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La segunda vida de los residuos de construcción. Propuesta para reutilizar como agregado árido reciclado y residuos de material aislante.

The second life of construction waste. Proposal to reuse recycled fine aggregate and residues of insulating materials.

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Resumen— El artículo presenta los resultados de una investigación propia que confirma la posibilidad de reutilizar materiales de desecho: la fracción fina del hormigón que se recicla como sustituto de arena, residuos de material aislante (lana de roca y fibra de vidrio) y arena reciclada. Se realizaron ensayos de Resistencia a compresión y flexión, absorción de agua por capilaridad y dureza superficial. Los resultados muestran que todos los materiales descritos podrían servir como solución aceptable para la reducción del uso de recursos naturales - arena natural (por ejemplo) o, como relleno. La reutilización de residuos en el mundo debe llevarse a cabo debido a la carencia de recursos naturales

Palabras Clave— Relleno reciclado; residuos de hormigón; productos de cal de arena modificados; residuos de material de aislamiento; lana de la roca; fibra de vidrio; residuos de construcción y demolición.

***Abstract*—The paper presents the results of own research confirming the possibility of reusing a waste material: fine fraction from concrete recycling as a filler in sand lime products and residues of insulating materials (rockwool and fiberglass) and recycled sand using as a insulating materials. The compressive strength, bending, water absorption, surface hardness and structural research were carried out. The results show that the all of describing materials could be acceptable solution to reduce natural resources - natural sand (for example) or be a filler. Reuse of waste materials to new composites is expected in this world because of lack of natural resources.**

Index Terms— Recycled filler; concrete rubble; modified sand lime products; insulating waste; rock wool; fiberglass; construction and demolition waste

I. INTRODUCTION

WIDESOREAD USE OF CONCRETE as a construction material causes that it is used on a mass scale. Estimates say that even 25 billion tons of concrete every year it is produced all over the world. The consequence of this is 510 million tons of construction waste generated in Europe, about 325 million tons in the USA and about 77 million

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tonsin Japan (Ferrari et al. 2014). Consequently, the issue of concrete recycling is widely described by many researchers, which proves that the subject is up-to-date and the need to improve the treatments and processes that enable the most efficient use of secondary products. A lot of attention is paid to recyclable coarse aggregates (according to PN-EN 206: 2014 fractions ≥ 4 mm) and their suitability for newly designed concretes (Behera et al., 2014 and Thomas et al., 2013). In addition to the coarse fractions during secondary aggregate production processes, significant amounts of the fine fraction are obtained according to the regulations, it cannot be used as an aggregate for concretes, and in practice it is used for leveling the ground, backfilling, etc. For a few years, there have been conducted research in the world to use also small recycling fractions for the production of cement composites (Schoon et al., 2015; Bołtryk and Kalinowska-Wichrowska, 2016; Kalinowska-Wichrowska and Pawluczuk, 2015).In these tests, different amounts of recycled powder (fraction <63µm) were used mainly for the production of clinker, obtaining promising long-term results, as well as reducingabout 30% CO2 emissions (Gastaldi et al., 2015;).

On the other hand, the technique of adding fibers in construction, is a procedure used since antiquity. Nowadays it is booming because, the good insulation properties of these fibers make them essential to the increase of thermal and acoustic requirements marked by the increasingly demanding construction regulations that seek to contribute to saving of energy and improve thermal comfort. This progression of the use of insulating materials has caused an alarming growth of mineral wool residues, since it is the most used insulation in the European Union (Väntsi and Kärki 2014), so it is essential to recycle or reuse it.However, although in recent times there has been extensive research on the inclusion of fibers in various matrices, there are few studies on the use of mineral fiber residues in cement mortars (Cheng, Lin, and Huang 2011; Piña et al. 2018).

All this has led to the present research work, whose main objective is to evaluate the reuse of both recycled aggregate and mineral fibers from landfill, analyzing their viability in cement mortars, in order to reduce environmental impact.

II. OBJECT AND METHODOLOGY OF OWN RESEARCH

A. *Characteristics of materials from recycled concrete rubble*

The characterization and testing of these materials are carried out at the Bialystok University of Technology (Poland).

A lime-sand mixture obtained from the SILIKATY Białystok production plant was used for the tests, after the lime quenching. Its composition is a trade secret. The recycling filler was created during a complex process of thermal-mechanical treatment of concrete debris based on the technology described in ("The method of separating the hardened mortar ...." PAT.229887), consisting in separating the coarse aggregate from the hardened cement mortar during. The recycled fine fraction is waste from the processing of concrete rubble by the derived from C30 / 37 concrete.

The fine material (<4 mm) obtained as a result of this process was additionally sieved, the fraction <2 mm was added in the amount resulting from the research plan to the finished lime-sand mixture recyclable material. Figure 1 shows percentage share of individual particle sizes found in the recycler filler (Bołtryk i Kalinowska-Wichrowska, 2017).

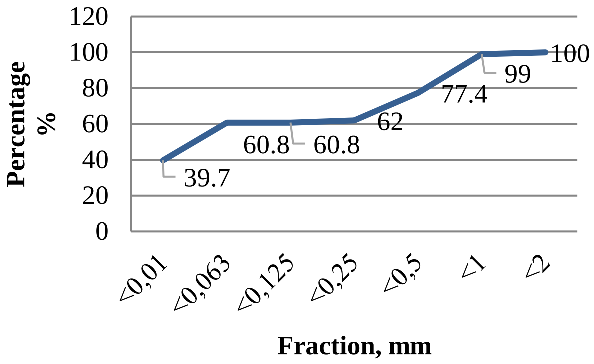

Fig. 1. Percentage share of individual particle sizes found in the recycler filler.

In order to determine the binding capacity of the recycled materials produced, they had subjected them with a calorimetric test (Fig. 2). Hydration tests of materials were made using a conductive calorimeter. Keeping the ratio w / s = 0.5, a sample was prepared, which was recycled material in the amount of 10 g and distilled water in an amount of 5 g. The calorimetric vessel was equipped with a syringe that feeds water to the binder sample (here a recycled material), which made it possible to measure the heat of hydration from the moment of mixing the ingredients. The results obtained for CEMI 42.5R cement were used as a reference sample.

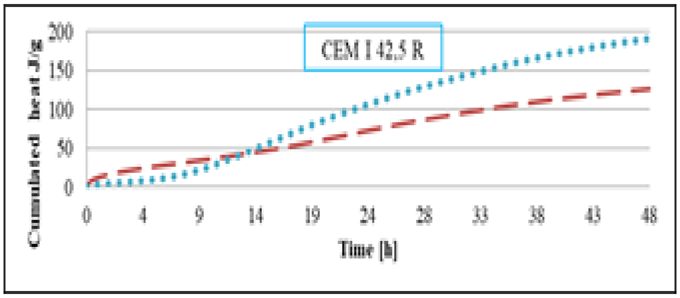

Fig.2. Changes of hydratation heating during the measure.

The obtained cumulated heat results confirm the validity of thermal processing in obtaining valuable small fractions of recycled materialsin order to activate their binding properties. The calcined material exhibits some binding properties, the heat accumulated during the measurement gradually increases and after a 2 days observation period it was at 125 J / g, a decrease of 35% for the cement sample.

The thermal analysis of TG / DTA shown in Figure 3 indicates in principle on the lack of endothermic effects associated with dehydration, among others calcium silicate type C-S-H, which may suggest that the earlier thermal treatment at 650°C of the recycled mortar led to their decomposition.

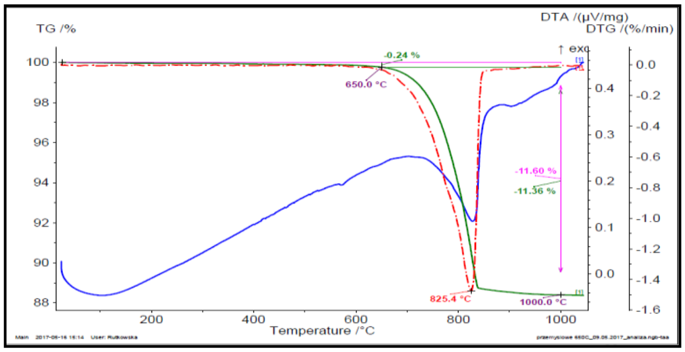

Fig.3. Thermogravimetric analysis for recycled fine fraction.

In the fine fraction obtained as a result of thermo-mechanical treatment there is no peak from the Ca (OH)2 portlandite. A high endothermic effect was observed at a temperature of 825°C, during which decomposition occurs due to the decarbonation of calcite (CaCO3). This corresponds to the change in sample weight by approx. 14% registered on the TG curve. The high content of calcium carbonates in the recycled mortar after thermo-mechanical treatment probably results from the release of aggregate residues into the test sample.

B. Characteristics of materials derived from insulating waste and recycled sand

The characterization and testing of these materials are carried out at the Technical School of Building - Polytechnic University of Madrid (Spain).

The most relevant behavior and properties of mortars with mineral wool fiber residues from CWD have been studied by replacing all the river sand used in the mixtures with recycled aggregate, in order to determine whether to use recycled aggregate in place of normal aggregate. The effects produced by the recycled aggregate in the mortars with fiber residues are also analyzed as their percentage of addition increases.

Residues of fibers

Three different types of mineral wool waste have been used, all of them from the Center for the Integral Treatment of Construction Waste and Demolition of the N-1 motorway towards Irún Km 40, located in the town of El Molar in the Community of Madrid, and managed by the company GEDESMA SA Subsequently, the rock wool and fiberglass residues have been selected and separated, and another sample of the mixed mineral wool waste has been kept unselected, as they were in the landfill. In the Fig.4 rock wool, fiber glass and mix both used in experiment are shown.

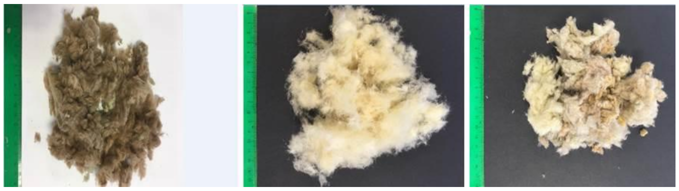

Fig.4. Material used in experiment, from the left: rock wool, fiber glass and mix both.

Recycled aggregate

The recycled aggregate used is mixed recycled aggregate, that is to say from the treatment of waste of different nature and with a content of ceramic particles and concretes less than 20% and 90% respectively, likewise it has been sieved by a sieve of 4mm in diameter. These aggregates have been collected at the Tec-Rec recycled aggregate treatment center (Tecnología y Reciclado, S.L.), located in the Community of Madrid.

Only the granulometry of the aggregates and the percentage of fines has been proven, since the complete characterization of these recycled aggregates can be found in Sáiz's research (Saiz,

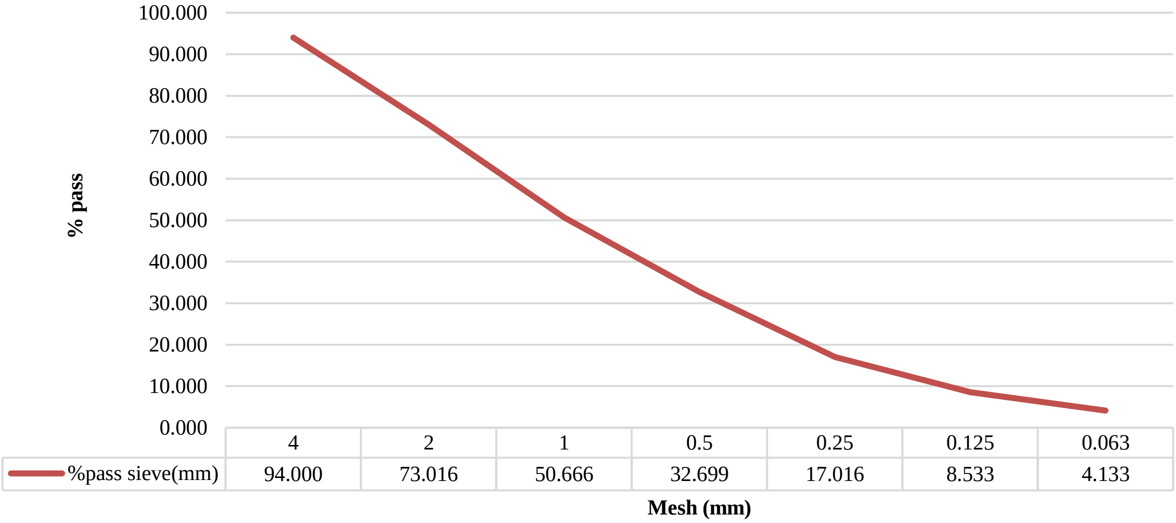

Fig. 5. Granulometric curve of recycled sand.

Gonz, and Fern 2015).

The granulometric analysis according to standard UNE-EN 993-1 of the mixed recycled aggregate in the trials of phase 3 of this study is shown in Figure 5. This test was performed on samples of recycled aggregate size 0.063 / 4 mm while the fines content was performed on the fraction 0/4 mm thereof.

It is verified that fulfilling the requirements of the UNE-EN 13139 standard, all particles are less than 8 mm, and particles greater than 5.6 mm do not exceed the 5% set as limit.

Also, it can be seen in Figure 5 that the granulometric line is continuous and within the limits established in the standard taken as reference NBE-FL 90. This continuous distribution indicates that there is a uniform distribution in the different sizes, which provides a greater interaction between the particles and therefore an improvement in the properties of workability, compactness and strength, over which the aggregates have a direct influence. The percentage of fines passing through the 0.063 sieve is 4.13%, which is 4.4 grams of the total dry mass of 600 grams, not exceeding the maximum established 8% for masonry mortars, although it almost doubles the value of the normalized aggregate used in the rest of the present investigation (2.3%).

III. EXPERIMENTS

A. Sand- lime product with recycled fine fraction

In order to determine the impact of the mortar from recycling on selected properties of autoclaved sand-lime products, a research experiment consisting of 6 test series was planned in which 8 samples were made. The experiment included one variable - X1 -% of the content of the recycler filler in the sand-lime mixture (0, 5, 10, 15, 20, 25%). The composition of series includes Table 1.

TABLE I
COMPOSITION OF INDIVIDUAL SERIES OF MADE CALCAREOUS SAND PRODUCTS WITH A RECYCLABLE FILLER FOR 1 KG OF MASS

Series No.	**1**	**2**	**3**	**4**	**5**	**6**
Percentage of recycled fine fraction in all mass [%]	0	5	10	15	20	25
Mass of recycled fine fraction [kg]	0,0	0,05	0,1	0,15	0,20	0,25
Mass of Sand lime mix [kg]	1,0	0,95	0,90	0,85	0,80	0,75

Execution and care of samples

A sufficient amount of recycler filler (resulting from the test plan) was added to the sand-lime mixture and mixed using an automatic laboratory blender (Figure 6). The appropriate amount of water was then added to obtain the assumed 6% humidity. The obtained material was divided into portions and placed in steel molds, 10x10x10 cm each. Then samples in molds, they were pressed for a period of 2 minutes with a force of 200 kN. After demolding, they were subjected to a 6.5-hour autoclaving cycle. On 6 random samples from each series compressive strength was determined according to PN-EN 12390-3 Concrete testing - Part 3: Compressive strength of test specimens, and for 3 randomly selected samples, absorbability test acc. to PN-B-06250.

Fig.6. Materials using in experiment and sand- lime samples with recycled fine fraction.

B. Cement mortars with waste insulation materials and recycled sand

In Table 2 the series of elaborated specimens are shown.

TABLE II
COMPOSITION OF INDIVIDUAL SERIES OF MADE WITH RECYCLED FIBER AND RECYCLED SAND

Series	**% Addition**	**Type of fiber**	**Designation**	**Format (mm)**
1	0%	---	Ref-AR	160x40x40
2	30%	Rockwool	30% RW-AR	
3	30%	Fiberglass	30% FG-AR	
4	30%	Mixture	30% MIX-AR	
5	40%	Rockwool	40% RW-AR	
6	40%	Fiberglass	40% FG-AR	
7	40%	Mixture	40% MIX-AR	
8	50%	Rockwool	50% RW-AR	
9	50%	Fiberglass	50% FG-AR	
10	50%	Mixture	50% MIX-AR	

The Shore D surface hardness, flexural and compressive strength have been carried out.

Execution and care of samples

The surface hardness is determined according to the standard UNE-EN 13279-2 (AENOR A. E., UNE-EN 13279-2, 2006) measuring the footprint left by a certain force on the surface of the test piece. A durometer is used as a device with which the 2 flat and smooth faces of the prismatic specimen are pressed, performing 5 random values on each of the two faces.

It is determined flexural strength and compression in accordance with the specifications demanded by the UNE-EN 1015-11 (AENOR A. E., UNE EN1015-11: 2000, 2000). The test was conducted in the laboratory of materials from the Higher Technical School of Building of the Polytechnic University of Madrid.

It is carried out with three prismatic specimens of dimensions 40x40x160 mm for each batch made. The molds are filled in two tiers, each compacted in a compacting machine model Iberest CIB 801, with 25 strokes (Figure 7).

Fig. 7. Filling specimens on mechanical compactor.

Afterwards, they are leveled to remove the remaining mortar and the mold is transferred to a climatic curing chamber. After 24 hours, the mold will be demolded and reintroduced into the chamber (Figure 8), where it will remain for a total of 28 days. At a temperature of 20 ± 2 ° C and relative humidity 95% ± 5%.

Fig 8. Cured specimens in a humid chamber.

For the flexural strength the specimens are placed in the work unit where a load is applied at progressive and constant speed until the break, and the obtained value is recorded (Figure 9). The compressive strength of the mortars is determined on the broken halves of the specimens tested by bending, by applying a constant progressive load on two opposite faces of the specimen until rupture. The test pieces are placed between two plates (40 x 40) mm ± 1mm, 10 mm thick. The axis of rotation of the lower plate is centered on the surface of the specimen tested.

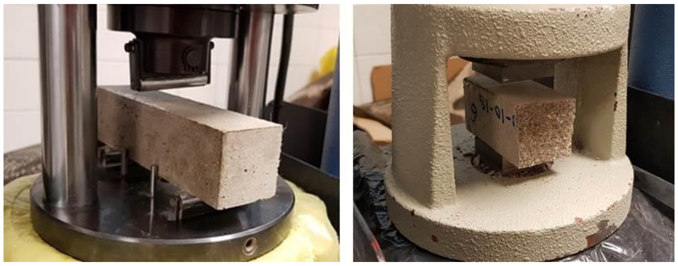

Fig 9. Test for flexural (left) and compressive (right) strength.

IV. RESULTS AND DISCUSSION

A. *Results of sand lime products with fine fraction Compresssive strength and water absorption*

Tables 3 and 4 presents, respectively, the results of compressive strength and water absorption tests of samples lime-sand products with a recycled fine fraction.

TABLE III
COMPRESSIVE STRENGTH OF SAND-LIME PRODUCTS WITH RECYCLED FINE FRACTION [MPA]

0	5%	10%	15%	20%	25%
30,25	27,3	24,52	21,72	23,39	21,61
29,35	28,5	26,43	24,39	20,88	20,45
28,09	27,3	24,85	23,31	19,82	23,09
26,07	28,5	25,26	23,58	22,135	21,77
27,79	27,2	25,8	23,9	21,6	22,3
28,31*	**27,76***	**25,37***	**23,38***	**21,56***	**21,84***

***Average**

The results appear in Tab.3 illustrate that the addition of the fine fraction to lime-sand products generally reduces their compressive strength. The dosage of fine fraction in the amount of 5% of the mass causes a negligible (because only 2%-percent) drop in strength. At higher ratios (10-25%) the loss of strength becomes significant and ranges from 11-23%.

TABLE IV
WATER ABSORPTION OF SAND -LIME PRODUCTS WITH RECYCLED FINE FRACTION [% MASS]

0	5%	10%	15%	20%	25%
12,88	12,91	12,95	13,3	13,4	13,65
12,89	12,86	13,3	13,28	13,35	13,8
12,87	12,85	13,2	13,25	13,4	13,9
12,88*	**12,87***	**13,15***	**13,28***	**13,38***	**13,78***

***Average**

Analyzing the results of absorbability (Tab.4) It can be concluded that the effect of the fine fraction additive on this property was small - at 5% of the additive, the absorbability compared to the control sample did not increase, while the 25% of the fine fraction additive showed an increase of about 7% . From the point of view of this feature, fine fraction dosing in these variability ranges does not play a significant role.

Referring to the ones obtained in Tab.3 and Tab.4 the results of the research should be considered to modify the composition of the composite - a change in the proportion of lime - sand or an increase in the degree of fineness of the fine fraction - striving to improve the strength of the composite. Nevertheless, it should be noted that the obtained test results were certainly influenced by the conditions of their conduct. The lime-sand pulpit was delivered from the plant outside the laboratory, which could directly affect its properties. Undoubtedly, the obtained test results are a prerequisite for further analyzes on the use of fine fraction in autoclaved products.

In order to determine the function describing changes in compressive strength of sand-lime composites, the results of the research were subjected to statistical analysis. The calculations were carried out using the Microsoft Excel v.2010. The function describing changes in compressive strength of lime-sand products depending on the content of the recycler filler is as follows (1):

$$y= 28,48 - 0,302\ X_1\ ,\ R^2= 0,94 \qquad (1)$$

where: x_1- percentage amount of recycled fine fraction, %

Fig.10. is showed a graphical interpretation of the obtained compressive strength tests results of composites depending on the value of variable x_1 (x_1-content of the recycled filler), (1).

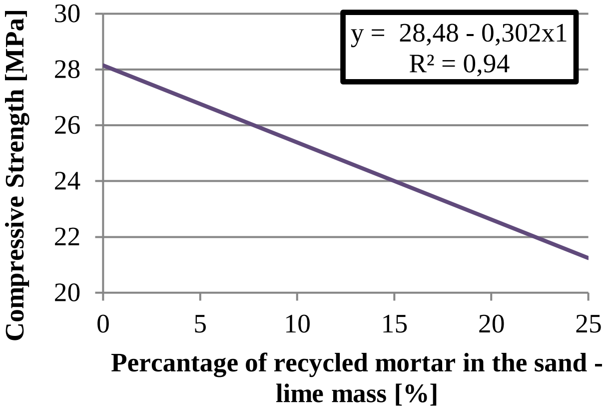

Fig.10. Dependence of compressive strength of cementitious composites from the percentage of recycled filler.

On the basis of the obtained results, it can be concluded that the content of the recycled fine fraction in the amount (5%) of the lime - sand mixture does not significantly reduce the compressive strength of autoclaved lime - sand products. Exceeding these values significantly influences the decrease in strength of the tested composites.

In order to observe the structure of autoclaved products using the recycled fine fraction, observations were made using scanning microscopy. The scanning photos are shown in the Figure 11.

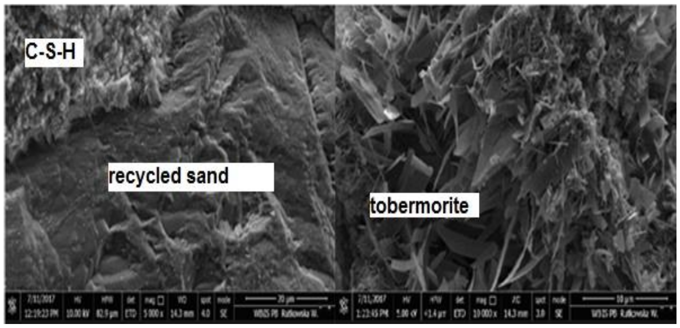

Fig. 11. SEM photos of recycled fine fraction in sand-lime products.

The formation of hydrated calcium silicates depends primarily on the solubility of the starting materials CaO and SiO2. In hydrothermal conditions, the solubility of SiO2 increases significantly, and the solubility of calcium hydroxide decreases and the SiO2 reacts with calcium hydroxide quickly. As a result, hydrated calcium silicates are formed. Hydrated calcium silicates in the first period are amorphous or poorly crystalline, only when time passes and the temperature in the autoclave increases, they form crystalline forms. The strength of autoclaved concrete is mainly influenced by the C-S-H and tobermorite phases (Gębarowski et al., 2015).

In silicate products created in the autoclaving process, there are hydrated calcium silicates with an ordered structure (tobermoryt) or a disordered structure (C-S-H phase). Tobermorite, referred to as the most perfect form of the C-S-H phase, most often takes the form of a lamellar form. In the classic silicate, tobermorite occurs in places and is not the dominant phase.

B. Results of composites with residues of insulating materials and recycled sand

Shore D hardness test

Figure 12 and 13 shows graphically the results obtained from the Shore D surface hardness test for mortars with fiber residues and recycled aggregate.

As can be seen, the test pieces made with recycled aggregate and mineral wool residues have a better surface hardness compared to the reference mortar, except for the case of mortars with 50% glass fiber.

It is found that the values of the surface hardness are lower compared to the mortars made with river sand, which results in spite of this admissible values.

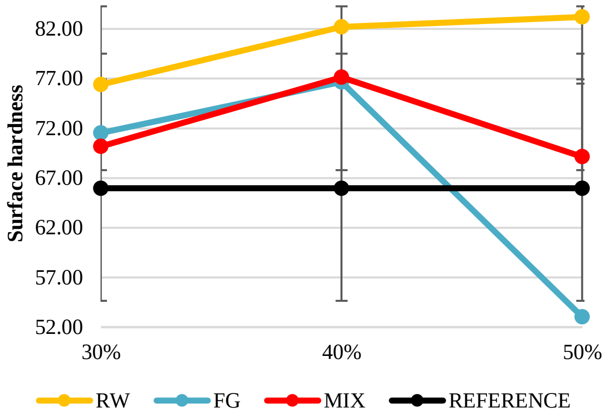

Fig. 12. Shore D surface hardness of the compounds with recycled aggregate.

It is noted that the best values are obtained in mixtures with 40% and 50% for the ore residue fibers rock wool, and the worst for the 50% addition of waste fiberglass, as happened in mortars with river sand, but with lower resistances with recycled aggregate.

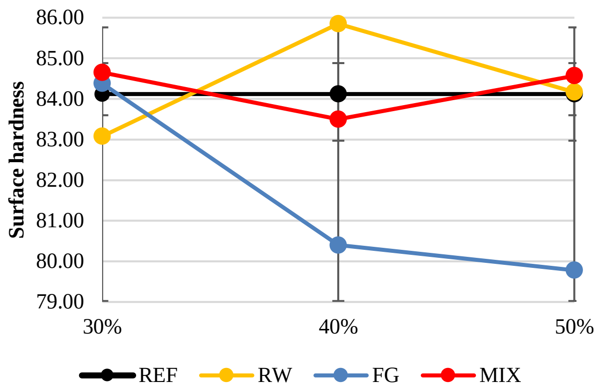

Fig. 13. Shore D surface hardness of the compounds with river sand.

Flexural strength

Figure 14 and 15 shows graphically the results obtained from the flexural strength for mortars with fiber residues and recycled aggregate. Although the current regulations do not establish a minimum value of flexural strength, it has a special importance in the durability of mortars.

The resistance to flexion improves significantly with the incorporation of mineral fiber waste for the three types of fibers, as well as what happened in mortars with river sand. It is observed that with the incorporation of fibers at 30% it improves the resistance to flexion of the mortars in an important way with respect to the reference, while at 40% of incorporation they remain stable, abruptly lowering this resistance with the mortars additive to 50%. It should be noted that mortars with rock wool fiber residues are those that best behave when flexed.

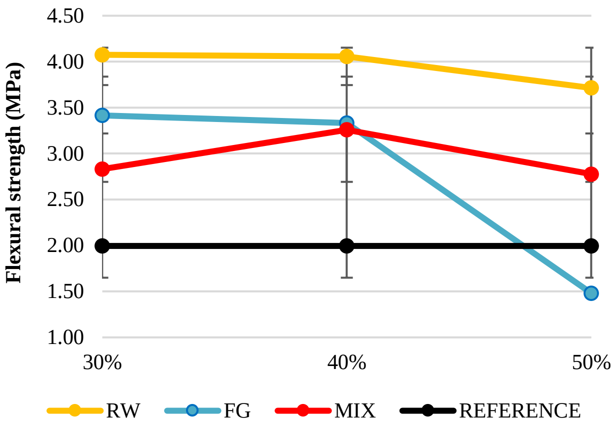

Fig. 14. Flexural strength (MPa) of the compounds with recycled aggregate.

Analyzing both graphs (Fig.14. and 15.), it is observed that in comparison with the mortars with river sand, the values of resistance to flexion for the three types of fibers of mortars with recycled aggregate are below half compared to those made with river sand.

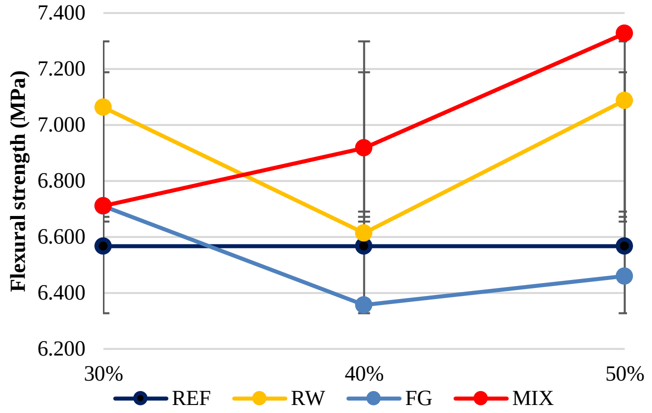

Fig. 15. Flexural strength (MPa) of the compound's river sand

Compressive strength

Figure 16 and Figure 17 show graphically the results obtained from the compressive strength for mortars with fiber residues and recycled aggregate, as well as processed with river sand.

The data shows that, unlike what happens in mortars with river sand, the incorporation of fiber residues in mortars with recycled aggregate significantly improves their compressive strength.

The values obtained in the compression resistance test are higher than the reference without fibers, except mortars with 50% glass fiber residue, and except for this percentage the rest comply with the provisions of standard UNE-EN 998-1 "Specifications of mortars for masonry" that establishes a resistance to compression comprised between 0.4 N / mm² and 7.5 N / mm², admitting higher values.

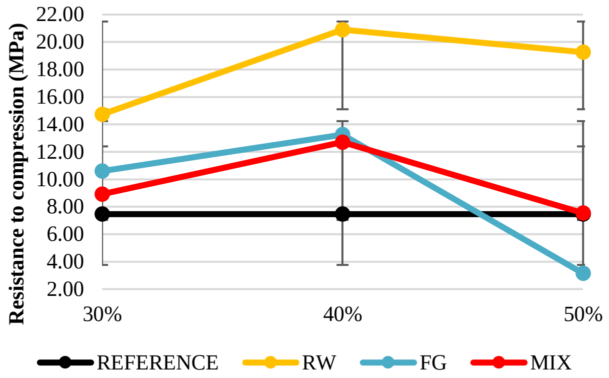

Fig. 16. Compression strength (MPa) of the compounds with recycled aggregate.

While mortars reinforced with fiberglass waste and mixed waste show very similar results, the best performance of the specimens with the addition of rock wool residues for the three addition percentages, which are still in values, stands out. of compression below, commercial mortars reinforced with glass fiber.

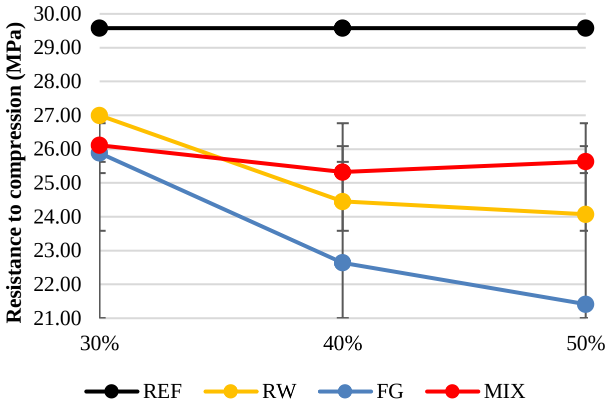

Fig. 17. Compression strength (MPa) of the compounds with river sand.

It is noted by comparing the graphs in Figures (12 -17) that the use of recycled aggregate in mortars with fiber residues has a very unfavorable influence on mechanical compression behavior.

V. CONCLUSIONS

The use of fine fraction from recycling concrete in an appropriate amount (in the analyzed case it is 5% of mass) may be a component of autoclaved products, not impairing its strength and absorbability. As evidenced by the presented research results, the recycled material produced according to the process described in PAT.229887, shows some latent binding properties, which can probably be intensified during the autoclaving process. This can be testified by the numerous tobermorite clusters on the recyclable sand grains included the fine fraction. The tests were a part of the own research on manufacturing and the use of valuable recycled material in lime-sand products and require further modification. It is necessary to conduct further analyzes allowing to specify the optimum content of the recycled filler in autoclaved products.

The use of recycled aggregate in cement mortars with mineral wool residues causes a significant worsening of their mechanical properties, in comparison with the same mortars made with natural sand. The values of superficial hardness are admissible, but the worsening of the values of resistance to flexion and to compression do not allow the viability of the mortars for construction works. Therefore, it is recommended to use mortar additives to improve their mechanical behavior with recycled sand, in order to obtain highly sustainable mortars.

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