Concrete with thermal insulating properties - a double benefit in terms of money and environmental protection

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Abstract. A main part of building operating costs and energy consumption is represented by the costs of heating and cooling. To reduce these costs and to obtain an inside thermal comfort, a general solution used nowadays in many countries is the application of supplementary insulation materials on the building envelope. But this means other costs. So, appear the necessity of developing new building materials with better thermal performances than those used up to now for house building. A such type of building material is represented by lightweight concrete made with artificial or natural lightweight aggregates. This study aims to present the characteristics of lightweight concrete made with expanded polystyrene, its disadvantages and, also, its applications. Also, it is presented a natural alternative to expanded polystyrene beads, namely vegetal aggregates made of chopped sunflower stalks.
Key Words: lightweight concrete, expanded polystyrene, vegetal aggregates, sunflower stalk.

Introduction. To have a benefit in terms of money when is about the life cycle of a building, it has to find solutions in order to reduce the building energy usage. This means a lot of possible measures on different directions, from the used material up to intelligent ecological systems of heating and cooling of buildings. A main part of building operating costs and energy consumption is represented by the costs of heating and cooling. Moreover, the present and future tendency is the adoption of more and more constraints regarding the energy efficiency of buildings in order to ensure a reduced environmental impact and economical benefits (Tasmedir et al 2017). According to the update from 2016 of 2012 Energy Efficiency Directive, the European Council established as target the improvement of energy efficiency by at least 30% comparative to 1990 levels (Maree & Riad 2014).

In general, the brick walls need supplementary insulation materials to be applied on, in order to obtain an inside thermal comfort and to reduce the heating and cooling costs. Supplementary insulation materials mean, beside their cost, workmen and scaffolding costs also. So, it is desirable to find ways to develop new building materials with better thermal performances than the ordinary brick.

From the building materials point of view, an energy saving option is the use of products characterized by low heat transfer with the purpose of reducing the heat losses from inside to outside the building and to maintain the same temperature inside (Tasmedir et al 2017). In time, there were developed different types of innovative products for building walls with enhanced thermal properties compared to the normal brick, such as hollow bricks filled with lightweight concrete (LWC), sandwich brick-lightweight concrete or panels of lightweight concrete or very lightweight concrete. A this kind of material is represented by lightweight and very lightweight concrete. Lightweight concrete means a concrete made with lightweight aggregates such as expanded perlite, expanded clay, recycled brick, expanded blast furnace slag, diatomite, pumice, tuff and others and its unit weight is between 800-2000 kg m^{-3}. The very lightweight concrete has the unit weight between 400 and 800 kg m^{-3}, according to the Romanian Technical Regulation C155-2013, Normative for lightweight concrete production. The concrete unit weight is in direct relationship with thermal conductivity (Tasmedir et al 2017).

Lightweight concrete can be obtained by many different ways that imply the lightweight aggregates. The aggregates play a very important role in the concrete properties because they represent around 75% of its volume, so depending on the aggregates properties, the resulted lightweight concrete will have different applications.

The main advantage of LWC is the decreasing of the structural dead load and foundation load (Madandoust et al 2011; Maree & Riad 2014; Tang et al 2014). The smaller mass will diminish the lateral load that is imposed on the building structure during earthquakes and, in this way, the structure damage. This is the reason according to which the global cost of the structure can be decreased by LWC using (Maree & Riad 2014).

The physical and mechanical properties of the lightweight concrete depend on the type and quantity of the used aggregates (Tasmedir et al 2017). In general, lightweight aggregates are porous materials that absorb high quantity of the water from the fresh concrete mix. This leads to supplementary quantity of added water in order to attain an acceptable workability and, also, to a higher cement content to ensure the same concrete strength (Madandoust et al 2011).

Lightweight aggregates can be natural (diatomite, pumice, volcanic cinders, scoria, tuf), or artificial (expanded clay, shale, slate, perlite, vermiculite) (Karakurt & Özen 2017).

Expanded polystyrene (EPS) beads are from the artificial category, being a variant of ultra-lightweight non-absorbent aggregate made of a thermoplastic polymeric material expanded by steam and expansive agents use (Madandoust et al 2011). It is non-toxic, biologically inert and chemically resistant to acids and alkalis (Ferrándiz-Mas & García-Alcocel 2013). Their closed cell structure contains 98% air (Madandoust et al 2011). An EPS slab of density 20 kg m^{-3} has a thermal conductivity value of 0.035W/(m K), measured at mean temperature 10^{o}C (Gnip et al 2012). Water absorption of EPS beads, measured at 1 day, is 0.7% by volume. The expanded polystyrene beads are spherical lightweight aggregates, with particle size between 2 and 8 mm; their density varies in inverse direction with the particle size, and can be between 13 and 54 kg m^{-3}. This small density recommends the EPS beads use in lightweight concrete obtaining. Expanded polystyrene beads are recommended to be used only for insulation purposes due to the significant reduction of the concrete compressive strength (Tasmedir et al 2017). EPS beads are commercially available all over the world (Madandoust et al 2011). EPS can be used to produce gypsum and plaster plates and panels or light inorganic polymeric materials (light geopolymers) (Ferrándiz-Mas & García-Alcocel 2013).

This study aim to present the characteristics of lightweight concrete made with expanded polystyrene, its disadvantages and also its applications. Also, it is presented a natural alternative to expanded polystyrene beads, namely vegetal aggregates made of chopped sunflower stalks.

Polystyrene aggregate concrete - characteristics. The concrete unit weight decreasing means the reduction of its compressive strength and modulus of elasticity. Concrete with expanded polystyrene beads has a smaller compressive strength than the concrete with pumice, expanded perlite or than the autoclaved aerated concrete. The production of lightweight concrete with expanded polystyrene beads requires less water due to smooth surface of the particles and their non-absorbing character (Tasmedir et al 2017).

Lightweight concretes seems to have higher creep comparing to normal weight one, this being dependent on its moisture content and the water absorption ability of the lightweight aggregates. But because EPS beads are impermeable, it is not the case. Nevertheless, the low modulus of EPS beads leads in negligible restraint to deformation and higher creep and compressibility. PAC (polystyrene aggregate concrete) has a high creep potential because the creep of the cement paste matrix cannot be restrained by the low modulus polystyrene aggregates and because the EPS beads can suffer volume changes in time due to their high compressibility. The researches revealed that it increases with the polystyrene aggregates increase in the concrete mix and the ratio between creep recovery and creep strains slightly decreases (Tang et al 2014).

Ferrándiz-Mas & García-Alcocel (2013) studied the durability of mortars made with different types and concentrations of commercial and recycled EPS foam and additives (an air-entraining agent, water retainer additive and a super plasticizer) for a better workability. Their research results showed a decrease of the capillary absorption coefficient according to the increase of EPS foam content and an increase of compressive strength of the specimens subjected to heat cycles and to freeze-thaw cycles. The improved behavior on freeze-thaw cycles is explained by the authors through the fact that the pressure of ice crystallization is partially absorbed by EPS particles. EPS improves the durability of the mortars by ensuring a smaller absorption coefficient than the conventional mortars. The authors concluded that the super plasticizer additives ensure the optimum behavior of EPS mortars regarding the durability after freeze-thaw cycles.

The mechanical properties and the creep behavior of PAC are highly influenced by the curing and storage conditions; its creep recovery does not depend on these conditions. In the precast concrete plants are used steam curing beds to improve the binder strength and the compressive strength of the concrete. The concrete with higher strength will develop less creep deformation at loading, over time. This is a reason that makes PAC to be interesting to be used in precast concrete products. Tang et al. 2014 studied the creep behavior of PAC cured in water at room temperature and in water warmed at 60^0C; the result was a significant decrease in creep strains in the second case. The authors obtained an increase between 101 and 880% of the specific creep of the PAC, compared to reference concrete, the creep rate increasing along with the increase of PA content. The ratios of creep recovery to creep strains were smaller in the case of PAC than the conventional concrete (Tang et al 2014).

Liu et al (2016) studied the impact response of EPS concrete using a drop hammer system. The authors observed that EPS concrete suffered progressive damages, initiated from the upper part to downward and, in final, results in an avalanching collapse of the structure; the EPS concrete capacity of energy dissipation under low-speed impact is independent by the EPS volume fraction in the case of EPS content between 70.20 and 80.30 % by volume. The concrete with 80.30% by volume EPS registered an increase of 18.60% in energy dissipation under 4 m s^{-1} impact.

Regarding the bond performance of glass-fiber-reinforced polymer (GFRP) bars, it was found that it increases with the increasing of compressive strength and density of the concrete with polystyrene aggregates. The failure mode on testing the bond performance between GFRP bars and PAC has two patterns: splitting failure with longitudinal crack and splitting failure only; first pattern become the second along with the decreasing of the concrete density and strength. Higher bond strength is achieved in the cases of shorter embedment lengths and with the increase of concrete density and compressive strength (Tang et al 2008). The concrete with 80% of polystyrene beads have the GFRP bars-concrete bond strength reduced by 35-60% compared to conventional concrete. In the case of steel bars-concrete bond, a concrete with 30% polystyrene beads registered a value of 3 times smaller than the reference concrete (Mo et al 2016).

Polystyrene aggregate concrete - disadvantages. EPS aggregates have a major disadvantage represented by their very easy floatability due to their extremely lightweight and hydrophobic nature, this leading to unsuitable vibration and inefficient distribution of the lightweight aggregates in the concrete mix, these having the tendency to rise up to the concrete surface. To counteract this disadvantage, it is recommended that the EPS aggregates to be used in self-compacted concrete, in this case being necessary to balance the self-compactibility and weight of the self-compacted lightweight concrete (SCLWC). The passing ability of the SCLWC decreases along the increase of EPS percentage of mineral agregates replacement in the mix. The float tendency of EPS aggregates can be solved also by the use of bonding additives or silica fume addition, the result being an improved dispersion of the EPS beads (Madandoust et al 2011).

Another disadvantage of the EPS concrete is the smaller compressive strength than the conventional concrete. Some solutions that lead to the improvement of this property are to reduce the water/cement ratio or to use advanced nanotechnology materials as nano-SiO_2, for example. Nano-SiO_2 represents an activator that improves the pozzolanic reaction and a better solution to be applied regarding the concrete workability than water/cement ratio reduction (Madandoust et al 2011).

The uneven dispersion of the EPS aggregates in concrete is also a problem that is more frequently met in concretes with the density smaller than 1900 kg m^{-3} (Madandoust et al 2011).

Polystyrene aggregate concrete - applications. The PAC applications can be structural and non-structural, depending on the EPS percentage used in the concrete mix. For structural purposes, PAC density must be in the range of 1410-2100 kg m^{-3} and with a compressive strength of minimum 17 MPa (Tang et al 2014). Structural lightweight concrete is a very important material in building industry due to its cost effectiveness and its advantages (Maree & Riad 2014). Structural LWC with up to 22.5% EPS, with a higher density than 1900 kg/m^3 is a self-compacting concrete (Madandoust et al 2011). Maree & Riad (2014) developed a LWC with polystyrene foam particles (PF-LWC), combining the characteristics of a normal density concrete, cellular concrete and high workability concrete. The partial replacement of normal weight aggregates with polystyrene foam particles lead to reduction of the concrete's unit weight but maintained its strength. The developed concrete had a dry unit weight of 18.50 kN m^{-3}, smaller with 15-20% than the normal weight concrete, and a high workability, this reducing the compaction cost. The authors obtained PF-LWC with a dense and homogeneous hardened internal structure, with minimum voids and uniform concrete strength; these characteristics lead to a high level of finish and durability of the building structure (Maree & Riad 2014).

As non-structural applications of PAC can be mentioned the insulating screens and rendering, non-load bearing elements or thermally load bearing courses of highway pavements (Tang et al 2008).

EPS concrete has applications also in highway foundations and marine platforms. Its energy absorption property, good resistance to corrosion, to water attack and to severe variation of service temperature recommend it to be used in military or civilian protective structures (Liu et al 2016). Mortars with EPS foam represent a sustainable solution to be used in masonry, stucco and plaster mortars (Ferrándiz-Mas & García-Alcocel 2013).

EPS represents 0.1% of total municipal solid waste that has to be recycled. Its use in concretes and mortars is a way to solve an environmental concern related to waste disposal. A high content of EPS waste can be used in masonry, rendering and plaster mortars (Ferrándiz-Mas & García-Alcocel 2013).

Sunflower aggregates as sustainable alternative to EPS beads from concrete mix. A natural, ecological and sustainable alternative for artificial aggregates of expanded polystyrene can be represented by the vegetal aggregates of sunflower stalks. The justification for this is represented by the fact that the marrow from the structure of the sunflower stalk is composed of 95% of the air (Chabriac et al 2016), a value very close to that of the EPS beads.

The sunflower stalk is made up of a wooden part, peripheral, called bark, and a central, very light, compressible part, called marrow (Chabannes et al 2015). The bark is composed of cellulose, lignin and cutin, with a density of about 500 kg m^{-3}. Marrow of the sunflower stalk is not a wood material; it is composed of 95% air (Chabriac et al 2016). It accounts for about 60% of the sunflower stem volume. Sunflower aggregates have a low bulk density of 105 ± 2 kg/m^3 and a water content of 9.4%, measured at 20±2°C and 35±5% relative humidity. Their thermal conductivity is quite close to that of EPS beads, 0.05W/mK, being mainly provided by the marrow (Chabannes et al 2015).

Sunflower stalks can be processed by chopping in order to be used in the ecological concrete composition as lightweight aggregates (Chabannes et al 2015; Gradinaru et al 2017). Due to their increased porosity and their internal structure, they have the disadvantage of a high water absorption and retention capacity of 550% after 2 days of soaking (Chabannes et al 2015). This leads to the decrease of the mechanical properties of the concrete on the principle of a poor interface link between plant aggregates and cement paste. On the other hand, the high water absorption of the sunflower stalks can be advantageous when these vegetal aggregates are used in concrete compositions in hot climates because they supports internal water supply of the concrete, in order to avoid the shrinkage.

Research on concrete with sunflower stalks is relatively low. The concrete with sunflower aggregates has been shown to have improved acoustic and thermal properties (Maree & Riad 2014). Replacing mineral aggregates with sunflower plant aggregates leads to a decrease of the concrete mechanical properties, mainly due to a water/cement ratio that is higher than in the case of the standard concrete, but also due to the low density of the plant aggregates, that implies a high compressibility. By applying a treatment to reduce the water absorption of plant aggregates, such as sodium silicate solution, the water/cement ratio from the concrete mix was reduced; also, a significant improvement of the concrete compressive strength by 146.5% and of its tensile strength by 79% compared to the untreated plant aggregate concrete was registered, for a 50% by volume replacement rate of the mineral aggregates (Gradinaru et al 2017).

Comparative to standard concrete, lignocellulosic concretes are characterized by a higher permeability and lower thermal conductivity, density, and compressive strength. From compressive strength point of view, these types of concretes are not recommended as bearing materials; they are suitable as insulation materials, reducing the heating and cooling consumptions for buildings (Nozahic et al 2012). They also have promising acoustical characteristics (Binici et al 2014; Chabriac et al 2016).

Conclusions. In this paper were presented some characteristics of lightweight concrete made with expanded polystyrene and sunflower stalk aggregates. The following conclusions can be drawn:

- concrete with expanded polystyrene beads has a smaller compressive strength than the concrete with pumice, expanded perlite or than the autoclaved aerated concrete;
- EPS beads have a low modulus that leads in negligible restraint to deformation and higher creep and compressibility and to a high creep potential of PAC;
- an increase of EPS foam in concrete mix results in a decrease of the capillary absorption coefficient according to the increase of EPS foam content and an increase of compressive strength of the specimens subjected to heat cycles and to freeze-thaw cycles;
- the mechanical properties and the creep behavior of PAC are highly influenced by the curing and storage conditions;
- the bond performance of glass-fiber-reinforced polymer bars increases with the increasing of compressive strength and density of the concrete with polystyrene aggregates;
- EPS aggregates present very easy floatability due to their extremely lightweight and hydrophobic nature, this leading to unsuitable vibration and inefficient distribution of the lightweight aggregates in the concrete mix;
- the PAC applications can be structural and non-structural, depending on the EPS percentage used in the concrete mix;
- a natural alternative for artificial aggregates of EPS beads can be represented by the aggregates of the sunflower stalk. Their thermal conductivity values are quite close;
- sunflower stalks can be processed by chopping to be used in the ecological concrete composition as lightweight aggregates. Replacing mineral aggregates with sunflower plant aggregates leads to a decrease in the mechanical properties of concrete,

but by applying a treatment to reduce the water absorption of plant aggregates can be obtained a significant improvement of the compressive and tensile strength of the concrete;

- sunflower concrete is not recommended as bearing material, being suitable as thermal and acoustic insulation material.

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