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FACULTY OF CIVIL ENGINEERING AND ARCHITECTURE

in cooperation with
UNIVERSITY OF NOVI SAD
FACULTY OF TECHNICAL SCIENCES
DEPARTMENT OF CIVIL ENGINEERING AND GEODESY

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GRAĐEVINSKO-ARHITEKTONSKI FAKULTET

u saradnji sa
FAKULTETOM TEHNIČKIH NAUKA U NOVOM SADU
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PhIDAC 2019 PhIDAC

V INTERNATIONAL SYMPOSIUM FOR STUDENTS OF DOCTORAL STUDIES IN THE FIELDS OF CIVIL ENGINEERING, ARCHITECTURE AND ENVIRONMENTAL PROTECTION

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EDITORAL NOTE:

The Faculty of Civil engineering and Architecture of University of Nis organizes the Fifth International Symposium of Doctoral Studies' Students in the fields of Civil Engineering, Architecture and Environmental Protection "PhIDAC 2019".

The first Symposium of the Doctoral Studies' Students "PhIDAC 2009", held in September 2009 in Nis, confirmed the expectations of Prof. Slavisa Trajkovic and Professor emeritus Radomir Folic, the founders of this symposium, that the two-day meetings of the students of Doctoral studies and their professors would be of invaluable use both for young researchers and their tutors. Namely, a great number of published and presented papers, as well as open discussion on the quality of paper, directions in further researches and relationships between doctoral students and tutors demonstrated that the Symposium fulfilled the expectations of the participants and that the organization of new meetings should be continued.

At the Second Symposium "PhIDAC 2010" held in Novi Sad, the symposium programme was expanded, i.e. the field of environmental protection was also introduced as the third thematic field with the expectation that this multidisciplinary area should be more closely introduced to young researches in the fields of civil engineering and architecture.

The organizers of the Third Symposium "PhIDAC 2011", also held in Novi Sad, decided that the symposium should be international and thus they opened new possibilities for affirmation and development of young researches from Serbia, as well as of their colleagues from the Balkans.

There were 66 papers dealing with topics in the fields of civil engineering, architecture and environment protection that were submitted for the fourth international symposium of students of doctoral studies "PhIDAC 2012". The papers covered a wide range of scientific topics. All the papers were reviewed. On the basis of the reviews, it was concluded that the young researchers provided a significant contribution to the development of scientific thinking.

Members of the international scientific committee actively participated in the preparation of the symposium and reviewing of the papers. For this symposium too, the proceedings including papers in English and Serbian were included, which provides better and more productive communication and exchange of experience with the colleagues from abroad.

We would like to thank all the authors and co-authors of the papers and their mentors, and it is our wish that the young researchers would continue their successful careers and persist in realization of the goals they have set.

Nis, October 2019 Editors

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PhIDAC 2019 PhIDAC V INTERNATIONAL SYMPOSIUM FOR STUDENTS OF DOCTORAL STUDIES IN THE FIELDS OF CIVIL ENGINEERING, ARCHITECTURE AND ENVIRONMENTAL PROTECTION

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EFFECTS OF FINE CRUSHED CERAMIC WASTE ADDITION TO LIME - BASED COATING FOR RESTORATION OF HISTORICAL BUILDINGS

Abstract: *Since lime renders have slow development of strength, especially in conditions of increased humidity, different types of additions were often used trough history, in order to improve their resistance and durability. This paper presents the effects of locally produced fine crushed tile aggregate addition on physical and mechanical properties of lime-based coating, representing final outer layer of traditional renders, both in normal and increased humidity conditions. This aggregate has been used as partial replacement of natural river aggregate, with granulation 0/0,5 mm in amount of 25, 50, 75 and 100% by volume. Flexural and compressive strength, capillary water absorption, ultrasonic pulse velocity, dynamic modulus of elasticity and open porosity were tested on prismatic samples at the ages of 14, 28 and 60 days. Results show the positive effects of crushed ceramic addition at all ages, especially for the samples cured in humid conditions.*

Key words: *crushed ceramic aggregate, lime renders, compatibility, historical mortars*

1. INTRODUCTION

Lime based renders were most commonly used outer coatings on historical buildings whenever the natural stone did not fulfill the aesthetic and functional standards [1]. They were usually placed in three layers, each of them having different design and properties. Final (outer) layer was designed with higher binder content (binder:aggregate ratio equalled 1:1-2, by volume) using aggregate of finer gradation and different origin. White sand or powdered marble or chalk were often used to achieve a light colour of this layer [6].

When natural pozzolanic additions were not available, crushed ceramic aggregates were used as a partial or complete replacement of sand in lime based renders. The degree of pozzolanic activity of heat treated clays depends on several factors, such as: amount of silica and alumina available to react with calcium hydroxide, degree of crystallinity, specific surface area of the particles, clay mineralogy and heating temperature [3].

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Research performed in this area can be divided in two categories. One group of scientists performed characterization of pre-existing air lime mortars with ceramics, while second group was interested in the possibilities of applying crushed ceramic waste produced today as aggregate for cement and lime based renders. Possible challenges in this research are connected to the fact that the production procedure of ceramic products and temperatures applied for heating of the clay today differ from the ones used in the past [2].

Possible advantages of application of ceramic waste in lime based mortars are [2]:

1) these mortars can show a high degree of compatibility with old buildings' masonry systems, particularly when compared to mortars with hydraulic binders,
2) ceramic waste aggregate can induce better cohesion between aggregate and the binder, because of the shape and the composition of the particles,
3) durability of lime based mortars could be improved, due to the changes in their micro structure.

When they are used as final coatings, the important issue could also be the colour of the product. Most of the ceramic waste used is of reddish coloration, which gives a characteristic pink hue to the mortars. The final colour of render depends also on the amount of ceramic aggregate added.

Since the outer render coatings are usually prepared with finer aggregate, it is expected to also use finer crushed ceramic aggregate as its replacement. This enables the pozzolanic reaction between the binder and the aggregate and therefore contributes to the increase in mechanical properties of the render. Denser structure should also lead to reduction in capillary water absorption coefficient.

This paper presents investigation of influence of locally produced fine crushed ceramic aggregate used as a partial and complete replacement of natural aggregate in lime based mixtures designed for an outer render layer.

2. MATERIALS AND METHODS

In order to test the influence of the crushed ceramic aggregate on the physical and mechanical properties of lime renders, five mixtures (one reference mixture and four mixtures containing 25, 50, 75 and 100% of crushed ceramic aggregate by volume) were prepared.

2.1. Materials

Lime putty produced by "Javor", Veternik (Serbia) was used as a binder in all of the mixtures. This putty was produced by slaking of quicklime from "Jelen Do" quarry, Požega (Serbia) with water in excess. At the time of mixing, the lime putty was 18 months old (preserved for 6 months by the producer, and then 12 months in sealed plastic containers). Total content of active CaO+MgO was 95.4%. Bulk density of the putty was 1390 kg/m^3, while bulk density of lime was 600 kg/m^3.

Table 1- Chemical composition of the component materials used (%)

Component	Natural sand	Crushed ceramic aggregate
SiO_2	69.57	64.06
Al_2O_3	4.20	12.68
TiO_2	0.52	0.88
Fe_2O_3	5.17	8.43
CaO	8.02	5.78
MgO	2.15	2.37
Na_2O	1.30	1.14
K_2O	1.18	2.88
Cl^-	0.05	0.06
Sulfats that desolve in water	0.02	0.08
Sulfats that desolve in acid	0.03	0.05

Natural river aggregate originating from Danube river (Serbia) in gradation 0/0.5 mm was used, with bulk density of 1400 kg/m^3.

Crushed ceramic aggregate produced by „Salgor", Kikinda in granulation of 0/0.5 mm (after sieving original material sized 0/2 mm through 0.5 mm sieve) was used in the mixtures as partial or complete replacement of natural aggregate. Bulk density of this aggregate was 1200 kg/m^3.

Chemical composition of crushed ceramics and sand, determined by chemical analysis, is presented in Table 1, while their particle size distibution is shown in Figure 1.

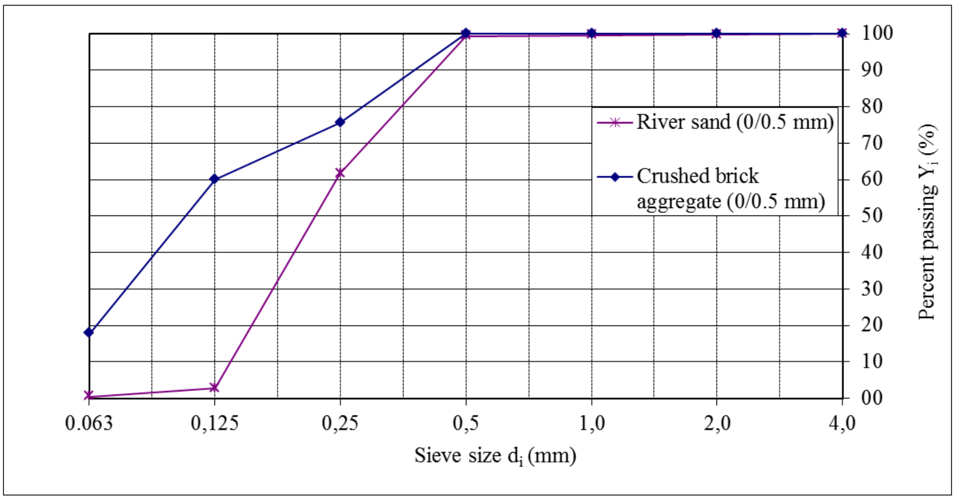


Figure 1 –Particle size distibution of natural sand and crushed ceramic aggregate

2.2. Mixtures

Composition of the mixtures is presented in table 2. River sand was replaced by ceramic aggregate in the amount of 25, 50, 75 and 100%. The reference mixture was designated as 1/1 according to the volumetric ratio of the total amount of aggregate and lime. Mixtures prepared with crushed ceramic aggregate were marked according to the percent of replacement of aggregates (for example, in mixture 1/1-25 25% of river aggregate by volume, was replaced by crushed ceramic aggregate).

Table 2- Mixture design

Mixture	Lime putty (kg/m^3)	River aggregate (kg/m^3)	Crushed ceramic aggregate (kg/m^3)	Additional water (kg/m^3)
1/1	544	1015	-	239
1/1-25	544	761	217	239
1/1-50	544	508	435	239
1/1-75	544	254	652	239
1/1-100	544	-	870	239

All of the mixtures were prepared by the same procedure using standard RILEM-CEM mortar mixer. First the lime putty and additional water were mixed for one minute, and then aggregate was added and mixed for another two minutes. After the cleaning of the material in excess from the walls of the pot, mixing was continued for additional 2 minutes.

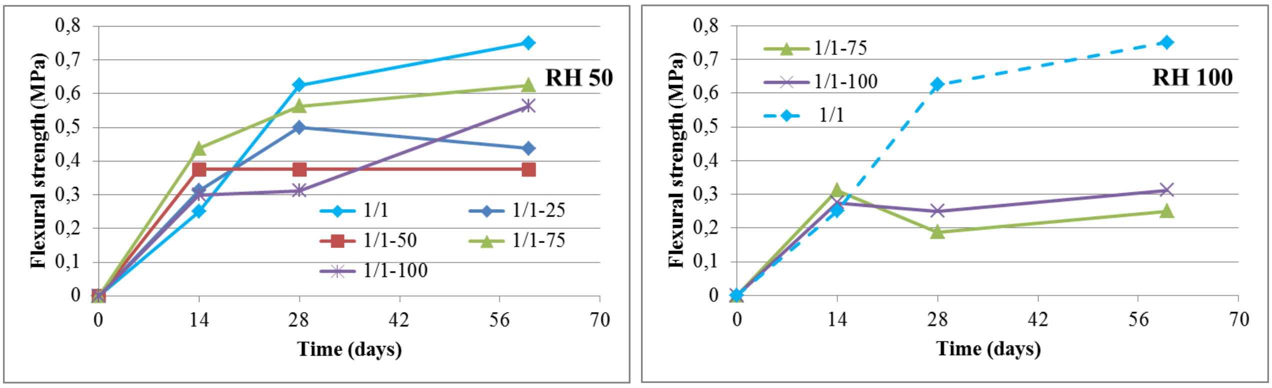
2.3. Methods

Prismatic samples (dimensions 4x4x16 cm) were prepared for testing of physical and mechanical properties of renders at the ages of 14, 28 and 60 days. All of the samples were held in molds in the humid conditions for five days, and then taken out and cured in laboatory conditions (t=20±2˚C, relative humidity (RH) of 50±10%) designated as RH 50. In order to measure the possibility of strength development through pozzolanaic reaction, samples containing higher amount of ceramic aggregate (75% and 100%) were divided in two groups, where one group was cured in laboratory conditions and another group was kept in humid conditions (in plastic containers above water surface), designated as RH 100, up to the testing age. Before testing, the samples were dried for 72 hours on 60˚C, and then cooled for one hour in laboratory conditions.

3. RESULTS AND ANALYSIS

3.1. Compressive and flexural strength

Testing of mechanical properties was conducted according to the standard EN 1015-11:2008. Flexural and compressive strength of all mixtures at different ages and different curing conditions, are presented in the Figures 2 to 4.



a) mixtures cured in laboratory conditions *b) mixtures cured in humid conditions(reference mixture is presented only for comparison)*

Figure 2 – Flexural strength at the ages of 14, 28 and 60 days

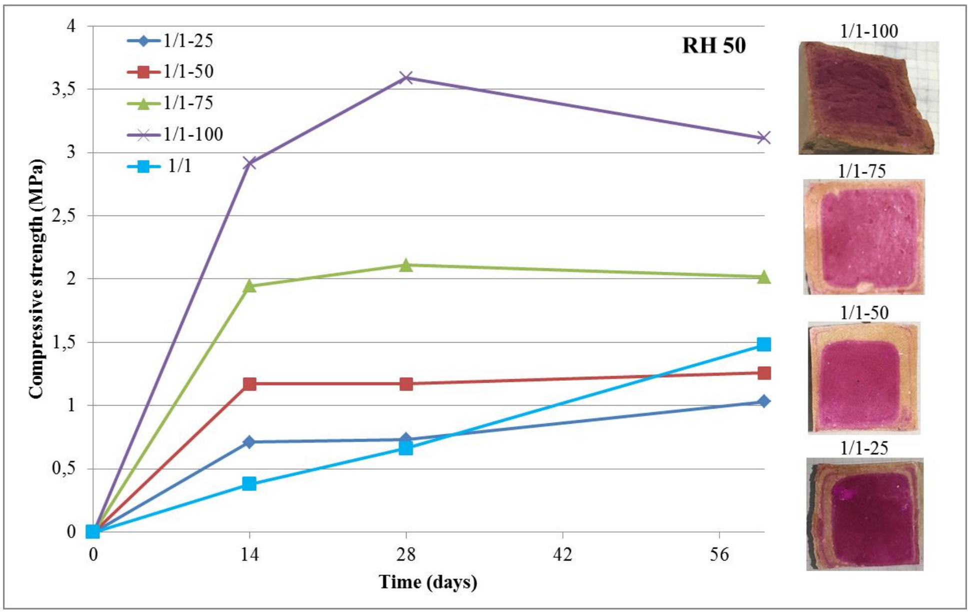


Figure 3 – Compressive strength at the ages of 14, 28 and 60 days of the mixtures cured in laboratory conditions with carbonation test at the age of 60 days

Flexural strength was determined as an average value of two measurements, while compressive strength represents the average value of four measurements. Carbonation of the samples cured in laboratory conditions at the age of 60 days was tested using phenolphalein solution. Sections of the tested samples are shown in Figure 3.

Regarding both humidity conditions, at the age of 14 days flexural and compressive strength were higher for all of the tested mixtures compared to the reference mixture, as it was expected, since the curing conditions were such that during the first five days, mixtures were held in humid conditions. In the period between 14th and 28th day, the increase in compressive strength is slower for mixtures held in laboratory conditions. This is the period of their gradual drying when pozzolanic reaction is being replaced by carbonation process. The situation changes at the age of 60 days, since mixtures marked as

1/1-25 and 1/1-50 have lower compressive strength at this age. Results of the test with phelophtalein solution show that the mixtures have not reached their final strength at this age, since the carbontion process has not been finalized. Mixtures with higher amount of crushed ceramic aggregate (75 and 100%) had higher values of compressive strength (1.5 to 2 times higher value when cured in laboratory conditions, and 2.5 and 6.75 times higher than reference mixture when cured in humid conditions). Flexural strength is decreasing with the addition of crushed ceramic aggregate, especially for the mixtures that were cured in humid conditions.

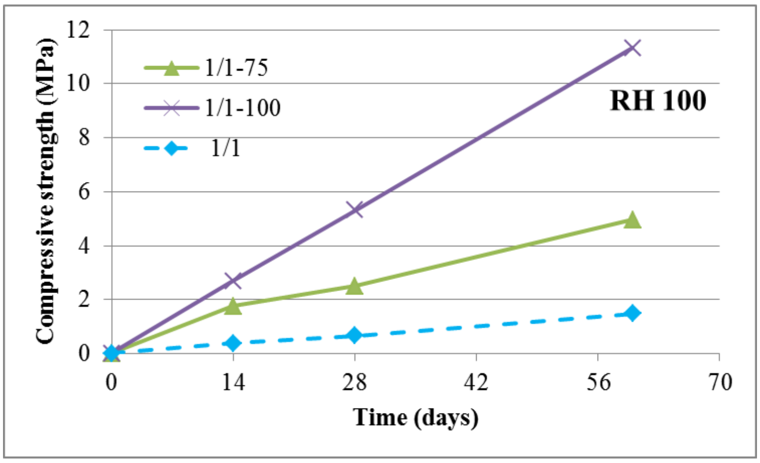


Figure 4 – Compressive strength at the ages of 14, 28 and 60 days of the mixtures cured in humid conditions (reference mixture is presented in this figure only for comparison)

3.2. Water absorption and open porosity

Samples for the test were prepared according to the standard EN 1015-18:2008. After drying and cooling, the samples were covered with paraffin layer over all lateral sides and then split into two halves (app. 4×4×8 cm each). Prepared samples were then positioned in the box in the way that the broken surface was in contact with the water. Water level was held constant at 10 mm above the broken surface. The mass of the samples was measured in shorter intervals than stated in the standard. Measurement was conducted after 2, 5, 10, 20, 30, 60 and 90 minutes, and also 48 hours after the beginning of the test. Capillary water absorption coefficient was determined as a slope of the first part of the diagram presenting dependence of the absorbed water per surface unit from square root of time. Open porosity was tested following the recommendations of the standard for determination of open porosity of natural stone (EN 1936:2006). The test results are presented in Figure 5.

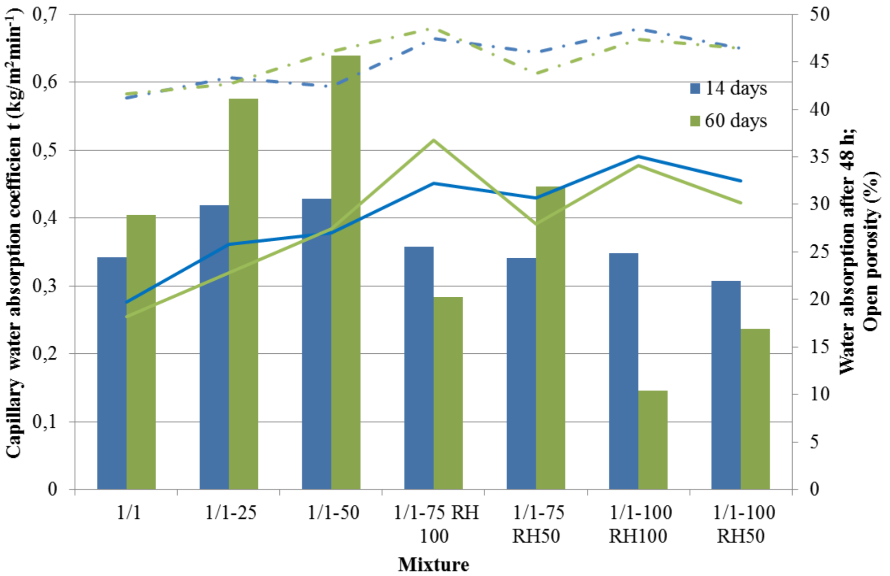


Figure 5 – Open porosity (dash-dot line), capillary water absorption coefficient (bars) and water absorption after 48 h (line) for all of the tested mixtures and curing conditions at the age of 14 and 60 days

Lower percent of aggregate replacement (25 and 50%) led to increase of capillary water absorption coefficient, water sorbtion after 48 hours and open porosity at all ages. Values measured at the age of 60 days are higher than the values recommended in liteature (30-45%) [5]. Higher percent of replacement led to decrease in the capillary water absorption coefficient at the age of 60 days, especially for the mixtures cured in humid conditions. The water absorption and open porosity increased when compared to reference mixture. These results imply that the structure formed through pozzolanic reaction has smaller percent of capillary pores although their open porosity is increased for 10% (in the case of mixture marked 1/1-75) and 2% (for the mixture 1/1-100) with the alteration in curing conditions.This decrease in the pore dimensions leads to more compact transition zone between binder and the crushed ceramic aggregate, and therefore enables development of high compressive strength values for these mixtures.

3.3. Drying capacity

After complete saturation, the specimens used for capillary water absorption tests at the age of 60 days were kept in constant conditions at the temperature of 20±2°C and relative humidity of 50±10%, with periodical weightings performed in the period of one month. Drying curves presented in Figure 5 show the change of water content in the samples during this period of time (presented as square root of time expressed in seconds). Drying curves are also described by cubic functions, that are shown in Table 3.

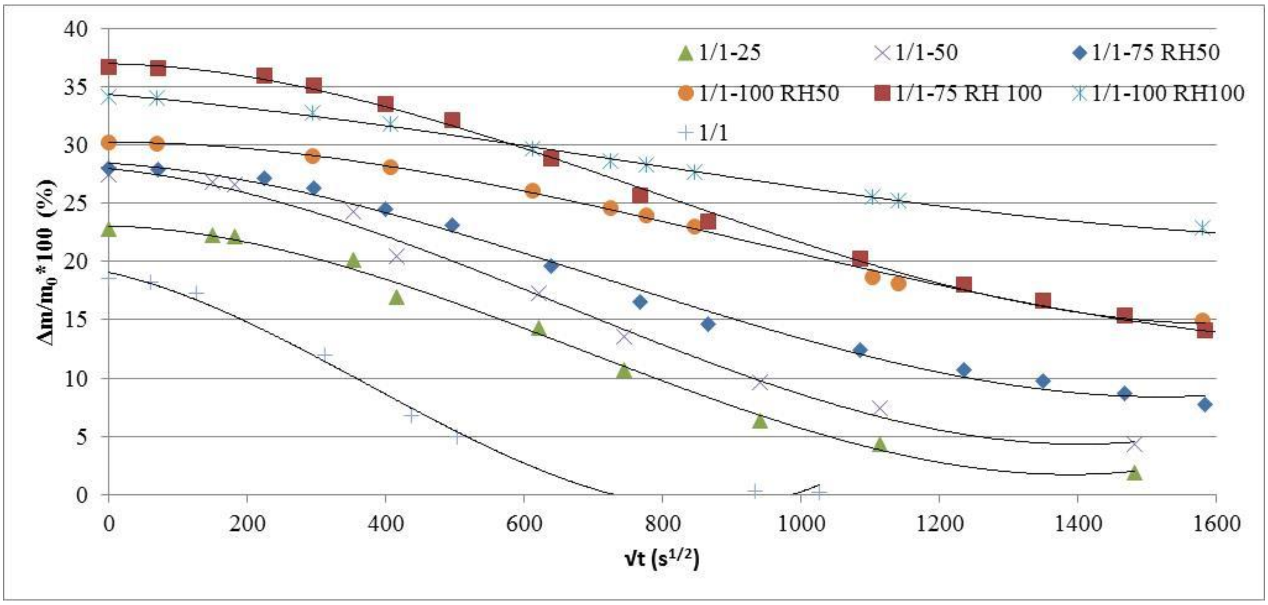


Figure 6 – Drying curves of the tested mixtures at the age of 60 days

The increase in the crushed ceramic aggregate content led to increase of the period of time necessary for the drying of the samples. After 30 days of drying, samples containing 100% of recycled clay aggregate reduced their humidity for 10% (samples previously cured in humid conditions) and 15% (samples previously cured in laboratory conditions). On the other hand, the reference mixture reached constant mass after only 6 days of drying.

Table 3- Regressions describing drying behavior of the tested mixtures at the age of 60 days

Mixture	Regression function
1/1	$y = 5 \cdot 10^{-8} \cdot x^3 - 5 \cdot 10^{-5} \cdot x^2 - 0.013 \cdot x + 19.065$
1/1-25	$y = 2 \cdot 10^{-8} \cdot x^3 - 3 \cdot 10^{-5} \cdot x^2 - 0.0014 \cdot x + 23.055$
1/1-50	$y = 1 \cdot 10^{-8} \cdot x^3 - 3 \cdot 10^{-5} \cdot x^2 - 0.0055 \cdot x + 27.966$
1/1-75 RH50	$y = 1 \cdot 10^{-8} \cdot x^3 - 2 \cdot 10^{-5} \cdot x^2 - 0.0038 \cdot x + 28.440$
1/1-100 RH50	$y = 5 \cdot 10^{-9} \cdot x^3 - 2 \cdot 10^{-5} \cdot x^2 - 0.0002 \cdot x + 30.225$
1/1-75 RH100	$y = 1 \cdot 10^{-8} \cdot x^3 - 2 \cdot 10^{-5} \cdot x^2 - 0.0010 \cdot x + 36.981$
1/1-100 RH100	$y = 2 \cdot 10^{-9} \cdot x^3 - 6 \cdot 10^{-6} \cdot x^2 - 0.0049 \cdot x + 34.339$

3.4. Ultrasonic pulse velocity and dynamic modulus of elasticity

Ultrasonic pulse velocity was measured using Pundit ultrasonic tester. The relation between calculated ultrasonic pulse velosity and compressive strength of all mixtures cured in laboratory conditions is shown in Figure 7.

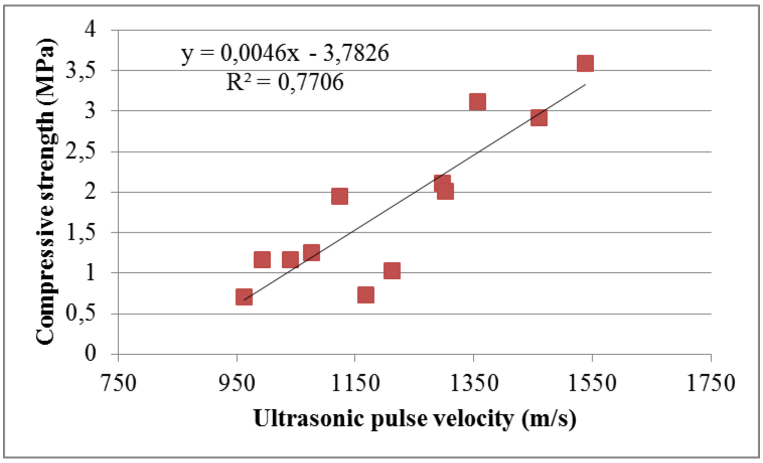


Figure 7 – Compressive strength vs. ultrasonic pulse velocity of tested mixtures cured in laboratory conditions

Ultrasonic pulse velocity was lower for mixtures with small percent of replacement. These measurements are in good correlation with compressive strength results, as shown in Figure 6. Measurements performed for the mixtures cured in humid conditions were 1.08 - 3.70 times lower than the values recorded for same mixtures at the same age cured in laboratory conditions, although their compressive strength was much higher. These results are in accordance with the measurements of open porosity and water absorption after 48 hours.

Both resonance frequency measurements and ultrasonic pulse velocity were used for calculating the dynamic modulus of elasticity of the tested mixtures at the age of 60 days. The results are presented in Figure 8. Dynamic modulus of elasitcity was lower for mixtures containing crushed ceramic aggregate and ranged between 0.6 and 2.0 GPa, placing them to the lower limits for lime-based renders, according to Veiga et al. [7] at the age of 90 days. Dynamic modulus of elasticity was higher when calculated using ultrasonic pulse velocity measurements than through resonant frequency measurements between 20 and 30%, as it was expected.

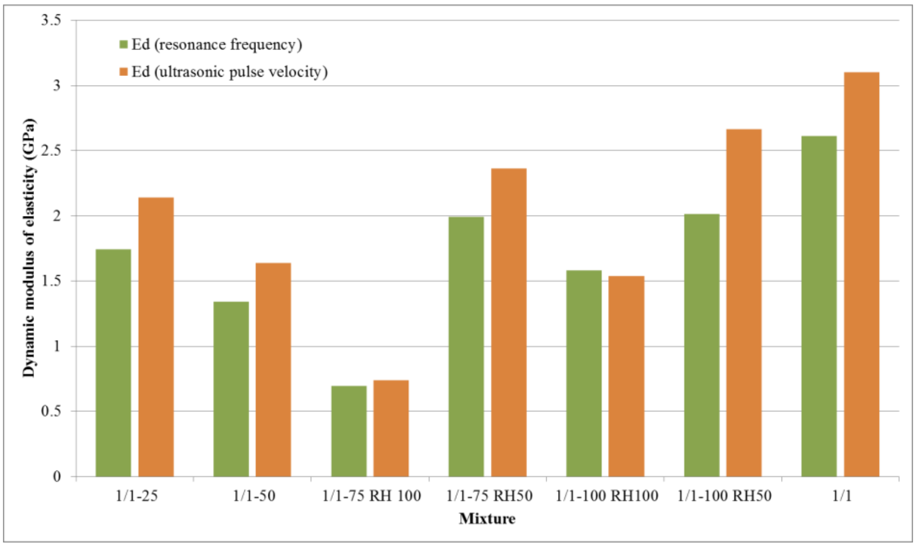


Figure 8 – Dynamic modulus of elasticity at the age of 60 days

4. CONCLUSION

Physical and mechanical properties of the tested mixtures were analyzed through influence of the amount of crushed ceramic aggregate used, and also through influence of curing conditions for mixtures containing 75 and100% of this aggregate. Increased content of crushed ceramic aggregate influenced:

- increase in compressive strength of the mixtures at the ages of 14 and 28 days. At the age of 60 days mixtures containing 75 and 100% of crushed ceramic aggregate had 1.5-2 times higher strength than reference mixture, when cured in laboratory conditions and 2.5-6.75 times higher strength than reference mixture when cured in humid conditions;
- decrease in flexural strenght for all of the mixtures (1.1 to 1.9 times at the age of 60 days). Still all of the mixtures follow the recommended values between 0.2 and 0.7 MPa at the age of 90 days [7];
- increase in water absorption after 48 hours and open porosity, and decrease in capillary water coefficient at the age of 60 days for mixtures containing 75 and 100% of clay aggregate;
- increase in drying period necessary for reaching the constant mass;
- decrease in dynamic modulus of elasticity, which remained in recommended limits (2-5 GPa) [7], apart for the mixtures cured in humid conditions.

The addition of crushed ceramic aggregate shows potential beneficial influence of lime based render properties, especially regarding compressive strength development and capillary water absorption coeffeicient. Among the mixtures tested, mixture 1/1-75 had the most of the properties within recommended values in both curing conditions.

ACKNOWLEDGMENTS

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