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Recycled sand in lime-based mortars

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ABSTRACT

The increasing awareness of the society about safe guarding heritage buildings and at the same time protecting the environment promotes strategies of combining principles of restoration with environmentally friendly materials and techniques. Along these lines, an experimental program was carried out in order to investigate the possibility of producing repair, lime-based mortars used in historic buildings incorporating secondary materials. The alternative material tested was recycled fine aggregates originating from mixed construction and demolition waste. Extensive tests on the raw materials have been performed and mortar mixtures were produced using different binding systems with natural, standard and recycled sand in order to compare their mechanical, physical and microstructure properties. The study reveals the improved behavior of lime mortars, even at early ages, due to the reaction of lime with the Al and Si constituents of the fine recycled sand. The role of the recycled sand was more beneficial in lime mortars rather than the lime–pozzolan or lime–pozzolan–cement mortars as a decrease in their performance was recorded in the latter cases due to the mortars' structure.

1. Introduction

Historic mortars usually are based on lime and often contain sand of river origin, most commonly of 0–4 mm granulometry (Papayianni, 2006). The addition of aggregates to a binding system has proved to confer technical advantages as they contribute to volume stability, durability and structural performance (Stefanidou and Papayianni, 2005). Apart from the different available aggregate types, as far as their mineralogy is concerned, their volume content in the mixture, as well as their maximum size and gradation, influence the structure of a binder–aggregate mixture (Baronio et al., 1997). Properties such as rheology, strength, shrinkage, porosity are strongly based on the type, the ratio, and the gradation of the aggregates (Cortes et al., 2008; Westerholm et al., 2008). Sands of different origins have been used in mortars and different flow ability, strength and stiffness have been recorded (Tasong et al., 1998). Additionally, an increased water demand was recorded in cases where angular in shape aggregates have been used, while the binder–aggregates transition zone in those cases improved even though porosity had increased (Gonçalves et al., 2007). All the sands that are characterized as suitable for use should be of selected maximum size, present an even granulometry and be free of organics and soluble salts.

The incentive to use sand from building demolition in repair mortars derives from different needs: natural sand originating from rivers is becoming rare, while the extraction of aggregates from quarries carries an increased administrative cost due to new legislation, both at National and European level (COM/2008/699; FEK 2076 B, 2009). Both practices are not considered environmentally friendly and, thus, the criteria and legislation for sand extraction are becoming more strict and demanding, while in some places good quality natural sands are not available. On the other hand, the increased waste production offers the availability of large volumes of recycled materials and public concern about the environment pushes towards their utilization.

Mixed construction and demolition waste (CDW) aggregate is produced by crushing waste originating from various construction sites and building rubble and may contain concrete, ceramic, gypsum, glass and bituminous particles. As expected, CDW aggregates show great variations in quality since the presence and amount of impurities depend on the origin of the CDW and the various processes of the recycling plant. In Greece, the amount of generated CDW reached 6.8 and 2.1 million tonnes for 2008 and 2010, respectively, and the recycling rate is lower than 5% while, at the same time, natural aggregates are consumed at high rates (Eurostat, 2012).

Many researches performed during recent years converge to the result that the coarse fraction of construction and demolition waste can be used to substitute natural aggregates in concrete successfully (Kou et al., 2012; Lovato et al., 2012; Martín-Morales

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et al., 2011; Rao et al., 2007), despite the expected reduced strength and increased porosity (Agrela et al., 2011; Guedes et al., 2013). Such findings have led to the adaptation of relevant standards such as the EN 12620 (CEN, 2002a), in order to include recycled aggregates as well. However, fine recycled aggregate has proven more difficult to incorporate into concrete, mainly due to water demand and fresh concrete workability problems (RILEM, 1994a), and its use in concrete is limited (Evangelista and de Brito, 2010; Khatib, 2005). Their current main application is in landfills (Kourmpanis et al., 2008; Rao et al., 2007) and research towards increasing the possible uses for such materials is still needed.

Efforts have been made to examine the addition of recycled sand in cement-based mortars by either substituting a part of the natural sand (Lima and Leite, 2012; Miranda and Selmo, 2006a, 2006b) or by using 100% recycled fine aggregates (Corinaldesi et al., 2002; Jiménez et al., 2013; Martínez et al., 2013; Neno et al., 2013). The results show that cement-based mortars with recycled sand present lower compressive strength, improved values of bond strength, higher porosity, high shrinkage and absorption capacity. Martín-Morales et al. (2011), even propose improvement of the quality of the recycled sand by washing and sieving, by manually removing gypsum, or by mixing with natural sand, in order to upgrade its quality.

The purpose of this study was to test the use of recycled sand from mixed construction and demolition waste in traditional mortars in comparison to natural and standard sands. Since the sensitive approach to historic buildings demands rigorous tests on the suitability of materials, a detailed characterization of the recycled sand is firstly presented, followed by tests on traditional mortar mixtures with lime and pozzolan as the main binders. The mortars were tested for their physical and mechanical properties, microstructure and durability and their performance in respect to composites with natural sands was assessed.

2. Materials and methods

2.1. Materials

The binders used in the test mortars were hydrated lime, natural pozzolan and white Portland cement I42.5. A polycarboxylic-based superplasticizer was also used in some of the mortars with recycled sand, in order to compensate for reduced workability. Three different sands were used in this study as fine aggregates in traditional mortar mixtures: standard AFNOR sand, natural river sand and recycled sand originating from the fine fraction (<4 mm) of CDW aggregates. The CDW aggregates used in the present paper are commercially available and were obtained from a recycling plant in the area of Thessaloniki, in Macedonia, Greece, without any treatment.

The natural sand used originated from the river Axios in the area of Thessaloniki and it had been cleaned and sieved previously in order to be suitable for construction. The standard sand used was siliceous of standard gradation and composition conforming to the EN 196-1 standard (CEN, 2005).

A series of tests on the raw aggregate was decided in order to determine its suitability for use in traditional mortars. The constituents of the recycled sand were identified visually, while FTIR (32 scans, resolution 2 cm^{-1}) using tablet KBr 1% and XRD analysis using Philips PW 1710 diffractometer with Ni-filtered Cu Ka radiation were carried out in order to determine its mineralogical composition and the presence of organic impurities. Wet chemical analyses on natural river and recycled sands were also carried out while soluble salts were determined by ionic chromatography (Thermo Scientific, Dionex ICS-1100) which is a fully quantitative method. Some of their physical properties, including granulometry, density, water absorption, sand equivalent, fineness and sphericity were measured according to relevant standards (see Table 1).

2.2. Mortar mixtures design

Three different binding systems, often used in repair works, were selected for the test mortars using hydrated lime (*L*), a combination of lime and natural pozzolan (*P*) in 1:1 proportion (by weight) and a combination of lime–natural pozzolan and white cement (*C*) in 1:0.8:0.2 ratio (also by weight). The three different sands were used for each of the binding systems in binder/aggregate ratio, 1/3 by weight. Water was adjusted in order to achieve a consistency of 150 ± 10 mm in the flow table according to EN 1015-3:1999 (CEN, 1999a) (Table 2). The mortars with recycled sand showed significantly increased water demand due to their water absorption, which was not taken into account when determining the effective (available) water to binder ratio. Since the aggregates used in mortars and concrete are considered to be in

Table 1
Physical properties of recycled and natural sand.

Sample	App. specific density (kg/m^3)	Water absorption (%)	Sand equivalent (%)	Fineness modulus (%)	Sphericity (measured under microscope)
Procedure	EN 1097-6	EN 1097-6	EN 933-8	EN 12620	
Natural sand	2650	1.5	98.0	3.63	0.825
Recycled sand	2450	8.0	66.6	4.97	0.721

Table 2
Mixture proportions by weight and workability of the test mortars.

Mortar constituents	LSS	LNS	LRS	LRSsp	PSS	PNS	PRS	PRSsp	CSS	CNS	CRS	CRSsp
Hydrated lime (*L*)	1	1	1	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
White cement (*C*)	–	–	–	–	–	–	–	–	0.1	0.1	0.1	0.1
Natural pozzolan (*P*)	–	–	–	–	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.4
Standard sand (*S*)	–	3	–	–	–	3	–	–	–	3	–	–
River sand (*N*)	3	–	–	–	3	–	–	–	3	–	–	–
Recycled sand (*R*)	–	–	3	3	–	–	3	3	–	–	3	3
Water/binder	0.80	0.80	1.06	0.95	0.84	0.80	1.09	1.00	0.85	0.76	1.00	0.92
Effective *w*/*b* ratio	0.76	0.76	0.82	0.71	0.80	0.76	0.85	0.76	0.81	0.72	0.76	0.68
Superplasticizer (sp)	–	–	–	0.015	–	–	–	0.015	–	–	–	0.015
Flow table workability (mm)	160	140	148	143	160	154	150	153	160	150	145	150

L: lime, *P*: pozzolan, *C*: cement, SS: standard sand, NS: natural sand, RS: recycled sand, sp: superplasticizer