ISSN 1330-3651(Print), ISSN 1848-6339 (Online)
UDC/UDK 666.973.2.015.8:678.746.2

LIGHTWEIGHT CONCRETE WITH RECYCLED GROUND EXPANDED POLYSTYRENE AGGREGATE

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Original scientific paper
This article describes the possibilities in using recycled, ground expanded polystyrene (EPS) as aggregate for lightweight concretes as thermal insulation or as a structural concrete. The article presents a rich experience and provides explanation on the benefits of using ground EPS aggregate compared to virgin EPS beads in making lightweight concrete. A reinforced lightweight concrete structure made by SU-styrol – technology is also presented. Although the compressive strength of this lightweight aggregate concrete is six times less than that of ordinary concrete, the deformation (deflection) and the load-bearing capacity of the reinforced slab and that of the Su-styrene reinforced concrete and of the ordinary reinforced concrete slab are the same, which is very interesting. The authors have provided a physical interpretation of this behaviour, with the conclusion that the reinforced SU-styrol lightweight concrete is compatible with steel, unlike ordinary concrete. The authors hope that this paper will be a positive motivation for other researchers to explore this interesting topic.

Keywords: *ground polystyrene, insulation, lightweight concrete, recycled, stress, strain*

Laki betoni s recikliranim mljevenim agregatom od ekspandiranog polistirena

Izvorni znanstveni članak
Ovaj rad govori o mogućnostima uporabe mljevenog ekspandiranog polistirena kod proizvodnje lakih betona s primjenom od termoizolacijskih do konstruktivnih zahtjeva. U radu se prikazuje bogato iskustvo i daje jasno objašnjenje prednosti mljevenog ekspandiranog polistirena u odnosu na EPS kuglice kod izrade lakih betona. U radu je prikazan armirani laki beton po tehnologiji SU-stirol s tlačnom čvrstoćom koja je šest puta manja od čvrstoće običnog betona. Deformacija (progib) i nosivost toga istog SU-stirol betona je potpuno identična običnom betonu mnogo boljeg kvaliteta, što nije potpuno logično. Autori rada su dali fizikalno tumačenje takvog ponašanja sa zaključkom da je laki armirani SU-stirol beton kompatibilan čeliku za razliku od običnog betona, koji to nije. Autori se nadaju da će ovaj rad biti pozitivan poticaj drugim istraživačima da istražuju ovu zanimljivu temu.

Ključne riječi: *čvrstoća, dilatacija, izolacija, laki beton, mljeveni polistiren, reciklirani*

1 Introduction

Styropor® or Styrofoam® is expanded polystyrene (EPS) that consists of about 98 % air and 2 % polystyrene. Thanks to its extremely low density, it is primarily used for packaging food and fragile products as well as an insulating material. Although the constant increase in the price of crude oil has a direct impact on the price of EPS also, still the production continues to grow. According to statistics, on a volume basis, EPS forms nearly 7 % of solid waste in landfills in some countries. Since it is a non-biodegradable material, EPS contributes significantly to the pollution of the environment, and in many European countries these products are being totally banned from landfills, with the originating manufacturer being responsible for their collection, recycling, or disposal.

Expanded polystyrene aggregate concrete (EPSAC) or the so called "Styropor-beton" was originally developed by BASF in West Germany during the 1950′s, shortly after their invention of expanded polystyrene. In 70’s lightweight aggregate concretes (LWAC) with EPS beads began to be developed and applied throughout the world. Since EPS beads are very hydrophobic, ordinary and homogeneous mixing of such concrete was always difficult. The problem was usually solved by previous chemical treatment of beads to increase their stickiness to the cement paste (e.g. epoxy resins, polyvinyl propionate solutions) or by increasing the cohesion in fresh concrete by adding silica fume or fibres [1].

Expanded polystyrene aggregate concrete made with virgin EPS beads (Fig. 1) is not widely used. Due to the hydrophobic behaviour of virgin EPS beads and since they are few dozen times lighter than water, EPS concrete is prone to segregation during mixing and casting. Another reason for poor application is the high cost of virgin EPS beads, the semi-products for producing new packaging and insulating materials - in contrast to recycled EPS which is a cheap waste material.

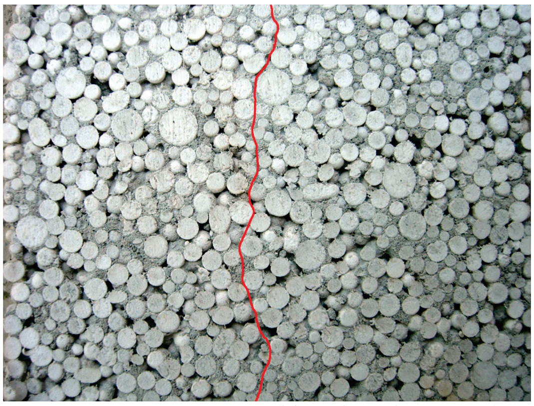

Figure 1 EPS-aggregate concrete with a schematic presentation of the way of heat transfer

Table 1 Properties of different types of lightweight aggregates

	Solid density / kg/m^3	Bulk density / kg/m^3	Water absorp. by weight / %	Part. porosity / %
Ground EPS	900 ÷ 1050	5 ÷ 15	50	95
Expanded Glass	2200 ÷ 2600	175 ÷ 875	4 ÷ 22	35 ÷85
Saw Dust	300 ÷ 700	120 ÷ 200	10 ÷ 35	35 ÷ 55
Expanded Clay	2400 ÷ 2600	300 ÷ 900	2 ÷ 20	40 ÷ 75
Perlite	2200 ÷ 2400	30 ÷ 150	10 ÷ 30	80 ÷ 95
Pumice	1500 ÷ 2000	450 ÷ 880	20 ÷ 30	40 ÷ 90

Next to EPS aggregate and sometimes fibre, cement is a component that participates most in the final cost of EPSAC. In previous research works, mixtures were often used with more than 500 kg/m^3 or even more than 600 kg/m^3. A large amount of cement in concrete made with EPS aggregate increases the cost irrationally making it unpopular for practical use. Good adhesion between the aggregate and cement paste, compactness, better workability and acceptable strength of EPSACs can also succeed, using cement in smaller quantities, as it will be shown.

Besides the economic aspect, a large amount of cement (especially in the case of CEM I and CEM II) is in contradiction with the principles of sustainable development and environmental protection. Therefore, priority should be rather given to blast furnace and pozzolanic cements and composites, and when it is possible, even to the use of fly ash instead of sand [2].

Researches on lightweight aggregate concrete with EPS beads have been carried out since 1984 at the Faculty of Civil Engineering in Subotica. Vast experience was gained from tests made in the Laboratory for Building Materials & Constructions, and applications of this type of concrete led to the first patent report on this subject in 1998 [3], where recycled, shredded EPS was used as a lightweight aggregate instead of EPS beads.

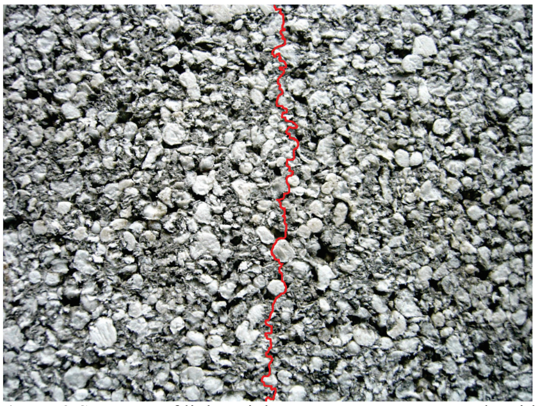

Figure 2 Structure of lightweight aggregate concrete made with recycled, ground EPS with a schematic presentation of the way of heat transfer

This change in aggregate caused a big difference not only in physical and mechanical characteristics of LWAC but also made a significant technological improvement in production technology by simplifying it at the same time. By using recycled EPS aggregate, segregation does not appear any more. Many variations of lightweight concrete mixes with recycled, ground EPS aggregate were designed and used for very wide and diverse application: lightweight mortars with a density of 350 kg/m^3, floor screed, insulating-formwork masonry units, reinforced lightweight concrete walls and reinforced lightweight concrete slab constructions for the range of up to 6 m. Lightweight concrete panels with one outer steel plate were used to build a 1500 m^2 factory (Fig. 6).

2 Experiences and practical applications of concrete made with ground EPS

Lightweight concretes made with recycled ground expanded polystyrene by patented technology of the Faculty of Civil Engineering in Subotica [3, 5] are light, highly malleable materials in their fresh state. In hardened state they can have significant plastic deformation without a classical, brittle failure mechanism that normal weight and other lightweight concretes usually have. Henceforth this type of concrete will be called "SU-styrol lightweight concrete" (SSLC). The density of SSLC can be designed from 350 kg/m^3 to 1600 kg/m^3 and it will be the function of its physical and mechanical properties. Lower density will result with a lower coefficient of thermal conductivity and lower strength, and vice versa.

The ground recycled EPS, which was used, is an industrial waste material, gained by cutting EPS blocks in thin insulation boards and other shapes. In the process of grinding by mills, EPS beads are shredded into pellets with open pores in which water and cement paste can enter. This way, in the process of mixing, ground EPS beads are not bound to float anymore and are not prone to segregation in the cement paste. They are properly deployed in a homogeneous mix of lightweight concrete (Fig. 2). The result is a very lightweight plastic mixture with good workability whose upright feedbacks were received from builders with practical experience (Fig. 3).

Figure 3 Semblance of fresh SSLC made with ground recycled EPS aggregate

Figure 4 Fresh lightweight mortar made with ground recycled EPS aggregate during its application

As mentioned above ground recycled EPS has open porosity, giving it high advantage compared with virgin EPS beads. The order of the dosage components in the mixer is irrelevant and the additional chemical treatment of the beads is not needed. SSLC made with ground recycled EPS aggregates has good adhesive properties and is highly malleable making it possible to be applied as lightweight mortars for rendering even in a single layer with thickness of up to 50 mm (Fig. 4).

In the case of LWAC made with whole virgin EPS beads, the problem of cohesion within the concrete often occurs during the mixing and placing, as the migration of lightweight EPS beads towards the surface of fresh concrete is apparent. In SSLC, this type of upward segregation of lightweight aggregate in the concrete is not observed even when the density of concrete is greater than 1800 kg/m^3, i.e. the volume fraction of lightweight aggregates is very small ($V_{EPS} < 10$ %).

As already mentioned, there are a number of buildings in which SSLC made with ground recycled EPS aggregates was applied with great exploitation characteristics. One example is the production of "Eco-keko" formwork-insulation building blocks, applicable for reinforcement and filling with concrete [6, 17]. These hollow blocks were made by vibro press machine using SSLC with dry density of 500 to 550 kg/m^3 (Fig. 5).

Figure 5 "Eco-keko" formwork - insulation hollow blocks for masonry made from SSLC (left) and a reinforced, core-filled concrete block structure made with these blocks

Another example of the application SSLC by technology of FCE Subotica is an industrial building in Subotica (Fig. 6). The wall and roof panels were made with SSLC by filling in a profiled metal sheet. The inside surface of the building was composed of hardened SSLC while the profiled sheets were on the outside. This way, an excellent thermal and sound insulation is achieved, which is very important from the aspect of industrial noise and vibration reduction. The SSLC is made with ground EPS and due to its open porosity the lightweight concrete is an excellent sound absorber.

Figure 6 Wall and roof panels made with SSLC in profiled metal sheets

In addition, SSLC efficiently absorbs water vapour which is a very important feature in summer conditions, because additional ventilation of air is needed only for dedusting of the space. These panels are also 120 minutes fire rated. Lightweight concrete with recycled ground EPS was even used as fireproof material (Fig. 7 "Vulcanus" - 120 minute fire rated door) [4].

Particularly important applications of SSLC are floor screeds. This way, the weight of the screed can be lessen by 60 % and at the same time the insulation is improved. With a common, thin vibroinsulating layer under the SSLC, sound transfer to the floor slabs can be reduced drastically.

Figure 7. Fire resistant doors of 120 minutes - Technology SSLC

Table 2 Comparing SSLC with ordinary and gas concrete

Properties	SSLC	Gas concrete	Normal weight concrete
Dry density / kg/m^3	350 ÷ 1100	400 ÷ 600	2200 ÷ 2400
Thermal conductivity coefficient λ / W/(m·K)	0,074 ÷ 0,26	0,09 ÷ 0,17	1,7 ÷ 2,3
Sound insulation and absorption	Good absorption, hence open porosity	Weak absorption	Sound reflection Echo-effect
Fire resistance	Highly resistant	Highly resistant	Incombustible - Conducts the heat
Frost resistance	Very resistant	Poorly resistant	Conditionally resistant

3 Structural lightweight concrete with ground EPS aggregate used as reinforced concrete slab structures

Investigations of SSLC application were made using the mix design given in Tab. 3.

Table 3 Target mix design

Component material	kg
Cement CEM II/B-M(S-V-L)32.5R	350
Sand "Moravac" 0/4 mm	600
Water	250
Polypropylene fibers Sika Fibers length 12 mm	1
Ground EPS aggregate (density 15 kg/m^3 - before grinding)	16,5

The ground EPS aggregate we used had the bulk density $\gamma_{GR.EPS}$ = 25 kg/m^3 and a granulation 0/5 mm (Fig. 8).

CEM II / B-M (SVL) 32.5R cement was used because in Serbia this is the most common type. For lightweight structural concretes, it would be more appropriate to use higher class cement (42.5 or even 52.5), but for lightweight insulating concretes and mortars, the use of higher class cement is not crucial. Since they have a large specific surface area, for these types of lightweight concretes, cements with lower specific gravity should be used; practically additional aggregate (fine and crushed) in the mixture is not needed any more because it would only decrease the heat insulation properties and increase the weight of the concrete.

The density of fresh lightweight concrete was 1216,5 kg/m^3. Laboratory tests were made to investigate the physical and mechanical properties of lightweight concrete made with ground EPS aggregate and the results were compared with other similar studies with EPS aggregate concrete.

In these research references, virgin EPS beads were used as aggregate with similar grain size (0 ÷ 4 mm) and density. In regard to lightweight concretes, one of the most important features is their density. All mechanical and physical parameters are related with the density and porosity of concrete. From research references, design mixes and their properties, with the closest density, were compared in Tab. 4 since the classification of lightweight concrete concerns its density.

Figure 8 Ground expanded polystyrene aggregate

Higher water-cement ratio in SSLC by patented technology FCE Subotica is achieved because ground EPS has opened pores in which water can partly enter.

Table 4 Mixes and basic characteristics of SSLC used in this study, compared with results of other studies with virgin EPS-aggregate concretes [2, 7, 8, 9]

Results		SSLC by patented technology of FCE Subotica	Lightweight concretes with virgin EPS – beads from other research studies			
			[7]	[8]	[9]	[2]
Design mixes	Cement / kg	350	550	250	350	450
	Sand 0/4 / kg	600	330	750	500	340
	EPS aggregate / kg	0,66	0,49	0,51	0,53	0,53
	Water / kg	230	200	120	175	180
	PP fibers / kg	1	6,6	-	-	-
	w/c ratio	0,65	0,364	0,46	0,5	0,4
Wet density at age 28 days / kg/m^3		1090	1130	1076*	1035,53	1040
Compressive strength at age 28 days, f_{cs} / MPa		5,67	7,73	2,53	6,2	6,7
Flexural strength at age 28 days, f_{fs} / MPa		1,72	2,52	0,82	0,39	n/a
f_{fs}/f_{cs}		0,31	0,33	0,32	0,06	n/a
Modulus of elasticity / MPa		4135	6600	n/a	n/a	n/a
Drying shrinkage at age 28 days / mm/m		0,9	n/a	n/a	n/a	1,3
Freeze/thaw resistance after 100 cycles		0,92	n/a	n/a	n/a	n/a

It was noted that SSLC is not so hydrophobic and is saturated after a few days. For concrete with a given mixture, measured water absorption was w = 7,05 %. This result is comparable with ordinary normal weight concrete and usually has less than other types of lightweight concrete. Measured water absorption helps predict the reinforcement in SSLC that can protect from corrosion in a similar way the ordinary normal weight concrete can. Although this is a lightweight concrete, logical explanation for a low absorption can be explained through hydrophobic nature of EPS material, which is difficult for water and water vapour to pass.

The strength of lightweight concrete is much lesser than that of normal weight concrete. Most of its volume consists of pores, voids in the structure of concrete (e.g., cellular concrete) or within the aggregate. Lower density favourably affects many properties of lightweight concrete (thermal conductivity, sound insulation, weight reduction, etc.), which is the original goal and their development. The strength of lightweight concrete is often a secondary requirement in design, but it is also important (e.g., for handling units, panels). Compressive strength tests were made on 150 mm cubic specimens at age of 1, 3, 7, 14 and 28 days. In addition to compressive strength tests, flexural and shear strength testing was also performed, at the age of 28 days of specimens, during which they were cured in water at a temperature of 20 ± 2 °C, done in accordance to the standards. The gain in strength of tested SSLC is a bit slower than normal-weight concrete as it is shown in Fig. 9. In the case of lightweight aggregate concrete this cannot be considered as a general rule [10].

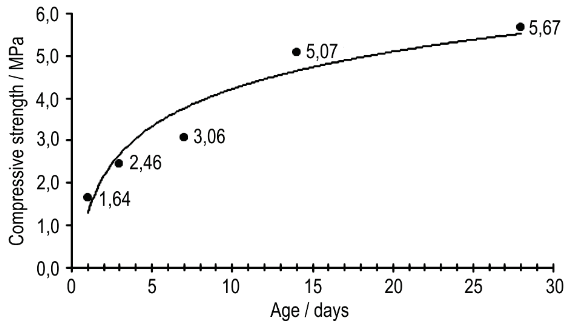

Figure 9 Compressive strength versus time

Flexural strength was tested according to ISO 4013 center-point loading method, on the sample size 40 × 10 × 10 cm (Fig. 10).

Shear strength is rarely tested, so results cannot be compared with tests made on LWAC with EPS beads. Shear strength test was performed on prismatic specimens 40 × 10 × 10 cm, with concrete age of 28 days, Fig. 10. The measured shear strength of τ = 1,7 MPa is very close to the value of flexural strength. Shear and flexural strengths are related in the same way in normal weight concrete.

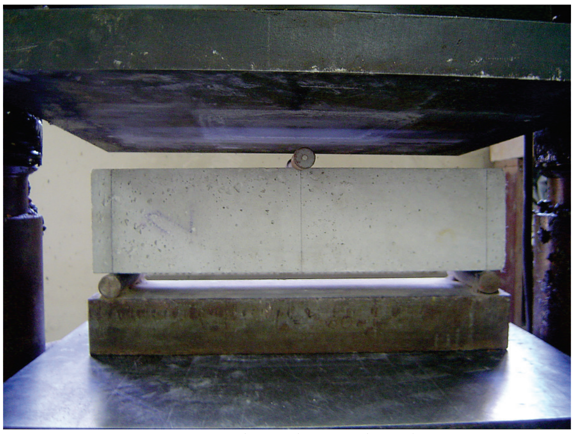

Figure 10 Flexural strength testing

Drying shrinkage of concrete was tested according to SRPS U.M1.029 on prismatic samples at a temperature of about 20 °C and a relative humidity of ~50 %. Values listed in Tab. 4 were measured after 2 months and can be considered as the final values. Certainly, lightweight concrete has higher shrinkage than normal weight concrete, due to EPS beads high porosity and negligible modulus of elasticity; it has been also confirmed by measurements. However, the measured value of shrinkage in SSLC is less than that in concrete made with virgin EPS beads [2]. This difference may be prescribed to the effect of reinforcement with polypropylene fibres but also to a better adhesion within the structure of concrete with ground EPS aggregate.

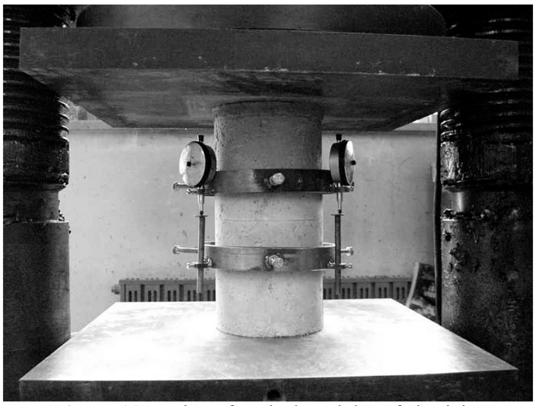

Figure 11 Testing of statical modulus of elasticity

Testing the modulus of elasticity, beside the flexural strength testing, best showed the beneficial contribution of fibres and confirmed a significant improvement in mechanical properties of SSLC using ground EPS aggregate. Static modulus of elasticity in SSLC was determined on standard cylindrical specimens with dimensions ∅150×300 mm, Fig. 11. The determined value was E = 4135 MPa. The static modulus of elasticity of concrete in practice is rarely measured but rather calculated based on the characteristic compressed strength of the concrete or in better case, on the basis of uniaxial tensile strength testing. Based on Eurocode 2 for this type of light concrete (using aggregate with open porosity) empirical relation cannot be applied. Interestingly however, in calculating the density of SSLC concrete and its compressive strength at age of 28 days, the predicted modulus of elasticity, E_{lcm} = 4250 MPa is very close to the measured values [11].

For the SSLC (made with ground EPS aggregate) of density γ = 560 kg/m^3, thermal conductivity coefficient λ = 0,0763 W/(m·K) [12] was measured. For EPS aggregate concrete, made with virgin EPS beads, of the same density, the conductivity coefficient λ = 0,14 W/(m·K) [13] was determined [16].

Unfortunately, thermal conductivity for given design mixture of SSLC with oven dry density γ = 1090 kg/m^3, was not measured. Still, it can be evaluated based on EN 1745 and results of previous measurements on SSLC. The estimated thermal conductivity coefficient in this case would have a maximum value of λ = 0,15 W/(m·K) [14]. It can be found in other scientific articles that for EPS concrete density from γ = 1000 kg/m^3 to 1050 kg/m^3 were measured values of λ = 0,26 ÷ 0,31 W/(m·K), respectively [2, 15]. As measurements [12] confirmed, SSLC has a significantly lower coefficient of thermal conductivity opposed to lightweight concrete with whole EPS beads [13]. The logical explanation for it is that heat passes through the SSLC in a much longer and wider way, or in other words, the thermal resistance of this material is much better, an important advantage of SSLC as insulating material (Figs. 1 and 2).

In Fig. 13 testing of two different slab model is shown. In Fig. 13a is a reinforced slab model (60 cm wide and 400 cm long) made with SSLC by FCE Subotica – technology, with a design mix given above and a compressive strength of 5,67 MPa and with rebar surface in tension area 2,2 cm^2. The second model (80 cm wide and 400 cm long), in Fig. 13b is a classical semi-precast FERT floor slab made of concrete with compressive strength of 34,3 MPa with rebar surface in tension area 1,53 cm^2. The cross-sections of both models are shown in Fig 12.

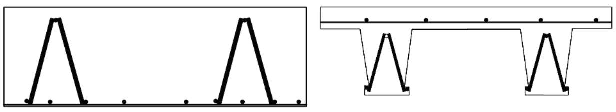

Figure 12 Cross-section of the reinforced slab made with SSLC (left) and ordinary semi-precast FERT floor slab (right)

The thickness of both models was 20 cm. With interesting result, which can be seen even in Fig. 13, in spite of very large differences in the compressive strengths of concrete in two models, practically the load bearing capacity and deflections are equal. As mentioned, in reinforced slab made with SSLC the measured compressive strength of lightweight concrete was 5,67 MPa and had a density of 1090 kg/m^3. The measured deflection at midspan of plate was 0,92 cm = L/413 at total load expected in exploitation of 4,3 kN/m^2. At maximum load, which is 6 kN/m or per m^2 is 10 kN/m^2, the load deflection was not measured – not only is it risky for the operators in testing but also for the measuring instruments. It can be clearly visible in Fig. 13 that deflection of the slab was very small at such amount of load, even if the SSLCs compressive strength was only a fraction of the strength of ordinary concrete.

Figure13 a) Testing of 4 m span reinforced concrete slab made with SSLC and b) an ordinary semi-precast FERT floor slab with the same span range

In the second model of Fig. 13b which is an ordinary semi-precast FERT floor slab, the measured compressive strength of concrete was 34,3 MPa. Deflection at midspan was 0,91 cm = $L/414$ at normal working load of 5,5 kN/m^2. The conclusion is that in model Fig. 13a, the stress distribution in SSLC and reinforcement is not similar like in ordinary concrete and rebar in traditional FERT- floor slab construction under bending load (Fig. 13b). SSLC is very flexible and deformable. Strain values of lightweight concrete at elastic stage are much closer to strain values in rebar contrary to ordinary concrete which is less deformable compared to steel (Fig. 14). Strain in SSLC can follow the deformations in steel rebar much better without cracks not only in elastic stage but even in the plastic stage.

This conclusion is clearly indicated in Fig. 14a) where the neutral axis in the section of plate is located around the middle of the height, opposed to ordinary concrete where the neutral axis is closer to the zone of compression in concrete (1/3 to 1/4 of the height of concrete slabs). This example represents a positive provocation for all those who are involved in concrete and reinforced concrete structures. Ordinary concrete and steel when observed separately are completely different, incompatible materials, especially regarding their strains. This incompatibility has an unfavourable effect when combined into one material called reinforced concrete. Steel in the tension area of concrete deforms to the extent the concrete cannot follow and cracks appear and run until the neutral axis (Fig. 15).

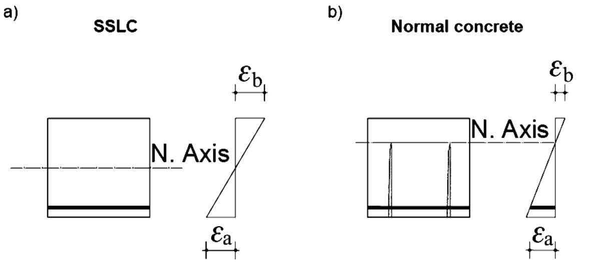

Figure 14 Schematic representation of strain distribution in concrete and reinforcement in models with a) SSLC and in b) conventional concrete

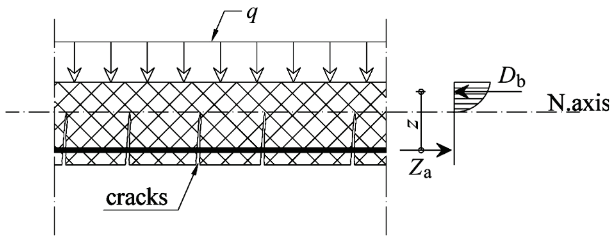

Figure 15 Stress distribution of ordinary reinforced concrete

4 Conclusion

The idea that expanded polystyrene beads represent potential aggregate for making lightweight concrete is present for many years. It continuously develops and increases the field of applications. Although EPS lightweight aggregate concrete offers many advantages, the troubles at mixing, the weak cohesion between aggregate and cement paste, the difficulties during placing, etc., are just a few to mention the problems concerning it and offered solutions only made the production even more complex, more expensive and more experience-dependent. By using recycled ground expanded polystyrene aggregate by the technology of FCE Subotica, many disadvantages were overcome. In addition, as the analysis showed, the use of ground EPS aggregate, in even a relatively small quantity of cement, can result in lightweight concrete (SSLC) which possesses mechanical characteristics that provide opportunities for all-round use. Particularly interesting is the application of SSLC as load-bearing reinforced concrete floor. Compatibility in terms of stress and strain between SSLC and reinforcing steel is much better compared to the latter and ordinary concrete.

This article was written with the intent to spread the idea of application of this type of lightweight concretes. SSLC was tested and already applied but it should be spread in the construction market more. We hope that other researchers would check and confirm our results and that they will join in and test SSLC in a wider range of analysis.

It should be emphasized that this recycled aggregate, a waste material, which in the 21st century, from the aspects of sustainable development and environmental protection, special importance should be given to the resulting product, a lightweight concrete with EPS aggregate. Using SSLC we can count on the benefits of insulating lightweight concrete, with simpler production and application, using environmentally friendly and justified material.

Acknowledgements

The work reported in this paper is a part of the investigation within the research project III 42012 "Energy efficiency enhancement of buildings in Serbia and improvement of national regulative capacity for they are certification", supported by the Ministry for Science and Technology, Republic of Serbia. This support is gratefully acknowledged.

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