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# Pervious concrete mix optimization for sustainable pavement solution

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**Abstract.** In order to fulfill requirements of sustainable road construction, new materials for pavement construction are investigated with the main goal to preserve natural resources and achieve energy savings. One of such sustainable pavement material is pervious concrete as a new solution for low volume pavements. To accommodate required strength and porosity as the measure of appropriate drainage capability, four mixtures of pervious concrete are investigated and results of laboratory tests of compressive and flexural strength and porosity are presented. For defining the optimal pervious concrete mixture in a view of aggregate and financial savings, optimization model is utilized and optimal mixtures defined according to required strength and porosity characteristics. Results of laboratory research showed that comparing single-sized aggregate pervious concrete mixtures, coarse aggregate mixture result in increased porosity but reduced strengths. The optimal share of the coarse aggregate turn to be 40.21%, the share of fine aggregate is 49.79% for achieving required compressive strength of 25 MPa, flexural strength of 4.31 MPa and porosity of 21.66%.

## 1. Introduction

Road construction, compared with other branches of civil engineering is the biggest consumer of natural resources, largely depending on the availability of natural materials, such as gravel and stone as main constituents of all road facilities. Large quantities of natural materials are embedded in the newly built, or for the reconstruction of deteriorated roads, while the concept of sustainable development requires environmental protection, energy savings and more efficient waste materials disposal. Within this concept, researches are conducted in order to find more efficient way for road built by imposing new materials and building techniques for roads building and reconstruction. The main objective within sustainable practice in asphalt industry is in a view of energy savings during asphalt production and introduction of new asphalt mixtures like warm and cold asphalt. According to some studies, warm mix asphalt production requires 10%–24% less energy as compared to hot mix asphalt mixtures (depending on the binder type and aggregate source) [1, 2] while in the life cycle of pavements energy consumption can be reduced by 22.4% [3]. Although, asphalt is dominant pavement material [4], concrete industry is one of the leading industries within civil engineering and concrete pavements are also widely constructed mainly because of a greater durability and resistance comparing to asphalt pavements. With its wider application, special concrete made by special mix design and different additives are introduced with the aim to achieve optimal performance for each of the specific applications. One such concrete is pervious concrete for pavements.

Pervious concrete pavement represent an innovative solution as a material that contains a significantly higher amount of pores than conventional concrete (void content is between 11% and 35%) [5, 6], it absorbs and drains substantial amounts of water and hence it can be considered ideal for use in road construction. Typical pervious concrete sample, with demonstration of its main advantage (water permeability) is presented in figure 1.

**Figure 1**. Pervious concrete sample.

First usage of pervious concrete in pavement construction follows the end of World War II [7]. Destructions during the war prompt utilization of new materials and building methods. In Germany, lack of raw materials and high amounts of waste, particularly demolition waste motivates investigation of porous concrete. Since then, pervious concrete has been used over 30 years in many countries, especially in USA and Japan [8].

The main characteristic of pervious concrete is high porosity, but consequently also reduced strength. Even though, pervious concrete presents a sustainable solution for concrete pavements in a few ways. However, cement industry is known to be one of the biggest air pollutant with large volumes of $CO_2$ emitted, representing 5–7% of the total $CO_2$ anthropogenic emissions [9], need for reducing natural aggregate usage in concrete industry is also increasingly emphasized. Typical aggregate usage in conventional concrete is about 60-75% while pervious concrete presents possibility of its reduction on 50-65% [10]. According to [11], in France alone on average 400 million tons of aggregates is consumed each year, and in the United States the production is expected to increase to more than 2.5 billion tons per year by the year 2020. Therefore, production and replacement of conventional concrete by pervious one, on suitable application such as low volume roads or parking lots presents a valid solution for natural aggregates resources preservation. The compaction of pervious concrete can result in a layer of cement paste at the bottom of the concrete structure that would negatively affect pore connectivity and, consequently, permeability. In figure 2 consistency test according to standard HRN EN 12350-2 and result of too high compaction energy are presented. Therefore, the compaction of this type of concrete is restricted [12] which can also be interpreted through the aspect of saving energy that would be usually required for plain concrete installation into a pavement construction.

**Figure 2.** Pervious concrete compaction specifics.

Pervious concrete has an advantage over ordinary concrete in terms of the runoff water reduction, improvement of water quality near pavements and parking lots, reduction of the heat island effect and traffic noise in urban areas. Paving of large urban areas by impervious pavement such as asphalt, or conventional concrete, urban heat islands are created acting as heat storages during hot days and releasing the heat back to the atmosphere during night times. This phenomenon is not just discomfort problem, but also higher energy consumption load for cooling purposes and increased $CO_2$ emissions [13]. Another problem within urban areas is the noise, resulting from the interaction between tires and the pavement which is increasingly recognized as a significant environmental issue since there is a connections between traffic noises and diseases including cardiovascular and neuro-vegetative diseases [14, 15]. Concrete pavements are generally worse choices compared to asphalt pavements with respect to tire/road noise impact. The only type of a concrete surface course that can be considered as "quiet" corresponds to pervious concrete.

Pervious concrete, as a material with increased porosity is also addressed as environmentally friendly material, recommended by the Environmental Protection Agency (EPA) of United States [16] allowing storm water to infiltrate into the deeper ground recharging and retaining pollutants such as sediments, organics, chemicals, and other contaminants from reaching groundwater. Purification of storm water can be classified into three categories as presented in [13]. Physical purification is manifested in removing solid suspended particles within pervious concrete porous structure. While, chemical purification is manifested in pervious concrete alkaline nature and biological in a number of microbial activities consuming the suspended materials and dissolving them within material pores. Also, some research have found that a pervious concrete with a smaller size of aggregate and a higher void content have the ability of phosphorus and nitrogen removal [17].

However, high porosity causes significant reduction of strength so the pervious concrete has limited application in highway pavement structures. In order to produce optimal pervious concrete mixture with satisfying mechanical characteristics, but also with preserved advantages over conventional concrete, i.e. drainage characteristics (porosity) and aggregate saving optimization model was used. Nowadays, due to the resource consumption rationalization, various mathematical optimization tools and techniques are often used for solving such problems in road construction (e.g. from problems of optimization the transportation the hot mix asphalt in regard to its allowed temperature drop [18], to optimization of the preparation of the warm mix asphalt rubber with additives [19] etc.)

The main aim of this paper is to present optimal pervious concrete mix composition in order to produce material with satisfactory mechanical characteristics (compressive strength and porosity) along with aggregate consumption optimization.

## 2. Laboratory program and results

In this study, four mixtures of pervious concrete were prepared with variation in aggregate fractions distribution. In all mixtures, crushed dolomite stone was used with two different aggregate fractions (4-8 mm and 8-16 mm), 10% of sand from the Drava River, and their mix compositions. The densities of crushed dolomite aggregate and sand were 2.75 and 2.65 kg/dm$^3$ respectively according to EN 1097-6:2013. For all mixtures, the water to cement ratio (*w*/*c*) was 0.33 with water from water supply. The cement was ordinary Portland cement, CEM II/A-M(S-V) 42.5 N according to EN 197-1:2011, with a density of 3.0 kg/dm$^3$ according to EN 196-6:2010. The cement content was 300 kg/m$^3$ for all mixtures. Table 1 presents the proportions of all constituents in the mixtures.

Aggregates used for preparing concrete, were firstly saturated and then surface-dried. This was achieved in an artificial way, namely by dipping aggregates into a water tank for 24 h, taking them out and then wiping their surface of excess water. Aggregates, cement and water were mixed together for 5 minutes in a pan mixer (DZ 100VS, Diemwerke).

Three specimens were prepared in order to determine each property. Specimens of all concrete mixtures were cast with a compacting rod by rodding 25 times. All specimens were extracted from the molds 24 hours after the casting and placed in a water tank for 27 days at a temperature of 20°C ± 5°C according to EN 12390 2:2009.

**Table 1**. Mixture composition.

| Characteristics | C1 | C2 | C3 | C4 |
|---|---|---|---|---|
| w/c | 0.33 | 0.33 | 0.33 | 0.33 |
| Cement [kg] | 300.0 | 300.0 | 300.0 | 300.0 |
| Water [kg] | 99.0 | 99.0 | 99.0 | 99.0 |
| Aggregate [kg] | 1783.7 | 1783.7 | 1783.7 | 1783.7 |
| Sand 0–2 mm [%–kg] | 10 - 178.4 | 10 - 178.4 | 10 – 178.4 | 10 – 178.4 |
| Dolomite 4–8 mm [%–kg] | 90 - 1605.3 | - | 60 – 1070.2 | 30 – 535.1 |
| Dolomite 8–16 mm [%–kg] | - | 90 - 1605.3 | 30 – 535.1 | 60 – 1070.2 |
| *Total [kg]* | 2182.7 | 2182.7 | 2182.7 | 2182.7 |

At the 28th day, the properties of the hardened pervious concrete specimens were tested as follows: compressive strength was tested on cube specimens of 15-cm edge length with a constant rate of loading of 0.5 MPa/s according to EN 12390 3:2009; flexural strength was tested on prism specimens of measurements 10 × 10 × 40 cm by loading them with a constant rate of 0.05 MPa/s according to EN 12390 5:2002. Total porosity was determined by the standard method of specimen weighing in water and air, determining its dry mass, saturated surface-dried mass and calculating density, apparent density, solid material volume and isolated pore volume using the assumption that the total volume of the specimen is a sum of solid material volume, isolated pore volume and connected pore volume. Results of laboratory tests are presented in Table 2.

**Table 2.** Results of hardened concrete tests.

| Characteristic | C1 | C2 | C3 | C4 |
|---|---|---|---|---|
| Compressive strength [MPa] | 21.1 | 14.3 | 21.90 | 26.60 |
| Flexural strength [MPa] | 3.21 | 2.41 | 4.90 | 4.00 |
| Porosity [%] | 24 | 27 | 21 | 22 |

## 3. Optimization model

Based on the data gained by the experiment (shown in Section 2), optimization model was structured for determining the optimal ratio of the aggregate regarding to its fractions and respectively to its unit prices. The model is structured as a linear programming (LP) model and thus simplex LP solver was used. The objective function of the optimization was set to be minimization of the total aggregates unit costs (Equation 1):

$$min\, Z = \sum_{i=1}^{3} c_i \cdot x_i;\ \sum_{i=1}^{3} x_i = 1.0 \tag{1}$$

where "$c_i$" are unit prices of the aggregates and "$x_i$" denote variables of aggregates' share in regard to their fractions (i.e. $i$=1, 2, 3; 1 denotes the share of the "coarse aggregate"; 2 denotes the share of the "fine aggregate"; 3 denotes sand which is taken as a constant value of 10%). The unit prices of aggregates were taken as the current market prices in Croatia:

*c1= 71.00 kn/t ≈ 9.45 €/t*
*c2= 64.50 kn/t ≈ 8.60 €/t*
*c3= 50.00 kn/t ≈ 6.67 €/t*

Pervious concrete mixtures can develop compressive strengths in the range of 2,8 MPa to 28 MPa [20, 21], flexural strengths generally ranging between 1 MPa to 3,8 MPa [20] and porosity between 11% and 35% [5, 6]. Generally, properly placed pervious concrete pavements with compressive strengths of 20.5 MPa and flexural strengths of more than 3.5 MPa is suitable for most low-volume pavement applications [20]. With that fact in mind, structural constraints were divided as: hard constraint was the target value of 25 MPa of the concrete's compressive strength where the compressive strength "$f_{ct}$" was defined as linear function in regard to the share of "coarse aggregate" (Equation 2), while soft constraints were concerning the flexural strength "$f_{ct,fl}$" (i.e. greater or equal to minimal allowed of 3.5 MPa)

(Equation 3) and porosity percentage "$p$" (i.e. suggested to be in the interval of 11% - 35%) (Equation 4).

$$f_{ct} = -15.6667x_1 + 31.3 = 25 \quad (2)$$

$$f_{ct,fl} = 3x_1 + 3.1 \geq 3.5 \quad (3)$$

$$11 \leq p = -3.3333x_1 + 23 \leq 35 \quad (4)$$

Due to the relatively simple nature of the problem, Microsoft Excel solver for its solving was used. The solution was gained in matter of milliseconds and confirmed as optimal.

## 4. Discussion and conclusions

Analyzing the results of laboratory research conducted within this investigation, presented in Section 2 and in Table 2, it can be concluded that comparing single-sized aggregate pervious concrete mixtures, coarse aggregate mixture result in increased porosity but reduced strengths which is in accordance to previous research [22]. The influence of different proportions of finer and coarser fractions on pervious concrete mixtures cannot be unambiguously demonstrated. So, for proper aggregate size proportion optimization model is proposed within this research.

The optimal share of the "coarse aggregate" turn to be 40.21%, the share of "fine aggregate" is 49.79% while the other 10% is the share of the sand. The compressive strength is as required 25 MPa, while the flexural strength is 4.306 MPa, with the 21.66% of porosity. The total unit costs are 65.66 kn/t (i.e. 8.75 €/t). Furthermore, authors gave the sequence of aggregates shares, bending strength and porosity in regard to the compressive strength in the interval from the minimal required 20,5 MPa to targeted 25 MPa (Table 3.).

**Table 3.** Optimal shares of aggregates in regard to the compressive strength.

| | compressive strength [MPa] | | | | | |
|---|---|---|---|---|---|---|
| | 20.5 | 21 | 22 | 23 | 24 | 25 |
| coarse aggregate [%] | 68.94 | 65.74 | 59.36 | 52.98 | 46.60 | 40.21 |
| fine aggregate [%] | 21.06 | 24.26 | 30.64 | 37.02 | 43.40 | 49.79 |
| sand [%] | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 |
| flexural strength [MPa] | 5.17 | 5.07 | 4.88 | 4.69 | 4.50 | 4.31 |
| porosity [%] | 20.7 | 20.81 | 21.02 | 21.23 | 21.45 | 21.66 |

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