52. The use of structural eco-efficient mortars. A critical review from a SWOT analysis.

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Abstract. One of the main climate trigger are CO_2 emissions. In the field of architecture and construction, one of the most harmful materials is the cement due to its employment and its polluting power (about 5 and 8% of the worldwide CO_2 emissions). Thus, the search of an alternative material is essential.

This paper shows the possibility of using eco-efficient mortars as structural materials, in order to guarantee both safety and environment preservation in the strengthening/refurbishment/retrofitting of structures. In those mortars, the binder can be substituted by organic or inorganic materials (e.g. fly ash, ground granulated blast furnace slag, rice husk ash, palm oil fuel ash). From this strategy, the waste reduction is promoted, as wastes are immobilised without polluting the environment essential. Thus, it is encouraged the re-use of architecture which is an essential factor to get a more sustainable habitat. The obtained results allow setting a guide that makes easier the selection of eco-efficient mortars (guaranteeing both structural safety and environment preservation) to the agents involved in processes of structural works.

Keywords Structural retrofitting, Refurbishment, Mortar, Eco-efficient.

1 Introduction

Over the last decade, the structural rehabilitation of existing buildings has increasingly attracted the attention of society.

In addition, environmental contamination is, at present, a main concern. The construction of a new building is highly responsible of contamination due to energy demand and CO2 emissions. Thus, the use of eco-efficient building materials and the re-use/recycling of building structures are great challenges for the present-day architecture.

One of the most contaminant materials due to the amount of energy that needs to be generated is the cement, Fig. 1. Alternatives to Portland cement are regarded in codes (EC2, EHE2008), and are a current area of research.

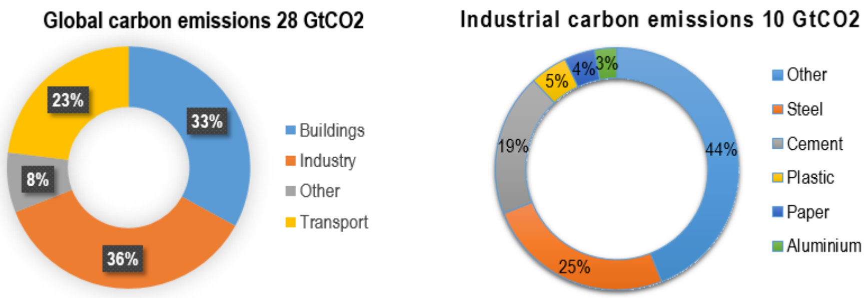

Fig. 1 Analysis of global CO2 emissions in 2006 demonstrating the importance of five key materials (Allwood J. et al, Material efficiency: A white paper, Resources, Conservation and Recycling, Volume 55, Issue 3, January 2011, Pages 362–381)

2 Eco-efficient mortars

In the following paragraphs a review on new materials which are formed replacing partially or totally cement by other material is provided. On the basis of the literature review, this classification has been established:
(i) Cement binder mortar with organic substitutes; (ii) Cement binder mortar with inorganic substitutes; (iii) Lime binder mortar; (iv) Lime binder mortar with organic substitutes; (v) Lime binder mortar with inorganic substitutes.

2.1 Cement binder mortar with organic substitutes

Different organic materials have been proposed to replace partially the cement:

- *Rice husk ash* (Aprianti, Shafigh, Bahri, & Farahani, 2015): the advantages of using rice are: (i) it produces a high volume of rice husk, which is a low-density residue of the process (Khan, Jabbar, Ahmad, Khan, Khan, & Mirza, 2012) and (ii) is one of the most abundant products worldwide. For instance, around 740.2 million tonnes of rice were produced in 2015 (Seguimiento del mercado del arroz de la FAO, 2015) where China produced more than 200 million tons in 2013 (Yang, Xue, Wu, Xiao, & Zhou, 2016). Rice husk ash (RHA) is a carbon neutral green product gained from raw rice husk that is changed to ash using the combustion process. The fineness of RHA is its main characteristic, because it influences the rate of reaction and gains in mortar strength, workability, water-cement ratio, shrinkage and creep of concrete too. It is possible to achieve a compressive strength until 25 MPa at 28-d when 20%wt of cement is substituted (Potty, Vallyutham, Yusoff, Anwar, Haron, & Alias, 2014). The aforementioned data were obtained following the prescriptions of ASTM C109, with water-cement ratio of 0.50 and binder/sand 1:3.

- *Palm oil fuel ash* (Karim, Hossain, Newaz Khan, Zain, Jamil, & Lain, 2014): it should be noted that thousands of tons of palm oil fuel ash (POFA) are produced annually worldwide (59.23 million tons of palm oil in 2014 (Fedepalma. Statistical Yearbook The Oil Palm Agroindutry in Colombia and the World 2010–2014, 2015)). Thailand and Malaysia are the main producers of POFA, for instance, the last one produces 3.13 million tons annually (Abutaha, Abdul Razak, & Kanada, 2016). This production is growing every year and it is disposed on landfills, which now became a noticed problem. Regarding the mortar composition, ~~of~~ the binder-sand ratio is 1:2.75, and w/b ratio is 0.55. Additionally, if cement is substituted by 10%wt POFA, the compressive strength raises the highest value, 48 MPa, measuring cubic specimens of 50 mm each side (Usman, Sam, Sumadi, & Ola, 2015).

- *Sugarcane bagasse ash* (Aprianti, Shafigh, Bahri, & Farahani, 2015): during the milling process of sugarcane is generated the raw sugar and the sugarcane bagasse. After that, the bagasse ash is generated from the cogeneration and combustion process. The worldwide production of sugarcane is around 1.68 million tons annually, being Brazil the main producer, with 43% of the total world production (Food and Agriculture Organization of the United Nations). About its mechanical properties, Ganesan et al. (Ganesan, Rajagopal, & Thangavel, 2007) demonstrated that if the mortar contains 10%wt bagasse ash and presents a proportion of w/b radio of 0.53 and binder/sand 1:3, the specimens raise a 28-d compressive strength of 28.31 MPa, using cubic specimens of 100 mm.

- *Wood waste ash* (Ramos, Matos, & Coutinho, 2013): nowadays, more than 70% of the wood waste is disposed into the environment in various forms. Part of that waste, it is used as pellet and is burnt in plant fuel pellets. That quantity is estimated around 13 million tons annually in Europe, which is the main area consumer of this product (Pirraglia, Gonzalez, Saloni, & Wright, 2010). Besides, it has a valuable use as a replacement of cement. García and Sousa-Coutinho (Garcia & Sousa-Coutinho, 2013) have demonstrated that this eco-efficient mortar can reach a compressive strength of 44 MPa at 28-d using a mixture of w/b 0.50, binder:sand 1:3 and 5%wt cement substituted. It is tested following the EN 196-1 Standards.

- *Bamboo leaf ash* (Aprianti, Shafigh, Bahri, & Farahani, 2015): bamboo is one of the highest yielding natural resource having a fastest growth and can be used as fibre and other significant purposes for construction materials. Around 20 million tons are produced annually mainly in China (Yiping, Yanxia, Buckingham, Henley, & Guomo, 2010). The optimum proportion for the best hydration is

20wt%, which is comparable to the ordinary Portland cement. In this case, using cubic specimens with w/b ratio 0.48 and binder:sand 1:2.7, 60 MPa of compressive strength is achieved.

- *Corn cob ash* (Adesanya & Raheem, 1996)*: the* compressive strength improves by 4.9% and 16.7% when 20% and 50% of ordinary Portland cement is replaced by corn cob ash, and when the proportion are w/b 0.40 and binder:sand 1:3. In addition, the compressive strength of corn cob ash mortar is lower than the plain mortar at the early age. The main advantage of the usage of this product is its high production. For instance, the annual production is around 589 million tons, of which 8.04 million tons are generated in South Africa, the largest country producer (Aprianti, 2016).

2.2 Cement binder mortar with inorganic substitutes

Other types of substitutes are the inorganics ones. Thus, it tries to reduce wastes which are produced by:

- *Fly Ash* (Yu, Spiesz, & Brouwers, 2015)*:* pulverized coal fly ash (FA) is an industrial by-product of coal fuelled power plants (Kazemian, Gholizadeh Vayghan, & Rajabipour, 2015). The global coal ash production is around 390 million tonnes annually (Malhotra, 1999) and that production is increasing in China and India (Hardjito, Wallah, Sumajouw, & Rangan, 2004). For instance, India produced 163.56 MT of fly ash in 2012-2013 (Central Electricity Authority., 2014). The pozzolanic reaction of FA begins at the age of 3 days after blending with cement and water, which is much slower than the Portland cement hydration. About the mechanical properties, cement binder with fly ash substitute can reach around 37 MPa at 28-day of compressive strength where the mixture is formed by 52% of cement substituted and a w/c radio 0.30 (Berry, Hemmings, & Cornelius, 1990).
- *Ground granulated blast furnace slag* (Liu, Zhu, & Yang, 2016): ground granulated blast-furnace slag (GGBFS) is a by-product from the iron manufacturing industry. According to the American Iron and Steel Institute (American Iron and Steel Institute, 2011) only in U.S. the blast furnace slag production in 2011 was estimated to be in the range of about 8 to 9 million tons, and world output, 263 to 328 million tons. Mixtures incorporating GGBFS generally develop strength more slowly than other ones that contain only Portland cement but can have similar or even superior long-term strength, release less heat during hydration, have reduced permeability, and generally exhibit improved resistance to chemical attack (van Oss, 2013). About mechanical properties, Barnett et al. (Barnett, Soutsos, Millard, & Bungey, 2006) the compressive strength with 35% of GGBFS at 20 ºC at 8-day is 24 MPa and at 32-day is 42 MPa with mixture proportions calculated from the concrete mixture proportions according to the requirements of ASTM C1074.
- *Limestone powder* (Yu, Spiesz, & Brouwers, 2015)*:* the activity of limestone powder is under debate. Many researchers have demonstrated that properties of

cement are not negatively affected by limestone powder added, but another grand group defended the contrary. Regarding mechanical properties, mortars formed with 10% of limestone substituting cement achieves 55.5 MPa compressive strength at 28-day (Benn, Baweja, & Mills, 2014). Regarding the flexural strength, with 10% of limestone 7.8 MPa is reached (Ghrici, Kenai, & Said-Mansour, 2007).

2.3 Lime binder mortar

Lime has been used as binder since the 6th millennium BC. Although the hardening and carbonation times are long, high strengths are obtained in the long term, and the strength-strain compatibility is guaranteed. (Pineda, Robador, & Perez-Rodriguez, 2013). According to Luso and Lourenço (Luso & Lourenço, 2016) lime mortar presents a good workability and, about mechanical properties, it reaches around 18 MPa of compressive strength.

2.4 Lime binder mortar with organic substitutes

Different organic materials have been proposed to replace partially the lime:

- *Hemp ash* (Chabannes, Garcia-Diaz, Clerc, & Bénézet, 2015)*:* the combination of water, hemp husk aggregates and a lime-based binder produces a building material with an excellent thermal and sound insulation. Regarding mechanical properties, it reaches a compressive strength of 1.01 ± 0.08 MPa after 10 months. Moreover, it has strongly ductile behaviour.
- *Elephant grass ashes* (Nakanishi, et al., 2014)*:* these ashes have been obtained from a Brazilian plant, the elephant grass. Brazil has the potential to produce 1.2 Gt of charcoal and a 2 Gt-average of bio-oils per year from elephant grass. Elephant grass ashes are mixed with least 85% of lime. According to Nakanishi et al. (Nakanishi, et al., 2014), this activation is enough to obtain future supplementary cementing materials as an alternative to traditionally pozzolans to achieve environmental and social-economic benefits.

2.5 Lime binder mortar with inorganic substitutes

The materials that have been studied are:

- *Fly ash and metakaolin* (Grist, Paine, Heath, Norman, & Pinder, 2015)*:* the characteristics of these inorganic wastes are well known. The mixture is composed by 70% of lime binder, 15% of fly ash and 15% of metakaolin. Regarding its mechanical properties, the compressive strength of this mortar can reach 22.1 MPa and the elastic modulus is around 21 GPa.

- *Silica fume* (Grist, Paine, Heath, Norman, & Pinder, 2015)*:* silica fume is a well-known pozzolan which is traditionally used in the civil construction industry. 30% of lime binder mortar is substituted by silica fume and it was able to reach 19.8 MPa and an elastic modulus of 11.5 GPa.
- *Silica fume and ground granulated blast furnace slag* (Grist, Paine, Heath, Norman, & Pinder, 2015)*:* the optimum substitution was 25% silica fume and 25% ground granulated blast furnace slag, leaving 50% of lime binder, in order to provide the best mechanical properties. This mortar can achieve a compressive strength of 28.1 MPa and an elastic modulus of 13.5 GPa.
- *Silica fume and fly ash* (Grist, Paine, Heath, Norman, & Pinder, 2015)*:* the best behaviour is obtained with this composition: 50% of natural hydraulic lime, 25% of silica fume and 25% of fly ash. With these proportions, can achieve 22.3 MPa of compressive strength and 20.5 GPa of elastic modulus.

3 SWOT Analysis

A SWOT analysis is performed for the organic-cement binder mortars, due to their highest contribution to sustainability. As aforementioned, cement is one of the most polluting construction products. Therefore it is necessary focusing efforts to replace it.

At the same way, it is important to encourage the use of vegetal ashes as they are obtained from combustion of biomass, and provide energy with the process.

- RHA-cement binder mortar: the properties provided to the mortar and the high production levels of this waste generate a valuable material in order to improve construction sustainability.

Table 1 SWOT of RHA-cement mortar

STRENGHTS	WEACKNESS
- High puzzolanic activity - Compressive strength enough to be used as retrofitting mortar	- Worse setting time due to its fineness, which requires more water to react
OPPORTUNITIES	THREATS
- One of the plant products most consumed worldwide.	- Handling and transportation of rice husk ash is problematic due to its low density

- POFA-cement binder mortar: it is worth highlighting the increase of POFA production as well as the-good properties provided to mortar.

Table 2 SWOT of POFA-cement mortar

STRENGHTS	WEACKNESS
- **High compressive strength value with 10% substituted**	- **POFA decreases the flow tendency due to the increased fineness.**
OPPORTUNITIES	THREATS
- **The high quantity of production and its growing of palm oil annually.**	- Inexistent mechanism to take advance of the increasing use of palm oil waste.

- SCBA-cement binder mortar: this mortar presents the best values of compressive strength.

Table 3 SWOT of SCBA-cement mortar

STRENGHTS	WEACKNESS
- **The compressive strength of SCBA-cement mortar increases directly to the amount of SCBA**	- **In the SCBA mortar, the higher porous texture increases the water demand, and consequently decreases the flow value, thus resulting in a reduced workability**
OPPORTUNITIES	THREATS
- **Ethanol from sugarcane has been recognised as the principal biofuel for the gasoline market, consequently, it provides the SCBA growing up.**	- The lack of sustainable system of management for their waste.

- WWA-cement binder mortar: in spite of the fact that this mortar does not improve the mechanical properties significantly, now it is one of the most abundant and affordable ash.

Table 4 SWOT of WWA-cement mortar

STRENGHTS	WEACKNESS
- Improving de mortar sustainability.	- Low pozzolanic activity
OPPORTUNITIES	THREATS
- The world's production of plant fuel pellets is growing and the ashes production in the same way. Pellets consumption in Europe is predicted as 50 million tons in 2020	- The incineration of wood waste produces relatively little fly ash

- BLA-cement binder mortar: this material is used in building construction as bamboo not-burned, but the BLA production has to be developed still.

Table 5 SWOT of BLA-cement mortar

STRENGHTS	WEACKNESS
- High puzzolanic activity.	- Compressive strength of BLA-cement mortar is comparable but less than reference OPC mortar
OPPORTUNITIES	THREATS
- Bamboo presents the fastest growth of plants studied in this research - The bamboo cane is used worldwide, but its leaf ends in landfills or burned in an uncontrolled manner	- The becoming bamboo leaf into BLA is not development therefore its use is limited.

- CCA-cement binder mortar: its advantages are focused in durability of mortar and increase production of energy from corn cob.

Table 6 SWOT of CCA-cement mortar

STRENGHTS	WEACKNESS
- Improving workability and durability of OPC reference mortar	- Low compressive strength at early ages
OPPORTUNITIES	THREATS
- Its use as animal feedstock guarantee the constant production worldwide.	- The production of CCA is carried out by combustion only, which generates hazardous and polluting products.

4 Conclusions

In this paper has been highlighted the possibility of using eco-efficient mortars as structural materials, in order to guarantee both safety and environment preservation in the strengthening/refurbishment/retrofitting of structures. Different alternative binder materials have been analysed, focusing on their structural and environmental characteristics. In those mortars, the binder can be substituted by organic or inorganic materials (e.g. fly ash, ground granulated blast furnace slag, rice husk ash, palm oil fuel ash). From this strategy, the waste reduction is promoted, as the wastes are immobilised, avoiding or minimizing to pollute the environment. Results from the literature review and SWOT analysis allow for setting a guide that makes easier the selection of eco-efficient mortars (guaranteeing both structural safety and environment preservation) within the building process.

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