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EVALUATION OF PROPERTIES OF MASONRY MORTARS BLENDED WITH CERAMIC WASTE POWDER

Abstract

Aiming to meet the principals of the modern circular economy, this study explores the possibility of using locally available waste materials in the production of innovative, eco-friendly mortar for masonry. The eco-binder, applied as a substitute for cementitious material, is ceramic waste powder (CWP) generated during the production of ceramic industry elements. Within the experimental program, compositions of twelve types of masonry mortars were designed with volumetric ratios of solid components 1:1:5, 1:0.7:4.2, and 1:1:4 (cement + eco-binder/lime/sand), varying the percentage of cement replacement with ceramic powder (up to 80%). The basic properties of masonry mortars were tested, including consistency, compressive strength, flexural tensile strength, capillary water absorption, and adhesion. The test results indicate that ceramic waste powder can be successfully used as a partial replacement for cement up to high substitution levels, yielding more sustainable masonry mortars for use in load-bearing or non-load-bearing masonry structures.

Keywords: masonry mortar, ceramic waste powder, cement replacement, sustainability

СВОЈСТВА МАЛТЕРА ЗА ЗИДАЊЕ СПРАВЉЕНИХ СА КЕРАМИЧКИМ ОТПАДОМ

Сажетак

У циљу испуњавања захтјева савремене циркуларне економије, у раду је урађено истраживање могућности примјене локално доступних отпадних материјала при производњи иновативних еко-прихватљивијих малтера за зидање. Еко-везиво, примијењено као замјењујући цементни материјал, је керамички отпадни прах (CWP) који настаје током производње елемената керамичке индустрије. У оквиру експерименталног програма, пројектовани су састави 12 врста малтера за зидање, запреминског односа чврстих компоненти 1:1:5, 1:0,7:4,2 и 1:1:4 (цемент+еко везиво/креч/пијесак) при чему је вариран проценат замене цемента керамичким прахом (до 80%). Испитана су основна својства малтера за зидање: конзистенција, чврстоћа при притиску и затезању при савијању, капиларно упијање воде и атхезија. Резултати испитивања показују да се отпадни керамички прах може успјешно користити као замјена дијела цемента до високих нивоа супституције, при чему се добијају одрживији малтери за зидање за примјену у носећим или неносећим зиданим конструкцијама.

Кључне ријечи: малтери за зидање, керамички отпад, замјена цемента, одрживост

1. INTRODUCTION

Recycling is a common technique to mitigate the negative effects of rapid industrialization, such as the depletion of natural resources and the generation of massive volumes of waste throughout the manufacturing, construction, and demolition processes. Thus, researchers are exploring the potential application of recycled materials processed from solid waste in new products or industries. Concrete, the world's most frequently used man-made material, has garnered substantial attention to utilizing recycled waste materials for increased mechanical, environmental, and durability characteristics.

Given that cement production accounts for 8% of worldwide yearly CO_2 emissions, numerous alternative byproducts are being examined as viable concrete constituents. Durable, renewable, and sustainable materials have recently gained popularity among researchers as a means of achieving cleaner and greener construction in the construction sector. The use of waste ceramic is unquestionably important for a greener global manufacturing and waste-based construction industry. The use of locally prevalent ceramic waste as a replacement for concrete materials may handle the essential environmental problem, as the limited utilization of cement and aggregates in locations where they are rare and costly.

Ceramic waste powder (CWP) is formed during manufacturing ceramic tiles, particularly in the process of final polishing. According to the literature reports 4.[1]4.[2], more than 22 billion tons of CWP are produced globally, generating significant negative environmental impacts in the form of soil, water, and air pollution. Several sorts of research have been undertaken on using ceramic wastes into cement-based composites, either as aggregates or cement substitutes. Some studies have investigated ceramic waste as coarse aggregates in traditional mortars and concrete 4.[3]4.[5]. Ceramic waste was shown to be an adequate (partial) replacement for natural coarse aggregates, however there was a decrease in compressive strength of concrete when replacement surpassed 25% by weight. It was also discovered that incorporating ceramic waste content as fine aggregate reduces the workability of fresh concrete, hence admixtures are necessary to mitigate such adverse effects. However, the performance of hardened concrete is not significantly impaired when fine aggregate is replaced by ceramic waste up to 50% (by weight) 4.[6]4.[7].

Studies concentrating on integrating CWP to partially replace cement are currently garnering interest, owing to its favorable chemical composition: high content of alumina and reactive silica. The majority of these experiments indicated the favorable pozzolanicity of finely powdered CWP and its role in the pozzolanic reaction at later ages 4.[8]4.[12].

So far, scarce research has been conducted on the utilization of CWP in masonry applications. Therefore, the authors of this paper investigated the effects of locally sourced CWP on various masonry mortar properties, such as workability, compressive and flexural strength, capillary water absorption, and adhesive bond strength. The study aims to substitute cement to a greater extent (up to 80%) in mortar formulations and create masonry mortar for structural and non-structural applications while improving the environmental impact and cost efficiency.

2. MATERIALS AND METHODS

2.1. MATERIALS

Ordinary Portland Cement (OPC), produced by the Lafarge cement plant in Vojvodina, was used. The cement has a Blaine fineness of 4.000 cm^2/g and a density of 3.1 g/cm^3.

Ceramic waste powder (CWP) was produced from ceramic manufacturing waste, consisting of damaged clay hollow blocks discarded in the production facility NEXE Stražilovo in Petrovaradin, Serbia. These elements were firstly roughly crushed and then finely ground in a lab ball mill up to the appropriate level of fineness. Table 1 summarizes the results of examining the chemical composition of the OPC and CWP. The main oxides of CWP are SiO_2 and Al_2O_3, which account for more than 75% of the total oxide weight. CWP is characterized with the pozzolanicity class 10, while it met the requirements regarding the activity index (the values of index at the age of 28 and 90 days are 93% and 99%, respectively), in accordance with EN 450-1.4.[13]

Table 1. Chemical composition of OPC and CWP

	LOI	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	K_2O	MgO	CaO	SO_3	P_2O_5	Cl^-	Reactive SiO_2
OPC	/	17,34	4,53	20,64	0,20	0,59	1,93	50,26	3,06	0,00	0,00	/
CWP	3,3	60,86	16,38	6,81	0,77	2,39	3,89	9,38	0,80	0,14	0,00	50.26

The river-derived sand was used as a fine aggregate for mortar production. The specific gravity and fineness modulus were measured to be 2.3 g/cm^3 and 0.97, respectively.
The water-to-binder ratio (w/b) was adjusted aiming to achieve the required workability of masonry mortar (175±10 mm), as prescribed by SRPS EN 1015-2.4.[14]

2.2. METHODS

The chemical composition of raw materials was analyzed using SRPS EN 196-24.[15] and ISO 29581-2.4.[16]
The workability of fresh mortar (flow value) was assessed using EN 1015-34.[17].
Mechanical properties (compressive and flexural strength) were determined according to EN 998-24.[18] and EN 1015-114.[19] standards.
The water absorption coefficient produced by capillary action in hardened mortar was obtained using EN 1015-18.4.[20]
The EN 1015-124.[21] methodology was followed to measure the adhesive strength of hardened mortars on substrates.

2.3. MIXING AND PROPORTIONING OF MORTAR

Ten different mortar mixtures were cast within the experimental program. The mixing ratios of reference cement-lime mortar (C) were: 1:1:5, 1:0.7:4.2, and 1:1:4 (cement/lime/sand), by volume. In the remaining seven combinations, cement was partially substituted with CWP. In the first mortar series (the mixing ratio of 1:1:5), cement was replaced with 50% CWP, while in the remaining two series, cement was substituted with 50%, 60%, and 80%, by volume – Figure 1. The labels and quantities of component components for each masonry mortar are shown in Table 2.

Table 2. Labels and component materials quantities for designed masonry mortars

Mortar	m_c (g)	m_l (g)	m_s (g)	m_{cwp}(g)	w/b	m_w (g)
C1	161.4	74.0	1350	/	1.15	270.7
CWP1-50	80.7	74.0	1350	61.8	1.30	281.5
C2	193.7	59.2	1350	/	1.05	265.6
CWP2-50	96.9	59.2	1350	74.2	1.20	276.3
CWP2-60	77.5	59.2	1350	89.0	1.20	270.9
CWP2-80	38.7	59.2	1350	118.7	1.25	270.8
C3	201.8	92.5	1350	/	0.90	264.9
CWP3-50	100.9	92.5	1350	77.3	1.00	270.7
CWP3-60	80.7	92.5	1350	92.7	1.05	279.3
CWP3-80	40.4	92.5	1350	123.7	1.07	274.5

m_c-mass of cement; m_l-mass of lime; m_s-mass of sand; m_{cwp}-mass of CWP; m_w-mass of water; w/b-water to binder ratio.

Figure 1. Binder materials for the preparation of masonry mortar

3. TEST RESULTS AND DISCUSSION

3.1. WORKABILITY OF FRESH MORTAR

Figure 2 shows the influence of the water-to-binder ratio on the workability of mortar.

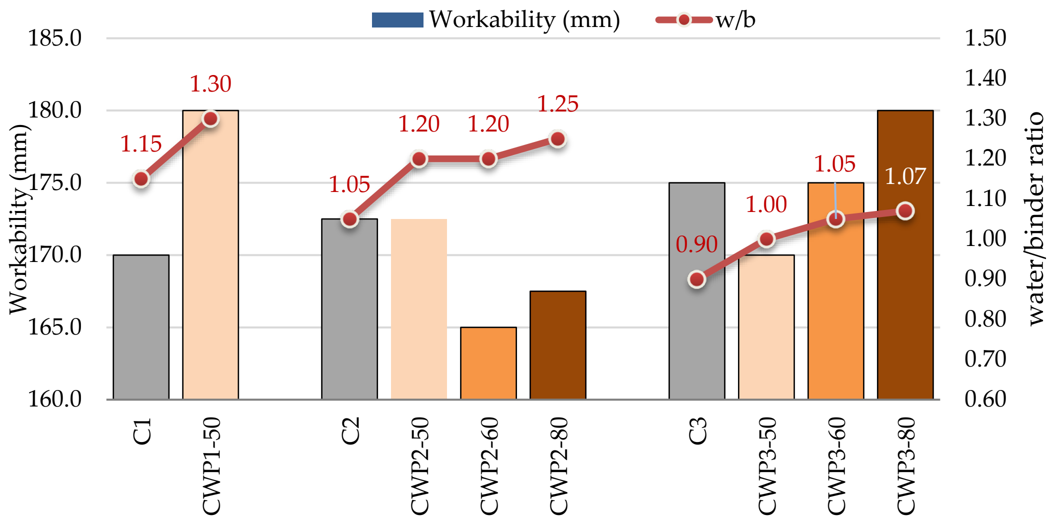

Figure 2. Flow values of fresh mortar

All blended mortar mixtures required more water to attain the desired flow value (175±10 mm). As the workability of cement composites is mostly determined by the shape of their particles, this impact can be attributed to the angularity and sharp edges of ash particles. As a result, w/b increases with CWP content.

3.2. COMPRESSIVE STRENGTH

Compressive strength results of the hardened masonry mortar are shown in Figure 3.

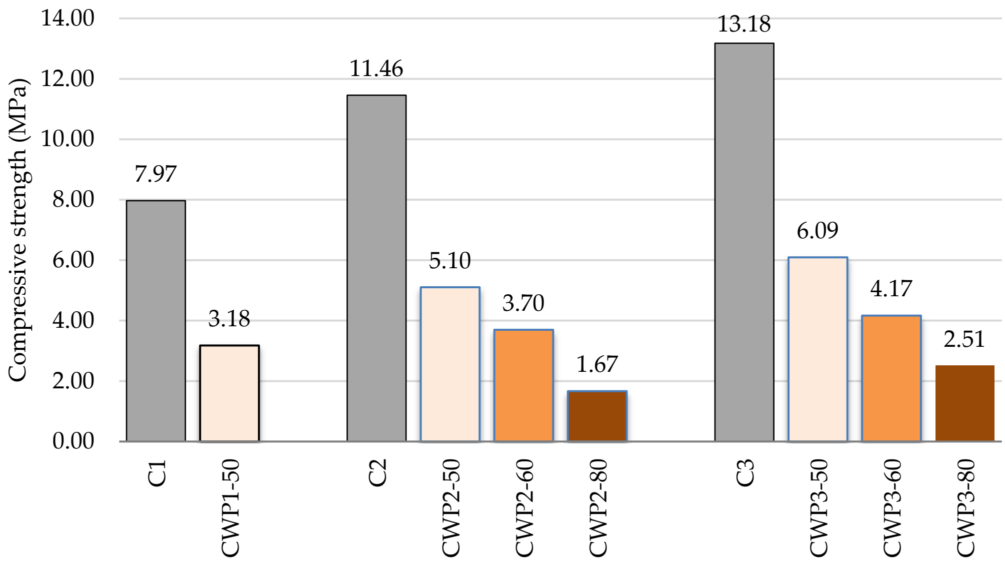

Figure 3. The compressive strength of mortars

When compared to the reference mix (C1), C2's compressive strength increased by 44% as the w/b ratio decreased from 1.15 to 1.05, while C3's strength rose by 65% as the w/b ratio decreased to 0.9.

In relation to the corresponding reference mortar values, the compressive strength of CWP1-50 was decreased by 60%, while for CWP2-50, CWP2-60, and CWP2-80, it was reduced by 55%, 68%, and 85%, respectively. Similarly, mortars CWP3-50, CWP3-60, and CWP3-80 showed a sharp strength drop of 54%, 68%, and 81%, respectively. These adverse effects can be explained by the increased effective w/b of blended masonry mortars. Higher w/b resulted in greater porosity and the permeability of the mix and, consequently, lower mechanical properties.

Masonry mortars are categorized into classes according to the mean compressive strength, as described by EN 998-24.[18]. Masonry mortars for load-bearing structures, classified as Class 5, require a minimum compressive strength of 5MPa, according to provisions of Eurocode 6 and Eurocode 8. Table 3 displays the average compressive strength and achieved class of each masonry mortar.

Table 3. Class of masonry mortars based on the achieved compressive strength

Mortar	C1	CWP1-50	C2	CWP2-50	CWP2-60	CWP2-80	C2	CWP3-50	CWP3-60	CWP3-80
Compressive strength (MPa)	7.97	3.18	11.46	5.10	3.7	1.67	13.18	6.09	4.17	2.51
Class	**5**	**2.5**	**10**	**5**	**2.5**	**1**	**10**	**5**	**2.5**	**2.5**

The reference mortars and mixtures CWP2-50 and CWP3-50 meet the criteria for masonry mortar for structural purposes, while the other mortars achieved the class of 2.5 and can thus be used successfully for non-load-bearing elements.

3.3. FLEXURAL STRENGTH

The results follow a similar pattern to the compressive strength tests. Figure 4 displays the results of the flexural strength of hardened masonry mortar.

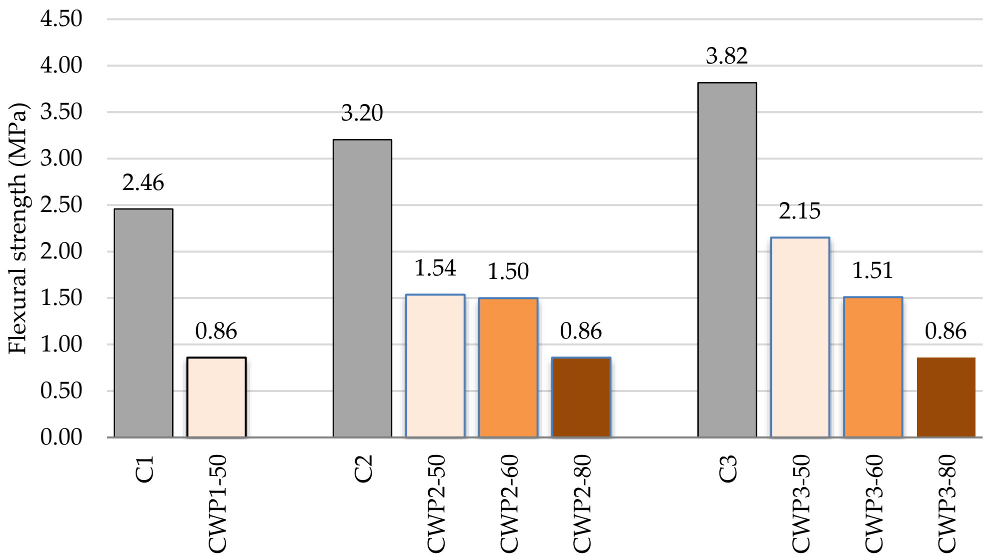

Figure 4. The flexural strength of mortars

The use of CWP as a cement substitute material resulted in a dramatic drop in flexural strength. At 28 days, the blended mixture CWP1-50 suffered strength loss of 65%, whereas CWP2-50, CWP2-60, and CWP2-80 achieved approximately 52%, 53%, and 73% of the reference flexural strength, respectively. Similarly, mortars CWP3-50, CWP3-60, and CWP3-80 showed a significant strength decrease of 44%, 60%, and 77% consequently. However, flexural strength is not the property of a greater importance for masonry mortars; hence, no criteria are provided in regulations.

3.4. CAPILLARY WATER ABSORPTION

Figure 5 shows the capillary water absorption coefficients of all examined mortar mixtures, as well as the limit values for the achieved absorption class.

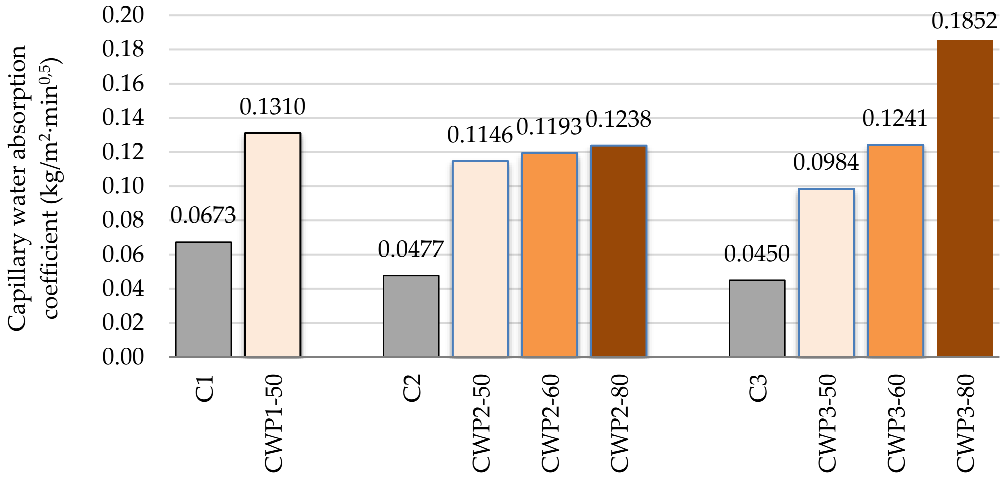

Figure 5. Capillary water absorption coefficients of mortars

Water absorption, which indirectly expresses capillary porosity, is one of the key elements determining the durability of cement-based composites. As a direct consequence of increased w/b, the capillary porosity of the mortar mixtures rose as the CWP content increased, resulting in a higher absorption coefficient. When compared to the reference mortar, the capillary water absorption coefficients of CWP1-50 increased by 95%, while those of CWP2-50, CWP2-60, and CWP2-80 rose by 140%, 150%, and 160%, respectively.

Masonry mortars CWP3-50, CWP3-60, and CWP3-80 followed the similar trend and exhibited significantly higher capillary absorption coefficients in relation to the reference values.

Masonry mortars can be classified into classes according to the computed water absorption coefficient at the age of 28 days, as recommended by EN 998-24.[18]. As all mortar formulations meet the W2 category criterion ($\leq$0.2 kg/m^{2}min$^{0.5}$), it can be stated that replacing cement with CWP does not affect this property to a greater extent.

3.5. ADHESIVE STRENGTH OF MORTAR

One of the most important requirements for masonry mortar is adhesive strength, since a lack or loss of adhesion reduces construction integrity and functional life. Figure 6 displays the adhesive strength test results.

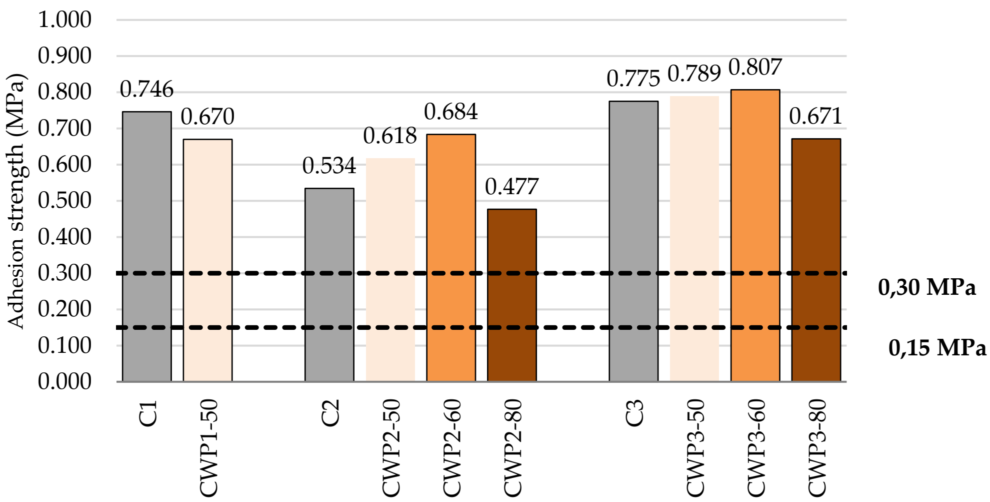

Figure 6. Adhesive strength of mortars

The results demonstrate that at a 1:1:5 mixing ratio, the adhesive strength of CWP1-50 is lowered by 10% when compared to the reference mortar. With a mixture ratio of 1:0.7:4.2, substituting cement by 50% and 60% (CWP2-50 and CWP2-60) resulted in a 16% and 28% strength improvement, respectively. However, CWP2-80 displayed the strength decline of 11% in relation to the reference value. There were no significant differences in adhesion measured at the 1:1:4 mixing ratio.
The EN 998-14.[18] mortar regulation requires a minimum value of 0.3 MPa for use in rendering or plastering, while the EN 998-24.[18] masonry mortar regulation requires a minimum value of 0.15 MPa. All tested mortar combinations satisfied the requirements for plastering and masonry applications.

3.6. COST EFFICIENCY

Cost efficiency is one of the major factors determining the sustainability of cement-based materials. The raw material unit costs were calculated using the Serbian raw material purchase price. The calculations did not include the costs associated with the transportation, handling, placement, and quality control. Table 4 lists the unit costs of all component materials used in masonry mortars.

Table 4. The unit costs of raw materials

Material	Sand	PC	Lime	Water	CWP
Price (EUR/t)	18	170	130	2	1

The incorporation of CWP in masonry mortar had a considerable economic impact, regardless of the mixing ratio used. The blended masonry mortars were less expensive than the reference mortars, as the price of CWP1-50 was lowered by 22%, while CWP2-50, CWP2-60, and CWP2-80 cut prices by 25%, 31%, and 40%, respectively. Similarly, mortars CWP3-50, CWP3-60, and CWP3-80 experienced considerable price declines of 24%, 28%, and 38%, respectively – Figure 7.

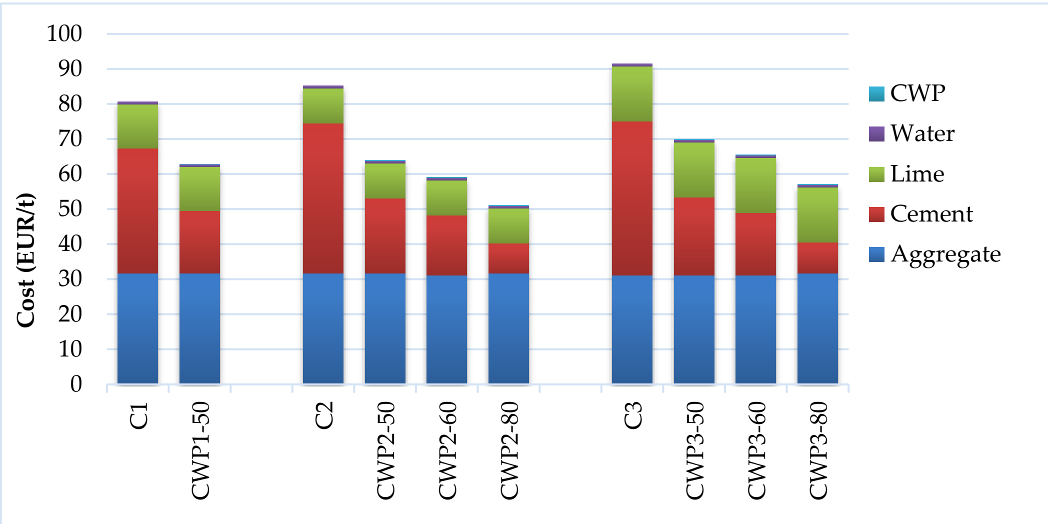

Figure 7. Cost price of analyzed mortar mixtures.

4. CONCLUSIONS

The principal findings of the study are as follows:

- Chemical composition of ceramic waste powder indicates a relatively high content of amorphous silica, which positively influences the pozzolanic activity and manifests in high activity index,
- CWP, as a conventional pozzolanic material, requires more water to ensure that the necessary workability can be attained when used as partial cement replacing material in masonry mortar,
- Considering the attained compressive strength, mixtures CWP2-50 and CWP3-50 meet the criterion for structural application, while the other mortars achieved the class of 2.5 and can thus be used successfully for non-load-bearing elements (such as partition walls),

- Due to the increased water to binder ratio, capillary water absorption of blended mortar increased significantly. Despite this trend, all mixtures had capillary water absorption coefficient values within the acceptable range of the W2 category,
- All tested mortar combinations met the required adhesive strength limit for the masonry mortar, exceeding the minimum value of 0.30 MPa,
- The incorporation of CWP in masonry mortar had a considerable economic impact, regardless of the mixing ratio used.

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