): 700-705.
- Péra, J., S. Husson and B. Guilhot (1999). "Influence of finely ground limestone on cement hydration." Cement and Concrete Composites **21**(2): 99-105.
- RILEM (1980). "Recommended tests to measure the deterioration of stone and assess the effectiveness of treatment methods." Materials and Structures **13**: 175– 253.
- Siddique, R. and R. Bennacer (2012). "Use of iron and steel industry by-product (GGBS) in cement paste and mortar." Resources, Conservation and Recycling **69**: 29-34.
- Walker, R. and S. Pavía (2010). "Effect of pozzolan properties on the properties of building composites."