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The Use of Steel Cord Scrap in Concrete

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Abstract **– Materials used for the study: Portland cement CEM I 42.5 R, 4/16 gravel, 0/4 sand. The fine aggregate in four concrete mixtures was substituted with steel cord scrap added at 1.5 %, 3.0 % and 4.5 %. Water absorption and compressive strength was measured in concrete specimens after 7 and 28 days of curing. Total, closed and open porosity was measured in the modified concrete specimens. The tests of predicted freeze-thaw cycles were done. Test results showed that the substitution of fine aggregate with steel cord scrap results in lower water absorption and higher compressive strength in the modified concrete specimens. The porosity parameters have also changed: the closed porosity has increased and consequently the freeze-thaw resistance of modified concrete has improved.**

Keywords **– Compressive strength, concrete, freeze-thaw resistance, porosity, scrap-tire steel cord.**

I. Introduction

Many researchers pay particular attention to the investigation, development and practical application of concrete mixes. Meanwhile, a lot of valuable research results have been successfully applied in the design of buildings and constructions, manufacture of concrete structures.

Disposal of used tires is a global environmental problem. Waste tire recycling has not only environmental but also economic implications associated with the re-use of raw materials.

Every year nearly 3 billion of tires are produced for passenger cars, SUVs, trucks and other vehicles, and demand for tires is growing. Meanwhile, about 1.4 billion of end-of-life tires (ELTs) are annually disposed to landfills and treated as waste. The composition of a tire is illustrated in Fig. 1.

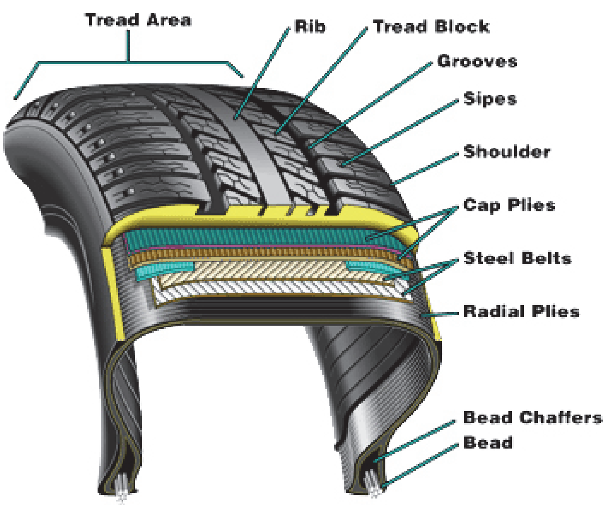

Fig. 1. Tire composition.

Eco-friendly disposal of tires is a rather difficult technological problem because a tire is a complex rubber product reinforced with steel wire and cotton cloth. Recently tires with steel cord have become more common because along with higher vehicle speeds more stringent technical criteria for tires are applied. Effective ways of separating rubber from the steel cord have to be found in order to develop a highly efficient ELTs recycling technology [1].

Tires are made of a mixture of different materials, including synthetic and natural rubber, butyl rubber, textile, steel, carbon black and a variety of chemical additives, which are cured at high temperatures during the manufacturing process. Tire burning is difficult compared to the ordinary fuel, even though the calorific content value of tires is much higher than the heating value of coal and is close to that of the natural gas. Higher temperatures and longer time is required to reach the heating in full and to oxidize the hydrocarbons to carbon dioxide and water. In the state of end-of-life, tires that have lost about 15 % to 20 % of their initial weight still contain about 75 % of natural rubber that can be recycled [2].

UAB Metaloidas is one of the biggest tire recycling facilities in the Baltic States and has the capacity to mechanically shred 30 000 tons of used tires per year. The shredding process yields about 12 000 tons of crumb rubber and 40 000 m^2 of rubber paving. However, the remaining textile and steel cord scrap has not been efficiently used yet.

With the growing demand for innovative recycling technologies and sustainable buildings some researchers propose to use crumb rubber and steel cord reclaimed from end-of-life tires in the designing of concrete mixes [3].

Steel fibre reinforced concrete is used not only in the construction of new buildings but also for the modification of currently used structures [4].

Concrete mix design requires deep knowledge about the behaviour of fibres in concrete under stretching conditions. It depends on various parameters, such as structure and geometry of fibres, binding strength between the fibre and the binder, the strength of the mix, the direction of fibres in concrete, etc. Efficiency of metal fibres in concrete can be tested experimentally or digitally [5].

According to the researchers, a well-designed concrete containing steel cord scrap is able to control crack propagation and therefore has better durability characteristics. The fatigue of the mixture properties depends on the content, type and geometry of added fibres [6]. Steel fibres in concrete improve impact resistance of the material [7]. Concrete mixes modified with steel cord have better compressive strength characteristics. This improvement depends on the direction of fibres, characteristics (type, size, proportion, etc.) and the quality of cement [8], [9].

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Researchers from Sheffield University have proved that steel cord obtained from recycled ELTs can be successfully used in concrete production. First of all, the authors studied the cracking behaviour and flexural strength of concrete and discovered that steel cord scrap improved the resistance of concrete to cracking and failure to bending [10].

Road construction using concrete with metal cord waste can lead to reduction of coating thickness by up to 26 % [11].

The design of the mix of concrete modified with steel cord scrap requires precise calculation of steel cord content in the concrete mix. In the case of wrong design of the mix the steel cord admixture can sink to the bottom instead of distributing evenly throughout the volume of the mix. Although metal cord particles dissipate in a concrete element randomly, the steel cord can be used in the production of two-layer fibered concrete beams of high-performance reinforced concrete columns [12].

The steel cord scrap from ELTs is much cheaper compared to manufactured steel fibres. Steel cord scrap of appropriate structure may become an alternative for the manufacturing of steel fibres. The image of steel cord obtained from recycled tires is presented in Fig. 2.

Fig. 2. Steel cord reclaimed from end-of-life tires.

The tests of mechanical and durability properties of concrete modified with steel cord scrap proved that the mix design met all requirements for the characteristics of concrete. In addition to laboratory tests, the economic study was conducted. According to the calculations, one cubic meter of concrete mix modified with steel cord scrap reduces the price of the finished product from 7 % to 33 % compared to concrete modified with new steel fibre. For these reasons steel cord scrap from end-of-life tires offers potential benefits [13].

II. Materials and Methods

CEM I 42.5 R cement was used for the tests (Table I). It is a classical binder used for concrete products.

Fraction 0/4 sand and fraction 4/16 gravel was used to make the test specimens. Physical characteristics of sand and physical – mechanical characteristics of gravel as well as particle-size distribution of fine aggregates were laboratory tested according to the methodology specified in the following standard EN 1097 series: EN 1097-7, EN 1097-6, EN 1097-5, EN 1097-3, EN 933-1, EN 1476-7. The tested physical properties of coarse and fine aggregates obtained are presented in Table II.

Clean potable water complying with standard EN 1008:2003, i.e. without any impurities that would retard the normal setting of concrete, was used to prepare the water-cement mix. Polycarboxylate ether-based superplasticizer was used for making the specimens. The characteristics of the plasticizer were as follows: resin concentration in the solution – 36.1 %, pH value – 5.05; electric conductivity – 1.480 mS/cm, solution density – 1040 kg/m^3. The recommended content of the superplasticizer is 0.2 % to 2.5 %.

Four concrete mixtures were designed. Mixture 1 was the control mixture without the steel cord admixture. In Mixture 2, 1.5 % of 0/4 sand was substituted by steel cord scrap. With the addition of 1.5 % of steel cord scrap, water content was slightly reduced (see Table IV) in order to maintain slump class S2. The cement content varied from 450 kg/m^3 to 483.3 kg/m^3. Mixture 3 contained 3.0 % of steel cord scrap, and Mixture 4 contained 4.5 % of steel cord scrap. Concrete mixtures are presented in Table IV.

TABLE I

Physical-Mechanical Properties of the Cement

Property	Portland cement CEM I 42.5 R
Specific surface, cm^2/g	3700
Particle density, kg/m^3	3200
Bulk density, kg/m^3	1200
Standard consistency paste, %	25.4
Initial setting time, min	140
Final setting time, min	190
Compressive strength after 7 days, MPa	28.9
Compressive strength after 28 days, MPa	54.6

TABLE II

Physical Properties of Gravel and Sand

Property	Gravel 4/16	Sand 0/4
Particle density, kg/m^3	2281	2498
Bulk density, kg/m^3	1672	1589
Voids, %	27	36
Moisture content, %	0.15	0.2

TABLE III

Properties of Steel Cord Scrap

Property	Amounts
Volume rubber, %	8
Volume steel, %	92
Steel cord length, mm	9–15
Steel cord diameter, mm	0.15

TABLE IV

Concrete Mixtures 1 M^3

Materials	Amounts			
Waste content, %	0	1.5	3	4.5
Waste amount, kg	0	13.0	26.8	39.0
CEM I 42,5 R, kg	450	455.8	458.5	483.3
Gravel 4/16, kg	950	950	950	950
Sand 0/4, kg	875	861.7	848.5	835.8
Plasticizer, l	2.25	2.25	2.25	2.25
Water, kg	160	164	165.1	174
W/C	0.36	0.36	0.36	0.36
Class of mobility	S2	S2	S2	S2

Concrete mixtures were mechanically mixed in laboratory conditions and 100 mm × 100 mm × 100 mm specimens were made in metal moulds. After 24 hours, the specimens were removed from the moulds and were kept in (20 ± 2) °C water for 28 days. After 7 and 28 days of curing in water the compressive strength was tested according to EN 12390-3:2009, the density was tested according to EN 12390-7:2009. The total water absorption of the specimens was tested by soaking them in water for 96 hours. The specimens were soaked in potable water of (20 ± 5) °C and kept there until the constant mass was reached. The specimens should be separated by 15 mm gaps and covered by 20 mm layer of water. The constant mass was reached when the difference between two weightings every 24 hours was less than 0.1 %. Before the weighting, the excessive water from the surface of the specimens was removed with a damp cloth.

The main indicators of concrete quality are compressive strength, density, freeze-thaw resistance. The quality and durability of concrete depends on the selection and evaluation of appropriate materials and their characteristics, the consistency of technological processes, starting with concrete mix design, preparation of fresh concrete and placing into moulds and finishing with concrete setting and demoulding. The sequence of mixing concrete components and mixing duration is presented in Table V.

TABLE V

THE SEQUENCE OF MIXING CONCRETE COMPONENTS

No	Components	Mixing duration, s
1.	Gravel + steel cord	120
2.	Gravel + steel cord + sand	60
3.	Gravel + steel cord + sand + cement	60
4.	Gravel + steel cord + sand + cement + water with superplasticizer	180
		In total: 420

According to the methodology proposed by the authors Sheikin (Шейкин) and Dobshic (Добшиц), the freeze-thaw resistance of concrete is predicted by means of freeze-thaw resistance criterion when the porosity parameters are available. The specimen is split in two parts and dried in the drying chamber for 24 hours at 90 °C. Afterwards the water absorption kinetics of the specimens is measured and overall, open and closed porosity and frost resistance of the concrete is calculated [14].

III. RESULTS

According to test results, steel cord scrap added to the concrete mix has the effect on the following properties of concrete: water absorption, compressive strength, porosity (closed, open and total) and predicted freeze-thaw resistance.

The test results are described below. Water absorption in the control mixture without any steel cord scrap was 3.57 % (Fig. 3). After substituting 1.5 % of 0/4 fraction sand with steel cord scrap, water absorption reduced by 3.36 %. 3.0 % of steel cord scrap reduced water absorption in the modified concrete by 3.14 %, and 4.5 % of steel cord scrap reduced water absorption in the modified concrete by more than 22.7 % compared to the control mixture. Laboratory tests with the modified concrete showed that the addition of steel cord scrap significantly reduces water absorption of concrete. This can be explained by the substitution of water absorbing sand by steel cord scrap that does not absorb water at all. Steel cord scrap also reduces open porosity and increases closed porosity of the modified concrete.

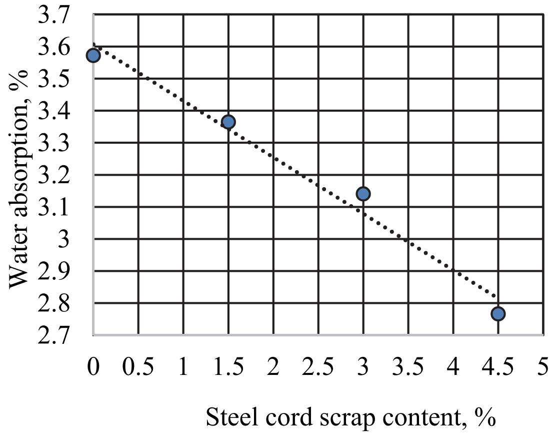

Fig. 3. Average water absorption values in steel cord scrap modified concrete.

Compressive strength of concrete was measured after 7 and 28 days of curing (Fig. 4). As expected, after 7 days of curing, compressive strength demonstrates lower values 2.4 MPa to 1.4 MPa compared to the specimens that were cured for 28 days. After 7 days of curing, the control mixture specimens showed compressive strength of 63.42 MPa, and after 28 days of curing compressive strength increased to 65.82 MPa. In the specimens containing 1.5 % steel cord scrap compressive strength after 7 days increased by more than 0.78 Mpa, and in the specimens cured for 28 days compressive strength increased by 0.69 MPa. The increase of metal cord scrap content was directly related with the increase in compressive strength of the modified concrete. After 7 days of curing, the steel cord scrap content of 3.0 % caused 3.44 % increase in compressive strength, and 4.5 % of steel cord scrap caused 6.02 % increase in compressive strength of the modified concrete. Compressive strength growth was also observed after 28 days of curing: 1.5 % growth with 3.0 % scrap content, and 4.43 % growth with 4.5 % scrap content. Thus, test results show that steel cord scrap increases the compressive strength of the modified concrete.

Hardened concrete is a porous material able to entrain gas and liquids. The pores can have an effect on the properties of the material in other ways too. Total porosity, size of pores and their distribution, size and form of the biggest pores and the relation between the pores first of all have an effect on compressive strength. Durability depends on freeze-thaw resistance and is controlled by the volume of air entrained in the pores and spaces between the pores [15], [16].

According to K. P. Mehta, the pores in the hardened cement paste can be classified by their form and size into three main groups: capillary pores, gel pores, and air voids [17].

Capillary pores (open pores) occur in concrete after evaporation of excessive water used to prepare the concrete mixture. According to A. K. Kallipi, capillary pores are open pores that are easily filled with water. The destructive effect of freezing and thawing depends on water content in concrete. It can be argued that the higher number of open pores and the bigger size of the pores directly relate to the lower freeze-thaw resistance of concrete [18].

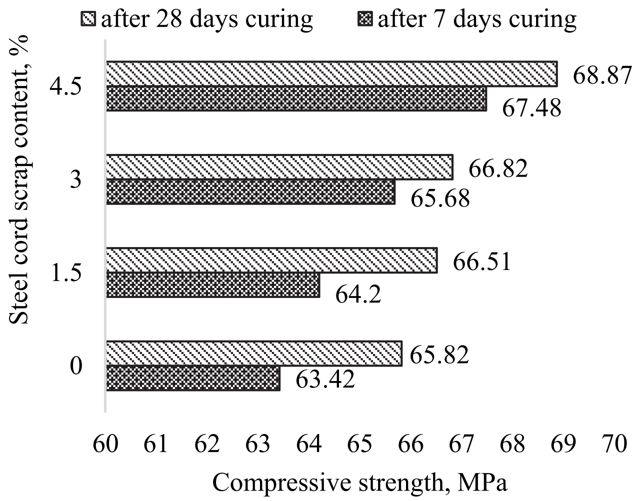

Fig. 4. The effect of steel cord scrap on compressive strength.

Closed pores result from entraining air from the environment and the contraction of hardening cement paste. Air entrainment can be promoted by special admixtures, whereas the contraction occurs naturally. Air voids and contraction pores are closed pores that increase the freeze-thaw resistance of concrete. Gel pores have no effect on freeze-thaw resistance because they are very small in size, from 1.5 nm to 2.0 nm [18]–[21].

The porosity tests showed that the addition of steel cord scrap reduces open porosity and increases closed porosity; consequently, the durability of steel cord scrap modified concrete becomes higher. The total porosity of the control mixture was 6.8 %, with 0.45 % closed pores and 6.3 % of open pores. The addition of 1.5 % steel cord scrap caused the growth of the total porosity up to 8.44 % with the slight increase of open porosity up to 7.25 %, and the increase of closed porosity up to 1.19 %. With the increase of steel cord scrap content up 3.0 % a significant growth of closed pores (up to 4.17 %) is observed along with insignificant increase of open porosity up to 7.64 %. With 3.0 % of steel cord scrap added the total porosity of 11.91 % is reached. With steel cord scrap content of 4,5 % the total porosity exceeds 15 %, the open porosity grows up to 8.73 %, and the closed porosity grows up to 6.31 %. The test results showed that compared to the control mixture the closed porosity of experimental mixtures increased more than 6 times (Fig. 5).

Open pores and air voids developed during the evaporation of free water from concrete affect the freeze-thaw resistance. The number of such pores and air voids depends on water/cement ratio. The more water is added to the cement mix, the higher is the content of unbound water and the bigger number of capillaries remain after water evaporation [22].

The main cause for the degradation, cracking, and crumbling of concrete is that the product is exposed to ice conditions, as water turns into ice, the volume increases. The density of water is 1 g/cm^3, and the density of ice is 0.917 g/cm^3. Ice takes 9 % larger volume compared to water. Ice crystals exert pressure on the walls of pores and capillaries of the hardened cement paste and by expanding can disintegrate the concrete item [23], [24].

Disintegration of the hardened cement paste as a result of freezing and thawing is the most common cause of destruction of concrete products. Water saturated hardened cement paste exposed to cyclic freezing and thawing can disintegrate like any other mineral solid body [22].

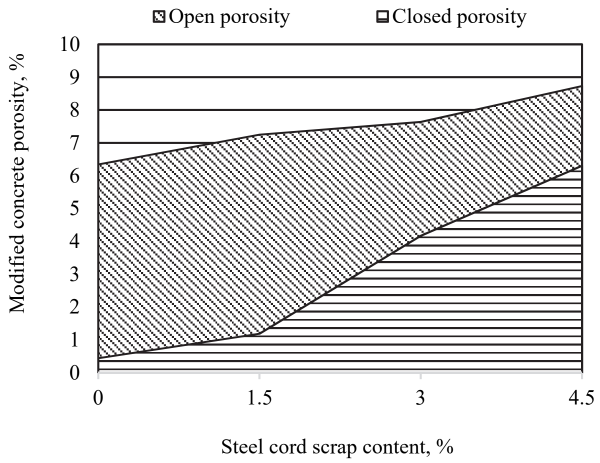

Fig. 5. Porosity of steel cord scrap modified concrete.

Freeze-thaw cycles were tested in order to evaluate durability of steel cord scrap modified concrete. Fig. 6 illustrates the increase in the number of freeze-thaw cycles with higher content of steel cord scrap. It is also related with water absorption and modified structure of the hardened cement paste by the addition of steel cord scrap (higher closed porosity). The control mixture sustains 65 freeze-thaw cycles, the mixture with 1.5 % of steel cord scrap bears 4.3 times more, i.e. 280 cycles. With the increase of steel cord scrap content up to 3.0 %, the predicted number of freeze-thaw cycles increases to 845. Steel cord scrap content of 4.5 % increases the durability of the modified concrete up to 1050 freeze-thaw cycles.

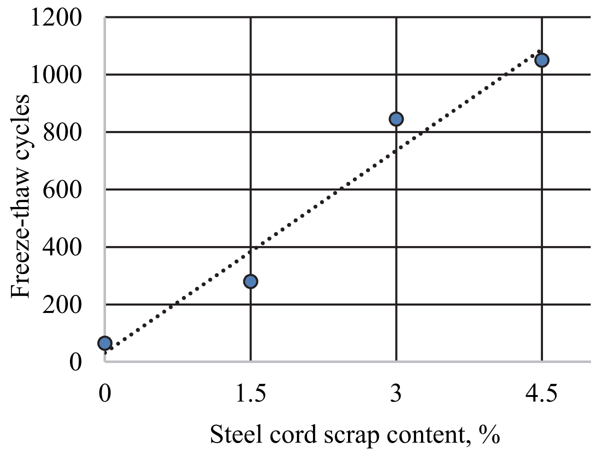

Fig. 6. Predicted freeze-thaw resistance of steel cord scrap modified concrete.

The described test results show that steel cord scrap added to concrete mixture reduces water absorption, increases compressive strength after both 7 and 28 days of curing, and also modifies the structure of the hardened cement paste, i.e. increases the closed porosity and reduces the open porosity.

Freeze-thaw resistance of concrete modified with steel cord scrap significantly increases.

IV. Conclusion

The detailed analysis of literature revealed:

- Almost 3 billion of tires are produced for different vehicles in the world every year. About 1.4 billion of end-of-life tires are disposed in landfills every year and are treated as waste.
- Recently steel cord reinforced tires have become more common.
- Steel fibre reinforced concrete is used not only in the construction of new buildings but also for the modification of currently used structures.
- Steel fibre used in concrete improves the shock resistance of concrete products.
- Compressive strength of concrete can be improved by adding steel cord scrap into concrete mixture.
- According to calculations, steel cord scrap added to 1 m^3 of concrete mixture gives a cost saving from 7 % to 33 %.

Experimental tests with steel cord scrap produced the following results:

- Steel cord scrap modified concrete has a significantly reduced water absorption value. Addition of 4.5% steel cord scrap reduces water absorption by 22.7 %.
- The substitution of fine aggregate with steel cord scrap yields higher 7 day compressive strength (6.02 %) and 28 day compressive strength (4.43 %).
- Steel cord scrap reduces open porosity and increases closed porosity of the hardened cement paste; subsequently, addition of 4.5 % of steel cord scrap into concrete mixture increases the closed porosity of te hardened cement paste 6 times.
- Steel cord scrap significantly increases the freeze-thaw resistance of the modified concrete.

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