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**Bede, Natalija; Torić Malić, Neira**

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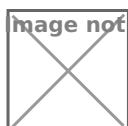


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**Natalija Bede**, natalija.bede@uniri.hr, Faculty of Civil Engineering University of Rijeka  
**Neira Torić Malić**, ntoric@uniri.hr, Faculty of Civil Engineering University of Rijeka

## EXPERIMENTAL INVESTIGATION ON LWC WITH COMPLETE REPLACEMENT OF COURSE AGGREGATE BY EPS BEADS

### *Abstract:*

In this paper, expanded polystyrene (EPS) lightweight concrete (LWC) was investigated. The main aim was to design EPS LWC with the specified density of  $1200 \text{ kg/m}^3$  according to standard concrete mix proportion. Mix proportion included total replacement of the conventional coarse aggregate by maximum possible amount of EPS beads, which ensures concrete workability and prescribed density. The results demonstrated that exactly defined mixture-proportioning and casting procedure are required to achieve designed density. For designed EPS LWC mixture properties of freshly-mixed concrete and hardened concrete were analyzed. Based on test results it is concluded that designed EPS LWC can be used for structural-insulating purpose such as floors and roofs.

*Keywords: EPS LWC, density, workability, mechanical properties*

## ЕКСПЕРИМЕНТАЛНА ИСПИТИВАЊА ЛАКОГ БЕТОНА (LWC) СА ПОТПУНОМ ЗАМЈЕНОМ ГРУБОГ АГРЕГАТА СА ЗРНИМА ОД ЕКСПАНИРАНОГ ПОЛИСТИРЕНА (EPS)

### *Анстракт:*

У овом раду је испитан лагани бетон (LWC) са експандираним полистиреном (EPS). Циљ је био пројектовање EPS LWC-а специфичне густине од  $1200 \text{ kg/m}^3$  према стандардној пропорцији бетонске мјешавине. Мјешавина укључује укупну замјену конвенционалног грубог агрегата максималном могућом количином EPS зрна, што обезбјеђује уградљивост бетона и прописану густину. Резултати су показали да је за постизање пројектоване густине потребна тачно дефинисана пропорција смјеше, те начин уградње. За пројектоване EPS LWC мјешавине анализирана су својства свјеже измијешаног бетона и очврслог бетона. На основу резултата испитивања закључено је да се пројектовани EPS LWC може користити у конструкционо-изолационе сврхе, као што су подови и кровови.

*Кључне ријечи: EPS, LWC, густина, уградљивост, механичке особине*

## 1. INTRODUCTION

The density of concrete is among the most important parameters for structural behavior. Based on the density (unit weight) concrete can be classified into three categories: normal weight concrete (NWC), lightweight concrete (LWC) and heavyweight concrete (HWC). LWC may have densities ranging from  $800 \text{ kg/m}^3$  to  $2000 \text{ kg/m}^3$  [1]. One of the most important properties of LWC is its low self-weight. On the other hand, its major disadvantage is reduction of strength due to decrease of density [2]. However, the compressive strength of LWC shows large oscillations ranging from 1 MPa up to 60 MPa [2]. The reason for such a big variation is the possibility of using various types and portions of lightweight aggregate. Further, the compressive strength is not only dependent on the aggregate but also on the amount and type of cement and the water-cement ratio. The amount of cement in the production of LWC is usually in the range of  $150$  to  $550 \text{ kg/m}^3$  [2, 3]. The second very important property of LWC is its increased thermal resistance. The thermal insulation properties of LWC are much better than of NWC. For example, for NWC, the coefficient of thermal conductivity ranges from  $1.4$  to  $2.9 \text{ W/mK}$  [4]. For LWC the coefficient of thermal conductivity ranges from  $0.05 \text{ W/mK}$  for insulation up to  $0.85 \text{ W/mK}$  for structural application [4]. The water permeability of lightweight concrete is much higher compared to conventional concrete due to its larger volume of pores that absorb water more easily. Hence, compared to NWC, LWC concrete has lower strength and durability but on the other hand much better thermal and acoustic insulation properties.

Depending on the purpose of use, LWC can be classified as structural and non-structural. When LWC is to be used for structural application minimum compressive strength of 15 MPa is necessary. For the insulating purpose compressive strength of LWC is less important and ranges from 0.5 MPa to 3.5 MPa. For compressive strength between 3.5 MPa and 15 MPa application of LWC falls about midway between the structural and non-structural [2]. In this work focus was on non-structural LWC, where for a lightweight aggregate is chosen expanded polystyrene (EPS).

LWC concrete can be defined as a type of concrete with partial or complete replacement of conventional aggregate with lightweight aggregate to reduce dead loads in structures. Lightweight aggregate is defined as aggregate with a density lower than  $1200 \text{ kg/m}^3$  [2]. Lightweight aggregates are classified as natural, such as scoria, pumice and tuff, and artificial, for instance, perlite, clays, vermiculite, expanded shell, fly ash or expanded polystyrene (EPS) [2]. When EPS beads are incorporated in LWC as a partial or complete replacement of natural coarse aggregate it is called EPS LWC [3].

Considering the development of the construction industry there is a strong increase in consumption of raw materials and production of waste materials which both negatively impact the environment. For those reasons, the topics associated with waste management and sustainability of materials have become very popular in last few years [3-7]. Hence, having in mind these facts, EPS beads seem to be a good choice for use in the production of LWC. EPS is a closed-cell widely used polystyrene. It is a lightweight material with low water absorption and high thermal insulation properties. EPS is non-biodegradable waste material. Therefore, its disposal is very demanding and complex. Accordingly, EPS LWC in civil engineering gives a contribution to solving environmental issues [7, 8]. EPS LWC has excellent thermal and sound insulation characteristics [5,8]. Also, the workability of concrete is very poor. The major drawback of EPS LWC is its low compressive and tensile strength, which varies depending on the incorporation of beads in the concrete mixture. With increase of the EPS beads content in concrete compressive and tensile strength decrease. Because of the properties listed above, EPS LWC is a widely used in many various structural and non-structural applications in civil engineering such as floor screeds, roofs, curtain walls, partition walls, bridge decks, pavement construction, impact sound insulation, floating marine structures etc. [2-8].

The aim of this work was to produce EPS LWC with a specific density of  $1200 \text{ kg/m}^3$  by the maximum possible portion of EPS beads. For that purpose, a straightforward mixture-proportioning of each ingredient was chosen on recommendation of a local company. The concrete mixtures were designed without conventional coarse aggregate. The required value of the density and the experimentally obtained values of trial concrete batches mixed with different casting procedures were compared. Additionally, tests of the fresh concrete mixture in terms of workability and of hardened concrete in terms of mechanical properties were conducted.

## 2. MATERIALS AND TESTING METHODS

Own experimental investigation was conducted to examine the required properties of EPS LWC. This section is divided into two parts. The first part, which describes mixing components and procedure to get the required density. The types of testing methods on fresh and hardened EPS LWC are described in the second part. All tests were performed according to HRN EN standards at the Faculty of Civil Engineering in Rijeka, Croatia.

### 2.1. Materials and mix proportions

The materials used to mix EPS LWC were locally available cement CEM II/B-M (S-V) 42,5 N, crushed limestone sand with a maximum grain size of 4 mm, EPS beads with a diameter ranging from 3 mm to 6 mm (see Figure 1), Stigopor - D additive and water. Low density of the EPS particles (approximately  $15 \text{ kg/m}^3$ ) in comparison with density of sand ( $2700 \text{ kg/m}^3$ ) may induce sand segregation in a cement paste. Hence, to ensure a good bond between the cement matrix and EPS beads, appropriate portion of additive have been added in the fresh mixture. Three mixtures were designed until achieving the required density of EPS LWC. Hence, the first two mixtures were trial concrete mixtures named as EPS1 and EPS2 while the last one was referent mixture named EPS3. The mix proportions of the constituents of the EPS LWC mixtures were given by local company. Please note that detail data are not available due to third-party restrictions. The water to cement ratio, amount of cement and additive were kept constant for all mixtures.

### 2.2. Mixing and casting procedure

In this chapter only mixing procedures are described while testing results will be presented in following Chapter 3. A laboratory mixer with a maximum capacity of 150 liters was used to mix the concrete (see Figure 2). Three concrete mixtures were mixed until achieving required density.

The first trial mixture EPS1 was mixed following the procedure from the literature [8]. First, the 2/3 of the total amount of water mixed with additive was supplied to the mixer. Further, the required amount of sand was added and mixed until the mixture became homogeneous. Then, to add cement and the remaining amount of water the mixer was stopped. Finally, the total amount of EPS beads was added to cement paste and mixed until the mixture became uniform. Immediately after lightly oiled cubic molds were filled with EPS LWC without any vibration.

During the mixing procedure of the second trial mixture EPS2, the order of adding ingredients in the mixer was changed. First, additive mixed with 2/3 of the total amount of water and EPS beads were introduced in mixer. Then the required amount of sand was added and mixed for about 60 s. At the end, remaining water and cement were added and mixed until the fresh mixture was uniform. The fresh concrete was poured into prepared molds in three layers. Each layer was compacted by wooden bar uniformly over the surface of the concrete as shown in Figure 3.

The last mixture EPS3 was created with a reduced amount of EPS beads. While the amount of EPS beads was decreased by 8% (mass percentage) the amount of sand was increased by 31 % (mass percentage) to keep a constant total amount of the mixture ingredients. Hence, the volume fraction of EPS beads was reduced from 80% to approximately 70%. The amount of the remaining mixture ingredients stayed unchanged. The concrete was mixed and cast in the same way as described for the second trial mixture EPS2.

While compressive strength is the most important parameter to characterize concrete properties and it is directly related to the structure of hardened concrete, each trial mixture (EPS1 and EPS2) was used to cast three cubes with 150 mm edge for compression test. The referent concrete mixture EPS3 was used to prepare three cube specimens of 150 mm edge and three of 200 mm edge for compressive strength testing, three cylindrical specimens of 300 mm height 150 mm diameter for tensile splitting tests and three prismatic specimens  $100 \text{ mm} \times 100 \text{ mm} \times 400 \text{ mm}$  for flexural tensile testing. Specimens prepared for testing EPS3 LWC mixture are shown in Figure 4. After demolding, the specimens were cured immersed in the water tank until the day of testing.



Figure 1. *EPS beads*



Figure 2. *Fresh concrete mixture*



Figure 3. *Casting of fresh concrete*



Figure 4. *EPS3 concrete specimens*

### 2.3. Testing fresh concrete

Since there is no standard methodology for testing EPS LWC standards used for normal strength concrete (NSC) have been followed. Laboratory tests on fresh concrete included measurement of density following the HRN EN 12350-6 [9]. To characterize workability of EPS LWC slump test following the HRN EN 12350-2 [10] and flow table test following the HRN EN 12350-5 [11] were used.

### 2.4. Testing hardened concrete

Mechanical properties were tested under the same conditions as NSC but with adjusted loading rates [12-14]. The applied loading rate was chosen in such a way to obtain maximum load in the range of 2 to 5 minutes from the beginning of testing (quasi-static loading). For each test type, the failure pattern was analyzed, the maximum force at failure was recorded and the strength according to the corresponding testing standard was calculated.

#### 2.4.1. Compression tests

For the compression tests a universal testing machine with a maximum load capacity of 3000 kN was employed (see Figure 5a). The compressive strength of concrete cube specimens of 150 mm as well as 200 mm was obtained according to HRN EN 12390-3 [12]. The loading was applied at rate of 0.05 MPa/s. A set of three (3) cubes were tested for each cube size.

#### 2.4.2. Tensile splitting tests

The split tensile strength test was performed according to standard HRN EN 12390-6 [13] on concrete cylinders 150 mm in diameter and 300 mm high by universal testing machine with a maximum load capacity of 3000 kN (see Figure 5b). The loading was applied with constant rate of 0.005 MPa/s. In total, three (3) specimens were tested.

#### 2.4.3. Flexural tests

Four-point bending setup was applied to test EPS LWC specimens to evaluate flexural strength [14]. Specimens were prismatic beams with a cross-section of 100 mm × 100 mm and a span length of 300 mm. Figure 5c shows the test setup used in the flexural test. The flexural tests were carried out

employing servo-controlled hydraulic machine with a maximum capacity of 300 kN. The tests were performed with the displacement control. Two Linear Variable Differential Transducers (LVDT) were used for measuring central point displacement, each on the middle of the longitudinal side of the beam as shown at Figure 5c. The loading and mid-point displacement of all three specimens were recorded during the experiment.



a) Compression tests



b) Tensile splitting tests



c) Flexural tests

Figure 5. Test setup

### 3. EXPERIMENTAL RESULTS

In this chapter results of the various tests conducted on trial mixtures and referent mixture EPS3 with achieved density, in their fresh and hardened state are presented. In the first subchapter, density and compressive strength of trial mixtures EPS1 and EPS2 are discussed. The required value of the density and the experimentally obtained values of trial concrete batches mixed with different casting procedures were compared. In the following subchapters, results obtained on the referent mixture EPS3 with achieved target density in fresh state such as workability and density and mechanical properties in the hardened state are analyzed in detail.

#### 3.1. Trial mixtures

To determine the density of fresh concrete the molds were weighted after filling with fresh concrete according to casting procedure described in section 2.2. The measured average density of fresh EPS1 LWC was  $715 \text{ kg/m}^3$ . The average density of the second trial mixture EPS2 was obtained as  $925 \text{ kg/m}^3$  which is 30% higher than the density of EPS1, but again the required density of approximately  $1200 \text{ kg/m}^3$  was not achieved.

In order to test EPS adhesion to the cement paste, compressive tests are performed. The cube specimens prepared of EPS1 were tested for compressive strength at the age of 14 days. The measured mean compressive strength was only 0.7 MPa. From Figure 6a it can be observed that the surface of EPS beads was not fully covered with cement mortar resulting in poor adhesion between EPS beads and matrix. Consequently, failure took place through cement paste - EPS beads interface. On the other hand, EPS2 specimen kept structural integrity after testing the compressive strength



(Figure 6b). Moreover, it can be observed that the bond between EPS beads and cement paste was much stronger. The mean compressive strength of EPS2 cubes tested after 7 days was 2.5 MPa. Hence, considering the difference in concrete age at time of testing, it can be concluded that mean compressive strength of the second trial mixture EPS2 is even more than 3.5 times greater than the mean value of the first trial mixture EPS1.

The higher mean value of density of EPS2 with respect to EPS1 can be attributed to compaction and better distribution of the EPS beads in the mixture. Consequently, this leads to better adhesion of the EPS beads to the cement paste which at the end contributes to the increase of the compressive strength. Based on that, it can be concluded that proper mixing procedure and compaction of concrete are one of the most important parameters to achieve designed properties of EPS LWC. To obtain the required density, it was necessary to change the mixing proportion of EPS beads in concrete mixture as described in section 2.2.

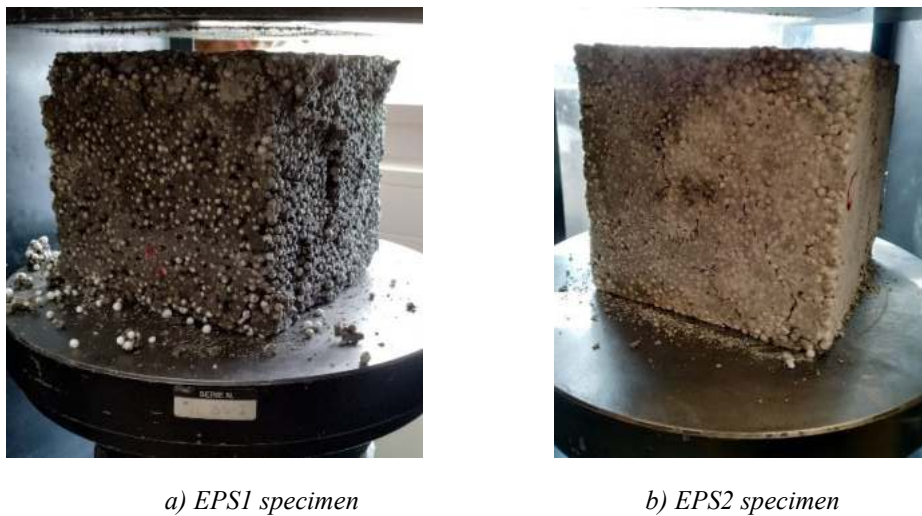


Figure 6. Compression test

### 3.2. Fresh concrete

This section describes the investigation of fresh properties of EPS3 LWC with required density. The average density of the mixture EPS3 was  $1176 \text{ kg/m}^3$ , approximately 27% and 64% higher with respect to the trial mixtures EPS2 and EPS1, respectively. Hence, this concrete mixture is taken as referent mixture. The EPS3 LWC mixture showed a zero slump value (see Figure 7a) and flow of 34 mm from flow table test (see Figure 7b) which indicates very low workability [7]. Moreover, except flow of the concrete was restrained, the crumbling also occurred, as shown in Figure 7b.

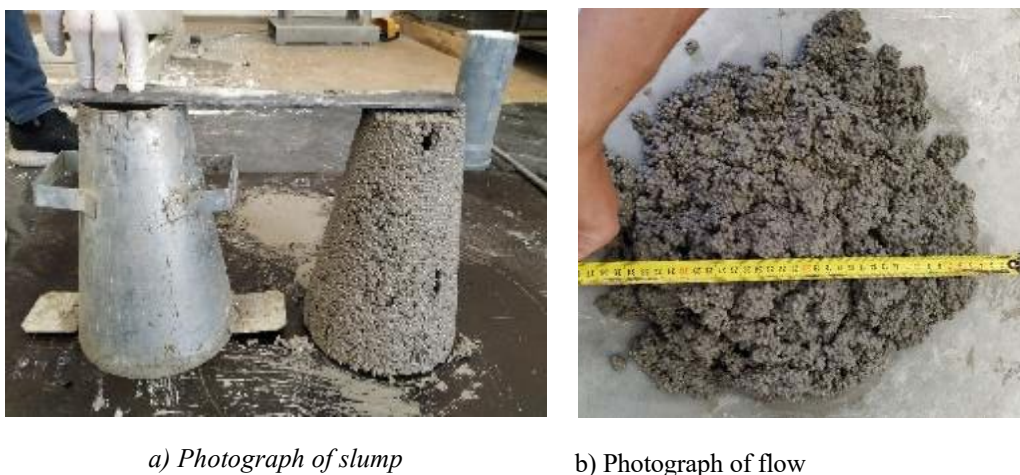


Figure 7. Testing fresh concrete

### 3.3. Hardened concrete

This section describes the investigation of mechanical properties of referent mixture EPS3 LWC with the density of 1200 kg/m<sup>3</sup>. All tested specimens were cast in one batch. Overview of test results and specimens used to obtain hardened material properties are summarized in Table 1. For each property exactly three specimens were tested and average values together with standard deviations are presented. Comparison of the given results are in accordance with literature for similar amounts of components and density [3]. After testing, specimens were visually inspected and failure surface was recorded. Note that all tests were performed on the saturated specimens at the age of 43 days.

Table 1. Overview of test results

Material Property	Specimen Type	Specimen Dimension	Mean values (S.D.) [MPa]
Compressive strength	Cube	150 mm × 150mm ×150 mm	5,3 (0,40)
	Cube	200 mm × 200 mm × 200 mm	5,9 (0,17)
Splitting strength	Cylinder	150 mm × 300 mm	0,7 (0,04)
Flexural strength	Prism	100 mm × 100 mm × 400 mm	1,3 (0,02)

#### 3.3.2. Compressive strength

The mean compressive strength of EPS3 LWC obtained on 150 mm cube and 200 mm cube specimens amounts 5.9 MPa and 5.3 MPa, respectively. Hence, an increase of the compressive strengths of 136% with respect to the EPS2 specimens was observed. Figure 8 represents the typical failure patterns observed after the compressive strength test. It can be seen that the shape of failure patterns visually corresponded to NWC.



Figure 8. Compression test - failure patterns

#### 3.3.3. Tensile splitting strength

The mean value of the splitting tensile strength equals 0.7 MPa. As expected, the splitting tensile strength is approximately 8 times lower than the compressive strength and approximately 2 times lower than flexural strength similar to by NSC. Further, EPS3 LWC exhibited the same failure behavior as NSC, by splitting along the longer side of the cylinder (Figure 9). However, EPS LWC failure mechanism is quite different from the failure of NWC. Because EPS beads are relatively weaker than the cement matrix, crack patterns go through EPS beads (Figure 9b). The EPS beads were uniformly distributed in concrete matrix as seen in Figure 9b. It can be concluded that EPS beads determine the concrete performance because their strength is lower than the strength of cement mortar and also cement paste - EPS beads interface.





a) Typical failure mode



b) Failure surface

Figure 9. Tensile splitting test

### 3.3.4. Flexural strength

Figure 10 shows the crack initiation and failure modes from the flexural test. It can be concluded that all failures are satisfactory i.e. failure crack is located in the range of the middle third of the distance between the supporting rollers. The mean flexural strength amounts 1.3 MPa. Further, the value of flexural tensile strength compared to compressive strength is similar as for NSC, approximately 5 times lower. Again, the failure surface shown in Figure 10 showed the typical failure mechanism for LWC.

There is not much information in the literature on the post-peak response of EPS LWC. Therefore, in this investigation, the load-displacement curves obtained for each prism are presented in Figure 11. It is interesting to observe that curves show straight pre-peak line while the post-peak response is more gradual. This result leads to the conclusion that EPS3 LWC did not have a flexural brittle behavior typically associated with the NWC.



c) Crack initiation



a) Typical failure mode



b) Failure surface

Figure 10. Flexural test

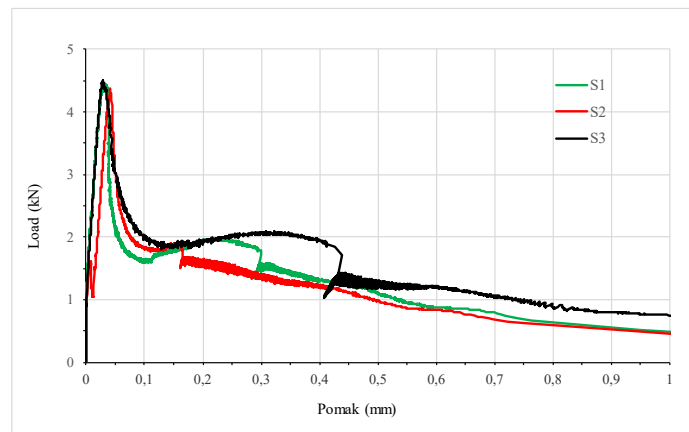


Figure 11. Load-displacement curves

#### 4. CONCLUSIONS

In the present work, an experimental investigation has been carried out on EPS LWC mixtures prepared with replacement of the conventional coarse aggregate with EPS beads. A study on the fresh concrete density as well as basic mechanical properties of the designed concrete was conducted. Based on the experimental results following conclusions are made:

1. EPS LWC does not require complex techniques of production. However, the order of dosage of mixture ingredients and mixing procedures as well as proper casting method are the most important factors in the production of EPS LWC to achieve a designed quality of concrete.
2. EPS LWC without coarse aggregate show very low workability
3. For EPS LWC with a density of approximately  $1200 \text{ kg/m}^3$ , relatively low amount of cement and high amount of EPS beads, satisfactory mechanical properties are achieved. However, obtained compressive strength of approximately 5.5 MPa suggests that designed EPS LWC is not suitable in a structural application. Meanwhile, designed EPS LWC can be used for structural - insulating applications such as in floors and roofs.
4. Compressive, flexural and tensile splitting strength of EPS LWC are related in the same way as in NWC.
5. Application of EPS beads in concrete as a complete replacement of aggregate can be one of the waste disposal method and energy-saving method. Hence, this type of LWC can be considered environmentally sustainable material for non-structural application.

Designed EPS LWC will be further investigated concerning water resistance, thermal and acoustic properties.

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