PARTICULARITĂȚI ALE COMPORTĂRII MECANICE A UNOR TIPURI DE BETON SUSTENABIL CU ADAOS DE MATERIALE RECICLATE
PARTICULARITIES REGARDING THE MECHANICAL BEHAVIOUR OF SOME TYPES OF SUSTAINABLE CONCRETE MIXES WITH WASTE MATERIALS

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The paper presents the experimental results in terms of mechanical properties obtained for some types of innovative micro-concrete (MC) mixes. This type of concrete utilises aggregates up to 8mm and the main intended use is for non-structural elements such as insulation panels. In this respect, two concrete mixes have been prepared using fly ash (FA) as replacement for 10% of the cement dosage, and two types of waste plastic materials: polystyrene (PO) granules and recycled polyethylene terephthalate (PET) bottles aggregate. They were introduced as substitution of the fine natural aggregate (FNA) (0-4 mm), in different proportions ranging from 30% to 100%.

The values of the experimentally determined mechanical strengths (compressive strength, flexural strength, split tensile strength) for both types of micro-concrete are smaller than the ones of the reference mix. The complete stress-strain curves of these materials subjected to compression have been established to evaluate the absorption capacity of the strain energy. The values achieved for the micro-concrete mixes with PET aggregates were higher than the ones of the mixes embedding polystyrene granules. By increasing the dosage of waste materials as natural aggregates partial replacement, a lightweight concrete was obtained.

Lucrarea prezintă rezultatele experimentale obținute în ceea ce privește proprietățile mecanice ale unor tipuri inovatoare de micro-beton. În acest sens, au fost preparate două rețete de beton utilizând cenușa de termocentrală ca înlocuitor a 10% din cantitatea de ciment și două tipuri de deșeuri: granule din polistiren și agregate obținute din PET-uri reciclate, adăugate în amestecuri ca substituient al agregatului natural fin (sortul 0-4 mm), în diferite proporții cuprinse între 30% și 100%.

Valorile rezistențelor mecanice (rezistența la compresiune, rezistența la întindere din încovoiere, rezistența la întindere prin despicare) determinate pe cale experimentală pentru ambele tipuri de micro-beton sunt mai mici decât cele obținute pentru rețeta martor. Curbele caracteristice complete tensiune-deformație specifică la compresiune au fost stabilite pentru a evalua capacitatea de absorbție a energiei de deformație a acestor materiale. Valorile experimentale obținute pentru rețetele de micro-beton cu agregate din PET au fost mai mari decât cele corespunzătoare rețetelor cu granule din polistiren. Prin utilizarea unor procente mai mari de substituție a agregatului natural cu materiale reciclate s-a obținut un beton ușor.

Keywords: *fly ash, waste PET bottles aggregate, polystyrene granules, mechanical strengths, complete stress-strain curves.*

1. Introduction

Waste materials disposal has become an issue of real concern of our days with major repercussions in many areas, ranging from environmental protection to economics and engineering domain. Recycling is a solution to the problem of excessive waste production, especially in urban areas, which contributes to the sustainable use of natural resources, decreasing the negative impact on the environment, reducing pollution, but also diminishing the production costs in various fields, including the building materials industry.

In the last decades, the use of wastes in building materials development has achieved an increased interest both from researchers and from manufacturers. New materials have been studied, tested and proposed to be used in Civil Engineering applications [1-4]. A large variety of wastes has been used in preparing various types of building materials (e.g. cement, plaster, concrete, brick, composite materials, etc.), including industrial by-products (silica-fume, blast furnace slag, fly ash, etc.) [5], vegetal and organic wastes (wood, cork, hair, wool, etc.). The wastes have been added as cement or aggregates substitution materials or as admixtures for improving the materials properties, to obtain certain mechanical characteristics, decreasing the materials cost or increasing their durability [6-15]. The use of some types of waste showed to be suitable also for producing lightweight concrete, for improving the thermal properties of concrete (polystyrene granules, wool, etc.) [16,17], or for improving the acoustic insulation capacity (rubber granules, polystyrene) [18, 19].

Mineral mixtures, such as silica-fume, fly ash and blast furnace slag generally improve the properties of concrete when added as mineral additives or as partial replacement of cement [20].

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Among these mineral additives, fly ash deserves special attention, as it is a residual product resulting from the combustion of coal, and because it is one of the main factors of atmospheric pollution. The fly ash is utilised in the production of concrete for over 50 years all over the world. It was embedded in conventional concrete and high-performance concrete mixes to improve the workability, but also the mechanical and durability properties of concrete [21, 22].

Polystyrene (PO) granules have a closed cell structure consisting essentially of air (98%) [23]. By incorporating them in different dosages in concrete mixes, in mortar or cement paste, a wide range of material densities can be obtained. Usually, polystyrene granules are added as aggregate to produce low density concrete for Civil Engineering applications [24].

Plastics are among the solid wastes with the most harmful effects on the environment, due to their long biodegradation period. Due to the enormous quantity of PET bottles disposed all over the globe, one of the most convenient methods of reducing their negative effects is the integration of these materials in construction domain, which is one of the industries with the highest capacity of embedding waste materials [25].

In this research program, three types of waste have been considered for developing some new concrete mixes. The short-term mechanical characteristics have been analysed for different cement and aggregate substitution proportions.

2. Experimental program

2. 1. Materials

The components of the reference concrete mix (MC) were the following: cement 430 kg/m^3, fine aggregate (0-4 mm) 1070 kg/m^3 and coarse aggregate (4-8 mm) 655 kg/m^3. The reference concrete mix was based only on the use of natural aggregates (NA). The water content was of 198 l/m^3. In this study, a high range water-reducing admixture complying with EN 934-2:2009 [26], T3.1/3.2 provisions was used. The cement type was CEM IIB-M-S-LL-42.5N that conforms to the Romanian standard SR EN 197-1:2011 [27].

For the design of micro-concrete mixes embedding waste materials, fly ash (FA) has been added as a substitute for 10% of the cement. The fly ash used in the experiments, resulted from the coal burning, was supplied by Holboca-Iaşi power plant. This material consists of many fine, glass-like particles ranging in size from 0.01 to 100 µm. From chemical point of view, FA contains oxides, hydroxides, carbonates, silicates, and sulphates of calcium, iron and aluminium. The main features of FA are: the colour varies from grey to black depending on the content of unburned carbon, the shape of particles is spherical, the specific surface is between 4800-5200cm^2/g, the density is between 2400 and 2550 kg/m^3.Fly ash type B meets the technical requirements of SR EN 450-1:2012 [28] for fine-grain replacement.

Polystyrene (PO) granules and polyethylene terephthalate (PET) particles have been used as partial replacement of the fine natural aggregate (0-4 mm).The polystyrene (PO) granules had different diameters ranging from 1 mm to 4 mm. The unit weight of polystyrene was of 1.6 kg/m^3.

The recycled PET aggregates have been obtained by shredding collected bottles into small pieces. For the purpose of the tests, the PET aggregates have been sieved and only the particles with the size up to 4 mm have been selected. The PET granules had an estimated unit weight of 433 kg/m^3.

Six new concrete mixes have been prepared by replacing 30%, 60% and 100% of fine natural aggregates (FNA) volume with equal volumes of each type of waste aggregates (PO and PET particles).

The specimens with PO granules replacing the natural aggregates were labelled as MC PO1 to MC PO3, and the specimens with PET aggregates were labelled as MC PET1 to MC PET3. Table 1 indicates the volume percentages

Table 1

Concrete mix proportions/ *Rețete de beton*

Concrete mix designation *Denumirea rețetei de beton*	Cement *Ciment*	Fine aggregate *Agregat fin* (0-4mm)	Coarse aggregate *Agregat grosier* (4-8mm)	Fly ash *Cenușă zburătoare*	PO granules *Granule de polistiren*	PET particles *Particule de PET*
	(%)	(%)	(%)	(%)	(%)	(%)
MC	100	100	100	0	0	0
MC PO1	90	70	100	10	30	0
MC PO2	90	40	100	10	60	0
MC PO3	90	0	100	10	100	0
MC PET1	90	70	100	10	0	30
MC PET2	90	40	100	10	0	60
MC PET3	90	0	100	10	0	100

Table 2

Average values of concrete density/ *Valori medii ale densității betonului*

Concrete mix designation/ *Denumirea rețetei de beton*	Density of fresh concrete/ *Densitatea betonului proaspăt*	Density of hardened concrete/ *Densitatea betonului întărit*
	kg/m^3	kg/m^3
MC	2100	2273
MC PO1	2000	2042
MC PO2	1800	1694
MC PO3	1305	1243
MC PET1	2267	2102
MC PET2	2160	2020
MC PET3	1667	1608

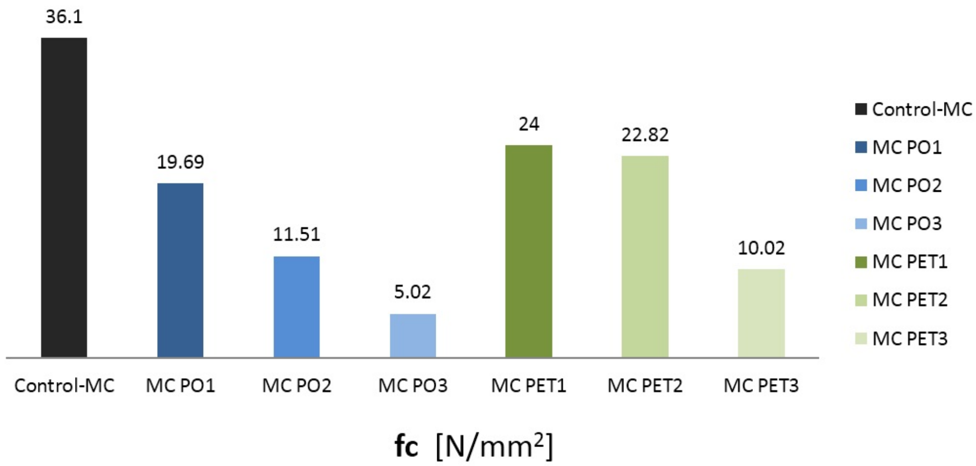

Fig. 1 - Variation of compressive strength for the tested concrete mixes/ *Variația rezistenței la compresiune a rețetelor de beton testate*

of cement and aggregates to be replaced for each type of micro-concrete mix.

2.2. Specimens

The concrete mixes preparation, casting, curing and experimental testing followed the specific standard procedures. Thus, three types of specimens were cast for each mix proportion: cubic specimens (100mm x 100mm x 100mm) for determination of the compressive strength (f_c), prisms (100mm x 100mm x 550 mm) for determination of the flexural strength (f_{ti}) and cylindrical specimens (100mm x 200mm) for determination of the split tensile strength (f_{td}) and of the complete stress-strain curves.

The specimens were cured at 20°C for 28 days until the experimental testing. According to the Romanian standard provisions [29-31], each test was performed on three specimens. The density of the fresh and hardened concrete was also determined according to the Romanian standard SR EN 12390-7:2005 [32].

The values shown below represent the average values obtained for the three specimens of each concrete mix.

3. Results and discussion

3.1. Density of micro-concrete

According to the studies carried out so far, it can be concluded that the average density of hardened concrete containing both types of waste materials is smaller than that of the reference concrete mix. Its values vary between 2042 kg/m^3 and 1243 kg/m^3 for the concrete mixes with PO granules, and between 2102 kg/m^3 and 1608 kg/m^3 for the concrete mixes with PET aggregates. All the obtained values are summarised in Table 2.

For both types of concrete mix, the density decreased as the percentage of the replacing aggregate increased. These results show that in order to obtain a lightweight concrete, the substitution of the fine natural aggregate must be more than 30% in both mixes.

3.2. Compressive strength

The values of the compressive strength obtained on the tested specimens are illustrated in Figure 1.

The values of the compressive strength for both types of micro-concrete mix with waste substitution are lower than the ones of the reference concrete mix. The compressive strength values for micro-concrete mixes with PO granules were smaller by 45.5% to 86.1% with respect to the reference concrete mix. In the case of micro-concrete mixes embedding PET particles, the decreasing percentages were between 33.5% and 72.2%. Therefore, MC PET specimens showed higher values of the compressive strength than those of MC PO specimens with different percentage of FNA substitution. The highest value of the compressive strength (f_c = 24.00 N/mm^2) was obtained for MC PET1 mix, compared to that of MC PO1 mix, which was of 19.69 N/mm^2.

In Figure 2 and Figure 3, the MC PO2 and MC PET3 specimens aspect after performing the compression test, are illustrated. The quasi-homogeneous distribution of the waste material can be observed.

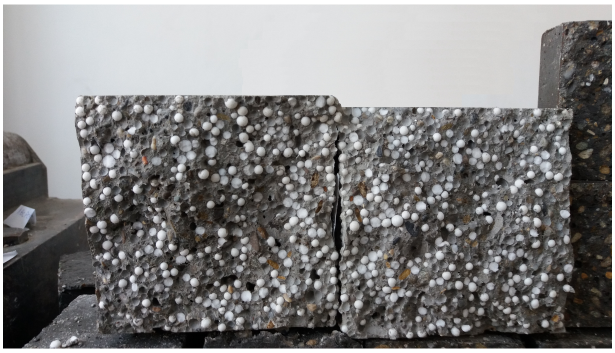

Fig. 2 – MC PO2 quasi-homogeneous distribution of PO granules/ *Distribuția cvasiomogenă a granulelor de polistiren în proba de beton MC PO2* .

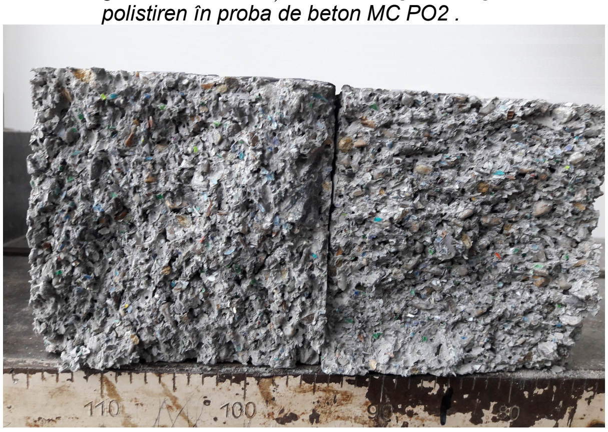

Fig. 3 – MC PET3 quasi-homogeneous distribution of PET particles/ *Distribuția cvasiomogenă a particulelor de PET în proba de beton MC PET3* .

3.3. Flexural strength

The values obtained for flexural strength on the tested specimens are illustrated in Figure 4.

Flexural strength values for both types of micro-concrete mix with waste materials insertion were lower than the ones of the reference concrete mix. The values obtained for the micro-concrete mixes with PO granules were lower by 37% to 69.4% with respect to the reference concrete mix. In the case of micro-concrete mixes with PET particles, the decreasing percentages were between 26.5% and 34.3% with respect to the reference concrete mix. The concrete specimens containing PET aggregate showed higher values of the flexural strength than those with PO granules for all the percentages considered for the substitution of the fine aggregate. The highest value of flexural strength, f_{ti} = 1.61 N/mm^2, was obtained for MC PET1 mix, compared to that of MC PO1 mix, equal to 1.38 N/mm^2.

Based on these results it can be stated that the behaviour of PET concrete mixes in bending is closer to that of the plain concrete mix.

3.4. Split tensile strength

The values obtained for split tensile strength are illustrated in Figure 5.

The split tensile strength values for both types of micro-concrete mix containing waste materials as FNA replacement were lower than the ones of the reference concrete mix. The split tensile strength values for the PO concrete mixes were lower by 44.8% to 75% with respect to the reference concrete mix. In the case of micro-concrete mixes with PET aggregate, the decreasing percentages were between 33.2% and 35.5% with respect to the reference concrete mix. The PET concrete specimens showed higher values of the split tensile strength than those of PO concrete for all the considered aggregate

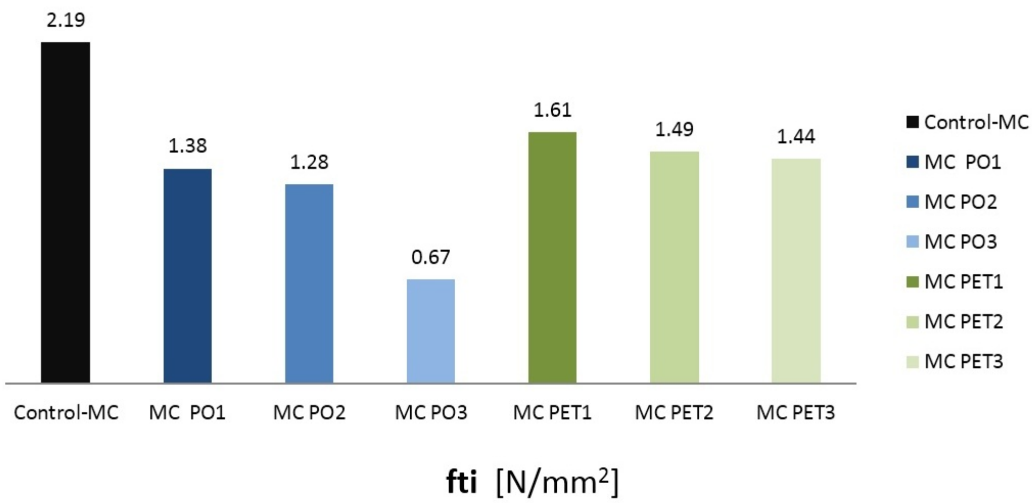

Fig. 4 - Variation of flexural strength for the tested concrete mixes/ *Variația rezistenței la întindere din încovoiere a rețetelor de beton testate* .

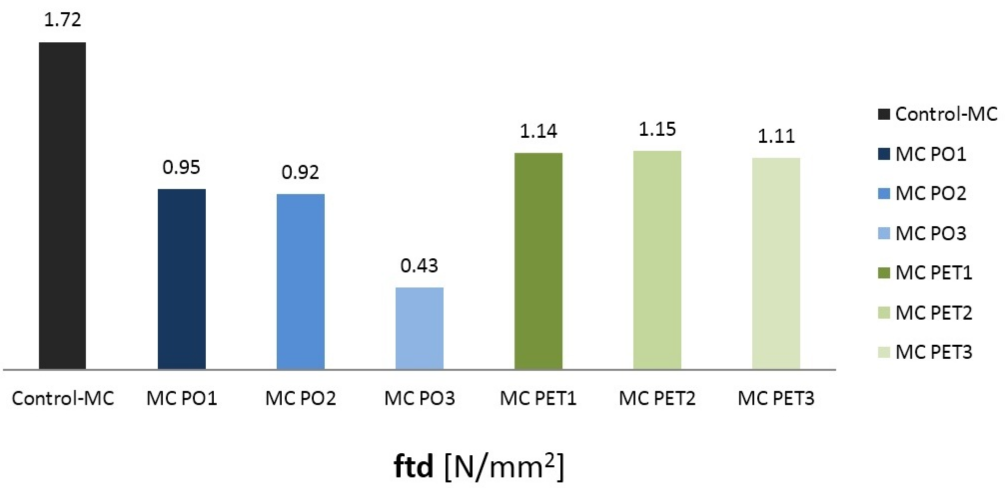

Fig. 5 - Variation of split tensile strength for the tested concrete mixes/ *Variația rezistenței la întindere prin despicare a rețetelor de beton testate .*

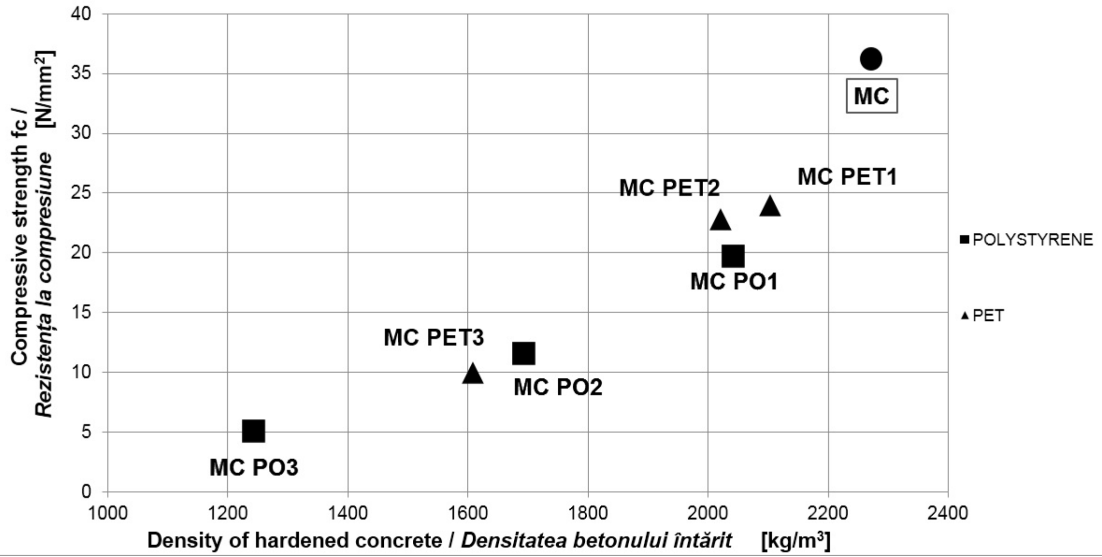

Fig. 6 – Correlation between the dry density and the compressive strength for the tested concrete mixes/ *Relația dintre densitatea betonului întărit și rezistența la compresiune pentru rețetele de beton testate*

substitution dosages. The highest value of the split tensile strength, f_{td} = 1.15 N/mm^2, was obtained for MC PET2 mix, compared to that of MC PO1 mix, equal to 0.95 N/mm^2.

Also in the case of split tensile test, it seems that the behaviour of PET concrete mixes is closer to that of the plain concrete mix.

3.5. Comparative study of the mechanical properties

Figure 6 shows the correlation between the compressive strength values (represented on the Y axis) and the corresponding densities of the concrete specimens determined at 28 days (represented on the X axis). It can be seen that the decrease in the density of concrete specimens is associated with the decrease of the compressive strength. It should also be noted that an increase of the waste materials percentage inserted into the concrete mixes leads to the decrease of the density of hardened concrete, since the waste materials have lower densities than the substituted aggregate.

From Figure 6 it can be observed that for both types of the micro-concrete mixes studied so far, the highest value of the compressive strength was achieved for the mixes with the highest density (MC PET1, MC PET2 and MBCPO1). For the concrete mix (MC PO3) with the lowest density, the lowest value of the compressive strength was obtained.

By comparing the two types of waste, PET aggregate is more rigid and heavier than PO granules, resulting in a heavier and more compact type of concrete even for higher replacement dosages, such as MC PET2 mix, containing 60% insertion of PET aggregate as FNA.

Analysing the relationship between the compressive strength and the flexural strength illustrated in Figure 7 it can be observed that in the

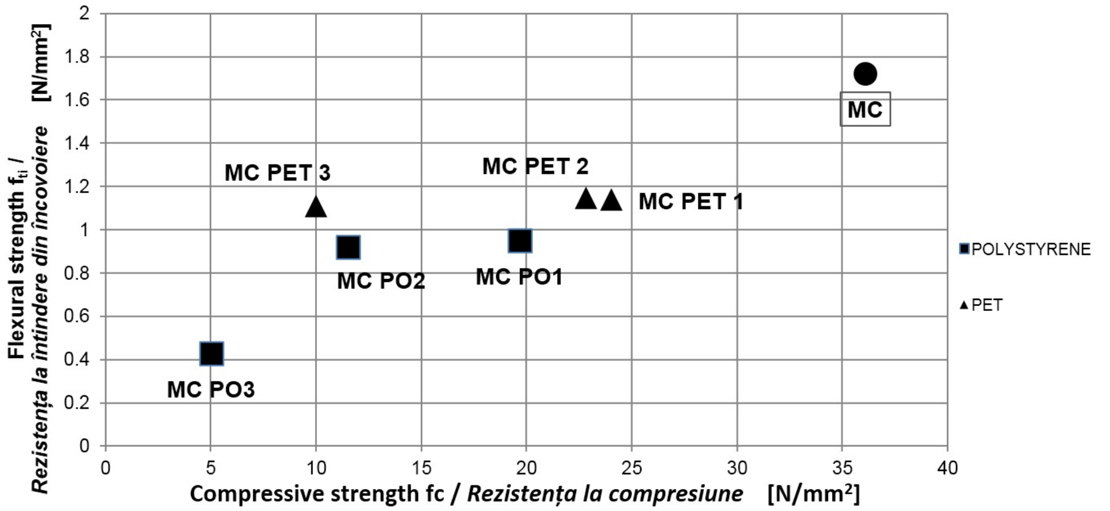

Fig. 7 – Correlation between the compressive strength and the flexural strength for the tested concrete mixes/ *Relația dintre rezistența la compresiune și rezistența la întindere din încovoiere pentru rețetele de beton testate*

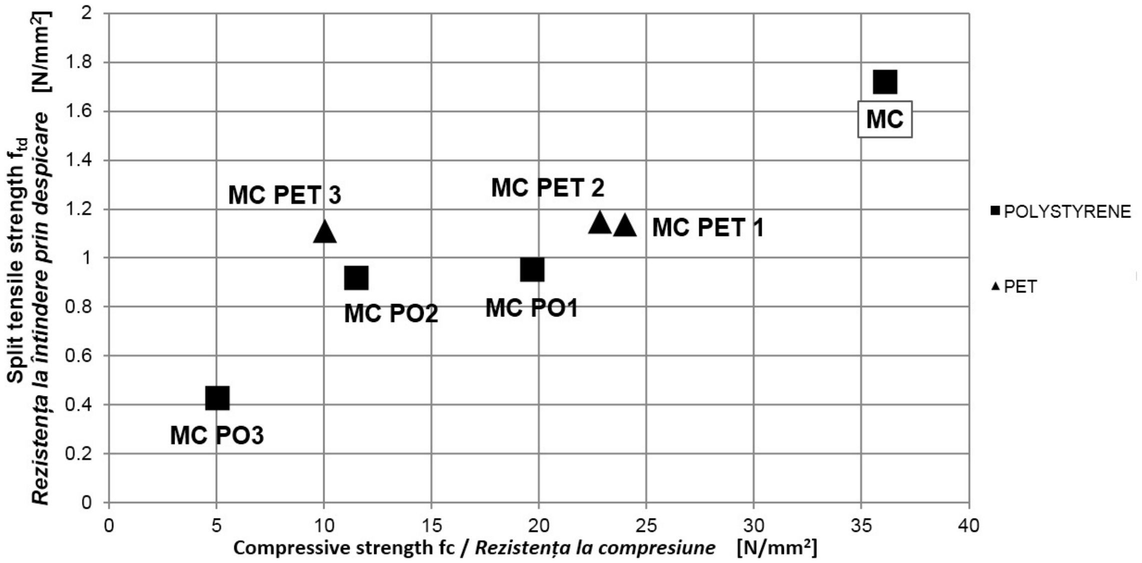

Fig. 8 – Correlation between the compressive strength and the split tensile strength for the tested concrete mixes/ *Relația dintre rezistența la compresiune și rezistența la întindere prin despicare pentru rețetele de beton testate*

case of PET concrete mixes the substituted aggregate dosage does not significantly affect the value of the flexural strength, the values being close to each other even for low compressive strengths (e.g. MC PET3). In the case of micro-concrete mixes with PO granules, the decrease in compressive strength is associated with a decrease in the values of the flexural strength. There is a more pronounced decrease of the flexural strength when the replacement percentage reaches 100%.

From Figure 8 it can be noticed that for the PET micro-concrete mixes, the split tensile strength does not depend on the compressive strength values. For all the analysed mixes, the values of the tensile strength were very close to each other even if the compressive strength decreased significantly. In the PO micro-concrete mixes, up to 60% replacement dosage, the split tensile strength values are not significantly reduced with the decrease of the compressive strength, but only for very low values of f_c.

3.6. Complete characteristic curves of concrete loaded in compression

A very important feature of each newly developed construction material is also its energy dissipation capacity, especially when it is designed for constructions located in seismic areas. The energy dissipation capacity, according to [33], can be established by determining the area between the horizontal axis and the characteristic curve of the material loaded in compression.

In this respect, the complete stress-strain curves for the concrete mixes analysed within this study have been also determined. The experimental program has been carried out using a testing device developed and patented at the Faculty of Civil Engineering and Building Services from ”Gheorghe Asachi” Technical University of Iași.

a) b)

Fig. 9 – Testing of the cylindrical concrete specimens loaded in compression for the complete stress-strain curve: a) MC PET specimen; b) MC PO specimen/ *Testarea probelor cilindrice din beton la compresiune pentru obţinerea curbelor caracteristice complete tensiune-deformaţie specifică: a) probă MC PET; b) probă MC PO.*

For each of the concrete mixes embedding waste material aggregates, three cylindrical specimens (100mmx200mm) have been tested at the age of 28 days. Before the experimental testing, the top and bottom sides of all the specimens have been machined in order to eliminate the effect of friction between the specimen and the testing machine plates, upon the recorded results. As shown in Figure 9, three LVDTs have been placed at 120° on the circumference of the loading plates [25, 34].

The obtained results are summarised in Figure 10, for concrete mixes with PO granules, and in Figure 11, for concrete mixes with PET aggregates.

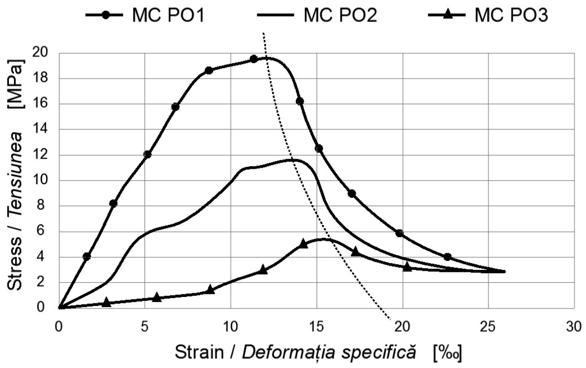

Fig. 10 – Complete characteristic curves for the concrete mixes embedding polystyrene granules, loaded in compression/ *Curbele caracteristice complete la compresiune pentru reţetele de beton cu adaos de granule din polistiren.*

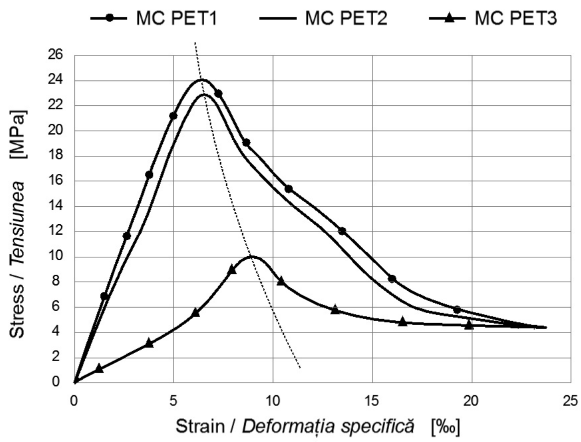

Fig. 11 – Complete characteristic curves for the concrete mixes embedding PET aggregates, loaded in compression/ *Curbele caracteristice complete la compresiune pentru reţetele de beton cu adaos de agregate din PET.*

Analyzing the previous curves, it can be observed that the increase of the recycled materials content in the concrete mixes from 30% to 100% leads to a decrease of the compressive strength. At the same time an increase of the axial strain corresponding to the peak stress is observed. The highest values of the axial strain have been recorded for the MC PO mixes. In case of MC PET mixes, the decrease of the compressive strength is more pronounced when the fine natural aggregate (FNA) replacement percentage reaches the value of 100% (MC PET3 mix). Consequently, the energy dissipation capacity decreases as the FNA replacement percentage increases, the lowest values being recorded in case of MC PO3 mix.

In case of concrete specimens embedding polystyrene granules, loaded in compression, the complete characteristic curves have an unusual shape related to other curves, obtained for the construction materials. This peculiar behaviour occurs due to the uninform dispersion of the polystyrene granules that make the concrete specimens to become less stiff. The well-known brittle failure in case of medium or high strength concrete specimens does not occur any more. Instead of it, a continuous redistribution of stresses is produced.

In case of concrete specimens embedding PET aggregates, loaded in compression, the complete characteristic curves reveal the fact that substituting the fine aggregates in concrete by PET aggregates does not affect too much the value of the axial strain corresponding to peak stress. Also, the recorded values of the peak stress are much higher compared to those of the concrete mixes with polystyrene granules.

Consequently, the complete characteristic curves of the analysed concrete mixes embedding the above mentioned waste materials, under compressive loading conditions, relieve an improved capacity of strain energy absorption compared to the regular concrete mix. Thus, in case of regular concrete subjected to compression, the axial strain corresponding to the peak stress does not exceed 3 ‰, according to [33], while the PET concrete mixes recorded values between 6-9 ‰, and the PO concrete mixes values between 13-16 ‰.

4. Conclusions

Within the current research work, some fly ash concrete mixes with two types of waste material substituting the fine natural aggregate (FNA) have been studied. In both cases, the fly ash replaced 10% of the cement dosage. The fine natural aggregate (FNA; 0-4 mm) has been substituted with polystyrene (PO) granules and recycled PET (polyethylene terephthalate) bottles aggregate in different percentages ranging from 30% to 100%.

For both types of micro-concrete mixes, the short-term mechanical strengths recorded lower values than those of the reference concrete mix.

The micro-concrete specimens with waste PET aggregate (MC PET mixes), showed higher values for all the mechanical strengths compared to those of the micro-concrete specimens with PO granules (MC PO mixes).

For lower dosages of FNA replacement (i.e. 30% substitution of FNA) in both cases of concrete mixes, the mechanical strengths recorded the highest values.

A lightweight concrete was obtained for increased aggregate substitution dosages for both types of waste material.

The MC PET mixes showed a good compressive strength for a 30% substitution of FNA, the obtained results being comparable with the ones of the regular concrete.

Flexural strength and split tensile strength do not decrease as much as the compressive strength, these two characteristics having close values, for up to 60% replacement of the natural aggregate for either types of concrete mixes embedding waste materials.

The complete characteristic curves of the analysed concrete mixes embedding the mentioned waste materials, under compressive loading conditions, relieve an improved capacity of strain energy absorption compared to the regular concrete mixes.

Therefore, the use of the concrete mixes with such waste materials represent a viable solution when the deformation capacity of the material is an important feature.

Because the PET concrete mixes showed higher values of the mechanical properties than the PO concrete mixes for small replacement dosages of FNA, they might be suitable for the construction of load bearing elements.

The PO concrete mixes, having lower mechanical strengths, are recommended for non-structural elements with insulation functions.

All the experimental tests carried out so far, have been focused on the short-term behaviour of the studied materials. The next objective is to continue the experimental program with the assessment of the long-term properties that will be published in a later paper.

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