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EFFECT OF MILLED ELECTRICAL CABLE WASTE ON MECHANICAL PROPERTIES OF CONCRETE

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Abstract. The article focuses on investigation of mechanical and fracture properties of concrete containing electrical cable waste as well as some microstructural features of such concrete. Added to concrete, electrical cable waste reduces the overall concrete bulk density. Compressive, flexural, tensile splitting strengths and elastic modulus decreased when electrical cable waste was admixed to conventional and polymer modified concretes. The best mechanical properties of concrete samples containing electrical cable waste were identified in polymer modified concrete containing 5% of electrical cable waste. Electrical cable waste particles increase the deformability of polymer modified concretes and have almost no influence on normal concrete. Consequently, the optimal amount of electrical cable waste particles can provide concrete with desirable strength that is required for different applications.

Keywords: electrical cable waste, concrete, fine aggregate, polymer modification, mechanical performance, deformability.

Introduction

Sustainable construction should look for ways to recycle waste as well as reduce energy consumption, pollution and waste. Reduced use of primary construction materials and a greater share of recycled materials should be regarded as priorities of the industry. Consumption of such everyday materials as plastics and tyre rubber is growing every year.

Numerous researches focus on the use of polymeric wastes – tyre rubber, oil palm shells, waste polyethylene terephthalate (PET) bottles – as a partial substitution for mineral aggregates in concrete production. Incorporation of plastic particles modifies the properties of ordinary cement concrete. Recycled plastic reduces the overall concrete bulk density, compressive strength, tensile splitting strength and abrasion resistance. The greater is the percentage of plastic aggregates in concrete mixtures, the greater is the reduction in these properties. Recycled plastic can be used in a variety of applications such as utility components (e.g., drains for acid wastes, underground vaults and junction boxes, sewer pipes, and poles for electrical lines (Asokan *et al.* 2009; Panyakapo, P., Panyakapo, N. 2008; Siddique *et al.* 2008). Addition of crumb rubber into concrete results in the decrease of compressive strength, density and modulus of elasticity. The decrease depends on the percentage of crumb rubber in concrete. In addition, small amounts of crumb rubber added into concrete initially caused a decrease in water absorption; however, addition of greater quantities resulted in increased water absorption. Reduction of small amounts of crumb rubber into concrete produced no significant change. Abrasion resistance, noise and thermal insulation increased with increased amounts of added crumb rubber (Shtayeh 2007). The research (Grinys *et al.* 2013) demonstrated that crumb rubber can be used in concretes as a partial alternative to metal and polypropylene fibres.

As a recycled material, waste tyre rubber was used in the study (Yung *et al.* 2013) as a replacement for a part of fine aggregate to produce self-compacting rubber concrete (SCRC). The addition of 5% waste tyre rubber powder brought about a significant increase in anti-sulphate corrosion Compared to ordinary concrete, SCRC has high electrical resistance properties. The use of waste tyre rubber powder can enhance the durability of SCRC.

Tests results of another research showed that the compressive strength of concrete samples prepared using the vibrating or static pressure methods decreased

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with the increase in the volume fraction of rubber particles (Yang *et al.* 2014).

Two types of water-soluble polymers (dispersible latex powder and polyvinyl alcohol powder) and waste tyre-rubber powders were added to concrete as admixtures in order to improve bending toughness and fatigue performance of brittle cement-based composites (Lee *et al.* 1998; Chen *et al.* 2014). The results showed that the effects of dispersible latex powder on bending toughness and fatigue life of concrete were better than those of polyvinyl alcohol powder. The multiscale chemical physics mechanisms show that high bonding effect and high elastic modulus of polymer films as well as good elastic property and crack-resistance of waste tyre-rubber powders are beneficial for improving bending toughness and fatigue life of cementitious composites (Chen *et al.* 2014).

Other studies tested concrete specimens reinforced with fibres made from waste polyethylene terephthalate (PET) bottles. Bottles were cut to obtain fibres, which were added to concrete mix or were used as discrete reinforcement of specimens and little beams to substitute steel bars. The obtained results were very interesting, especially the adherence between PET and concrete, suggesting possible use of this material in the form of flat or round bars, or networks for structural reinforcement (Saikia, de Brito 2014; Foti 2013).

Four recycled fillers (powdered, tyre rubbers, micronized tyre fibres, and milled electrical cable waste) have been used to formulate new polymer mortars. The comparison of their mechanical properties and microstructures with plain polymer mortar indicates that the presence of recycled waste affects the physical–mechanical behaviour. The use of silane coupling agents has been also considered and their effect in leading to more compact materials has been reported and discussed (Bignozzi *et al.* 2000, 2002).

In the current research, electrical cable waste was added into concrete as a secondary raw material to test the potential sustainable construction concept. The main suppliers of this type of waste are companies that produce or use cables. This paper presents the development of lightweight aggregate concrete using fine aggregate manufactured from recycled electrical cable waste. This particular research focused on the effect of specific and poorly investigated waste (ECW) and determined physical and mechanical properties of the concrete. The paper contains a literature review of any data concerning concrete containing ECW and polymer additives for reduction of the amount of entrained air in the concrete mixture.

1. Experimental

Concrete samples – cubes (100×100×100) mm and prisms (400×400 ×1600) mm were cured in conditions according to EN 12390-2 (2009) and tested after 28 days. The density of concrete was determined according to EN 12390-7 (2009), compressive strength – EN 12390-3 (2009), flexural strength – EN 12390-5 (2009), tensile splitting strength – EN 12390-6 (2009) and modulus of elasticity – ISO 6784 (1982). The structure of hardened cement paste was studied using a high resolution scanning electron microscope FEI Quanta 200 FEG with a Schottky field emission *gun* (*FEG*).

Produced by the private limited company *Akmenes cementas*, Portland cement CEM I 42.5 R was used as a binding material. The initial setting time of Portland cement is 140 min, the final setting time – 190 min (EN 196-3 2009), and the mineral composition contains: C_3S – 62.0; C_2S – 12.0; C_3A – 7.5; C_4AF – 11.0. The 0/4 fraction sand from Kvesai quarry was used as fine aggregate and 5/16 fraction granite macadam – as coarse aggregate. Chemical admixture super plasticizer Sika Viscocrete D187 based on polycarboxylic resins and Sika Baudispersion (a liquid polymer additive based on carboxylated styrene butadiene latex) were used in experimental testing. Sand was replaced by electrical cable waste (ECW) at 5% and 10% of the fine aggregate by volume amount. The density of electrical cable waste particles was 1302 kg/m^3 and the bulk density was 417 kg/m^3 (for comparison, the density of sand was 2650 kg/m^3 and the bulk density was 1605 kg/m^3). These particles were finer than 1.5 mm. Sieve analysis data of sand, granite macadam and ECW are shown in Figure 1. ECW particles are shown in Figure 2.

Different mixtures were made under laboratory conditions in order to determine the mechanical properties and microstructure of hardened concrete. The water-cement ratio was 0.50. Other constituents are given in Table 1. Two types of concrete samples were prepared: conventional concrete (0, 5, 10) and polymer modified concrete (0P, 5P, 10P) with the polymeric additive in the latter. A part of fine aggregate in both types of concrete samples was replaced by ECW. Only natural aggregates (sand and granite macadam) were used in reference samples of conventional and polymer modified concretes.

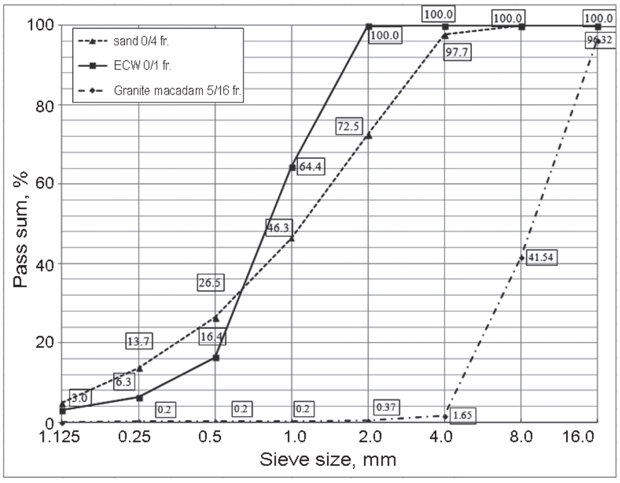
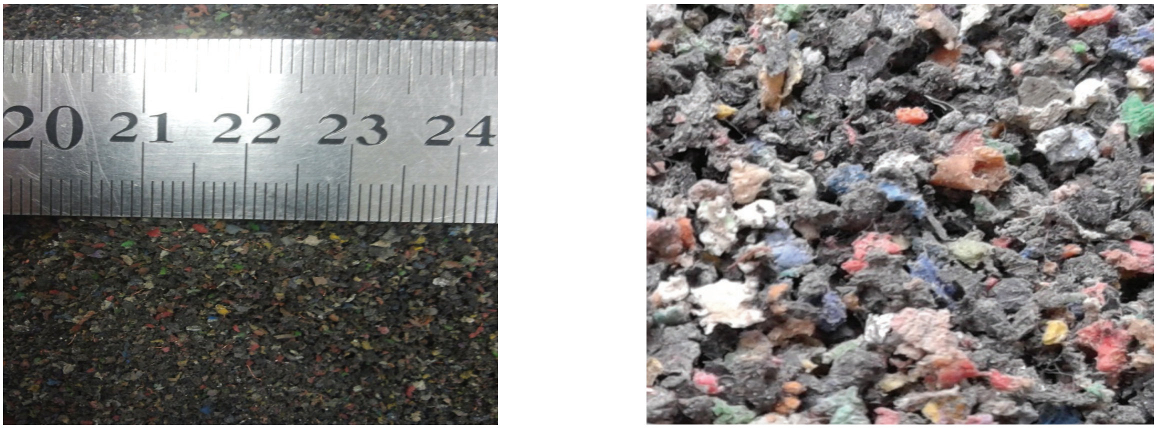


Fig. 1. Sieve analysis data of sand, granite macadam and ECW



a) b)

Fig. 2. Electrical cable waste particles used in this research

Table 1. Composition of 1 m^3 of concrete mixtures (concrete mix design was calculated by the Absolute Volume Method)

Samples	W/C	Water, *l*	Cement, kg	Fine aggregate			Coarse aggregate, kg	Super plasticizer, *l*	Polymer, *l*
				0/4 fraction sand, kg	ECW, %	ECW*, kg	5/16 fraction granite macadam		
0	0.5	165	330	831	0	–	1034	2	–
5	0.5	165	330	737	5	36	1034	2	–
10	0.5	165	330	644	10	72	1034	2	–
0P	0.5	165	330	814	0	–	1013	2	30
5P	0.5	165	330	722	5	35	1013	2	30
10P	0.5	165	330	631	10	70	1013	2	30

2. Results and discussions

The effect of ECW amount on density of concrete was determined first. The density of samples decreased with the increasing amount of ECW in concrete composites (Fig. 3).The reduction of density in investigated concrete samples can be explained by a lower density of ECW (1302 kg/m^3) compared with the density of fine aggregate (sand) particles (2650 kg/m^3). Recycled plastic aggregates usually present lower density, greater porosity, and water absorption, and, sometimes, lower strength than that of natural aggregates (Albano *et al.* 2005; Siddique, Naik 2004).

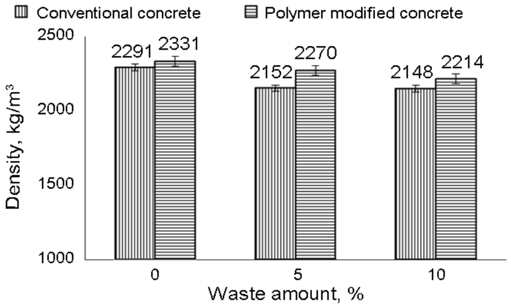
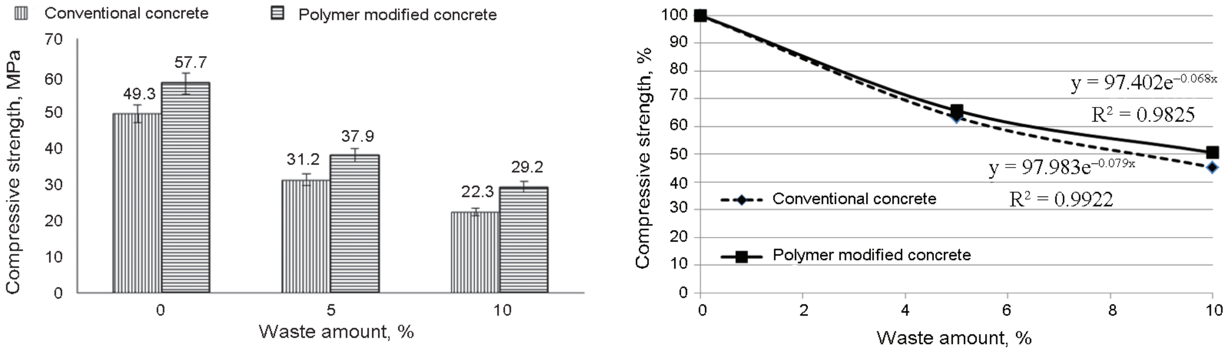


Fig. 3. The influence of ECW amount on concrete sample density

Water-soluble polymers hardly contribute to an improvement in the strength of modified systems. The principle of modification of cement composites with monomers is the same as with liquid resin modifications except that it involves the addition of monomers instead of liquid resins. The density of the samples was greater than conventional concrete sample densities in all investigated cases of polymer modified concrete. This is because both polymerization and cement hydration occur at the same time, during curing, to make a monolithic matrix which binds aggregates (Ohama 1995).

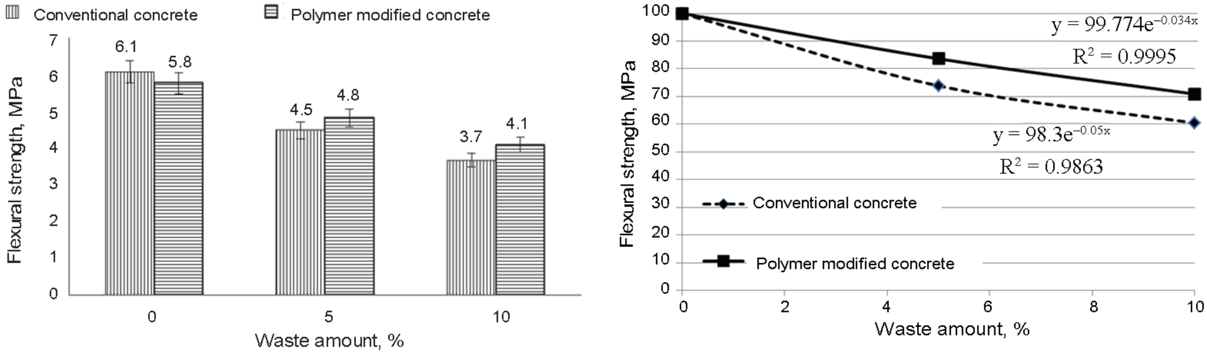
The effect of ECW amount on compressive strength, flexural strength and tensile splitting strength of concrete is significant. Concrete samples containing ECW exhibited lower mechanical properties than normal conventional concrete (Figs 4, 5 and 6).

The reduction of compressive strength, flexural strength and tensile splitting strength in concrete samples may be explained by two points: firstly, ECW particles are softer (elasticity deformable) than the surrounding cement paste; therefore, cracks can initiate quickly, on loading around the ECW particles in the mix accelerating the failure of the ECW–cement matrix. The second explanation can be lower compressive strength of ECW particles compared to the strength of conventional aggre-



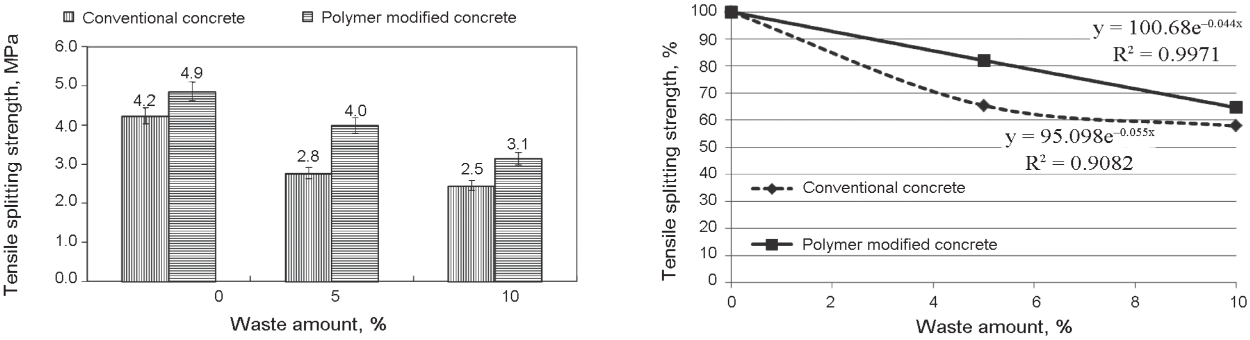
a) b)

Fig. 4. Influence of the amount of ECW on the compressive strength of concrete samples in MPa (a) and in % (b)



a) b)

Fig. 5. Influence of the amount of ECW on the flexural strength of concrete samples in MPa (a) and in % (b)



a) b)

Fig. 6. Influence of the amount of ECW on the tensile splitting strength of concrete samples in MPa (a) and in % (b)

gates. A similar explanation for the decrease in strength was obtained when tyre rubber was added into concrete (Skripkiūnas *et al.* 2007, 2009). The dependence of compressive strength on different amounts of added ECW can be mathematically described by the polynomial equation of the second degree. The data obtained from diagrams in Figure 4b show that compared to the control samples, the biggest drop in compressive strength is observed in case of the highest amount of added ECW amounting to 10% of the fine aggregate amount and in conventional concrete. Figure 4 shows that 10% of ECW reduced the compressive strength down to 45% and down to 51% with polymer modified concrete.

Figure 5a shows the flexural strength values. As expected, the flexural strength decreases due to ECW additive. It changes from average 6.08 MPa for the control sample to 3.67 MPa for the conventional concrete sample containing 10% of ECW additive. Values of flexural strength for polymer modified concrete samples were higher when compared with conventional concrete samples containing 5% or 10% of ECW. The flexural strength of R can be predicted using mathematical functions shown in Figure 5 b. Compared to the control samples, the bigger drop in flexural strength is observed in case of addition of ECW and in conventional concrete. The addition of ECW (10%) reduced the flexural strength down to 60% and the addition of ECW (10%) to polymer modified concrete flexural strength reduced down to 71%. The difference between the flexural strength of conventional concrete and polymer modified concrete varied by about 10%. A lower decrease of the flexural strength of polymer modified concrete may be attributed by a higher influence of cement paste adhesion to aggregates or ECW.

According to the data on the compressive strength and flexural strength of concrete samples, which was presented in Figures 4 and 5, it was determined that the compressive strength reduces from 2.0 to 2.2 times using 10% of ECW additive in concrete compared to control sample, while the flexural strength reduces only from 1.4 to 1.7 times. A lower decrease of the flexural strength for concrete samples may be attributed to the later formation of cracks in the cement matrix during the flexural test. It could be associated with small ECW reinforcing effects (e.g., fibre reinforced concrete is more effective in resistance to the flexural stress rather than the compressive stress).

Figure 6 shows the effect of ECW replacement on the tensile splitting strength of concrete. It was found that ECW reduces the tensile splitting strength of concrete to the extent by which the amount of ECW particles is increased. The average tensile splitting strength of reference concrete samples is 4.24 MPa (conventional concrete) and 4.86 (polymer modified concrete), while the tensile splitting strength of concrete with ECW particles decreases from 2.45 MPa (conventional concrete) to 3.14 MPa (polymer modified concrete) using 10% of ECW additive.

According to experimental results, the use of ECW in concrete causes a decrease in the tensile splitting strength exponential. Regression equations of the tensile splitting strength and multiple regression correlation coefficients of specimens are shown in Figure 6b. It provides that correlation coefficient values vary from 0.90 to 0.99, depending on the type of concrete samples.

Meanwhile, the elastic modulus of both concretes without ECW decrease by 37% (17.16 GPa) and 32% (19.84 GPa) compared to concrete with 10% of ECW (Fig. 7).

Furthermore, all investigated mechanical properties of concrete simultaneously containing polymer and ECW powders are greater than those of concrete with only one type of additive (ECW). Generally, polymer films in cement paste matrix and in cement-aggregate interfacial zone have positive effects on mechanical properties of cement-based composites.

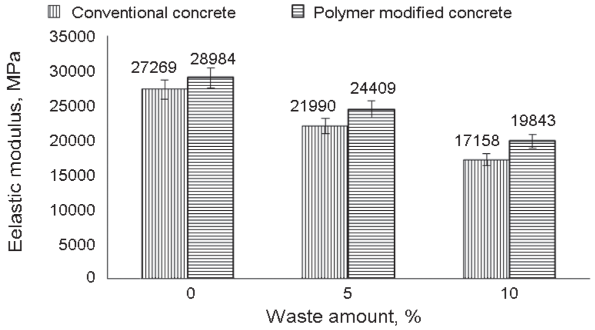


Fig. 7. Influence of the amount of ECW on elastic modulus of concrete samples

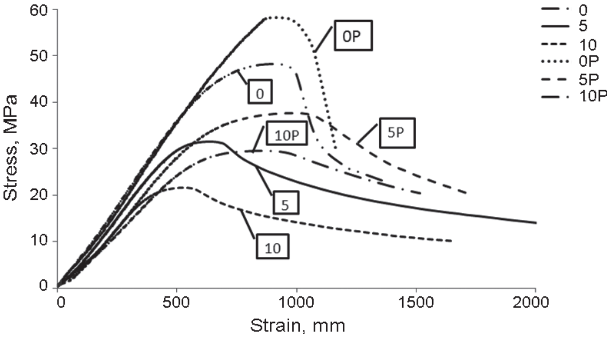


Fig. 8. Typical compressive stress–strain response by ECW amount

The stress-strain curves for the investigated conventional concretes and polymer modified concrete types without ECW and with ECW are shown in Figure 8. The curves indicate that the behaviour of ECW concrete is more nonlinear compared to that of the reference concrete, implying a different failure type for ECW concrete (especially for polymer modified concrete with ECW). The nonlinear behaviour for ECW concrete mixtures may also be due to the lower compressive strength and the effect of ECW additions to these samples. The nonlinearity index for all samples increases with the increase in ECW content.

The fracture mechanism for normal concrete and polymer modified concrete without ECW is similar, only normal concrete fails at a lower load. Meanwhile, the fracture mechanism of the polymer modified concrete with ECW is more plastic and nonlinear (Fig. 8). It can be explained by better adhesion between ECW and the cement matrix; polymer modified concrete with ECW absorbs more concrete plastic strains and increases concrete deformability (Fig. 8).

The substitution of ECW with polymer modified concrete for mineral aggregates appears to permit more uniform crack development and provides gentler crack propagation compared to conventional concrete. Considering the stress-strain curves, ECW concrete specimens experience larger deformations compared to conventional concrete samples under the same loading conditions. ECW particles increase the deformability of polymer modified concretes, but have almost no effect on normal concrete with ECW. This demonstrates that ECW particles have better adhesion to the polymer modified concrete matrix than in conventional concrete (Fig. 8). Hence, these curves support the opinion that ECW particles result in concrete failures with larger deformations and higher energy dissipation, especially in case of polymer modified concrete.

Many empirical equations for predicting the modulus of elasticity as a function of compressive strength can be found in the current literature (Noguchi *et al.* 2009).

One of them is given below:

$$E_{calculated} = k_1 k_2 \cdot 1.486 \times 10^{-3}\, \sigma_B^{1/3} \gamma^2, \tag{1}$$

where: k_1 is the correction factor corresponding to coarse aggregates; k_2 – the correction factor corresponding to admixtures; σ_B – compressive strength in MPa and γ – unit weight in kg/m^3.

Thus, the existing equations are not tested for many polymer aggregates. This is due to the fact that mechanical properties of concrete are highly dependent on types and proportions of used aggregates. For many different types of aggregates characterising coefficients k_2 are proposed; however, no coefficient for ECW aggregate is found. The relationship between the calculated modulus of elasticity (Eqn (1)) and ECW amount in conventional concrete and polymer modified concrete with ECW is similar. However, with 5% of ECW, Eqn (1) provides a larger error (Table 2).

It is, therefore, necessary to assess adaptation of k_2 coefficients for ECW aggregates. This research proposes to use k_2 coefficients comparable to the range from 0.961 to 1.103 to get the most accurate results (Table 2). They depend on the content of used polymer aggregate.

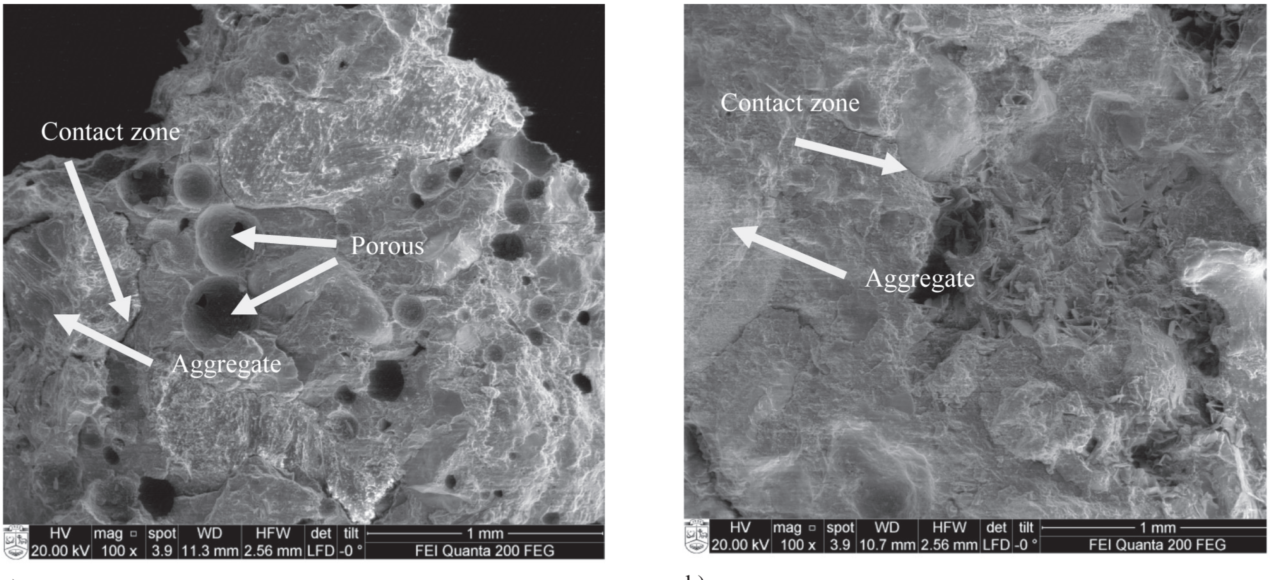
Microstructure of the conventional concrete samples is more porous. SEM tests showed that the interface bonding between fine and coarse aggregates and hardened cement paste was better in the polymer modified concrete than that of between aggregate particles and hardened cement paste in conventional concrete samples (Fig. 9).

Table 2. Correction factors for coarse aggregate and ECW

No.	k_1 and k_2 coefficients estimate the coarse aggregate and ECW influence for *E* modulus calculation		Ratio E_{real}/$E_{calculated}$ underestimate the ECW influence (when $k_1 = 0.931$ and $k_2 = 1$)	Ratio E_{real}/$E_{calculated}$ estimate the ECW influence with suggested k_2 ($k_1 = 0.931$)
	k_1*	Suggested k_2 for ECW		
0	0.931	1.000	1.04	1.04
5	0.931	1.103	1.10	1.00
10	0.931	0.965	0.96	1.00
0P	0.931	1.000	1.01	1.01
5P	0.931	1.031	1.03	1.00
10P	0.931	0.961	0.96	1.00

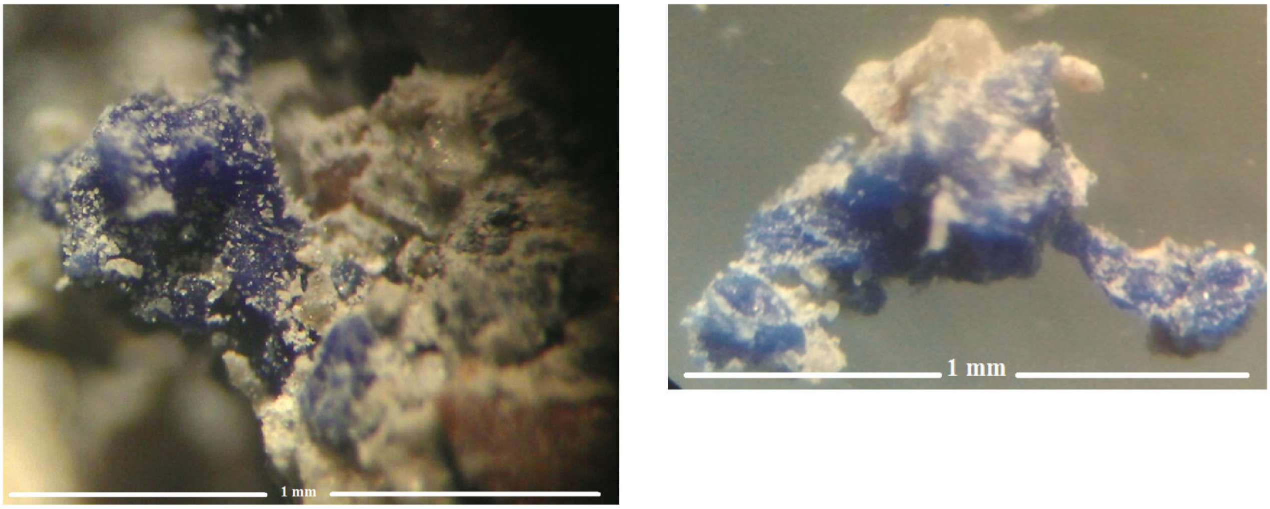
* – where k_1 corresponding granite macadam (Noguchi *et al.* 2009)

Microscopic observations (Fig. 10) showed that ECW particles are above 1 mm in size and have an irregular shape with high surface area. The shape of an ECW particle and large surface area affect good adhesion of the contact zone between the cement matrix and an ECW particle. Similar results were obtained using rubber particles in concrete samples (Grinys *et al.* 2012). Just as surfaces of rubber particles, surfaces of ECW (Fig. 10) are much rougher than the surface of sand, which is smooth and even; therefore, the hardened cement paste has a better adhesion to rubber or ECW particles.



a) b)

Fig. 9. SEM images of concrete microstructure with 10% of ECW after 28 days: conventional concrete (a) and polymer modified concrete (b)



a) b)

Fig. 10. Contact zone between the cement matrix and an ECW particle (a) and an ECW particle of the size up to 1 mm (b)

A potential use of this relatively new construction material includes concretes with limited strength requirements and high fracture toughness/energy demand such as those used in bridge barriers.

Conclusions

1. The use of ECW in concrete reduced the overall concrete bulk density. The bulk density was reduced by 6.1–6.3% for concrete containing ECW ranging from 5% to 10% in conventional concrete samples compared to conventional concrete and in polymer modified concretes the bulk density was reduced by 2.6–5.0%, respectively.
2. Compressive strength, flexural strength, tensile splitting strength and elastic modulus of ECW admixed conventional concrete and polymer modified concretes decrease with increasing additions of investigated waste. The lowest decrease of concrete mechanical properties was obtained by using 5% of ECW for polymer modified concrete from the volume of concrete fine aggregate. This is due to lower mechanical properties of ECW compared with natural aggregate. Accordingly, the optimal utilisation amount of ECW should be no more than 5% instead of small aggregate volume in concrete.
3. ECW particles increase the deformability of polymer modified concrete but have almost no effect on normal concrete with ECW particles. In polymer modified concrete, due to the substitution of mineral aggregates with ECW, flexural test appear to permit more uniform crack development and provide gentler crack propagation compared to conventional concrete. Due to better adhesion of ECW in the polymer modified concrete such waste could be used in concrete where less brittle fracture mechanisms are studied on.

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