Menard Kilumile

Secondary materials in mortars for use in historical buildings.

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DECLARATION

Name: Menard Kilumile
Email: mwagito.kilumile@gmail.com
Title of the MSc Dissertation: Secondary materials in mortars for use in historical buildings
Supervisors: Prof. Dr. Marilida Barra & Dr. Diego Aponte.
Ext. Supervisor: Prof. Dr. Enric Vázquez
Year: 2015/2016

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University: Universitat Politècnica de Catalunya
Date: July 15, 2016
Signature:
DEDICATION

This work is dedicated to my beloved father late B. Kilumile, mother A. Mgaya and my lovey fiancée O. J. Mwilongo.
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ABSTRACT

Natural lime has been used in historical mortar since antiquities. Air lime mortars are poor and needs air to set, the reason for its proneness to environmental damage in high humid areas. In struggle to improve strength properties of historical mortars, man has used every possible material including additives such as slag and silica fume. In 19th century, the discovery of the high strength developing cement started to replace lime in both construction and repair of the historical constructions. Incompatible behavior of cement with the lime and the historical substrates aggravated the pathologies. For this reason, in recent years there has been efforts put in revival of the lime based mortars for the reparation of historical buildings. Most of these buildings are found in areas of high moisture. It has therefore been found important to use lime mortars with improved properties. Hydraulic lime which sets both in water and air suffices the purpose. The improvement in strength is not only the function of the binder characteristics but also that of the aggregates. For this fact, it is important to look for alternative fine aggregates to the natural sand that has long been used.

This study is focused on examining the properties of hydraulic lime mortars with natural river sand, recycled concrete fine aggregates and recycled brick sand. The containing natural sand has been used as the reference mortar. The study was achieved through laboratory experimentation of the material and mortar samples containing the respective aggregates. Assessed were the mechanical, physical and thermal properties. Also, the mechanical characteristics and failure pattern and the thermal behavior of reduced scale stack bonded masonry brick walls for each respective mortar imitating the historical masonry walls are developed. The suitability of the examined mortars is discussed in comparison to the reference mortar and different results from different literatures reviewed.
RESUMEN

La cal ha sido usada en morteros en construcciones desde la antigüedad. Los morteros de cal área tienen baja resistencia y necesitan de aire para fraguar y endurecer, motivo por el cual tiende a daños en áreas de alta humedad. Con el fin de mejorar las propiedades resistentes de los morteros en construcciones históricas, se ha usado diferentes materiales incluidos escorias y puzolanas naturales. En el siglo 19, el descubrimiento de cementos con altas resistencia generó el remplazo de la cal, tanto en la construcción como en la reparación de construcciones históricas. Algunos comportamientos incompatibles del cemento con la cal en substratos agravan las patologías de las construcciones. Por esta razón, en recientes años se han realizado esfuerzos en para volver a utilizar los morteros de cal en la reparación de construcciones históricas. Muchos de estas construcciones se encuentran en áreas de alta humedad, por lo cual es importante utilizar morteros de cal optimizados en sus propiedades. La cal hidráulica que fragua en aire como bajo agua puede cumplir con esta función. La mejora en la resistencia no sólo depende de las características del aglomerante sino también de los áridos. Por este motivo, es importante dar una mirada a áridos finos alternativos y no sólo a los áridos naturales que han sido utilizados hasta el momento.

Este estudio se enfoca en la determinación de las propiedades de morteros de cal con arena natural de río, áridos finos reciclados de hormigón y de material cerámico. Los morteros con árido natural han sido tomados como mortero de referencia. El estudio fue llevado a cabo a través de experimentación en el laboratorio estudiando los morteros con diferentes tipos de áridos. Las propiedades medidas fueron las mecánicas, físicas, higrícas y térmicas. También las características mecánicas, el tipo de fallo y las propiedades térmicas en muros a pequeña escala para cada tipo de mortero fueron analizadas. La idoneidad de los morteros estudiados es discutida en comparación con el mortero de referencia y con resultados de otras investigaciones obtenidas de la literatura.
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1. INTRODUCTION

Ancient lime mortars are weak and poorly set in high humid areas in which most of the historical structures are found. Most of historical buildings are founded in areas where the environmental dynamics are high. As a result, in some parts mortars in historical buildings have failed to resist the environmental damage. However, irrespective of the environments, old mortars in other historical buildings are still strong and intact (Borges, et al., 2014). Studies on characterization of historical mortars reveals the presence of additives in strong and durable mortars (Moore, 2010). Naturally mortars are weakened and damaged by moisture driven forces, environmental pollutants, chemicals, biological attack and temperature variations. Owing to their cultural, economic and educational values, there have been efforts put to intervene the damages developed in ancient buildings. For mortars, developed in the 19th century was the Portland cement which substituted the lime mortar both in newly constructed and repaired buildings. However, the attempt has proven to cause compatibility issues (Elert, et al., 2002; Mitchell, 2007; Rodríguez-Navarro, 2012).

Type and nature of aggregates affect significantly the engineering properties of mortars (Lanas, et al., 2004; Stefanidou, et al., 2014). With hydraulic lime some clayey construction and demolition wastes in presence of water undergo pozzolanic reactions forming hydration products responsible for the strength of mortars (Nuno, et al., 2008; Stefanidou, et al., 2014; Guadalupe Cabrera-Covarrubias, et al., 2015).

Natural sand is a non-renewable resource. Over exploitation of this resource leads in the first place to its scarcity for construction and also environmental degradation. Construction industry not only generates wastes but also consumes about 40% of all extracted natural resources (Neno, et al., 2014). The management of the construction and demolition wastes is increasingly hard. An alternative to reduce natural resources consumption, minimize waste disposal, and to supply the construction industry with suitable aggregates while striking the balance between the sustainability of the industry and the environment is to use recycled aggregates as construction material (Lima & Leite, 2012).
Exploration of use of different construction and demolition wastes in mortars which would result to development of better material compatible with historical masonry has not been exhaustively done. In this study, the examination of the influence of recycled concrete and brick sands on engineering properties of historical mortars is presented. The study is concluded on the basis of the suitability of such materials in relation to the natural river sand for use in historical mortars.

1.1 Problem statement

Historical buildings are located in areas where humidity is high. Mortar such buildings is thus vulnerable to environmental damage. Ancient mortars found in most of the buildings is the air lime which sets poorly in humid areas. Historical repair mortars should therefore develop high early strength enough to support the elements of the buildings. Natural hydraulic lime which is compatible with historical binders is therefore suitable for repair of ancient buildings.

Population pressure and the growth of construction industry with modern designs has resulted to the replacement of old structures with new ones leading to the accumulation of the construction and demolition wastes that requires sites for disposal, the process which litters the nature. The demand and exploitation of the non-renewable construction materials on the other hand has led to the depletion of the same and environmental degradation.

Most of such construction and demolition wastes however have undergone heat treatment during their manufacture processes converting their chemical compositions and forming more reactive compounds when activated. Ceramics for example contain clay and some recycled aggregates are calcite. With lime, the materials undergo Pozzolanic reactions forming hydration products or phases that are responsible for strength development of the matrix (Stefanidou, et al., 2014; Nuno, et al., 2008).

It is thus possible to recycle and examine carefully the engineering properties of the secondary aggregates mortar matrices which if found suitable will provide double advantages; the improvement of the engineering properties of historical lime mortars and the conservation of the environment for the future generations at minimum possible expenses.
1.2 Objectives

The principal objective of the study is to assess the suitability of the secondary fine aggregates for use in historical mortars. This will be achieved through several auxiliary objectives. Among others, the objectives are;

i. To examine mechanical characteristics of mortars, brick units and their respective reduced scale masonry walls,

ii. To study the physical characteristics of mortars consisting of the individual aggregates in both fresh and hardened state,

iii. To evaluate the hygric behavior of mortars with recycled fine aggregates in relation to the natural river sand mortar and

iv. To assess the thermal behavior of mortars, masonry bricks units and the particular representative small masonry walls.

The establishment of the results from the mention objectives will serve as the basis for the judgement of the compatibility of the mortars and the influence of the use of the secondary aggregates in historical mortars.

1.3 Outline of the thesis

The study is developed through literature review and laboratory experimentation. In literature review, works of various scholars on related subject have been studied and some of their results used for discussion and comparison purpose. The responses of the mortars, historical brick units and the reduced scale masonry walls to loads and environmental variations have been established through experimentation in the simulated laboratory environments. The thesis is divided into five chapters synopsized below;

Chapter 1 carries an introductory part of the thesis in which the problem statement and the objectives are defined.

Chapter 2 consists of the literature review. A short survey on historical masonry units, repair mortars, lime binder, secondary fine aggregates in historical mortars and thermal properties of historical masonry units is presented.

Chapter 3 resides on material and experimental setup. Material characterization and a detailed laboratory work is offered.
Chapter 4. This section comprises of the results and discussion. An in-depth analysis of the results, both physical and mechanical properties of brick units and mortars with recycled fine aggregates in relation to the reference mortars and the stacks is uncovered.

Chapter 5 concludes the thesis on the basis of the efficacy of the obtained results and suggests future studies on the subject.
2. LITERATURE REVIEW

The terms masonry refers generally to brick, tile, stone, concrete-block or combination thereof bonded with mortar (MSRIT, 2015). In some cases, dry joints are applicable. The use and evolution of material in Historical buildings has been a result of human civilization in which the application and discovery of simple working tools has had enabled production of simple portable units. During the ancient period, it was a tradition to use local available material. The function of the building and the richness of the owner are among other factors affected the choice and quality of the construction materials. Wood, earth, bricks, stones and iron materials have been for a long time used in not only construction but also repair of Historical buildings. Among other material used in historical buildings include the binders which differed depending on the environment and cost of production in terms of cost and energy requirements. In this part, the use of adobe and burnt bricks and masonry stones units in Historical structures will be discussed in a nutshell. Mortars used in ancient buildings are also mentioned.

2.1 Historical masonry materials

2.1.1 Adobe and fired brick units

Adobe can be referred to either earthen constructions or buildings with sun dried bricks. The focus of the subject is on the sun dried bricks. The adobe, or sun-dried brick, is one of the oldest and most common building materials known to man. Traditionally, adobe bricks were never kiln fired. Unbaked adobe bricks consisted of sand, sometimes gravel, clay, water, and often straw or grass mixed together by hand, formed in wooden molds, and dried by the sun (Nelson, 1978). The strength of the units depends on the amount of the clay in the sand. Higher amount improves the strength. However, the main problem with the material in constructions is the dimensional and strength instability when moisture varies. In some areas the problems were combated by incorporation of stabilizing agents into the sand matrix during brick making. Unburnt bricks can absorb as high as 35% of their weight in water (MSRIT, 2015). Fired bricks technology introduced a magnificent development in historical building materials. With the introduction of kilns, it was possible to
produce bricks of relatively higher stability and strength even at elevated moisture content. The need for fuel however was a setback in production of large quantity of bricks in most of the regions limiting the use of fired bricks to a few areas of importance such as spiritual buildings and to some dwellings of rich people.

The engineering properties of historical brick units vary greatly. The variations are reported to be resulted by multidimensional factors. Among other factors include; variability in production, environmental pollution and differences in age of production (Fernandes, et al., 2009). Kiln type and the burning temperature which influenced heat distribution during firing are other causes of strength and density disparity of the historical brick units (Laefer, et al., 2004). Bricks in the 18th and 19th century were soft and porous absorbing 20-25% of their weight in water (MSRIT, 2015). A study by Mc Burney in 1929 (Laefer, et al., 2004) reports the range of some engineering properties of the bricks in the 19th century. Compressive strength ranged from 19,375 kN/m² to 71,019 kN/m², 1,531 to 4,144 kN/m² for tensile strength, 4,358 to 10,136 kN/m² bending strengths and 7,585 to 24,477 kN/m² for shear strengths.

In Historical buildings, masonry brick units could be found in the Great Wall of China, Rome – Coliseum (72 – 80 AD), Sakkara, Egypt – sun dried brick pyramid – 3,900 BC, the ancient city of Ur, Iraq: 2125 – 2025 BC, and the ancient city of Babylon (MSRIT, 2015)

2.1.2 Masonry stone units

Granite stones, limestone and sandstones are among other materials used in construction of historical structures. The stones varied in strength not only between buildings but also within the building or the element. The choice of the type of the stone for a particular building was a function of the proximity of the quarry. The Great Wall of China for example consists of several sections of different stones quarried from nearby mountains.

The properties of historical stones units are vary depending on the area of formation. Physical properties depend on composition and texture or geological origin of the lock in the given locality (Robertson, 1982). In mechanical point of view, stones are brittle and behave elastically to failure, have high compressive strength and for
porous sandstones, the strength is dependent on the porosity and is weakened when subjected to water under pressure. Of the important physical properties which affect the mechanical properties are porosity and permeability which decides the amount of water ingress into the units leading to decay and corrosion of the masonry (Robertson, 1982).

2.1.3 Ancient Mortars

Mortar is a plastic mixture of sand, water and a binder. In masonry, mortars bind the masonry units together, cancel the effect of the irregularity of the stones or bricks units to facilitate stacking of the units and prevent concentration of stresses by distributing uniformly the compression stresses. Ancient mortars were non-hydraulic (SAHC, 2015). Studied in history of construction and conservation (SAHC, 2015), was the following types of mortars; Mud. This was mostly used in adobe units. Discovery of fire bricks necessitated the use of higher strength mortars, for which the use of bitumen (in Mesopotamia), gypsum (in Egypt) and lime in other parts of the world was adopted. The mortars however were poor and the properties were greatly influenced by the environment. Bitumen melts in high temperatures, gypsum, although it is abundant in nature, requires less energy than lime during production and it can easily be extracted, it is problematic as it sets quickly, it is hygroscopic and has high water absorption capacity (Mileto, et al., 2011).

Old non-hydraulic lime mortar required low humidity and air for hardening. Unfortunately, most historical constructions were found in high humidity areas. This further led to discovery and use of cementitious materials. In 300 BC as an example, Romans used a mixture of slaked lime and volcanic ash named pozzolana and other admixtures such as animal fat, milk and blood. Pozzolana cement is reported to have been used in 200 AD to build the vault of the Pantheon in Rome (SAHC, 2015). In 18th century, the discovery of Portland cement substituted ancient historical binders in mortars used for both construction and intervention purposes.

2.2 Requirements of the historical repair mortars

Historical mortars were normally porous and had weak early mechanical characteristics. Most of historical buildings were constructed in environments where
The environment is harsh. As a result, the poor and porous aerial lime mortar that in most buildings was commonly used is in damaged state. In the struggle to keep the structures, there have been efforts directed towards maintenance and repair of the damaged material. In the process, the use of different and better material has been the practice. This has been resulted by the need of higher early strength which normally is provided by fast setting materials that are characterized by hydraulic behavior. The use of additives such as rice soup in China during the Ming dynasty that aimed at improving the characteristics of the mortars is an example of the practices. The discovery of cement in the 18th century which replaced lime in historical constructions was thought a better development of material for not only construction but also repair of the damaged historical mortar during the 19th century. This had an ill effect though. The damage was magnified instead. The increase in damages was resulted by several incompatible behavior of cement mortar with that of the existing historical lime mortar. Such incompatibility could have been mechanical in terms of strength and stiffness, physical characteristics such as coefficient of thermal expansion or chemical constituents that includes presence of soluble salts in cement. These side effects have called for the reuse of Historical material and where not possible the use of material with the following performance requirements that can both heal the pathologies and not cause more damage to the existent materials.

2.2.1 Compatibility with the existent mortar and the substrate

Compatibility is defined as using materials that do not have negative consequences on the authentic materials (Schueremans, et al., 2011). Mortar for repair of historical buildings should be compatible in terms of mechanical, physical and chemical properties. The repair mortar should not be stronger and stiffer than the mortar to be repaired. Its response to the physical changes should be comparable to that of the repaired masonry structure. It should be free of soluble salts which can react with pollutants from the atmosphere causing chalking as a result of loss of cohesion and formation of efflorescence due to dissolving salts on wall masonry or crystallization of material forming expansive.
compounds which can induce stresses in to the wall leading to the formation of cracks. The requirement should not only be between the repair and repaired mortar but also the repair mortar and the substrate (masonry units). Compatibility requirements must be met to ensure durability, in combination with the structural and environmental resistance requirements, and also considering the properties of the substrate (Hughes, 2012).

2.2.2 High durability

Most of historical buildings are located in adverse environments where the relative humidity is very high. Mortars replacing weak aerial lime mortar that was used during erection of the structures should therefore be strong enough to withstand the environment and the periodic actions the structures have been suffering. For this reason, a fast setting repair mortar is needed. Hughes describes durability as a function of the compatibility of the repair material.

2.2.3 Minimal intervention needs

Repair of historical constructions requires that large part of the architectural, structural and historical texture of the building is kept. The minimum intervention principle is applied to enable maximum preservation as possible (Schueremans, et al., 2011). For this reason, the repair mortar should respect the authenticity of the original material and the structure.

2.2.4 Reversibility or Retreatability

Materials in historical buildings, be it the original or the repair mortar are not eternal. With time some can wear out calling for repair. The repair material should be chosen such that it is easy repairable in case of later damages. Retreatability is described as applying a repair mortar (material and techniques) that does not jeopardize future treatments (Schueremans, et al., 2011). The eighth article of the Italian charter for restoration, ITALIAN CARTA DEL RESTAURO of 1972 (SAHC, 2015) states that any intervention must be carried out in a way and with such materials that it ensures that in the future they will not prevent another safeguard or restoration intervention. Cement mortar as an example is not retreatable. Removal
of the damaged mortar would damage the substrate of the masonry units causing more damages to the structure.

2.3 Lime

Lime is a product of calcination of the calcite. On heating, the calcite loses carbon dioxide to form a white porous, alkaline quick lime (calcium oxide). Quicklime is unstable. On exposure to air it reacts with carbon dioxide forming the parent calcite. For this reason, it is normally stored in a slaked state. However, the reaction with carbon dioxide to form the carbonate is speeded up by the addition of water to the quicklime (in the slaked form). Slaking is explosive, is should therefore be done by introducing the quicklime into water and not the reverse. In construction industry, this reversible process (carbonation of quicklime) is an advantageous process. It makes it possible to cause hardening of lime in mortars. Depending on the ability to set (gain strength), lime is normally classified as non-hydraulic or hydraulic. As it is clarified in the next parts of non-hydraulic and hydraulic lime (mortar), the former sets in air while the later sets under water.

2.3.1 Lime mortars in Historical Constructions

It is not clearly known when lime mortar started being used for the first time. However, there are evidences of the use of lime in historical constructions during the Roman times. It is well documented, however, that the Roman Empire used lime based mortars extensively. Vitruvius, a Roman architect, provided basic guidelines for lime mortar mixes (Graymont, 2016). Scotland has a long tradition of building with stone and lime stretching back to Roman times (Mitchell, 2007). Mitchell further explain that lime mortars for both construction and finishing was used in large proportional of buildings in Scotland before 1920. In other sources, it is indicated that the earliest documented use of lime as a construction material was approximately 4000 B.C. when it was used in Egypt for plastering the pyramids. In China, with a sticky rice juice (the rice soup) as an admixture, the lime mortar was used 600 years ago in construction of the Ming dynasty sections of the Great Wall (Moore, 2010). The making of quicklime by heating limestone in kilns, and preparing mortars, plasters and whitewash from it, is an ancient practice, mentioned in the Old Testament (Cadw, 2004).
According to Mitchel (2007), the introduction of Ordinary Portland Cement and the use of its mortar in the mid of the 19th century started replacing lime and during the 20th century OPC mortar started being used to repair tradition buildings that were originally built using lime mortar. However, the difference in mechanical and physical properties of cement mortar to that of the lime mortar caused compatibility issues that in most cases have elevated the damages. Recently, such incompatibility has called for recovery of the use of the lime mortar for reparation of the historical buildings mortars. In recent years, a revival of lime mortar application for the repair of historic buildings has taken place, due to recognition of the unfavorable properties of Portland cement mortars, including brittleness, high strength, and a thermal expansion coefficient which can be twice as large as that of lime mortars and most types of bricks and stones (Elert, et al., 2002). Compared with cement, lime is more compatible from a mechanical, physical and chemical point of view when applied in historical structures (Rodríguez-Navarro, 2012). Next sections present a short review on non-hydraulic lime and hydraulic lime and their respective mortars and properties.

2.3.2 Non hydraulic lime

Non hydraulic lime is formed when calcite is burnt to drive off carbon dioxide and form a soft porous quick lime. Being very reactive, the lime is kept in slaked form. The slaked lime can be in either of the two forms; a dry powder (lime hydrate) or putty (plastic paste). Its existent in such forms depends on the amount of water used during slaking. According to Cadw (2004) in the Technical Conservation Note 2, in powdered form, the added water should only be enough to avoid loss of heat during hydration (if excess water is added) leading to the formation of unsound lime. In other words, water in lime hydrate should only be enough to form chemical bond with the quick lime. A dry hydrate is produced by mixing one part by weight of quick- lime with about 0.5 to 0.75 part of water, depending on the reactivity of the quicklime (Elert, et al., 2002). Owing to the loss of water by evaporation during the hydration reaction, an addition of excess water of 24.5% of the weight to ensure complete hydration (Elert, et al., 2002). This form of the lime has problems in storage as carbonation starts whenever the lime is exposed to air.
The lime putty is formed when water in excess of the bond water in hydrated lime is added and soaked for at least 24 hours. Putty contains about 30-40% of free water that envelops the hydrate particles, in addition to the chemically combined water (Elert, et al., 2002).

2.3.3 Non hydraulic lime mortar

The mortar is formed when the required amount of fine aggregate is added to either of the two forms of the binder. According to Mitchell in an Inform of the information for historic building owners (Mitchell, 2007), Lime putty is most commonly used for internal plastering, and the dry powder (more commonly known as builders’ lime) is used as an additive to cement mortars to improve workability.

The properties of the lime mortar depend on the properties of the aggregates used, purity of the quick lime, temperature of calcination and the form of the lime used in production of the mortar. It has weak mechanical properties, sets poorly in areas with high relative humidity, has high amount of pores and low internal cohesion. The weak properties of lime mortar are responsible for its susceptibility to damage as a result of salt crystallization or freezing during water saturation (Elert, et al., 2002). However, different scholars have shown that such properties can be improved by either the addition of the pozzolanic material in the mortar or use of matured (aged putty). The pozzolanic material adds to the matrix of the mortar compounds that form hydration phases. In Technical Conservation Note 2 of April 2004 (Cadw, 2004), mentioned are different material which when added to the mortar improve the setting behavior of the mortar. Elert et al (2002) in the study of Lime Mortars for the Conservation of Historic Buildings found that aging of lime putty improves specific area, workability, water retention and mechanical properties, porosity and carbonation of the mortar. In addition to these properties, other properties affecting the properties of lime mortar (non - hydraulic lime) are similar to the properties affecting hydraulic lime mortars explained in the next part titled hydraulic lime.

2.3.4 Hydraulic lime

Hydraulic lime has the property of hardening under water. According to J. Lanas (Lanas, et al., 2004), the term hydraulic in a binding material is defined in relation to two specific properties; the capacity of hardening when water is added to the dry
binder and the property to harden under water. Hydraulic lime binder partly sets and hardens by chemical interaction with water and will harden under water, and partly sets by carbonation (Hughes, 2012). In this regard, hydraulic lime mortars set both in air and under water.

2.3.4.1 Production and Composition

Hydraulic lime can be produced by burning at 1000 – 1250°C limestone with high content of clays (6.5–20%) or mixing clay minerals with finely ground pure lime stones, quoted was J.I. Alvarez, 1997 in J. Lanas et al (2004). The reaction between the lime and SiO2 and Al2O3 leads to the formation of calcium silicates and aluminates. Hydration of these compounds (calcium silicates and aluminates) provides consistency to the mortar paste, which hardens (Lanas, et al., 2004). Depending on the burning temperature during the production of lime, other products (hydraulic phases) that affect its hydraulic characteristics can be produced. In Natural Hydraulic Lime, C2S is the major hydraulic phase (Lea, F.M., 1970). Gehlenite (C2AS), can be observed indicating the burning temperature of the Natural Hydraulic Lime was less than 1200°C (Lanas, et al., 2004). In case of overheating in the lime kiln, trace amount of hydraulic phase of cement can also be formed. C3S, C3A and C4AF could also be detected in Natural Hydraulic Lime, in small amounts, due to a local overheating in the limekiln. Calcium hydroxide(CH) also appears (Lanas, et al., 2004).

2.3.4.2 Hydraulic lime mortar

The mortar is prepared by mixing one part of lime by several parts of fine aggregates with water. The ratio 1:3 is commonly used in practical application for the Historical repair bedding mortars. In other Historical buildings however, the mix constituted of several parts of binder to one part of aggregate (Velosa, et al., 2013). The amount of water required for this purpose depends on several factors including the environment of application of the mortar, porosity and water content of the substrate and the initial rate of absorption of the aggregates. For the required consistency to be met, it is therefore important to carefully determine the amount of water taking into account all such factors. This is normally done using a shaking table. Depending on the use of the mortar, other binder – aggregate ratios are also possible. The
properties of the mortar in the wet and dry state are influenced by several factors as it has been worked out by several researchers. The following factors affect the properties of hydraulic lime mortars.

2.3.4.3 Binder content – aggregates ratio

Mortars with higher binder to aggregates ratio have higher compressive and flexural strength than mortars with low fractions of binder (Lanas, et al., 2004). This might be resulted by an increased cohesion in the mortar matrix.

2.3.4.4 Characteristics of the aggregate

Well graded aggregate and limestone based aggregate improves the strength of the mortar. Limestone aggregate exhibit higher strength due to the growth of the calcite in the mortar which develops strength enhancing the binder aggregate interface (Lanas, et al., 2004). Angular aggregate increases the strength of the mortar than round aggregate. The use of rounded-shaped aggregate increases the large pores due to poor cohesion between the binder and the aggregate, causing strength reduction. Angular aggregates form a better packed structure, pore reduction and strength increase (Lanas, et al., 2004).

2.3.4.5 Porosity of the mortar

Porosity and the nature of the aggregates cause formation of porous mortar. The increase in the amount of the binder increases porosity. Normally, such increase in porosity leads to the decrease in mechanical properties of the mortar. However, for lime based mortars this has not been the case as different researches postulate. M. Stefanidou et al (2014) findings show an increase in strength when using hydrated lime irrespective of the amount of porosity that can develop. This is said to be resulted by lime – silica reactions which obscure the effects of the pores to the strength of the mortar. For hydraulic lime, the formation of hydration product CSH is probably the reason for the increase in the strength of the mortar containing high amount of the binder (high porosity). “Large binder amounts show porosity increment but also a strength increment: more CSH phases and a faster and more complete carbonation can give an explanation to these facts” (Lanas, et al., 2004).
2.3.4.6 Curing duration

The increase in strength of hydraulic mortar depends on the formation of the hydraulic phase CSH and the carbonation of the Portlandite, CH. According to the study done by J. Lanas, et al (2004), the increase in strength is not constant. Depending on the amount of C$_3$S, the strength increases until the hydraulic phase is entirely consumed during hydration, a process which normally occurs until to the age of 28 days after which the slow process of hydration of C$_2$S and the carbonation of CH starts. During this transition period, compressive and flexural strength drop slightly followed by an increase in both then after. The amount of C$_2$S and the rate of consumption of CH during carbonation which depend on the exposure and porosity of the mortars also affect the curing process. Mortars with low binder – aggregates ratios has poor strength development after the first reaction, that is before 28 days (Lanas, et al., 2004). This is due to the low amount of C$_2$S and the total consumption of free CH by carbonation.

2.4 Secondary fine aggregates in Historical mortars

This part of the study encompasses the review of the general properties of recycled aggregates made mortars in which case, the effects of the recycled aggregates onto the properties of cement and blended binders will be discussed in short. The investigation on the use of the recycled aggregates in the production of historic repair mortar, the lime based binders as done by different scholars will also be reviewed separately. This will mainly focus on physical and mechanical properties of the mortar which was studied.

2.4.1 Cement binders

It has been shown that the use of recycled aggregates in production of cement mortar causes significant changes in both physical and mechanical properties of the mortar. Some properties are improved while others are worsened.

The replacement of natural sand by recycled aggregates improves the particle size distribution due to the addition of fines. Incorporation of concrete fines in cement mortar increase its bulk density in the hardened state (Braga, et al., 2012). This is said to be resulted by the compactness of mortar caused by the filler effect. Higher
content of particles that pass through a 0.150 mm sieve helps to decrease the air content, pack the mix particles better leading to an increased bulk density (Braga, et al., 2012). Water absorption decreases with increasing ratio of the recycled concrete fines in the mix (Braga, et al., 2012). This on the other hand indicates a reduction in porosity. According to Braga et al (2012) the reduction of porosity results in lower total water absorption by capillarity, while the smaller pore size leads to a decrease in the absorption rate (lower coefficient of capillarity) Figure 1 presents the variation water absorption and density with replacement ratio of natural sand with recycled aggregates.

![Figure 1. a) Water absorption due to capillary action of hardened mortar b) Dry bulk density of hardened mortar for the indicated incorporation ratios (Braga, et al., 2012).](image)

The incorporation of recycled aggregates on cement mortars improves the mechanical properties. However, the stiffness of the mortar is worsened by the addition of the recycled concrete fines. Replacement of natural sand aggregates by 15% improves the compressive, flexural, bond strength and the stiffness (Braga, et al., 2012). Studies by Braga et al (2012) show similar improvement in mechanical properties when ceramic material are incorporated in cement mortars. Research by Martínez et al (2013), although filler materials were also added to improve the particle size distribution shows similar improvement of the properties.

### 2.4.2 Blended binders

Pozzolana additives in lime mortars improves the mechanical properties of the mortar (Stefanidou, et al., 2014). The positive result in mechanical properties is contributed by the lime pozzolanic silica reactions. Artificial and natural pozzolans are able to produce a pozzolanic reaction with portlandite in presence of water (Nuno, et al.,...
2008). Strong combination of the binders, (lime – pozzolana – cement mortar) affect adversely the properties of recycled sand mortars. According to M. Stefanidou et al (2014), such negative response in mechanical properties is a result of high porosity and water content needed during preparation of the mortar. Lime – pozzolana blended mortar are slightly affected negatively with recycled sand as a result of increased porosity. The literature has also indicated similar worse effects on to the physical and durability properties of the lime – pozzolana – cement mortar with recycled sand as aggregates.

2.4.3 **Hydrated and hydraulic Lime binders**

The study of the use of lime as a binder and fine recycled material as aggregate in production of historic repair mortar as conducted by different scholars has yielded different results depending on the type of the used recycled aggregates and their grading. M. Stefanidou et al (2014), studied the properties of mortar from hydrated lime as a binder and recycled sand from construction and demolition waste as fine aggregate. V. Corinaldesi (2012) examined the Environmentally-friendly bedding mortars for repair of historical buildings, with cement as a binder and crushed bricks as aggregates in the mortar, the study in which explored was also the properties of hydraulic lime – crushed bricks mortar. In the study, two types of crushed bricks were used, fine crushed and coarse crushed bricks. In the first study, in terms of the mechanical characteristics, the results were positive and in the later, lower results than that of the reference mortar were obtained. In this regard, it should be noticed that the properties of the mortars formed are dependent on the material type and the grading and for the reference mortar the nature or type of the sand and its particle size distribution. The influence of such materials on the physical and mechanical properties of mortar as it was studied by the above scholars is presented below;

Hydrated lime – recycled sand mortar have high porosity (Stefanidou, et al., 2014), such increase in porosity is believed to have been resulted by high water content and the porous nature of the recycled aggregates. However, the capillary absorption of mortars with recycled sand is independent of the porosity (Stefanidou, et al., 2014).
With crushed bricks, porosity is function of the fineness of the particles. Mortar with fine crushed aggregates has higher total porosity and permeability than mortar with the course crushed brick aggregates (Corinaldesi, 2012).

The research conducted by M. Stefanidou (2014) shows that recycled sand aggregates improves mechanical properties of hydrated lime binder mortars. Compressive strength is improved. The improvement of the properties in lime-based mortars with recycled aggregates is attributed to the reaction between the lime and the silica constituents of the raw materials of the sand (Stefanidou, et al., 2014; Guadalupe Cabrera-Covarrubias, et al., 2015). The positive role of the recycled sand in lime mortars is attributed to the strong cohesion of the binder and the aggregates but also to the adhesion of the mortar to brick (Stefanidou, et al., 2014). However, the research further reports a decrease in flexural strength in recycled sand mortars. Testing conditions might be the cause as it has also been pinpointed that contrary to other mechanical tests, the flexural strength test was carried out in dry conditions.

Recycled brick aggregates, influence negatively both compressive and flexural strength of the hydraulic lime mortars (Corinaldesi, 2012). The kinds of binder and aggregate seem to influence mortar microstructure: the use of hydraulic lime replacing cement, as well as of crushed bricks instead of quartz sand, led to a more porous material, especially if the bricks are finely ground (Corinaldesi, 2012). On the other hand, the bond strength between the mortar and the bricks is high when recycled brick sand is used in lime mortars. This also was shown to be dependent on the strength and porosity of the bricks. “In terms of bond strength between mortar and brick, the best (excellent) result was obtained by coupling the ‘weak brick’ with the mortars prepared with fine crushed bricks; the reason probably is that a good mortar-brick adhesion mainly depends on the quality of the interfacial zone” (Corinaldesi, 2012).

2.5 Hygric properties of masonry units and drying shrinkage of mortars

Hygric properties are those related to the movement of water in the material. Capillarity suction, initial rate of absorption, desorption, permeability and water vapor transport are among of the examples of hygric properties. There are several factors that affect these properties. The nature of the ingredients and workmanship
production of the materials can significantly affect the response of the masonry units to water flow.

Water permeability is influenced by porosity microstructure of the materials and the amount of the fines present in the matrix (Farci, et al., 2005). Binder and aggregate content in the mortar and the generated pore system (pore size, shape and tortuosity), additives and formation of hydration phases affect water absorption kinetics of the mortar (Anna & Giuseppe, 2014).

Drying shrinkage is influenced by kneading water and cohesion between the ingredients and it leads to formation of pores that affect water transport in the mortar (Anna & Giuseppe, 2014). In the literature, temperature, relative humidity and ventilation are stated to be the factors that affect drying of porous surfaces.

Water binder content and long term carbonation which alters the pore network affect hygric properties of mortars (Mahsa & Wadsö, 2016). In old historical buildings with intact mortars, presence of crystalline salts and ettringite in pores modify the pore network increasing durability of the mortars (Borges, et al., 2014).

From the literatures, it is clearly understood that the hygric properties are dynamic over entire life of the structure. Salt attack can have both positive and negative effects on water transport kinetics of the material (mortars).

### 2.6 Thermal properties of historical masonry units

As it has been discussed earlier, historical repair material should be thermally compatible. Thermal incompatibility between materials in buildings induce thermal stresses which cause tensile stresses responsible for crack formation on the elements either due to elevated environmental temperatures or in events of fire attack. Therefore, it is necessary to examine the material and assess the factors which affect their thermal properties which if known can be used in reproduction of material with matching thermal characteristics. Thermal properties considered in this study are the thermal conductivity ($\lambda$), heat capacity ($pC_p$), heat diffusivity ($\alpha$) and the coefficient of thermal expansion ($\alpha_1$). Below are the general factors affecting thermal properties of materials and their matrices studied by different researchers.
The thermal conductivity of lime based mortars depend on the density of the material, porosity and its moisture state (Pavlíková, et al., 2008; Vejmelková, et al., 2011). It increases with increasing density and moisture content and decreases with increasing porosity. I. Palomar et al (2015) reported similar results with lime – cement blended mortars, and further stressed that particle size distribution and the type of the aggregates affect the thermal conductivity of the mortars. Use of recycled aggregates lowers thermal conductivity of recycled concrete and the rate of decrease is dependent on the size, with larger particles which are more solid having lower rate than the fine particles that have higher porosity due to damage during production (Zhu, et al., 2015). A study by A. Siwin´ska et al (2011) on thermal conductivity coefficient of cement-based mortars as air relative humidity function reports a linear dependence of conductivity on moisture content of the material and that the test method adopted has a significant influence on the results. Use of additives in production of fired bricks reduce the bulk density and increase porosity resulting into a reduced thermal conductivity of the product (Phonphuak, 2013).

For cement mortars and pastes, the coefficient of thermal expansion decrease with increasing total porosity following a power law relationship (Zeng, et al., 2012). Geology of the aggregates, age and heating rate during testing affect the coefficient of thermal expansion of concrete matrices (Jahangirnejad & Buch, 2008).

The factors affecting thermal properties of different construction composites appear to be common. Thermal conductivity, heat diffusivity and coefficient of thermal expansion of material are reported to be mostly affected by geology, density, moisture content and porosity. Specific heat capacity is influenced by the nature of the material and its temperature during the testing process.
3. MATERIALS AND EXPERIMENTAL SETUP

3.1 Materials

3.1.1 Lime

Hydraulic lime type NHL – 3.5 produced and distributed by a Spanish company, Cemento Natural Tigre was used in this study as a binding material. It was produced according to CYS EN 459-1 (2015); Building lime – Part 1: Definitions, specifications and conformity criteria.

3.1.2 Natural sand

Natural river sand was used for production of the reference mortar. It was collected from Arid’s Catalunya, a Spanish company (Figure 2).

![Figure 2. Natural sand.](image)

3.1.3 Recycled concrete and brick sands

The recycled sand was collected from a company named Germans Cañet Xirgu specialized in waste recycling and transportation. The company has its plant located at Cassa de la Selva (Girona). The aggregates were used for production of mortars that were studied in relation to the produced reference mortar (Figure 3).
3.1.4 Brick units

The bricks were produced basing on recipes of historical bricks. These were used in the assessment of the influence of the recycled fine aggregates mortar on the mechanical and thermal properties of the reduced scale masonry walls (Figure 4). The bricks were manufactured by the Company “Ceramica Piera S.L.”.
3.2 Laboratory experimentation

3.2.1 Basic characterization of the material.

The basic characteristics included in this part are the size distribution, particle and bulk density, absorption, porosity, chemical composition and particle shape of the materials. For lime, determined was only the particle and bulk density and the chemical composition. Bricks were classified in terms of particle and bulk density, absorption and porosity. The basic characterization of the aggregates involved determination of all the properties mentioned above.

The particle size distribution of natural and recycled fine aggregates was determined to measure the mass scattering of the different particles in the material. To ensure similar distribution, aggregates coarser than 2mm were sieved and the amount of fines was reduced (balanced) to between 5% and 9% by washing part of the individual aggregates through a 0.063mm strainer and mixing to the remaining respective part. A sample of mass less than 1000 grams for each aggregate was prepared and the particle size distribution process conducted according to ASTM D 422 – 63 (2007); Standard Test Method for Particle-Size analysis of Soils-Sieve Analysis Values for Portion Finer than No. 10 (2.00-mm) Sieve. The grain size distribution curves for each aggregate type were drawn and from each curve determined was the aggregate index which describes not only the amount of fines but also the form of the curve from the smallest grains to the largest (Konow, 2006). The indices were determined from:

\[
AI = \frac{(c - b)}{[(b - a) \cdot a]} \tag{Ec.1}
\]

where AI represents aggregate index, a, b and c stands for the grain size corresponding to 10%, 50% and 80% sieve passage respectively (Konow, 2003; Konow, 2006).

The particle density of lime was effected using a specific gravity flask as per ASTM C188 – 15 (2015): Standard Test Method for Density of Hydraulic Cement. The procedure described in CPC 14.2 (RILEM TC, 1979): Bulk density of aggregates was
adopted in determination of bulk density of both lime and aggregates. Compaction was done by lifting the metallic cylinder to a height of about 10mm and leaving it freely hit the ground five times, refilled to overflow, levelled, re-compact and filled again and the surplus material were removed by levelling with straight edge of a blunt knife. Prior to testing, the aggregates were dried to constant weight. The apparent, dry and surface saturated dry density, water absorption and porosity of the fine aggregates was determined using pycnometer according to UNE-EN (2013); Tests to determine the mechanical and physical properties of the aggregates. Part 6: Determination of the particle density and the water absorption. The tested materials were in the condition of saturated surface dry prior to test commencement and for this reason the materials were not left to soak in the pycnometer placed in the water bath for 24 hours as described in the standard. The entrapped air was removed by gently rolling and jolting the pycnometer in a tipped position. The water absorption property of the material was later used for the determination of water required to increase the moisture content of the material to the surface saturated condition before using them for mortar preparation. All the tests were performed at room temperature of about 23°C.

With a suction pressure of 50 kPa, the saturation by vacuum absorption method as described in LUM A4 (RILEM TC, 1991): Water absorption and water porosity of masonry units was used in assessing the water absorption capacity of the bricks. In this process, used were four specimens of about 40 x 40mm, two from each type of the two bricks. Coupled with this method was the method defined in ASTM C 642 – 97 (1997): Standard Test Method for Density, Absorption and Voids in Hardened Concrete that was adopted for determination of density and porosity of the units. Instead of saturation by boiling the specimens as per the standard requisite, a modification was made to use vacuum saturation as stated above.

The determination of mineralogical compounds has been done through x-ray diffraction in powder, using a Bragg-Brentano PAN alytical X’Pert PRO MPD Alpha1 device.

The particles of the three aggregates was visually and image analyzed to determine the shape descriptors which encompass circularity, aspect ratio, roundness and
solidity. The descriptors were calculated using the software ImageJ basing on the following relations defined in ImageJ User Guide (Ferreira & Rasband, 2012) and a study by Eric Oslom (2011).

**Aspect Ratio**

Aspect ratio is the length divided by width. The value approaches 1 for round or square particles. It is a dimensionless value.

\[ AR = \frac{\text{Major axis}}{\text{Minor axis}} \]  
*Ec.2*

**Circularity**

Circularity is defined as the degree to which the particle is similar to a circle, taking into consideration the smoothness of the perimeter. This means circularity is a measurement of both the particle form and roughness. Thus, the further away from a perfectly round and smooth circle that a particle becomes, the lower the circularity value. Circularity is a dimensionless value.

\[ \text{Circularity} = 4\pi \cdot \frac{\text{Area}}{(\text{Perimeter})^2} \]  
*Ec.3*

**Solidity**

Solidity is the measurement of the overall concavity of a particle. It is defined as the image area divided by the convex hull area. Thus, as the particle becomes more solid, the image area and convex hull area approach each other, resulting in a solidity value of one. When the particles approach each other, the resulting solidity value is one. As the particle form digresses from a closed circle, the convex hull area increases and the calculated solidity decreases. Solidity is a dimensionless value.

\[ \text{Solidity} = \frac{\text{Area}}{\text{Convex area}} \]  
*Ec.4*

**Roundness**

Is a shape factor that has a minimum value of 1 for a smooth circle and larger values for shapes having a higher ratio of perimeter to area, longer or thinner shapes, or for
objects in which the edges are rough. It can also be estimated as the reciprocal of the aspect ratio. It is a dimensionless value.

\[
\text{Roundness} = 4 \cdot \frac{\text{Area}}{\pi \cdot (\text{Major axis})^2}
\]

\textit{Ec.5}

### 3.2.2 Preparation of mortars and stack bonded prisms

Three types of mortars were prepared. The mortar with natural sand aggregate which served as the reference mortar and the other two types contained fine recycled concrete and brick sands respectively. The ingredients for the mortar were mixed in the ratio 1: 2.5: 0.8 by volume of lime, fine aggregate and water respectively. Prior to mixing, the oven dried material were surface saturated with water and left to saturate for about 24 hours. The amount added for this purpose was equivalent to the water absorption of the particular material determined during the absorption test. The mixing process was realized using a machine and for each mortar it lasted in a duration of about 255 seconds. The formed mortar was tested for flow and subsequently cast into metallic molds to form specimens that were used for various tests. The mortar in the molds was compacted using a compaction machine by giving 15 strokes before levelling the top using a blunt knife edge to remove excess material. This lower number of blows was chosen to avoid excessive bleeding as it was studied when higher number was used. The molds were cured in moist condition in the humidity chamber with temperature of about 20°C and average relative humidity of about 95%. As a result of low early strength development of hydraulic lime mortars, the specimens were demolded after three days from casting as it is recommended in section A.6.2 of LUMA A6 (RILEM TC, 1991) and left in the humidity chamber for further curing.

The reduced scale masonry walls were prepared on hard flat floor following the B.1.2 clause of LUMB B1 (RILEM TC, 1991): Compressive strength of small walls and prisms. The walls were cured before testing in plastic bags for 28 days in a room with an average temperature of about 23°C. Used in this study were the stack bonded prism specimens. The top and bottom faces of the walls in contact with the platens
of the testing machine were smoothened by polishing for the sake of improving the contact between the specimen under test and the platens.

### 3.2.3 Fresh state properties of mortar

Table flow, water retention, air content and the fresh density are the fresh properties of the three types of mortars that were measured.

The flow test was conducted to examine the influence of the recycled concrete fine aggregates on to the consistency of the mortars. The test was achieved using the flow table according to ASTM C1437 – 15 (2015): Standard Test Method for Flow of Hydraulic Cement Mortar specifications. To ensure the mold placed at the center of the flow table was fully occupied by the material, the mortar was filled in two layers and each lightly tamped 25 times before levelling the top using a blunt knife edge, cleaning and drying the table and removing the mold slowly. The machine was then manually operated to give the spread by jolting the plate of the table 25 times at an average of 1 jolt per second.

The water retention test was performed to study the ability of the three mortars in holding water when subjected to the suction pressure by masonry units when laying. The test was performed according to ASTM C1506 - 03 (2003): Water Retention of Hydraulic Cement – Based Mortars and Plasters. The water retention was determined as the percentage of flow remaining after controlled suction. The standard requires the application of about 7 kPa of suction pressure for 60 seconds. However, the available machine could give a minimum suction pressure of about 14 kPa which is about twice the specified pressure. For this reason, the suction pressure was applied for 30 seconds instead of the specified spell. The test was executed in a room where temperature was nearly 23°C.

The air content test for the mortars was performed using air meter method as per ASTM C231 (2014): Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method. In this method, all ingredients in the mortar except the entrained air are assumed incompressible. The test was also performed in a laboratory environment in which the temperature was nearly 23°C.
The density of fresh mortars was determined as a ratio of the weight of fresh compacted mortar filled in the cylinder to the volume of the cylinder. Compaction was done by hitting the base and sides of the cylinder to remove any possible air entrapped during pouring the mortar in it. Although it is designated for fresh concrete, CPC 10.1 (RILEM TC, 1975): Density of compacted fresh concrete standard was assumed for this purpose. The test was conducted at the room temperature of about 22°C.

3.2.4 Hardened state properties

3.2.4.1 Physical properties

Referred in this part are the density, water absorption and porosity of the three types of mortars. Discussed in addition to those properties is the drying shrinkage of mortars and the dimensional changes of small specimens of the brick units with water sorptivity.

The testing techniques followed in determination of density, water absorption and porosity for the brick units were also adopted for the mortars. However, saturation was done by soaking the samples in water for 24 hours and not by vacuum saturation technique as the later method was found to cause cracks on the surface of the specimens. If used, the method would thus elevate the porosity of the mortars. The dry weight was measured after oven drying the samples at about 100°C for 24 hours. Two specimens for each type of mortar were used for this purpose and were derived from the halves remaining after the flexural strength tests. To evaluate the development of the properties with age the tests were conducted at the age of 7, 28 and 45 days.

The drying shrinkage test was done to examine the influence of the recycled concrete and brick sand aggregates in relation to the natural sand on the dimensional stability of historical mortar with loss in water. For each mortar, used were two 40 x 40 x160 mm specimens. The test was improved to commence after the age of six days from casting the specimens contrary to the standard which requires the test to start as soon as the early strength is gained. This delay was a result of using epoxy resin in sticking the pins in to the samples from which the dimensions were taken. The resin works well in relatively dry surfaces. The testing conditions adopted during the test
are expressed in MR 12 (RILEM TC, 1982): Determination of changes in length of mortar specimens. The test was executed in a room with an average temperature of about 23°C and 60% RH (Figure 5).

![Figure 5. Specimens used for establishing drying shrinkage of mortars.](image)

The dimensional variation behavior of the brick masonry units when subjected to varying moisture content from the environment or during brick laying was studied using two samples of dimensions 40 x 40 x 160 mm from two types of bricks. For this to be achieved two pins spaced at 100 mm were fixed to two opposite long faces of the brick specimens and the units immersed in water to a depth of 3 mm in a test set up similar to that of the initial rate of absorption. The change of the length with water uptake was measured after 0, 1, 5, 10, 15, 30, 60 minutes, 2, 4, 6 hours, 1, 2 and 3 days. The units were left to saturate and subsequently placed to room temperature of around 23°C to dry to constant mass. In the process of drying, the changes in dimensions were measured after an interval of every 30 minutes for the first two hours, in the third and fourth hour and in each day until the change in mass of the samples was found insignificant. The test is nonstandard.

### 3.2.4.2 Mechanical properties

The mechanical properties that were determined are compressive and flexural strength for mortar, brick units and the stack bonded prisms and modulus of elasticity for the brick units and the prisms.
For compressive strength of bricks, two samples of dimensions about 40 x 40 x 40 mm, one from each type of the two bricks were prepared. Two prisms 40 x 40 x 160 mm specimens one from each type of the bricks were also prepared. The prisms with slenderness ratio of 4 were first used for determination of modulus of elasticity and later for flexural strength. After the flexural strength test, the two halves from each of the two specimens were used for determination of the compressive strength as per LUM A1 (RILEM TC, 1991): Compressive strength of masonry. During the compression test, the specimens were loaded at 50N/s. For bending test, the samples were prepared and the flexural strength was determined according to LUM A2 (RILEM TC, 1991): Flexural strength of masonry units. 10N/s was the rate at which the load was applied during the test. The modulus of elasticity of the bricks was determined as the average slope of the last three of the four cycles of loading – strain curves when the specimens were subjected to a maximum load equal to one third of the ultimate compressive strength of the particular brick as per CPC 8 (RILEM TC, 1975): Modulus of elasticity of concrete. The load for determination of the modulus of elasticity was applied at a rate 0.008mm/s (Figure 6).

Three 40 x 40 x 160 mm specimens for each type of mortar were used for determination of flexural strength (Figure 7). The test was performed according to the conditions described in LUM A7 (RILEM TC, 1991): Flexural strength of mortar. The compressive strength was performed as per LUM A6 (RILEM TC, 1991): Compressive strength of mortar. Four halves of the specimens formed during the
flexural test were used for this purpose. However, modification was made to adopt the loading rate used during the determination of the mechanical properties of the brick units. Both tests for each specimen of the respective mortar were performed at the age of 7, 28 and 45 days.

![Figure 7. Determination of flexural strength of masonry units.](image)

Three stack bonded prisms of three courses each of half-cut bricks bedded on 10 mm thick mortar and dimensions of about 140 x 150 x 160 mm were used for compressive strength test with two being used for secant modulus test prior to testing for compression (Figure 8). Using three courses stacked prisms, the compressive strength was determined according to the standard LUMB B1 (RILEM TC, 1991) defined above and other literatures were also adopted (Peverini, 2014; Pelà, et al., 2016) and the secant modulus of elasticity was established basing on the standard adopted during the determination of the property for the brick units. The load was applied at a rate of 50N/s and 0.008mm/s during the compression test and the determination of the modulus of elasticity respectively. The tests were performed to investigate the influence of the recycled fine aggregate in mortars relative to natural sand mortars onto the behavior of the masonry walls under compressive loads.
3.2.5 Hygic properties

Hygic properties refer to the relative movements of moisture in the material. Material discussed in this context are the brick units and the three mortars with different aggregates. The properties measured include the initial rate of absorption (IRA), suction capillarity and desorption. The degree of pore interconnection and the drying indices of the material were also calculated.

The initial rate of absorption is the absorption of water from one chosen face of a unit when immersed for a period of 60 seconds in a maximum depth of 3mm of water (RILEM TC, 1991). To study this property, two samples for each of the two bricks and for each type of mortar were prepared, dried to constant mass for three days and condition in an oven at temperature of about 40°C. The test was carried out according to the specifications of LUM A5 (RILEM TC, 1991): Initial rate of suction (IRS) of masonry units. However, in order to study the influence of jacketing the side faces of the specimens as required in the capillary suction test, the IRA test was conducted for an extended duration of about three days (72 hours) as it was for the capillarity suction.

The capillarity suction test was performed according to ASTM 1585 – 04 (2004): Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic
Cement Concretes. The sides of two specimens for each material dried to a constant mass were first covered by fast curing silicon and left to cure in the oven at 40°C until constant weight was regained before testing. The specimens were then placed on top of the supporting plastic grids placed in tap water in a plastic basin containing water at a temperature of about 23°C in such a way that each sample was immersed to a depth of about 3mm. The level of water was maintained by periodic addition whenever it seemed to drop. The mass of the specimens was measured after 0, 1, 5, 10, 15, 30 minutes, 1, 2, 4, 6 hours and 1, 2, 3 days of water absorption. In this study, for clarity reporting the sorption results is modified to mass per square unit area and not the average height of rise of water as stated in the standard. For comparison purposes, IRA is also reported in the same units. The tests give an indicator of the velocity of water rising up into the historical material. The capillarity absorption coefficient \( C_{\text{cap}} \) which represents the velocity of absorption is calculated as the slope of the sorptivity – square root of time graph defined by:

\[
C_{\text{cap}} = \frac{m_c}{A\sqrt{t}}
\]

Where \( m_c \) is the total mass of water absorbed since the start of the test, \( A \) is the absorbing area and \( t \) the elapsed time (Wilson, et al., 1999).

After completion of the IRA and capillarity suction tests, the samples were left to fully saturate in water for two days before the desorption test commenced. The saturated samples were taken to the drying chamber conditioned at temperature of about 25°C and relative humidity of around 52%. The weight of the drying specimens was recorded in the same intervals of time as in the IRA and capillarity suction test for the first two days and after every 24 hours until constant weight was attained. The test aimed at studying the rate of drying if the moistened masonry in historical buildings are exposed to relatively high ambient temperatures. No standard procedure was adopted for the desorption test.

The whole process of sorption and desorption of the materials during the test as described above can therefore be summarized into three stages: (i) free sorption or capillary suction (ii) force sorption or saturated under water and, finally, (iii) free desorption or drying process as shown in Figure 9.
The degree of pore interconnection (Ax) and the drying index (Is) of the materials was calculated from the following equations:

\[ Ax = \frac{Af - A1}{Af} \cdot 100 \]  
\[ Ec.7 \]

With free absorption represented as A1 and saturation absorption as Af.

\[ Is = \int_{t_0}^{t_f} f \left( \frac{M_i - M_1}{M_1} \right) dt \]  
\[ \frac{(M_3 - M_1)}{(M_1)} \times t_f \]  
\[ Ec.8 \]

Where; M_i, M_1 and M_3 are the masses (g) of the specimens recorded during the drying process, in the dry state and in the saturated state respectively. \( t_f \) is the final test drying time. The formula is based on drying curves and it was adopted from the thesis done by Liliana Sofia Neno Páscoa (2012).

### 3.2.6 Thermal properties

The examined thermal properties are the thermal conductivity, heat capacity, heat diffusivity and the linear coefficient of thermal expansion of bricks and the mortars
from the three types of the aggregates, that is mortar with natural river sand, recycled concrete fine aggregates and the one with recycled brick fine aggregates. The thermal response of the stacked prisms for each type of mortar was also realized.

The thermal conductivity ($\lambda$), heat capacity ($\rho C_p$) and thermal diffusivity ($\alpha$) of mortars and bricks was examined using an electronic thermal analyzer termed Quick – 30 Thermal Properties Analyzer (Figure 10). The method was borrowed from the previous study (Palumbo, 2015). The analyzer uses a surface probe which is placed on the material of which properties are to be determined. The measurement is based on the analysis of the temperature response of the material to heat flow impulses induced by electrical heating using a resistor heater having a direct thermal contact with the surface of the materials. The appliance works at temperatures between -20 and 70 °C. the device calculates the volumetric heat capacity (a product of density of the material and its specific heat capacity) from:

$$\alpha = \frac{\lambda}{\rho C_p} \quad Ec.9$$

Specimens (Figure 10) used for this test were two 140 x 150 mm brick units and one 140 x 160mm block for each type of mortar. The samples were previously used for determination of the coefficient of thermal expansion of the particular material. The test was conducted in the laboratory with temperature of about 25°C.

![Figure 10. Test setup for determination of thermal conductivity, heat diffusivity and specific heat capacity.](image)
The coefficient of linear thermal expansion for the bricks and mortars was developed using a conventional technique in which four pins, two in each direction designated X and Y were fixed at a distance of 100 mm between them. Two specimens, one from each type of the two bricks and one specimen for each type of mortar were used for the test (Figure 11). In order to have relatively similar moisture content, the specimens were first placed in an oven at 40°C until constant weight was achieved. Using a universal oven, the bricks were heated from an ambient temperature of 24°C to about 65°C. The change in the distance between the pins and the temperature of each respective brick in the oven were measured and recorded in intervals of 60 minutes for a duration of 9 hours. The last interval after the 9 hours corresponding to the maximum temperature achieved was maintained for 30 minutes.

![Figure 11. Mortar specimen for characterization of thermal behavior.](image)

The coefficient of thermal expansion ($\alpha$) taken as average of the slope of the strain–temperature curve for the two directions was established and expressed as strain per Celsius rise in temperature using equation 10. The method adopted is closely related to the one presented in ISO 10545-8 mentioned in specification of the ceramic materials producing company (INSTITUT DE PROMOCIO CERAMICA, 2007) with a few adjustments in the temperature range used. The purpose of this experiment is to study the influence of the natural river sand and the recycled fine aggregates to the thermal properties of historical mortars and hence the thermal compatibility of the respective mortar with the brick masonry units.
\[
\alpha_1 = \frac{1}{L_0} \cdot \frac{\Delta L}{\Delta T} \quad [\text{°C}^{-1}]
\]

Ec. 10

Where, \(L_0\) is the distance between the pins at ambient temperature, \(\Delta L\) represents the increase in distance between the pins from the ambient temperature to 65°C and \(\Delta T\) is the increase in temperature.

To establish the linear coefficient of the stack bonded prisms, the test was performed using iron pins Figure 12 arranged in a similar method the thermal behavior of the masonry bricks units and mortars was realized. However, in order to measure the effect of the use of the recycled fine sand mortars in masonry walls, the measurements were taken not only within individual masonry units but also between the units across the mortar joints. A three courses wall for each individual mortar was utilized for the assessment.

*Figure 12. Test setup for assessment of thermal response of stacked prisms (where, B – brick and M – mortar).*
4. RESULTS AND DISCUSSION

4.1 Basic characterization

The particle size distribution of natural and recycled fine aggregates presented in Figure 13 and Table 1 show that the materials have similar particle size distribution with the recycled brick sand having the highest values of both the amount of fines and the aggregate index. The aggregate indices are shown in Table 2. The amount of fines and the aggregate index of the natural river sand lies between the respective values of the recycled brick and concrete sands. The recycled concrete sand contains the least amount of fines and the lowest aggregate index. The aggregate indices of the natural river sand and the recycled brick sand are about two times higher than that of the recycled concrete sand. The results agree with other studies (Konow, 2003) and (Konow, 2006) as the aggregate indices are proportional to the amount of fines in the respective material.

Table 1. Particle size distribution of the aggregates

<table>
<thead>
<tr>
<th>Sieve size (mm)</th>
<th>4</th>
<th>2</th>
<th>1</th>
<th>0.5</th>
<th>0.25</th>
<th>0.125</th>
<th>0.063</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% Passing Material</td>
<td>NS</td>
<td>RCS</td>
<td>RBS</td>
<td>NS</td>
<td>RCS</td>
<td>RBS</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>70</td>
<td>65</td>
<td>65</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>46</td>
<td>38</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.25</td>
<td>26</td>
<td>21</td>
<td>26</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.125</td>
<td>14</td>
<td>11</td>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.063</td>
<td>7</td>
<td>5</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The particle density, loose and compacted bulk density of the lime are as indicated in Table 2. The lime conforms to the EN 459-1 (EN, 2015) standard which specifies the range of bulk density between 0.45 to 0.75 for NHL 3.5 building lime.

Table 2 also contain results for water absorption, density and porosity of the natural sand (NS), recycled concrete (RCA), recycled bricks (RBA) aggregates and the brick units. For the densities measured, the natural sand is denser than the recycled aggregates. The water absorption of the recycled aggregates for both the recycled concrete and brick sands is about ten times higher than that of the natural sand. The properties of the recycle concrete and brick sands are similar. The higher porosity of the recycled aggregates accounts for both their lower densities and higher water absorption capacity. The high amount of pores in recycled material could be a function of the recycling process adopted. The similarity in properties between the recycled material could be explained in terms of the similarity in their particle size distribution and water absorption. Mohammed et al (2015) obtained similar relation in densities of natural and recycled material and a reverse trend in water absorption.

The bricks were found to be equally dense. However, the porosity and water absorption of brick 1 is higher than that of brick 2. The corresponding difference in porosity and water absorption is about 4.1% and 3.2% respectively. The dissimilarity
in these properties might have been caused by factors described by Fernandes and his colleagues (2009).

Table 2. Apparent, bulk, surface saturated dry, loose and compacted density, water absorption, porosity of the materials and the Aggregate Index of the fine aggregates.

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>Brick 1</th>
<th>Brick 2</th>
<th>Lime</th>
<th>NS</th>
<th>RCS</th>
<th>RBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apparent density</td>
<td>g/cm³</td>
<td>2.61</td>
<td>2.55</td>
<td>2.53</td>
<td>2.68</td>
<td>2.65</td>
<td>2.70</td>
</tr>
<tr>
<td>Dry density</td>
<td>g/cm³</td>
<td>1.82</td>
<td>1.81</td>
<td>-</td>
<td>2.60</td>
<td>2.08</td>
<td>2.08</td>
</tr>
<tr>
<td>S.S.S density</td>
<td>g/cm³</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.63</td>
<td>2.30</td>
<td>2.31</td>
</tr>
<tr>
<td>Loose density</td>
<td>g/cm³</td>
<td>-</td>
<td>-</td>
<td>0.60</td>
<td>1.54</td>
<td>1.18</td>
<td>1.18</td>
</tr>
<tr>
<td>Compacted density</td>
<td>g/cm³</td>
<td>-</td>
<td>-</td>
<td>0.66</td>
<td>1.65</td>
<td>1.25</td>
<td>1.28</td>
</tr>
<tr>
<td>Water absorption</td>
<td>%</td>
<td>16.6</td>
<td>16.1</td>
<td>-</td>
<td>1.1</td>
<td>10.3</td>
<td>10.7</td>
</tr>
<tr>
<td>Vol of pores</td>
<td>%</td>
<td>30.2</td>
<td>29.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Aggregate Index</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>17.1</td>
<td>9.2</td>
<td>18.5</td>
</tr>
</tbody>
</table>

4.1.1 Chemical composition

The chemical composition of the materials is shown in the Figure 14, Figure 15, Figure 16 and Figure 17.

The hydraulic lime consists mainly of calcite, portlandite, quartz and bicalcium silicate.
The natural river sand is largely composed of quartz, calcite, albite (feldspar mineral), microcline (feldspar mineral), chamosite (feldspar mineral) and mica (feldspar mineral).
The fine recycled concrete sand is chiefly composed of quartz, calcite, albite (feldspar mineral), microcline (feldspar mineral), chamosite (feldspar mineral) and mica (feldspar mineral).

Figure 15. Chemical composition of natural sand (NS).
Figure 16. Chemical composition of recycled concrete sand (RCS).

The main compounds in the fine recycled brick sand are quartz, calcite, albite (feldspar mineral), microcline (feldspar mineral), chamosite (feldspar mineral) and mica (feldspar mineral).
4.1.2 Particle shape

The visual analysis for the particles of the aggregates with size between 1 and 2mm Figure 18 reveals that both the natural river sand and the recycled aggregates are angular in shape. The natural sand has crystalline, reflecting and smoother surface texture than the recycled concrete and brick sands. The recycled concrete sand particles contain some visible pores.

Image analysis results presented in Figure 19 shows the shape descriptors. All the materials have nearly similar values of shape descriptors for circularity, roundness and solidity. The values are close to 1 (about 0.7 for circularity and roundness and 0.85 for solidity) implying that the aggregates are slightly round or symmetrical in shape. This can also be seen in aspect ratios of the aggregates for which all values are slightly larger than 1. In a nutshell, the image analysis shows that the particles
are rough, nearly round or square and solid. However, the results are only indicative as merely few images for each material were analyzed and the smaller sized particles (< 1mm) were not examined.

Figure 18. Images used for image analysis of particles (NS, RCS and RBS).

Figure 19. Shape factors of different sands.

4.2 Dosage and Fresh state properties of mortars

The mixing ratios of the ingredients for the mortars both in terms of volume and weight is as indicated in Table 3.
### Table 3. Dosage of mortars.

<table>
<thead>
<tr>
<th>Material</th>
<th>Volume (NS, RCS, RBS)</th>
<th>Dosage</th>
<th>Weight (g)*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>NS</td>
<td>RCS</td>
</tr>
<tr>
<td>Lime</td>
<td>1</td>
<td>236</td>
<td>236</td>
</tr>
<tr>
<td>Sand</td>
<td>2.5</td>
<td>1450</td>
<td>1203</td>
</tr>
<tr>
<td>Water</td>
<td>0.8</td>
<td>320</td>
<td>320</td>
</tr>
</tbody>
</table>

*Material necessary for one mold or three prisms.

The flow of the three mortars was slightly different. The highest flow corresponds to the recycled brick aggregate mortar and it is about 28% higher than that of the natural sand mortar. The mortar containing recycled concrete had a flow about 21% higher than that of natural sand mortar (Figure 20). Before preparation of the mortars, the aggregates were surface saturated and therefore it was expected to obtain closer flow results than the obtained measurements. These smaller differences might have been resulted by variations in temperature and relative air humidity, the factors which however were not studied during the tests.

![Figure 20. Table flow of mortars.](image)

The adhesion of the mortars (Figure 21) was traditionally tested using trowel and it was good enough for the mortars to be workable.
Water retention capacity of all the three mortars was found to be practically the same. The recycled concrete and brick sand showed about 1\% and 5\% respectively less water holding capacity than the natural aggregates. The values presented in Table 4 are only for the comparison purpose as the suction pressure employed during the test (14kPa) was much higher than the standard specified suction (7kPa).

The amount of air in all the three mortars was similar. The density of the mortar with recycled concrete and brick aggregate is the same. The natural sand mortar was found to be slightly denser than the mortar with the secondary aggregates.

**Table 4. Table flow, water retention, air content and fresh density of mortars.**

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>NSM</th>
<th>RCSM</th>
<th>RBSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table flow</td>
<td>cm</td>
<td>10.6</td>
<td>12.9</td>
<td>13.6</td>
</tr>
<tr>
<td>Water retention</td>
<td>%</td>
<td>57.8</td>
<td>57.3</td>
<td>55.0</td>
</tr>
<tr>
<td>Air content</td>
<td>%</td>
<td>4</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Fresh density</td>
<td>g/cm$^3$</td>
<td>2.03</td>
<td>1.83</td>
<td>1.82</td>
</tr>
</tbody>
</table>
4.3 Hardened state properties of materials

4.3.1 Physical properties

4.3.1.1 Density, water absorption and volume of pores of mortars

The dry density of natural sand mortar is higher than the densities of mortars with recycled materials. Figure xx a. indicates a slightly increase in the dry density of the reference mortar with age whereas there is practically no increase in density for the mortars with recycled sands.

At the age of 7 days, the apparent density of natural sand mortar was found to be slightly higher (about 1.2%) than that of mortars with the secondary material (Figure 22). There is low increasing trend of density of all mortars until the age of 28 days, with the recycled brick aggregate mortar having higher rate of increase (about 2%) than the natural sand mortar (1.2%) and the recycled concrete sand mortar (0.4%). After 45 days, the density of recycled concrete sand and natural sand mortars dropped slightly while that of the recycled brick sands mortar remained nearly constant. At this age, RBS and RCS mortars are respectively + 2% and – 1.2% denser than the natural sand mortar.

![Figure 22. Evolution of dry density and apparent density with curing age.](image)

Mortars containing recycled aggregates have higher absorption rate and porosity than the reference mortar (Figure 23). For the duration of 45 days, there is no significant changes in absorption and porosity for mortars with recycled material.
The reference mortar, the mortar that contains natural river sand reveals a slight fall in both the absorption and porosity with age. Comparing mortars with the recycled materials, the difference in water absorption and porosity of recycled brick sand and recycled concrete aggregates is insignificant.

![Figure 23. Evolution of absorption and volumes of pores with curing age.](image)

4.3.1.2 Drying shrinkage, loss of water and change in length of brick by movement of water

The bricks show high stability of dimensions when are exposed to water. The response of the two bricks to the process is slightly different. Brick 1 responded more to contraction (maximum value 0.005%) while brick 2 reacted more to expansion (maximum value 0.011%) (Figure 24).
Also, with the desorption process, the variations in dimensions is minor. As it was in the sorption process, brick 1 contracted more (about 0.006%) than brick 2 (0.003%). On the course of desorption, the expansion of the two bricks was establish to be the same (nearly 0.001%). Generally, as it is shown in Figure 24 and Figure 25, the effect of water movements to the dimensions of the burnt brick units is negligible.

Figure 24. Length change of bricks by absorption of water.

Figure 25. Length change of bricks by desorption of water.
The total drying shrinkage after 28 days of the test for all mortars was found to be the same (Figure 26, Figure 27, Figure 28). The mortar containing natural sand contracted by 0.21% as well as 0.22% and 0.23% for recycled brick and concrete mortar respectively. Observed was high initial rate of shrinkage for natural sand (0.15% in 96 hours) and low rate for the mortars containing recycled sand which contracted about 0.04% in 96 hours. The reason for this observation may be linked to the porous nature of the recycled aggregates.

Figure 26. Loss of weight and drying shrinkage of mortar with natural sand.

Figure 27. Loss of weight and drying shrinkage of mortar with recycled concrete sand.
With the absorption of about 10.3% and 10.7% for the recycled concrete and brick sands respectively mortars with RCS and RBS contained more water after mixing than the natural sand mortar with aggregates that had an absorption capacity of 1.1%. For the recycled sand mortars, the water loss from the surfaces of the specimen could easily be replaced by the water contained in the pores of the aggregates the process which stabilized the dimensions of the samples when drying. After 96 hours (4 days), depletion of water from the inner pores started and thus increasing the rate of shrinkage (Figure 29). This duration was enough for the samples containing natural sand aggregate to start stabilization. This ability of the recycled aggregates to hold water for a longer duration by replacing the surface losses is of paramount importance in hydration of hydraulic lime mortars, the process of which demands water. For the length of 28 days, the loss in weight of the samples was about 13%, 19% and 22% for the mortar containing natural river sand, recycled concrete sand and recycled brick sand respectively.

The loss in weight of the mortar samples is proportional to the water absorption (porosity) of the respective aggregates.
4.3.2 Mechanical properties

Brick 2 has higher mechanical properties than brick 1. The compressive strength of brick 2 is about 35.5% higher than the strength of brick 1. Similarly, the flexural strength and modulus of elasticity of brick 2 are 14.9% and 26.9% respectively higher than that of the other brick. The variation of the properties within the same material was also found to be high. For compressive strength, the coefficient of variation is 26% and 19% for brick 1 and 2 respectively. The corresponding flexural strength varies by 8% and 20% whereas the respective coefficient of variations in moduli of elasticity are 0.1% and 1.2%. The higher variations of the properties within the same unit are probably resulted by the anisotropic behavior of the material. The differences in the mechanical properties between the historical brick units may be a result of high variability in production, possible environmental damage depending on the exposure condition of storage, different age of production or experimental setup conditions (Fernandes, et al., 2009). The results are shown in Table 5. Using same batch of bricks other researches (Peverini, 2014; Pelà, et al., 2016) obtained related compressive strength results and different values of moduli of elasticity which however may be due to the different approaches adopted during the testing processes.
Table 5. Flexural, compressive strength and elastic modulus of brick 1 and brick 2.

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Brick 1</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>MPa</td>
<td>22 ± 6</td>
</tr>
<tr>
<td>Flexural strength</td>
<td>MPa</td>
<td>6.5 ± 0.5</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td>N/mm²</td>
<td>8072 ± 100</td>
</tr>
</tbody>
</table>

The evolution of the mechanical properties of natural river sand (NS), recycled concrete sand (RCS) and fine recycled brick aggregates (RBS) mortar with age are shown in Figure 30.

The flexural strength of the recycled aggregates mortars after curing age of 7 days is higher than the strength of the natural sand mortar. At this age, the RCS and the RBS mortar showed 44% and 131% respectively higher strength than the NS. The respective strengths at the age of 28 days are 68% and 300% higher than the strength of the NS mortar. After this age, the percentage increase in strength with respect to the reference mortar dropped slightly and a result after 45 days the flexural strength of the RCS and RBS was roughly 3% and 177% higher than that of the NS mortar.

Compressive strength follows similar evolution trend. The fraction increase in strengths of the RCS and RBS mortars with respect to the reference mortar at the age of 7, 28 and 45 days are about 12% and 14%, 20% and 133%, 2% and 113% respectively.

The exceptionally high mechanical properties of recycled brick sands mortars are a result of pozzolanic reactions (Nuno, et al., 2008; Stefanidou, et al., 2014; Guadalupe Cabrera-Covarrubias, et al., 2015).
The compressive strength of the stacked prisms is found to be the same regardless of the type of the mortar used. Stacks with recycled concrete sand mortar registered the mean strength about only 3.6% higher than the walls with natural river sand mortar. The strength of the prisms with recycled brick aggregate mortar is nearly 1.5% above those with natural sand mortar. The results show no significant influence of the type of mortar on the strength compressive strength of the masonry (Table 6).

The secant modulus of elasticity is slightly improved (Table 6). Prisms with fine recycled brick aggregates mortar are found to be about 24.5% stiffer than the stacks with natural river sand mortar. With recycled concrete sand mortar, the modulus of elasticity is nearly 28.8% higher than the stacked prisms with natural sand mortar. However, these differences are probably dependent on the mechanical properties of the masonry brick units and not the types of mortars.

When compared to previous studies (Pelà, et al., 2016), the compressive strength and the mean secant modulus of elasticity of stacks constructed from the same batch of bricks are different to the results obtained in this finding. The compressive strength is nearly two times higher than the value reported in their work. The highest modulus of elasticity that corresponds to the stacks with recycled concrete sand mortar is about 424MPa (17.4%) lower than the mean value reported in Pelà et al (2016). The differences might have been resulted by different in thickness of bed mortars and the

Figure 30. Evolution of strength of mortars flexural and compressive strength.
number of courses of the bricks in the stacks which means difference in slenderness ratio. The standard specifies a minimum of 5 courses as it was adopted by Pelà and his colleagues (2016). However, in this study, as a result of testing difficulties only 3 course two joint prisms were used. Nevertheless, the findings are in agreement with the results of the two joint cylindrical cored samples as studied by Pelà (2016).

Table 6. Compressive strength and modulus of elasticity of stacked prisms (mean and standard deviation) for different types of mortars.

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Stack prism w.r.t mortar type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>NSM</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>MPa</td>
<td>10.1 ± 1.51</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td>N/mm²</td>
<td>1888</td>
</tr>
</tbody>
</table>

Irrespective of the type of mortar used, all stacks portrayed similar failure patterns under compression loads. Nearly parallel cracks developed from either end bricks in contact with the platens and advanced into the inner units. Some units failed through edge shearing. All mortars failed by bloating followed by detachment (Figure 31, Figure 32, Figure 33).

Figure 31. Failure pattern of stack with NSM.
Observed during the determination of the modulus of the prisms was a slight drop in the maximum load before unloading cycle begins (Figure 34, Figure 35, Figure 36). This is thought to be caused by the crushing of mortars which has strength much lower than the upper limit of the load which is about one third the ultimate compressive strength of the brick units.
Figure 34. Loading cycles; load - duration curve and load - strain diagram for stacked prism with natural sand mortar.

Figure 35. Loading cycles; load - duration curve and load - strain diagram for prism with recycled concrete sand mortar.
4.4 Hygric properties

As it has been stated earlier in the previous chapter, the IRA was measured at several time intervals in order to study the rate of the evolution of the absorption process with time and simplify the comparison of the influence of the methods used for determination of IRA and capillarity suction.

Presented in Figure 37 are the results for the initial rate of absorption of brick 1 and brick 2. The total absorption for the duration of three days is nearly the same. This is due to the fact that both bricks have similar porosity and degree of pore interconnection. However, brick 1 has a higher velocity of absorption than brick 2. This means brick 1 reaches free saturation before brick 2 does. The coefficients of absorption are presented in Table 7.
Figure 37. Initial rate of absorption of bricks.

Natural sand (reference) mortar and RCS sand mortar have comparable coefficients of absorption with a difference of only 1.4%. The velocity of absorption of the RBS mortar is 46% lower than that of the reference mortar. RCS and RBS mortar has respectively 31% and 38% higher water absorption than the reference mortar (Figure 38). When subjected to moisture, masonry with mortar containing such recycled material could drain the units well than the natural sand mortar. Having lower absorption coefficient, RBSM is better for external use than both the reference and the RCS mortar as the later can easily be saturated allowing water to flow on the surface, a process that can easily cause erosion. The higher water absorption of the RCS and RBS mortars is attributed to their higher pore content. The degree of pore interconnectivity of the three mortars is related (Table 7). This indicates that the paths of water in the mortars is identical. The absorption coefficients in the interval 0-5min. and 10-30min. for bricks indicate higher and lower absorption rate in the first and second interval respectively for brick 1 and constant rate for brick 2. This implies that brick 1 has large open pores than brick 2 and therefore it is less resistant to frost attack (Konow, 2006). For mortars, the absorption rate is almost constant in both intervals. In comparison with the reference mortar, the recycled sand mortar has pore size similar to that of the natural sand mortar and pores in the recycled brick sands mortar has smaller size. For this reason, the RBS mortar is resistant to
the frost attack than the other two mortars. The reference mortar and the recycled concrete fine aggregates mortar are less resistant and equally vulnerable to the frost damage.

![Graph showing initial rate of absorption of mortars.]

*Figure 38. Initial rate of absorption of mortars.*

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Brick 1</td>
</tr>
<tr>
<td>Ccap</td>
<td>g/cm² min⁻¹/²</td>
<td>0.288</td>
</tr>
<tr>
<td>A1</td>
<td>%</td>
<td>16.83</td>
</tr>
<tr>
<td>Af</td>
<td>%</td>
<td>17.44</td>
</tr>
<tr>
<td>Ax</td>
<td>%</td>
<td>3.53</td>
</tr>
<tr>
<td>Is</td>
<td></td>
<td>0.091</td>
</tr>
<tr>
<td>*C₀-₅ min.</td>
<td>kg/m² h⁻¹/²</td>
<td>22.68</td>
</tr>
<tr>
<td>*C₁₀-₃₀ min.</td>
<td></td>
<td>7.37</td>
</tr>
</tbody>
</table>

*₅₀-₅ min. and *₁₀-₃₀ min. are the coefficients of absorption in time intervals of 0-5 minutes and 10-30 minutes respectively.

Table 7. Capillary absorption coefficient (Cap), free absorbed water content (A1), saturation absorption (Af), degree of pore interconnection Ax and drying index of the material after initial rate of absorption test setup.
In capillarity suction test results, the trend of absorption is similar to that developed in initial rate of absorption as shown in Figure 39, Figure 40 and Table 8. However, the velocity of absorption of each material is lower than the velocities obtained in the initial rate of absorption process. The interconnectivity of the pores is greatly affected. Brick 1 and natural sand mortar have practically the same degree of pore interconnectivity as in IRA and in brick 2 and RCS and RBS mortars it is nearly doubled. However, the degree of pore interconnectivity results seems to be against the results presented in Figure 37 and Figure 39 for IRA and capillarity suction respectively of the bricks.

![Graph of capillarity suction of bricks](image)

*Figure 39. Capillarity suction of bricks.*

Also, the interconnectivity of pores in mortars containing recycled aggregates is greatly reduced than the one with natural sand mortar. This is beneficial in the sense that with such materials water ingress in the masonry will significantly be reduced. However, the disadvantage is that draining water from masonry units in events of moisture attack will be impaired. The absorption of water in the intervals 0-5min. and 10-30min. is slightly altered but the general trend is similar to the results obtained using the initial rate of absorption setup.
Secondary materials in mortars for use in historical buildings

Figure 40. Capillarity suction of mortars.

Table 8. Capillary absorption coefficient (Cap), free absorbed water content (A1), saturation absorption (Af), degree of pore interconnection Ax and drying index of the material following capillarity suction test setup.

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Brick 1</td>
</tr>
<tr>
<td>Ccap</td>
<td>g/cm²min¹/²</td>
<td>0.230</td>
</tr>
<tr>
<td>A1</td>
<td>%</td>
<td>16.24</td>
</tr>
<tr>
<td>Af</td>
<td>%</td>
<td>16.85</td>
</tr>
<tr>
<td>Ax</td>
<td>%</td>
<td>3.65</td>
</tr>
<tr>
<td>Is</td>
<td>-</td>
<td>0.192</td>
</tr>
<tr>
<td>*C⁰.⁵ min.</td>
<td>kg/m²h¹/²</td>
<td>17.47</td>
</tr>
<tr>
<td>*C¹₀⁻³⁰ min.</td>
<td>kg/m²h¹/²</td>
<td>12.10</td>
</tr>
</tbody>
</table>

*C⁰.⁵ min. and *C¹₀⁻³⁰ min. are the coefficients of absorption in time intervals of 0-5 minutes and 10-30 minutes respectively.

Desorption of samples after the IRA test reveals that the bricks have the same drying rate. However, some amount of water remains in brick 2 while brick 1 is already dried as supported by Figure 41 and drying indices in Table 7. This difference is resulted by the poor pore connectivity of brick two. The non-uniform water removal process
may be the cause of localized pathologies in masonry walls. After ten days of desorption, all mortars attained almost the same water content. Mortars with recycled aggregates have identical drying pattern with drying indices higher than that of natural sand mortar which suggests that RCS and RBS mortars retained some amount of water during the drying process. Considering the age of the specimens and the similarities in the degree of pore interconnectivity of mortars, it is possible to say the larger values of drying indices may not only indicate the presence of water held in mortars but also a possibility of continued hydration, a process which uses water. In terms of drying, at the early age of mortars NS mortar seem to be better than mortars with the recycled concrete and bricks.

![Desorption of samples used in IRA test; bricks and mortars.](image)

*Figure 41. Desorption of samples used in IRA test; bricks and mortars.*

With capillarity desorption, it has been revealed that covering the specimens worsen the drying process. In each material, the drying index is about twice the index established during the desorption of the samples used during the IRA test. This means that twice as much absorbed water remains in the masonry structures during drying. The results are best presented in Figure 42 and Table 8. In practice this denotes that although hydrophobic material reduces water ingress in masonry, contra effect might be the damages related to dampness. Their use should therefore strike the balance between both absorption and desorption.
Comparing the two methods of absorption, the application of surface cover in capillarity suction test reduces slightly the velocity of absorption in relation to the untreated samples used in IRA test as the coefficients of absorption in table xx and table xx indicate. It has further been noticed that treatment of samples used in capillarity suction test reduce both the interconnectivity of the pore network and the loss of moisture from the material. In both cases, the total amount of water absorbed after saturation is the same.

The entire process of absorption and desorption for both test setups (initial rate of absorption and capillarity suction) is presented in Figure 43 and Figure 44.
4.5 Thermal properties

The important thermal properties described in this part are the thermal conductivity and the coefficient of thermal conductivity of both bricks and mortars. The results for specific heat capacity and the heat velocity (diffusivity) are also presented.
4.5.1 Thermal conductivity

The thermal conductivity of bricks and mortars are presented in Table 9. It has been discovered that brick 1 has higher thermal conductivity than brick 2. Also, mortars containing the recycled aggregates has similar conductivity and it is lower than that of the reference mortar. For bricks, the difference might have been resulted by variations in production processes (Fernandes, et al., 2009). The RCS and RBS mortars have more or less the same amount of porosity which is larger than that of natural sand mortar. This is the reason for the similarity in thermal conduction property which is lower than that of the reference mortar. For this reason, both recycled concrete and bricks aggregate mortars can be used for insulation in the historical buildings.

Both bricks and mortars have practically the same heat capacity. However, the velocity of spread of heat in the material is found to be proportional to the heat conduction.

Table 9. Thermal conductivity (λ), heat capacity (ρCₜₐₚ) and heat diffusivity (α) of bricks and mortars.

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Brick 1</td>
</tr>
<tr>
<td>λ</td>
<td>W/m³K</td>
<td>0.67 ± 0.10</td>
</tr>
<tr>
<td>ρCₜₐₚ (10⁶)</td>
<td>J/m³K</td>
<td>1.53 ± 0.08</td>
</tr>
<tr>
<td>α (10⁶)</td>
<td>m²/s</td>
<td>0.44 ± 0.04</td>
</tr>
</tbody>
</table>

4.5.2 Coefficient of thermal expansion

The results for the coefficient of thermal expansion of bricks and mortars are as shown in the figures and summarized in Table 10. The heating rate of the specimens measured is found to be similar to both bricks and mortars. Brick 1, brick 2, NS and RCS mortar have coefficient of thermal conductivity ranging between 4 and 5 (Figure 45, Figure 46, Figure 47). These material are therefore thermally compatible and can be used together in a historical masonry.
RBS mortar has shown the least thermal response in expansion (Figure 48). The reason for this can be attributed to the fact that ceramics, the brick sand have lower coefficients of thermal expansion. With the advantage of its low thermal conductivity, RBS mortar can be used for external enveloping as even at elevated temperatures there won’t be significant movement in the mortar - substrate interface that could otherwise develop shearing stresses and damage the bond between the materials at the interface.

Figure 45. Heating rate and thermal linear expansion of bricks.

Figure 46. Heating rate and thermal linear expansion of NSM.
Figure 47. Heating rate and thermal linear expansion of RCSM.

Figure 48. Heating rate and thermal linear expansion of RBSM.

Table 10. Heating rate ($r$), and linear coefficient of thermal expansion of bricks and mortars.

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Brick 1</td>
</tr>
<tr>
<td>$r$</td>
<td>°C/min.</td>
<td>0.0692</td>
</tr>
<tr>
<td>$\alpha_1$ ($10^{-6}$)</td>
<td>1/°C</td>
<td>5</td>
</tr>
</tbody>
</table>

$y = 0.0669x + 20.361$
$R^2 = 0.9936$

$y = 0.067x + 20.778$
$R^2 = 0.9901$

$y = 4E-06x - 0.0001$
$R^2 = 0.9902$

$y = 2E-06x - 5E-05$
$R^2 = 0.9499$
Figure 49 below illustrates the temperature response of natural sand, recycled concrete and recycled bricks aggregate mortars subjected to the temperature rise about 32°C. The strain developed in natural sand mortar is 12.5% higher than in recycled sand mortar and it is 50% above the strain developed in recycled brick mortar. Natural sand and recycled concrete sand mortar can thus be used in different plaster layers without significant damage due to temperature strains. RBS mortar – NS mortar combination is likely to cause damage as a result of the studied divergence in thermal response.

The thermal expansion of stacked prism is found to be highly influenced by the thermal properties of the masonry units.

With natural sand mortar, the expansion-temperature relationship of the prisms is similar to that of the natural sand mortar (NSM) as shown in Figure 50. This is due to the fact that both the natural sand mortar and the brick units have same coefficient of thermal expansion.

Figure 49. Comparison of linear thermal response of mortars.
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Stacks with recycled concrete sand mortar show somewhat higher thermal response than the mortar (Figure 51). The reason for this is that, the coefficient of thermal expansion of the mortar is slightly lower than that of the brick units.

Figure 50. Expansion-temperature relationship for stacks with natural sand mortar.

Figure 51. Expansion-temperature relationship for stacks with natural sand mortar.

Figure 52 below indicates the response of stacked prisms made with recycled brick sands mortar to temperature. The RBSM has lower response than the stack. As the other types of mortars, the difference in the reaction to temperature is resulted
by the significant divergence in coefficient of thermal expansion between the brick units and the mortar.

![Figure 52. Expansion-temperature relationship for stacks with natural sand mortar.](image)

From the above presented results, it is possible to say the thermal expansion of masonry walls greatly depend on the thermal behavior of the brick units. However, the influence of the orientation of the wall has not been studied which perhaps will reveal different response.
5. CONCLUSIONS AND FUTURE STUDIES

5.1 Conclusions

An intensive analysis of the laboratory test results shows that recycled concrete and bricks fine aggregates are suitable for use in historical hydraulic lime mortars. This deduction is on the basis of engineering properties required for historical mortars for which mortars containing recycled material have found to surpass mortar with natural river sand which in the study was used as a reference mortar. The following conclusions are based on specific:

- In terms of mechanical properties, the properties of historical bricks are found to vary greatly. Input parameters during analysis of historical buildings should therefore be carefully determined and preferably using a large representative samples.

RBS mortar attains higher early flexural strength and after seven days the rate of hardening increase steadily. This is due to the existence of pozzolanic reactions in the mix. For this reason, RBS mortar is a better repair material in historical buildings where high early strength is paramount. The development of mechanical properties in natural sand and recycled concrete sand mortars are comparable and are therefore compatible repair material. The mechanical properties of the stacked prisms are alike irrespective of the type of mortar used, and therefore it is possible to say the properties independent of the type of the mortar and greatly influenced by strength of brick units.

- Use of recycled fine aggregate in mortars improve significantly the physical properties of mortars. However, air content and flow table of the reference mortar and mortars containing the recycled fine sands seem to be similar. This might have been resulted by similarity in particle size distribution.

In both fresh and hardened state, mortars containing recycled concrete and bricks are less dense and thus can significantly reduce the dead weight of the building.

The characterized bricks units were found to be equally dense.
Bricks were established to have similar porosity and water absorption capacity. RCS and RBS mortars have higher porosity and water absorption than the natural river sand mortar.

- For hygric properties, the bricks have different water absorption velocities. The RCS and RBS mortars have high absorption velocity than the reference mortar. Such mortars can therefore be used as sacrificial finishes or material to drain masonry units in buildings. However, the desorption characteristic of the mortars with the recycled material seem to be poor than that of the reference mortar. At early age, this can have been resulted by hydration reactions the process that consume water.

With drying shrinkage, mortars with recycled aggregates holds significant amount of water which is useful for hydration and reduces formation of cracks. During the first 4 days, the contraction of mortars with recycled aggregates is much lower than that of the reference water. After 28 days, shrinkage of all the three mortars was the same.

- The heat conduction of the RCS and RBS mortars are comparable and lower than both the heat conduction of the reference mortar and the brick units. For this reason, the recycled fine aggregates are suitable for insulation mortars.

The coefficients of thermal expansion of recycled concrete aggregates and the recycled brick fine sands are lower than that of the reference mortar and the brick units. Thus, mortars with recycled materials can be used to envelop buildings against environmental deterioration.

The thermal response of masonry wall is greatly influenced by the thermal characteristics of the masonry units and not the mortar used.

- With recycled aggregates, it is possible to blend the materials to form mortars of different natural colors.

**5.2 Future studies**

The characteristics of recycled bricks and concrete fine sands mortars studied have been found suitable for historical mortar. However, the following, which have not been dealt with in this study and greatly affect the stability of both the repair and the repaired material should be explored;
- Bond strength influences the shear strength of the masonry walls and therefore bonding characteristics between the mortars with recycled aggregates and different substrates should be assessed.

- Stiff mortars are not suitable due to the reduced flexibility when the structure is subjected to movements. For this reason, it is necessary to establish the stiffness of the mortars which will ensure compatible use of the mortars and will avoid any possible damage due to concentration of stresses in masonry joints.

- The main problem with mortars in historical buildings are the salt attack (crystallization) and frost damage. The resistance of the studied mortars to such attacks has not been established. Hence, in the future it is important to examine the durability of mortars with recycled concrete and brick aggregates.

- Study on the evolution of the established characteristics in this thesis over a long period of time. The study has been conducted with in a duration of 45 days or less. The characteristics which have been found better within this short period may probably worsen with time. It is thus necessary to have a long term captured trend of such properties which will useful in maintenance and planning for repair works.
6. REFERENCES


Konow, T. v., 2003. Aggregate grain size distribution - A major influence on many properties of lime mortars for Restoration. Lausanne, EPFL.


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