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Porosity and Durability of Rubberized Concrete

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ABSTRACT

Concrete with mechanical crumbed rubber waste additive from used tires was investigated. Fractionated rubber waste (up to 30% from total aggregate amount) was used to replace fine aggregate in the concrete. Volume of open and closed air pores, size, distribution of air pores and freezing - thawing factor were investigated. The resistance to freezing and thawing of rubberized concrete were predicted according to the porosity of concrete. It was observed that addition crushed rubber waste aggregate added to the concrete increase the closed porosity in the cement matrix and the rubber additive particles working as reserved volumes when concrete is attacked by the freezing and thawing cycles. According to the results it can be stated, that rubberized concrete can be used in cement systems to improve concrete durability when concrete is exposed to the attack of freezing - thawing.

INTRODUCTION

Recently interest in the reuse of waste tire crumb rubber in concrete has increased. Crumbed rubber waste can be reused in producing higway concrete structures for road building, such as concrete and reinforced concrete elements of bridge. Replacing part of the sand aggregate with fine crumb rubber admixture produces more elastic concrete, which has higher resistance to specific loads (impact loads, vibration and cyclic loads) compared to the regular concrete.

Crumbed rubber waste obtained from truck tires is stiffer and harder compared to waste car tires. Thus waste truck tire rubber crumbs were found to be better as a concrete aggregate admixture [Papakonstantinou and Tobolski 2006; Stubblefield, Garrick, Eggers, Abadie and Huang 2004].

According to Raghavan, Huyn and Ferraris [2004], the replacement of 10 % of the cement by crumb rubber waste additive of 4.75 mm sieve size slightly improves the paste, compared to the control sample. Similar VEBE shift tendencies in rubberized concretes were observed by the authors [Sukontasukkul and Chaikaew 2005; Sukontasukkul and Chaikaew 2006]. Bignozzi and Sandrolini [2006] state that by replacing up to 33.3% of fine aggregate by rubber waste additive (up to 2 mm in size) the slump of the fresh concrete increased. Guneyisi, Gesoglu and Ozturan [2004] investigated the influence of different content of rubber waste additive on the slump of concrete with silica nano-particles and determined that the increase of rubber waste additive content up to 50% renders the concrete non-workable, and the slump reduces to 0 cm. According to the authors [Guneyisi, Gesoglu and Ozturan

2006], the increase of rubber waste up to 25 % of fine aggregate content in concrete modified with SiO_2 nano-particles reduces the slump by 200 mm (from 240 mm to 40 mm in control samples). If only rubber waste additive is used without SiO_2 nano-particles, the drop in slump becomes even higher. Papakonstantinou and Tobolski [2006] investigated concrete mixes with 60 mm long and 1.3 mm wide shredded tire rubber bands (up to 8% of the total aggregate content) and observed a 60 mm drop in the slump. The authors have noticed that the decrease in the slump was caused by the winding of the rubber bands into “balls” during mixing. Khatib and Bayomy [1999] investigated the workability of concrete mixes with rubber waste additive and determined that concrete slump reduces with higher content of rubber waste additive. They state in their paper that the replacement of 40% of the total aggregate content by rubber waste reduces the concrete slump almost down to 0 cm, and such concrete is not workable. Researchers Guneyisi, Gesoglu and Ozturan [2004] have also noticed that concrete mixes produced with fine rubber waste additive were more workable than concrete mixes with coarse rubber waste additive.

Benazzouk and Mezreb [2003] have determined that rubber waste admixture increases air entrainment in cement paste. It was determined that the maximum rubber waste admixture content of 40% increases air entrainment in control mixes from 2.0% to 11.5%. Li, Stubblefield, Garrick, Eggers, Abadie and Huang [2004] examined the influence of the same amount (15% of the total course aggregate content) of different rubber waste additive types on air entrainment in fresh concrete. Their investigations showed that air entrainment increased insignificantly (up to 0.5%) compared to control samples (samples without rubber waste additives). Papakonstantinou and Tobolski [2006] analysed the change of air entrainment in concretes and determined that fresh concrete samples without rubber waste additives had air entrainment of 1.7%, whereas samples containing 60 mm long and 1.3 mm wide shredded tire rubber bands added at 8% of the total aggregate content had slightly higher air entrainment up to 2.1%. High increase of air entrainment in fresh concrete with the use of fine rubber waste additives was also stated by Siddique and Naik [2004]. Increase of air entrainment in fresh concrete modified with rubber waste results from uneven texture of rubber crumbs. Such crumbs tend to entrain more air around them. After rubber waste is added to fresh concrete, more of water is displaced and more internal cavities are formed thus increasing the porosity of concrete [Siddique and Naik 2004]. MacInnis and Beaudoin [1973] analysed the dependence of the durability of concrete subjected to cyclic freezing and thawing on the degree of water saturation in concrete conglomerate and determined that one of the most important factors of concrete fracturing in the initial setting stage during freezing and thawing cycles is the pressure of water in capillary voids during freezing. Powers [1945; 1949] and his colleagues [Powers and Brownyard 1947; Powers and Helmuth 1953] analyzed water freezing and thawing processes in concrete microstructure during repeated freeze-thaw cycles.

Rubber waste additive reduce the modulus of elasticity and improve the structural parameters (porosity) of concrete. Higher frost resistance of concrete with rubber waste can be explained by a twofold effect of rubber crumbs – relaxation of stress in frozen concrete and modification of concrete structure (porosity type). According to the authors, the increase of rubber waste content is feasible only in those cases when concrete of low density, higher elasticity and higher frost resistance is required [Skripkiunas and Kersevicius 2001].

The disintegration of the conglomerate subjected to freeze-thaw cycles is caused not only by the expansion of freezing water in open and closed voids of the concrete but also by the frozen water in capillary voids. When the binder matrix is in water saturated state and the freezing processes in internal structure of the concrete follow the theory of hydrostatic pressure, after the water in the binder matrix freezes, the water in voids and capillaries is displaced into bigger air entraining voids and into ambient environment of the sample [Litvan 1973; Pentalla 2006]. Skripkiunas and Kersevicius [2001] in their experimental work have determined that rubber admixture in concrete creates air-voids and performs better than air entraining agents because it separates capillary voids and thus increases the number of voids and concrete resistance to freezing.

The goal of the experiment is to investigate the influence of rubber waste admixtures on technological parameters and porosity of fresh concrete modified with rubber waste. Porosity characteristics, namely the content of open and closed pores, the size of the pores and their distribution in the concrete have to be determined. The resistance of rubberized concrete to the freezing and thawing will be predicted from porosity parameters.

MATERIALS AND RESEARCH METHODS

Materials

Portland cement CEM I 42.5 R manufactured by Akmenės Cementas was used for the investigation. The water content to obtain the paste of normal consistency was at 25.4%, specific surface area was 360 m^2/kg, particle density was 3110 kg/m^3, bulk density was 1220 kg/m^3. A plasticizing admixture based on polycarboxyl ethers was used, dry matter content was 36.1%, solution density was 1.06 kg/l, solution pH was 4.4 and electric conductivity of the solution was 1.48 mS/cm.

The sand of 0/4 fraction and bulk density of 1560 kg/m^3 was used as a fine aggregate. Part of the sand was replaced with crumbed rubber waste additive (WR). Crushed gravel of 4/16 fractions with bulk density of 1480 kg/m^3 was used as the coarse aggregate. The total content of the coarse aggregate in all compositions of the concrete mix was the same. Waste car tire rubber crumbs were used for the research. Rubber waste additives were divided into 0 to 0.5 mm (0/0.5), 0 to 1.00 mm (0/0.1) and 0to 3 mm (0/3) sizes and had average particle density of 1020 kg/m^3.

Dry aggregates were used for concrete mixes. The cement and aggregates were added by mass, while water and chemical agents were added by volume. Chemical agents in liquid form were added to the mix together with water. Concrete pastes were mixed in a forced-action laboratory mixer for about 3 minutes. Technological parameters of fresh concrete were determined: the slump according to the EN 12350-2 and entrained air content according to the EN 12350-7. 12 samples of concrete with different size rubber waste additive and different admixture content (R) were produced. A control sample from concrete without rubber waste was also made (NR). Compositions of concrete mixes with different rubber waste content and different Rubber waste additive (RW) are presented in Table 1.

Table 1. Concrete compositions

Notation	RW fraction	Materials content for $1m^3$ of concrete mixture						
		Quantity of RW, %	RW amount, kg	Cement, kg,	Sand 0/4, kg	Crushed gravel 4/16, kg	Plasticizing admixture amount, kg	Water, l
NR	-	-	-	451	875	949	2,255	160
R 0/1_5	0/1	5	35.14	451	784	949	2,255	160
R 0/1_10		10	70.28		693			
R 0/1_20		20	140.55		510			
R 0/1_30		30	210.83		328			
R 1/2_5	1/2	5	35.14	451	784	949	2,255	160
R 1/2_10		10	70.28		693			
R 1/2_20		20	140.55		510			
R 1/2_30		30	210.83		328			
R 2/3_5	2/3	5	35.14	451	784	949	2,255	160
R 2/3_10		10	70.28		693			
R 2/3_20		20	140.55		510			
R 2/3_30*		30	210.83		328			

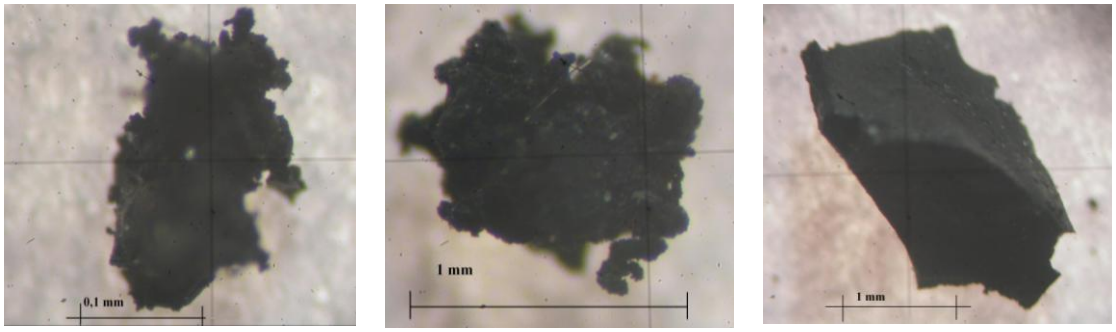
* - none technological mixture. The segregation of mixture was obtained. Therefore concrete mixture R 2/3_30 was not used in testing.

Concrete porosity parameters were determined from the kinetics of water absorption, which is characterized by the increase of sample weight in time. To determine the parameters one 100x100x100 mm size concrete block is crushed and three 50x50x50x50mm size samples are selected. Afterwards the samples are dried until constant weight can be recorded, weighted, soaked in water and weighed again in ambient air after 15 minutes, 1, 24 and 120 hours of soaking. The average void size, open and closed porosity are derived from the test results. The frost resistance factor K_f is computed from the open and closed porosity according to the method of predicting fracture resistance of concrete under repeated freeze-thaw conditions [Skripkiunas, Vaitkevicius Daukšys and Grinys 2008; Sheikin and Dobshits 1989; Sheikin, Chechovskij and Brusser 1979].

RESULTS AND DISCUSSIONS

Properties of waste tire rubber

The form and surface texture of rubber crumbs were examined with the microscope. Optical images are presented in Figure 1 a, b, and c. Rubber waste additive up to 3mm are more regular in form and have more uniform surface. The form becomes less regular with smaller particle size and numerous empty voids are observed on the surface. Higher complexity of rubber waste additive surface texture ensures better binding of cement matrix and rubber waste.



a) b) c)

Fig. 1. Rubber crumbs up to 0.5 mm a), up to 1.0 mm b) and up to 3.0 mm c)

Technological properties of fresh concrete with rubber waste additive

The change in the slump of the concrete paste after the addition of rubber waste is presented in Figure 2. The figure reveals that the slump of the concrete changes with the change of rubber waste size or admixture amount. Investigations have revealed that the slump of the concrete paste reduces after rubber waste is added. It was determined that the addition of rubber waste up to 5% of the total aggregate amount reduced the slump from 15.0 cm in control mixes to 10.0 – 13.8 in mixes with rubber waste, depending on the rubber waste particle size.

The slump continued decreasing with the increase of rubber waste additive amount. The addition of rubber waste additive up to 10% of the total aggregate content reduced the slump 150 cm down to 8.3 - 3.8 cm, and the addition of 20% of rubber waste additive reduced the slump to 4.75 - 1.0 cm respectively. The biggest drop in the slump was observed when the highest amount of rubber waste was added (30% of the total aggregate amount). With this amount of rubber waste the slump reduced to 1.5 - 0 cm, and when the rubber waste of particle size 2/3 was used, the mix became unworkable. The dependence of the change in slump on the amount and particle size of the rubber waste additive was derived from the test results (figure 2).

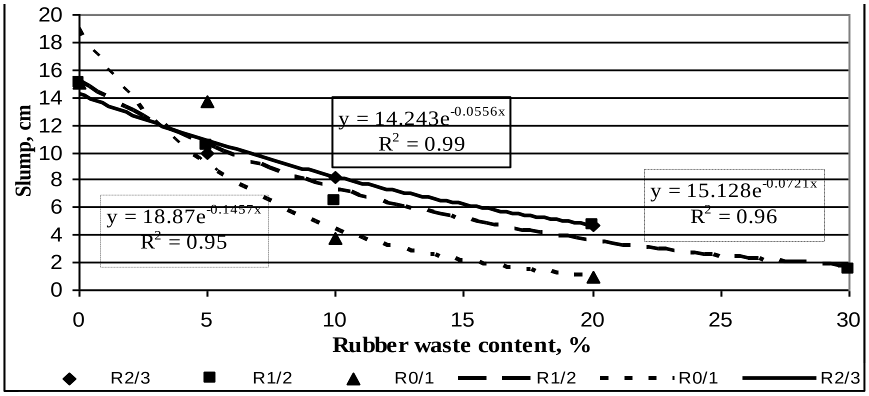


Fig. 2. Dependence of fresh concrete slump on the amount and particle size of rubber waste

The change in air entrainment in fresh concrete and its dependence on rubber waste amount and particle size is shown in Figure 3.

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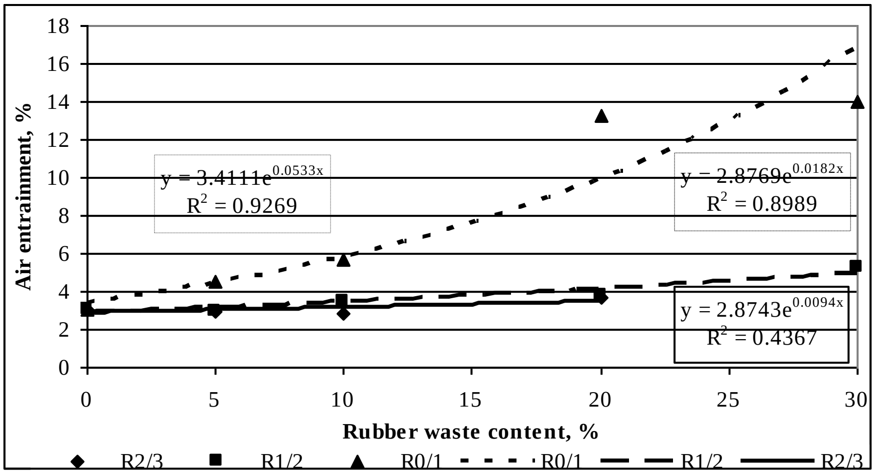

Fig. 3. Dependence of air entrainment in fresh concrete on the amount and particle size of rubber waste

Diagrams in Figure 3 show that the average air entrainment in samples without rubber waste was 3.1%; with the addition of rubber waste the air entrainment changed from 2.95 to 14 %, depending on the amount and particle size of rubber waste admixture. The content of air entrained in fresh concrete increases with smaller particle size of rubber waste. With 30 % of rubber waste of particle size 1/2 is added, the content of entrained air is 5.3%, whereas particle size of 0/1 increases it up to 14.0%, which is 5 times higher than entrained air content in fresh concrete without rubber waste admixture The increase of air entrainment in fresh concrete with rubber waste can be explained by more porous texture of rubber crumb surface compared to replace sand particles. Rubber waste particles of smaller size have irregular form and many surface voids. Dependence of the change in air entrainment on different amount and particle size of rubber waste was computed from the tests (Figure 6).

Strength of hardened concrete with rubber waste additive

The change of the compressive strength with the addition of different amounts of rubber waste can be mathematically described by the polynomial equation of second degree.

Diagrams in Figure 4 have revealed that the amount and grain size of the rubber waste additive significantly affect the concrete compressive strength. The tests have shown that samples without the rubber waste additive had the average compressive strength of 64.3 MPa. With the addition of rubber waste at 5 % of the total aggregate amount the concrete compressive strength dropped to 46.7 MPa and the drop was related to the size of rubber particles. These tests have shown that with the increase of rubber waste additive up to 10% of the total aggregate amount, the compressive strength of concrete mix with rubber waste admixture fraction ranging from 2/3 to 0/1 dropped to 33.8 MPa respectively. The compressive strength dropped even more when the rubber admixture was added at 20 per cent of the total aggregate amount. The compressive strength values dropped to 22.9, 22.2 and 14.2 MPa according to the rubber waste particle size.

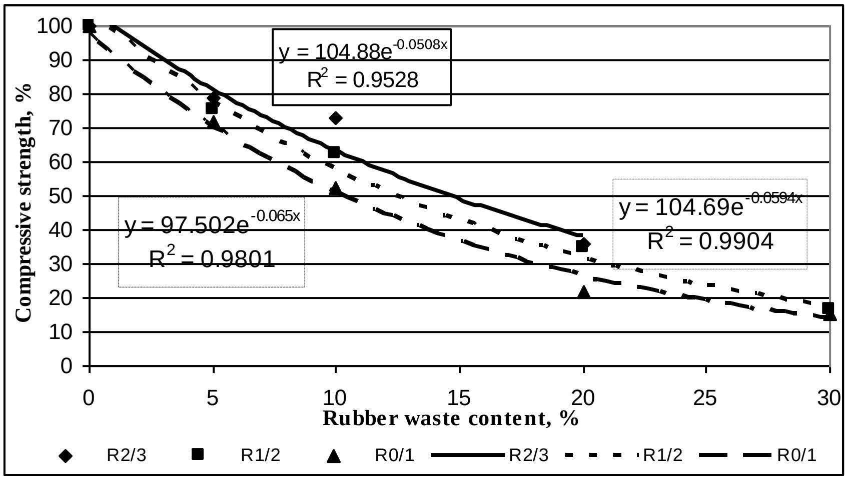

Fig. 4. Dependence of compressive strength of the concrete on the amount and particle size of rubber waste

Data obtained from diagrams in Figure 4 show that the biggest drop in compressive strength, compared to the control samples, is observed with the addition of the highest amount of rubber waste (at 30% of the total aggregate amount). This figure shows that 30% of rubber waste with size 1/2 reduced the compressive strength down to 84% and down to 85% with particle size fraction 0/1.

Porosity parameters of hardened rubberized concrete

With the increase of rubber content in fresh concrete the frost resistance increases after 28 days of hardening because the closed porosity of hardened cement increases (Figure 5-7). Figure 5-7 illustrates frost resistance parameters K_f of concrete samples with different rubber waste additives and the dependence of closed porosity P_c on the amount of rubber.

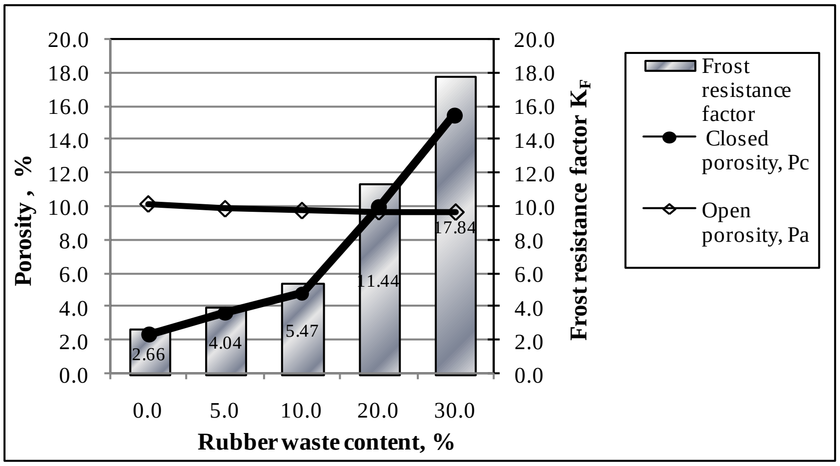

Fig. 5. Dependence of frost resistance factor K_f, open porosity P_a and closed porosity P_c on the amount of rubber waste particles size 0/1

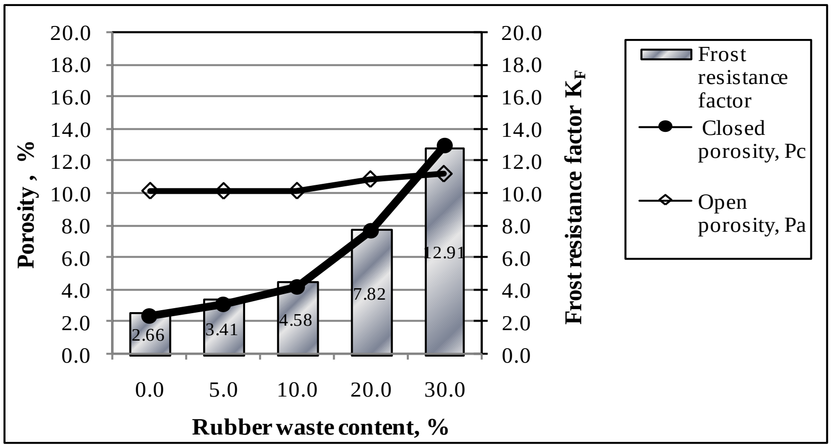

Fig. 6. Dependence of frost resistance factor K_f, open porosity P_a and closed porosity P_c on the amount of rubber waste particles size 1/2

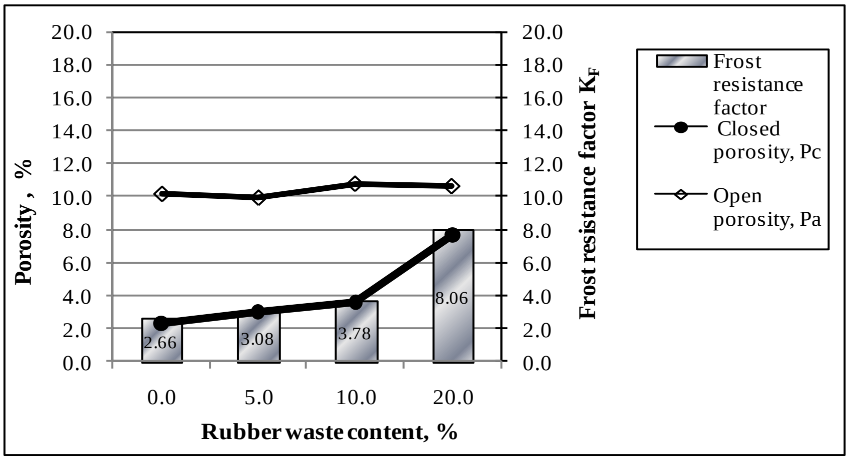

Fig. 7. Dependence of frost resistance factor K_f, open porosity P_a and closed porosity P_c on the amount of rubber waste particles size 2/3

The results obtained from the diagrams have shown that concrete closed porosity, which creates reserve pores and increases frost resistance of the concrete, reaches 2.34 – 15.53% in samples with different rubber waste additives. Smaller size of rubber particles increase closed porosity and frost resistance of hardened concrete. With 30 % of 1/2 particle size rubber waste the closed porosity is 13.02%, whereas samples with 0/1 particle size rubber waste had closed porosity of 15.53% or almost 7 times higher compared to non-rubberized concrete. As concrete's porosity is closely related to air entrainment in the fresh concrete and the porosity value usually is slightly lower than the air entrainment value, we may assume that with higher rubber waste content in fresh concrete the concrete has higher freeze-thaw resistance. According to the theory of hydraulic pressure [Litvan 1973; Pentalla 2006] concrete frost resistance depends on its open (capillary) and closed porosity. During the test the w/c ratio was the same, therefore the capillary porosity of the concrete did not change much. Subsequently, in our case the frost resistance of the concrete depends only on the closed porosity, which is shown in Figure 5 - 7.

The frost resistance factor K_f, computed from open and closed porosity of the concrete, ranges from 2.66 in non-rubberized concrete to 17.84 in concrete modified with rubber waste 0/1 particle size. From the frost resistance factor we may predict that concrete with rubber admixtures has frost resistance of about 100 – 600 freeze-thaw cycles, when concrete is soaked in salt solutions.

The average pore size factor λ in rubberized concretes ranges from 0.36 to 0.68 in the composition with 0/1 particle size rubber and between 0.47 and 0.68 with 1/2 particle size rubber waste. This shows that air-voids in these concretes are rather small and of appropriate size to obtain concrete with adequate frost resistance. Pore size homogeneity factor α is 0.3-0.5 in concrete with 0/1 particle size rubber and 0.30-0.40 in concrete with fr.2/3 particle size rubber; that shows the absence of big-size pores that may negatively affect the frost resistance of the concrete. With smaller size of rubber particles, the average pore size factor λ reduces, while pore size homogeneity indicator α increases with finer fraction of the additive. Finer particles of rubber waste cause the closed porosity and frost resistance if hardened concrete to increase. When 30 % of rubber waste size 1/2 is added, the average air-entraining is 5.3%, while samples with rubber waste size 0/1 rubber demonstrate air entrainment of 14.0% or almost 5 times higher compared to non-rubberized concrete. The increase of air-entrainment in rubberized fresh concrete can be explained by higher porosity of rubber particle surface compared to sand aggregate.

Figure 8 illustrates closed porosity in hardened rubberized concrete, closed porosity in the cement matrix of rubberized concrete and the value of air content in rubber waste.

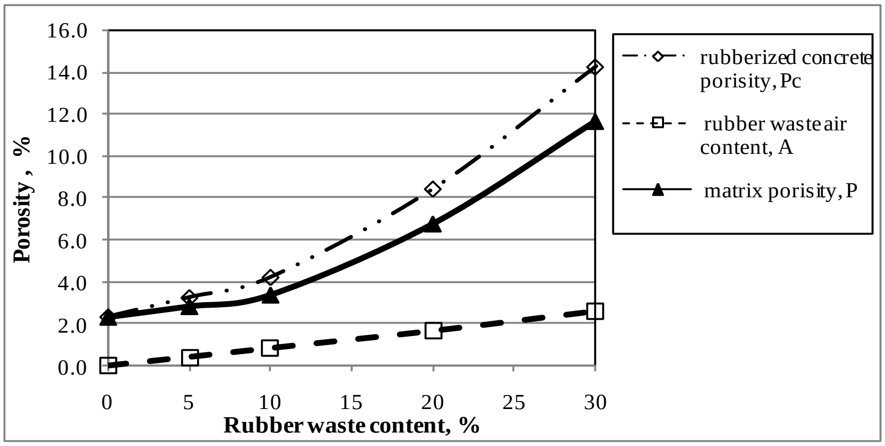

Fig. 8. Dependence of closed porosity in hardened rubberized concrete Pc, closed porosity in the cement matrix of rubberized concrete P and air content of rubber waste additive A amount of rubber waste

Diagrams in Figure 8 show that closed porosity in the cement matrix (without rubber waste additives) is 2.3 %, whereas closed porosity in rubber waste modified concrete changes from 3.1% to 15.5 %. Rubber particles in rubberized concrete act as an absorber and balance all internal stresses in concrete matrix caused by hydrostatic pressure. The influence of rubber waste particles on the cement matrix have been discussed in the papers of Skripkiunas, Kersevicius, Grinys and other researchers [Skripkiunas, Vaitkevicius Daukšys and Grinys 2008; Skrpkiunas and Kersevicius 2001]. The change in closed porosity in the hardened concrete may be explained by the air entrainment in rubber particles. In concretes mixes with rubber waste added at 5 per cent of the total aggregate amount, the amount of air entrained in the rubber increases from 0.38% to 0.44 %, in direct proportion to the smaller size of rubber particles. When rubber waste is added at 10% of the total aggregate amount starting the test from the biggest size rubber particles of 2/3 and moving to the smallest particle size of 0/1, the amount of air entrained in the rubber increased from 0.8 % to 0.9 % respectively. From the values presented in figure 8 we may state that, compared to the control samples, the highest air-entrainment is observed in concrete mixes with rubber added at 30 per cent of the total aggregate amount, where the entrained air ranges from 2.5 % (particle size 1/2) to 2.64 % (particle size 0/1).

CONCLUSIONS

The following general conclusions can be drawn from the study provided in the paper:

- Rubber waste particles have irregular form and uneven surface, which ensures good binding of the particles with the cement matrix.
- Slump in fresh concrete mix reduces with higher content of rubber waste admixture. The drop in slump depends on the amount of the rubber admixture and the size of rubber particles in fresh concrete. Dependence on the rubber additive size, the addition of rubber waste additive up to 10% reduces the slump from 8.3 cm to 3.8 cm, and the addition of 20% of rubber waste additive reduced the slump from 4.75 cm to 1.0 cm respectively.
- The compressive strength of rubberized concrete depends on the content of rubber waste additive and the size of rubber particles. The compressive strength reduces with higher rubber waste content and smaller rubber particle size.
- Addition of rubber waste additive to cement matrix increases the porosity of the matrix. Air-entrainment in the fresh concrete increases with smaller rubber particle size. Fresh concrete with rubber waste fraction 1/2 added at 30 % of the total aggregate amount have the average air-entrainment of 5.3%, while samples with rubber waste fraction 0/1 have air-entrainment of 14.0%.
- Rubber waste additive particles in rubberized concrete act as an absorber and balance all internal stresses in concrete matrix caused by hydrostatic water pressure.
- Frost resistance factor K_f can be used in designing compositions of frost resistant concrete. Rubber waste additive increases the closed porosity and frost resistant concrete can be produced without air-entraining agents by controlling the parameters of the cement and rubberized concrete.

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