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MULTI-CRITERIA ANALYSIS OF PLASTERING MORTARS WITH CONCRETE AND BRICK WASTE BASED ON PHYSICAL-MECHANICAL CHARACTERISTICS AND LIFECYCLE IMPACT ASSESSMENT CRITERIA

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Abstract: *Plastering mortars with construction and demolition waste (CDW) contents are considered a potential path to lowering the environmental damage caused by CDW. This paper presents an application of a multi-criteria decision-making analysis matrix based on physical-mechanical characteristics as well as life cycle assessment (LCA) criteria, from cradle to gate. Six new plastering mortars with concrete and brick CDW components, created for this study, were analyzed. The conclusion is that the mortar with 30% replacement of natural aggregates with concrete waste was the best overall performing mortar, followed by the mortars with 15% replacement with brick waste and 30% replacement with brick waste. The last section discusses practical implications and further research directions.*

Key words: *Life Cycle Assessment, Construction and Demolition Waste, Plastering Mortars, Multi Criteria Decision Making*

1. Introduction

Plastering mortars in which a part of the natural aggregates has been replaced by construction and demolition waste (CDW) are being developed as a solution to the necessity of transforming the construction industry into a sustainable one. As new mortars appear, there is an increasing need of multi-criteria decision-making models, enabling scholars and research and production (R&D) professionals to evaluate and prioritize the production of eco-efficient mortars, based on physical-mechanical characteristics as well as life cycle assessment (LCA) criteria. In general, the new

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plastering mortars with CDW have been found to perform similarly to the reference mortars or have even shown improvements of the physical-mechanical characteristics [4], [6], [7], [9], [12, 13, 14] compared to the standard mortars.

The positive results obtained by CDW plastering mortars on physical-mechanical characteristic are not sufficient, as an LCA criteria analysis is also required, in order to reach the environmentally conscious decision-makers that can make the legislative, business, and purchase decisions.

The LCA refers to the four stages that each product goes through: extraction, utilization, maintenance or reparations, and disposal. There are three stages of LCA: 'Cradle to gate' – from extraction to the end of the production stage; 'Gate to grave' – from putting it into circulation, to disposal; 'Cradle to grave' – from extraction to disposal. LCA assessments are regulated by EU [8] and by the ISO 14000 series of standards. [3]

There are numerous studies that investigate the LCA performance of CDW mortars [1], [3], [5], [8], showing that this is a concern in the academic literature. However, much of the literature focuses separately, either on the physical-mechanical performance of the CDW plastering mortars, or on the LCA. This study is part of a larger doctoral research in the field of Civil Engineering and Installations. The novelty of the present study is that it provides an easy-to-use method of assessing the physical-mechanical and LCA (cradle to gate) performance of the six mortars, demonstrated by using existing data from published research. It allows anyone to build a multi-criteria analysis and confers a common language across disciplines.

2. Objectives

This paper has the following objectives:

(1) Designing and applying a multi-criteria decision matrix based on the results obtained from physical-mechanical characteristics tests on 6 new mortars with locally sourced concrete and brick CDW as a natural aggregate replacement;

(2) Utilizing the results obtained by creating and testing 6 new plastering mortars with concrete and brick waste (hardened state: flexural strength, compression strength, and adhesion to the substrate, at 3, 7, 14, and 28 days); [10, 11]

(3) Evaluating the six recipes based on the mechanical characteristics and on the research results from the academic literature, on the topic of LCA impact of plastering mortars, by extracting the reference values and the method. [2, 3]

3. Materials and Methods

In this research, a decision-making matrix is applied to hierarchize six mortars with incorporation of CDW concrete and brick to replace natural aggregates at percentages of 15%, 30%, 45% by mass, each fraction (0-0.5 mm, 0.5-1 mm, 1-2 mm, 2-4 mm) being replaced according to a grain size distribution curve [10, 11]. The results will be briefly summarized here.

3.1. Methods

For the LCA assessment, the utilized values were obtained and tested by Farinha et al. [2, 3] for the reference mortar, based on ISO 14040, ISO 14044, and EN 15804 and by utilizing the software SimaPro. The mortars with concrete replacement of natural aggregates will be labelled MCRA (mortar, concrete, aggregate) followed by the percentage of replacement and MBRA (mortar, brick, aggregate): MCRA15% - 15% concrete replacement, MCRA 30%-30% concrete replacement, MCRA45%-45% concrete replacement, MBRA 15%-15% brick replacement, MBRA 30% - 30% brick replacement, MBRA 45% - 45% brick replacement.

The CDW were crushed and sieved. The previous LCA impact of the CDW was not considered. Only the 'cradle to gate' stage was accounted. At the beginning of the stage, it was considered that the CDW had only the LCA impact of the transportation to the reusing site. The materials have been sourced locally, from C&D sites in Cluj-Napoca. The assumption has been made that the materials arrive in bulk, being discharged into warehouses by gravity, where they remain until they are crushed, sieved, and mixed.

3.1. Environmental Impact Categories Analyzed

Three mechanical characteristics and eight environmental impact criteria demanded for Environmental Product Declarations (EPD) by EN 15804 [2, 3] have been considered (Table 1):

Description of criterion Table 1

Criterion name	The nature of the criterion	Description
Flexural test results	maximize	It is preferable that the plaster mortars have a resistance to stretching.
Compression test results	maximize	It is preferable that plaster mortars have a high compressive strength, to be able to withstand shocks.
Adhesion results	maximize	It is preferable that the plaster mortars have as much adhesion to the support layer as possible, so that they do not come off over time.
The potential - abiotic depletion (ADP): ADP – materials	minimize	It is preferable that the mortars have as little ADP - materials as possible.
ADP - fossil fuels	minimize	It is preferable that the mortars have as little ADP - fossil fuels as possible.
Global warming potential (GWP)	minimize	It is preferable that the mortars have as little GWP as possible, in order to protect natural ecosystems.
Ozone Depletion Potential (ODP)	minimize	It is preferable that the mortars have as little ODP as possible, so as not to increase the level of radiation, such as ultraviolet radiation.

Criterion name	The nature of the criterion	Description
Photochemical Ozone Creation Potential (POCP);	minimize	It is preferable that mortars have as little POCP as possible, in order not to keep toxic gases in the atmosphere.
Acidification potential (AP) of soil and water	minimize	It is preferable that the mortars have as little AP as possible to keep the soil and water within normal acidity limits.
Eutrophication potential (EP)	minimize	It is preferable that the mortars have as little EP as possible, in order not to overstimulate the development of aquatic plants.
Use of non-renewable primary energy resources (UR- NRe)	minimize	It is preferable for the mortars to have as little UR-NRe as possible, in order to avoid the consumption of fossil fuels.
The use of renewable primary energy resources (UR-Re)	minimize	It is preferable for mortars to have as little UR-Re as possible, in order to reduce energy consumption.

Calculations for the LCA indicators for the standard mortar have been taken from the literature.

3.2. Mortar production

There are five mortar production elements that are to be considered in assessing mortar LCA from cradle to gate: transport, cement, additives, natural aggregates, and the mortar production. These elements were also considered in the present study.

As it can be seen in Fig. 1, of all the elements, cement has the highest impact on all the LCA indicators. On the second place there is transport, and mortar production, followed by natural aggregates and additives. In the present case, the CDW was sourced locally and the processing of the CDW was maintained at the minimum, in order to maintain a low impact on LCA.

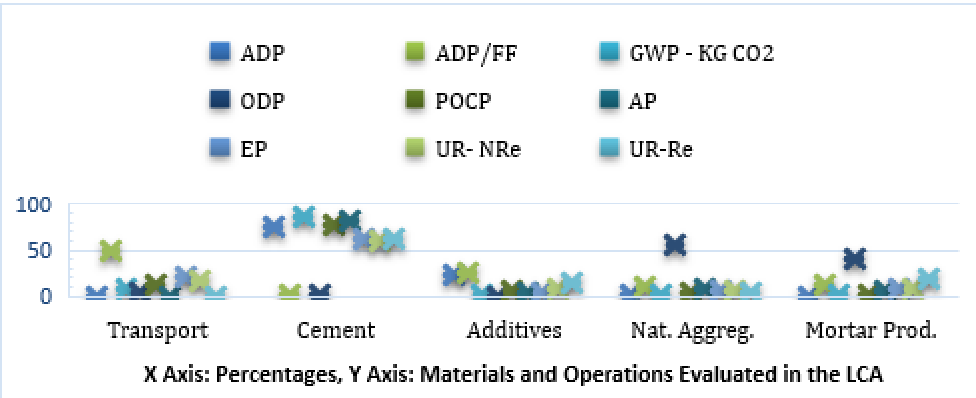

Fig. 1. *Impact proportions of the five mortar production elements on the 9 LCA Indicators, cradle to gate, on the reference plastering mortar, as found in the scientific literature*

3.3. Life Cycle of Reference Mortar

The data for the study was obtained from the European Cement Research Academy and the European Federation of concrete admixtures associations.

3.2. LCA Limitations

There are known limitations to LCA calculations, due to the fact that is a relatively recent requirement, and there is a lack of information and reliable databases in Romania. However, by being part of EU, Romania is subject to a certain level of standardization even in this field. For this reason, it can be considered that utilizing LCA data from other European studies (e.g., European Life Cycle Database), as in this case, is a valid reference also in the Romanian context.

3.3. Multi-criteria decision-making

Decision-making is a complex task when there are multiple criteria to be considered. The stages of this process are:

(1) Goal and objective setting: identification of optimal mortar recipes both in terms of physical-mechanical determinations and sustainability;

(2) Identification of the decision criteria;

(3) Creation of the matrix and evaluation of alternatives. Scores were assigned based on three physical-mechanical determinations performed in hardened state, in time (flexural, compressive, and adhesion strength). Then, the final ranking was created.

4. Results

4.1. Physical mechanical properties of studied mortars

The mortars were prepared, and determinations of the characteristics were made according to the standards in force, in the laboratories of the Building Materials Laboratory of the Faculty of Civil Engineering from the Technical University of Cluj-Napoca, Romania. All the mortars corresponded to the norms in force.

- The studied mortars with concrete and brick waste replacement MCRA 15%, 30%, 45% and MBRA 15%, 30%, 45% obtained rising scores of flexural strengths over time, comparable to the reference mortar CS IV. MBRA 15% obtained improved flexural strength compared to CS IV, as seen in Figure 2.

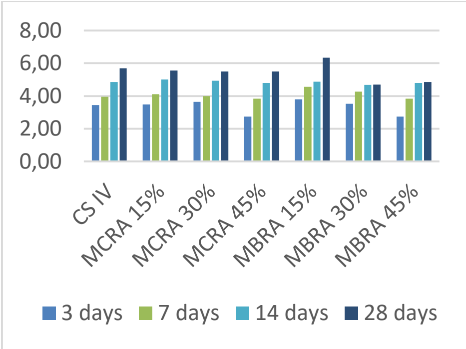

Fig. 2. *Average flexural strength values in time, reference mortar CS IV and new mortars*

• The mortars with concrete and brick waste replacement also obtained rising scores of compressive strengths over time, and the mortar MBRA 15% with brick replacement, obtained improved values in comparison with CS IV, as seen in Figure 3.

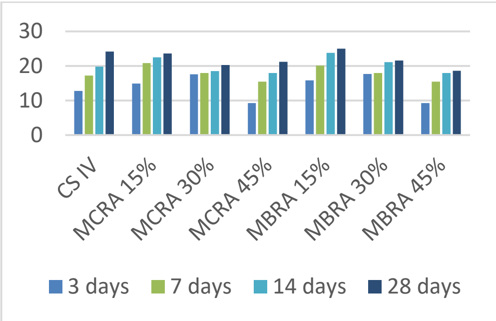

Fig. 3. *Average compressive strength values in time, reference mortar CS IV and new mortars*

• The mortars with concrete and brick waste replacement obtained adhesion strength values that were lower than the reference mortar. Notably, of all of the studied mortars, CS IV, MCRA 45% and MBRA 30% obtained ruptures in the mortar. The other mortars obtained ruptures between the substrate and the mortar, as seen in Fig. 4. This indicates that for CS IV, MCRA 45% and MBRA 30%, the strength values are higher than indicated by the testing apparatus.

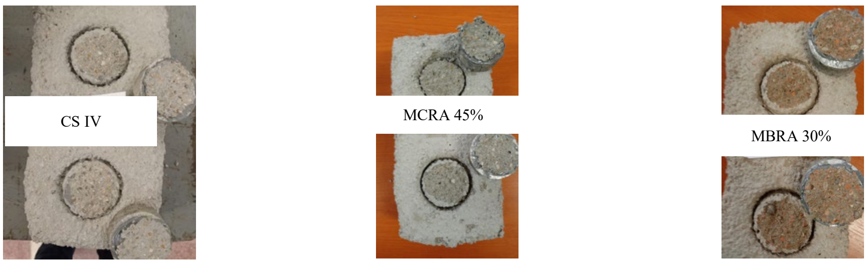

Fig. 4. *Ruptured specimens after the adhesion strength test for CS IV, MCRA 45% and MBRA 30%*

According to Table 2, of the six studied mortars, based solely on these 3 characteristics, the MBRA 15% mortar with 15% brick replacement is the highest performing mortar.

Table 2

Scores of the 6 studied mortars based on the physical-mechanical values

Indicator/ Mortar	Flexural strength	Compressive strength	Adhesion strength	Average score
MCRA 15%	3	3	3	3
MCRA 30%	3	2	3	3
MCRA 45%	3	2	4	3
MBRA 15%	**4**	**4**	**3**	**4**
MBRA 30%	2	2	4	3
MBRA 45%	2	1	2	1

4.3. The Impact of CDW replacement

The values for the 9 indicators have been estimated for the 6 new mortars with concrete and brick waste replacing the natural aggregates in percentages of 15%, 30%, and 45%, based on ECRA, ELCD and EFCA databases and state-of-the-art research [2, 3] Although in the case of mortars with brick and concrete, the LCA values are presumed to be lower than for the standard mortar, due to the CDW contents, it is not yet certain which would be the overall best performing mortar based on all of the indicators: physical-mechanical and life cycle impact assessment.

4.4. The nature of the criteria

It is preferable that the physical-mechanical criteria are maximized, i.e., the resistances are as high as possible. In this case, absolute average resistance values are compared, instead of relative improvements in comparison with CS IV. For the rest of the criteria, it is preferable that they are minimized, i.e., the impact on the environment is as low as possible. This is reflected in the final scoring, shown in Table 2:

- where the maximizable criteria were assigned a high score from 1 to 4 when the values were high,
- the minimizable criteria were assigned a high score from 1 to 4 when the values were low.

Table 3

Final scoring of the 6 new mortars, calculating the average between the mechanical strength score and the LCA score

Recipe	ADP	ADP/FF	GWP - KG CO2	ODP	POCP	AP	EP	UR-NRe	UR-Re	Average	Mech. score	Final score
MCRA 15%	1	2	2	1	1	2	2	1	3	2	3	2
MCRA 30%	**2**	**3**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**3**	**3**	**3**
MCRA 45%	1	3	3	3	2	3	3	3	1	2	3	2
MBRA 15%	**1**	**2**	**2**	**1**	**1**	**2**	**2**	**1**	**3**	**2**	**4**	**3**
MBRA 30%	**2**	**3**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**3**	**3**	**3**
MBRA 45%	1	3	3	3	2	3	3	3	1	2	1	1

As it can be seen in Table 3, comparing with Table 2, there are a total of three mortars that distinguish themselves: MCRA 30%, MBRA 15%, and MBRA 30%. This is a difference form Table 2, where only MCRA 30% showed a significant difference compared to the others.

4. Discussions

The construction industry is one of the most important pollutants across the globe. Efforts are being made to innovate new materials which would utilize CDW and save natural resources. Multiple studies have shown that replacing a part of the natural aggregates in mortars is achievable, with similar physical-mechanical performance values or even with improvements [4], [6, 7], [9, 10, 11, 12, 13, 14]. Similarly, studies show that replacing natural aggregates with CDW can be beneficial from the point of view of LCA. [3], [5]

This study fills a gap in the literature by combining two approaches: developing new mortars with CDW (concrete and brick) and the LCA assessment. Part of the research was creating and demonstrating a decision-making matrix, for choosing the best performing new mortar. The results showed that, from the 6 new mortars, three were most performant from the perspective of physical-mechanical as well as LCA characteristics: the mortars with 15% and 30% concrete replacement and the mortar with 15% brick replacement.

5. Conclusions

The following conclusions can be drawn from this study, in which the main research question was – which of the six new mortars should be further developed, based on their cumulated characteristics: physical-mechanical and LCA. The conclusions are summarized below:

- All the studied mortars, with 15%, 30%, and 45% concrete and brick replacement corresponded to the norms in force, based on the determinations.
- Generally, the values of the physical-mechanical characteristics lowered as the degree of replacement increased, which was to be expected, based on the existing literature.
- Of all the studied mortars, CS IV, MCRA 45% and MBRA 30% had the highest adhesion strength, due to the fact that the rupture occurred in the mortar. For the other mortars, the rupture occurred between the mortar and the substrate.
- A simple scoring matrix was developed for this multi-criterion decision-making process, which showed in the first stage, based solely on the physical-mechanical characteristics, that the MBRA 30% mortar was the best performing new mortar.
- By also computing the scores of the LCA indicators, the three best performing mortars were: MCRA 30%, MBRA 15%, and MBRA 30%, which could be further researched.

This study is not without limitations. A more thorough LCA analysis could be performed in the future, based on the local context, possibly considering the entire lifecycle of the mortar. Adjusting the recipes in order to improve the physical mechanical characteristics of the lower performing mortars could also be researched.

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