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The Use of Crushed Cable Waste as a Substitute of Natural Aggregate in Cement Screed

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Abstract: This research is focused on the utilization of cable waste originating during the recycling of wires as a partial substitution of natural aggregate in cement screed. The main goal of the work performed was to find an optimal level of substitution in terms of freezing–thawing resistance, which is a significant aspect for such type of concrete mixtures. The studied artificial aggregate was gradually dosed in cement screed by 5% in a volume of up to 30% of substitution. The influence of the substitution was also evaluated in terms of compressive strength, flexural strength, bulk density determination, and the ultrasonic pulse method. Gradual substitution led to the reduction of the bulk density and studied mechanical properties due to the considerable air-entraining effect. The utilization of cable waste reduced the value of modulus of elasticity and modified deformation behavior of studied mixtures, which exhibited significant softening during the flexural test. Studied screed mixtures incorporating waste material exhibited slightly lower values of the coefficient of freeze-thaw resistance in comparison with the control mixture, however, the attained values comply with technical requirements.

Keywords: cable waste; cement screed; freeze-thaw resistance; mechanical properties

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1. Introduction

The protection of unrenewable sources has become the main issue throughout the global scientific community. The re-usability of various materials performs a current trend in the research to reduce the negative impacts of human activities on the environment. Cement-based composites, especially concrete, are one of the used building materials worldwide, with increasing annual consumption. Attention is on the reduction of cement application due to high energy demand on its production and high amount of embodied carbon dioxide emissions. Portland cement production is responsible for approximately 7% of global CO_2 [1]. In addition, the production of cement-based composites is responsible for the high consumption of natural aggregate, accounting for approximately 80% of their volume. The present shortage, from the sustainability point of view, is partially reflected by the massive effort to utilize recycled aggregate (RA) originating from demolition waste [2]. Several studies have been conducted dealing with the substitution of natural aggregate by RA, however, predominantly coarse fractions are suitable for common use due to the physical properties [3,4]. Alternatively, the use of RA must be compensated by another technological approach [5]. Fine residues containing binding particles often essentially increase the dosage of water and entirely reduce the final mechanical and durability performance of hardened concrete. However, Silva et al. (2021) reported exactly the opposite trend, thus utilization of fine RA led to a similar mechanical performance in comparison with the reference mixture; respectively, utilization of coarse RA caused a significant decay [6]. Similar results were reported by Khatib (2005) [7]. The various role of fine and coarse RA is determined by very fluctuating properties and the nature of RA that was also highlighted and documented by Fan et al. (2016) [8]. Nevertheless, it is still very important to find other possibilities for the replacement of natural sand with other materials and protect non-renewable resources. Concurrently, the industry is generating a large scale of waste, which is accumulated, because of complicated or no practical use [9,10]. In recent years, various types of slags, rice husks, nutshells, etc., as partial substitution were studied [11,12]. However, plastic waste poses a crucial environmental problem.

Plastic waste exhibiting thermoplasticity is widely recycled [13,14], however, plastic waste originating from wires is hard to reuse because of the content of antifouling addition and mercaptan, which is added as a burning indicator. This waste material originates when end-of-life cables are scrapped. The recycling of cables is predominantly motivated by the exploitation of conductive metal, especially copper, which forms approximately 70 wt.% of the cable [15]. Just about 3.5 million metric tons were generated in 2015, according to European Economic Community (EEC) [16].

The mechanical separation of the metal and plastic particles is a more frequent recycling technique, than especially floating. This separation technique is very simple and efficient, however, when the metallic phases are reclaimed, a small metallic residue up to 1 wt.% remains in the grit. It is caused by very small differences in the weight of single particles. The contamination of cable waste grit by metallic powder could have a negative impact on the hydration process of used cement, especially in the case of copper exhibiting retarding effect, alternatively aluminum with an accelerating effect and accompanying emission of hydrogen leading to uncontrolled air-entraining. The advantage of cable waste is the limited risks of the presence of undesirable impurities in comparison with other types of plastic wastes, e.g., plastic waste originating from PET bottles recycling often contains residues of paper, fats, sugar, etc. reducing cohesion with cement paste and final mechanical and durability performance of the hardened composite [17,18].

Originated plastic grit consists of various plastics—polyvinyl chloride (PVC), crosslinked polyethylene (XLPE), or thermoplastic form (PE) [14,16]. Individual plastic forms should be additionally, however separately, reused. Unfortunately, the separation of single plastics from the grit is very complicated due to the very similar physicochemical properties. The flotation seems to be a very promising separation technology, in which various modifications were described by Barbakadze et al. [16]. However, a reliable procedure for the separation of the individual plastic forms from the grit has not been practically applied yet. Hence, the plastic grit originating from the life-end wires performs undesirable waste without practical use.

Studied waste material is of a granular nature with a grain size of up to 4 mm that corresponds well with commonly used natural sand. On the other hand, the studied material exhibits a significantly lower content of the fines, which is well visible in Figures 1 and 2.

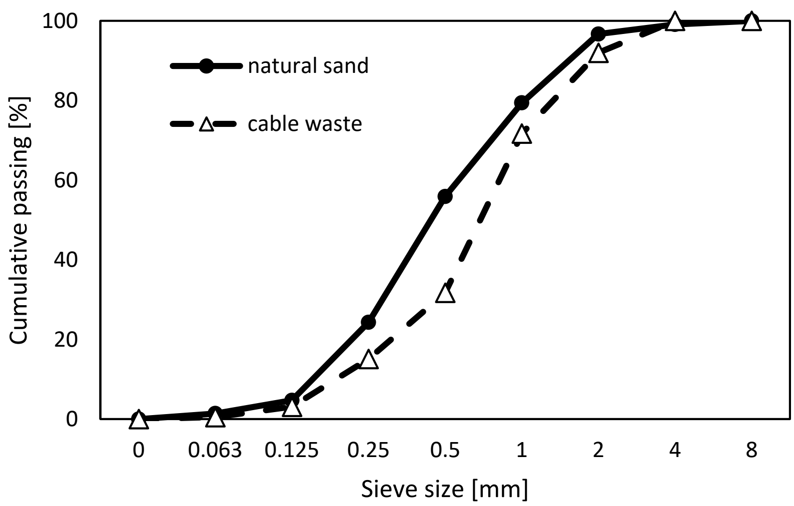

Figure 1. Cumulative passing of studied cable waste and replaced natural sand.

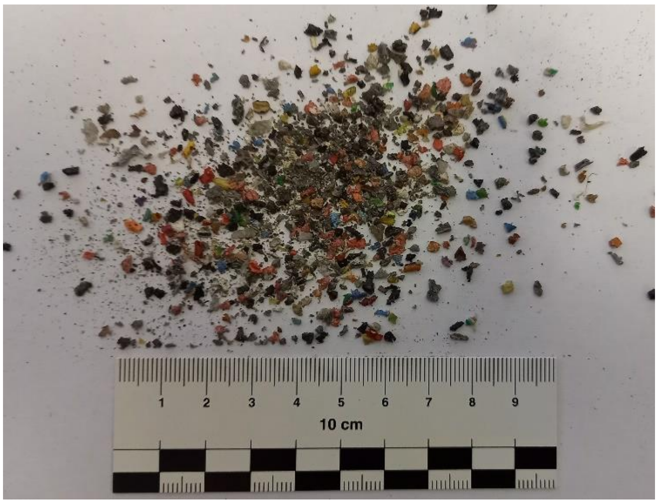

Figure 2. Studied cable waste.

The low wettability is a specific property of contained plastics, which causes the fixation of air bubbles when they are immersed in water, especially in the form of grit. The present work partially follows previous work [19], which was focused on the air-entraining effect of rubber particles on fresh concrete and on final resistance to freezing–thawing. The present work is focused on the replacement of natural sand, non-renewable material, by waste plastic grit, which originates as a residue after the recycling of life-end wires. Previous research was predominantly focused on the determination of basic physical, mechanical, and thermal properties of final composites [20,21]. Záleská et al. (2018) also studied the hydrothermal properties of development lightweight composites [22], which was motivated by the reduction of the bulk density of the final composites [23]. However, response to freezing–thawing of cement-based composites incorporating this waste material has not been studied yet. This program is motivated by the reduced permeability of the concrete, reported by Zéhil and Assad [24], which is caused by the repellent nature of plastic particles.

2. Materials and Methods

2.1. Materials and Mixture Design

The performed experimental program focused on the resistance to freezing–thawing of cement-based screeds incorporating cable waste as replacement of natural sand. In order to evaluate the influence of studied waste material, a set of 7 mixtures was designed. The studied cable waste was collected in the recycling link, where the cables were cut by jaw recycling link and then crushed to grit; metallic particles were reclaimed from the resulting grit using a flotation separator. The studied waste material was documented in Figure 1. This material was a mixture of PVC, PE, and XLPE granules of grading 0–4 mm and exhibiting a bulk density of just about 690 kg m^{-3}. The natural siliceous sand of grading 0–4 mm was partially replaced by cable waste up to 30% by mass. The composition and labeling of the mixtures are shown in Table 1.

Table 1. Composition of studied screeds.

Component	CWR	CW05	CW10	CW15	CW20	CW25	CW30
CEM I 42.5 R	500	500	500	500	500	500	500
water	300	300	300	300	300	300	300
sand 0–4 mm	1500	1425	1350	1275	1200	1125	1050
Cable waste	0	20.8	41.6	62.4	83.2	104	124.8

2.2. Methods

The content of air bubbles in fresh mixtures was determined using a pressure method in terms of ČSN EN 12350-7 [25] in order to assess the air-entraining effect of the increasing amount of cable waste. The air content was measured approximately 10 min after mixing.

The compressive strength of hardened screeds was determined after 28 days of curing under humid conditions according to ČSN EN 12390-3 using a set of 3 cubic specimens of edge 150 mm [26], which were prior testing weighted to determine the bulk density of tested specimens. The flexural strength was determined by using prismatic specimens of dimensions 100 × 100 × 400 mm according to ČSN EN 12390-5. The test was organized as a 4-point bending test with a support span of 300 mm, and loads were placed in the thirds of the span [27]. A set of 3 specimens was used for each measurement. The deflection was recorded by using a couple of inductive sensors (HBK Company, Hoba, Quatar) and a data recording software Catman DAQ (2014) (HBK Company, Hoba, Quatar) during testing of prisms after 28 days. The main aim of the experimental program was the determination of freeze-thaw resistance, which was performed in terms of ČSN 73 1322 by using prismatic specimens of dimensions 100 × 100 × 400 mm [28]. The freeze-thaw resistance was expressed by the ratio of flexural strength determined on specimens subjected to freezing–thawing and a control set of specimens tested before freezing–thawing (non-cycled after 28 days). The set of 3 specimens was tested every 25 cycles. The loading cycle consisted of a freezing phase lasting 4 h. After that, the saturated specimens were cooled to −18 °C and then kept for 1 h. Subsequently, the climatic chamber was automatically flooded by water at a temperature of 20 °C, causing the thawing of the specimens. The climatic chamber was automatically drained down after approximately 2 h, and the next freeze-thaw cycle followed with saturated specimens. The loading regime is illustrated in Figure 3.

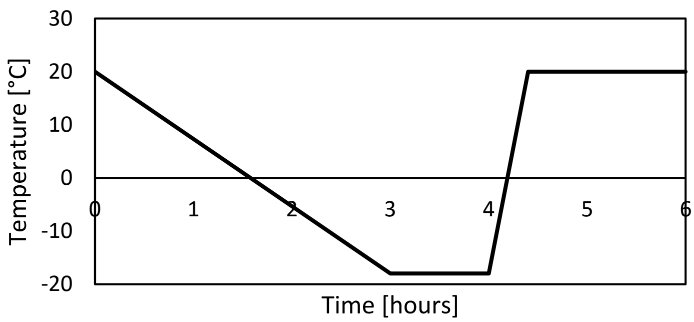

Figure 3. The regime of a freeze-thaw cycle.

The specimens were visually checked after each set of 25 cycles, and the loss of structural integrity was monitored by using non-destructive testing. The ultrasonic pulse velocity method was applied by using the PunditLab device (Proceq, Schwerzenbach, Switzerland) with a couple of 54 Hz transducers. The dynamic modulus of elasticity was calculated in accordance with Equation (1),

$$E_{dyn} = \gamma_b \cdot v_L^2 \cdot 10^{-6} \quad (1)$$

where E_{dyn} is the dynamic modulus of elasticity (GPa), γ_b is the bulk density (kg m^{-3}), and v_L is the speed of the signal (m s^{-1}).

3. Results

Properties of Fresh Mixtures

The incorporation of cable waste caused a significant air-entraining effect, illustrated in Figure 4. It was confirmed that each 5% replacement by mass increased the content of the air in a fresh mixture by approximately 1.2%. Although Zéhil and Assaad did not register the air-entraining effect of cable waste, it is to note that they applied a replacement of aggregate from 2 up to 6% by mass, thus quite lower [24]. The fixing of air was explained by Barbakadze et al. [16] through the hydrophobic nature of plastic particles and their tendency to attract air bubbles on the surface.

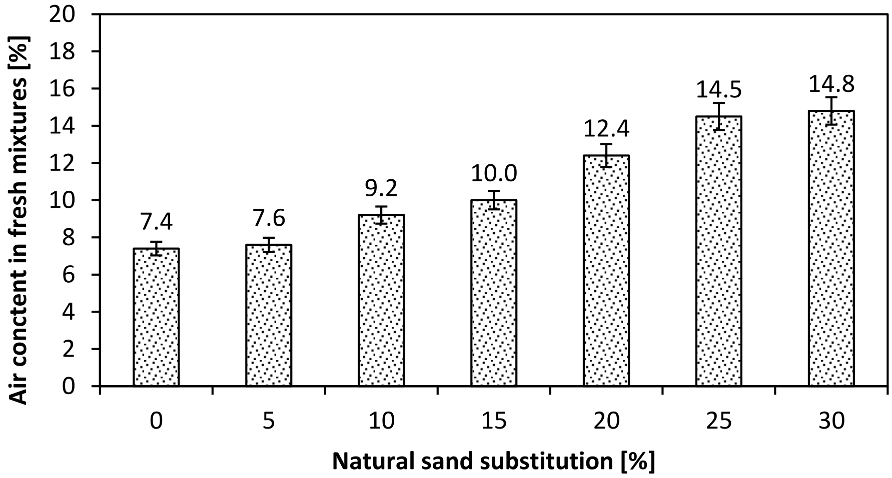

Figure 4. Content of air in fresh mixtures.

The increased air content in the fresh mixture significantly influenced the properties of hardened mixtures. There were depicted relations of cable waste content and values of compressive strength and bulk density after 28 days in Figure 5. The aggregate formed a solid skeleton in the traditional composite material, however, in this case, the load transition was ensured by the cement paste because of the significantly lower modulus of elasticity of used cable waste. Hence, the loss of mechanical properties was expected. The gradual decay of mechanical properties was reported by Zéhil and Assaad [24], Záleská et al. [29], Saikia and De Brito [30]. On the other hand, Azhdarpour et al. (2016) [31] reported a slight improvement of compressive strength for replacement of up to 10%. This anomalous behavior was explained by the reinforcing effect of the particles, which during loading exhibited a similar strengthening effect, such as the PVC fibers.

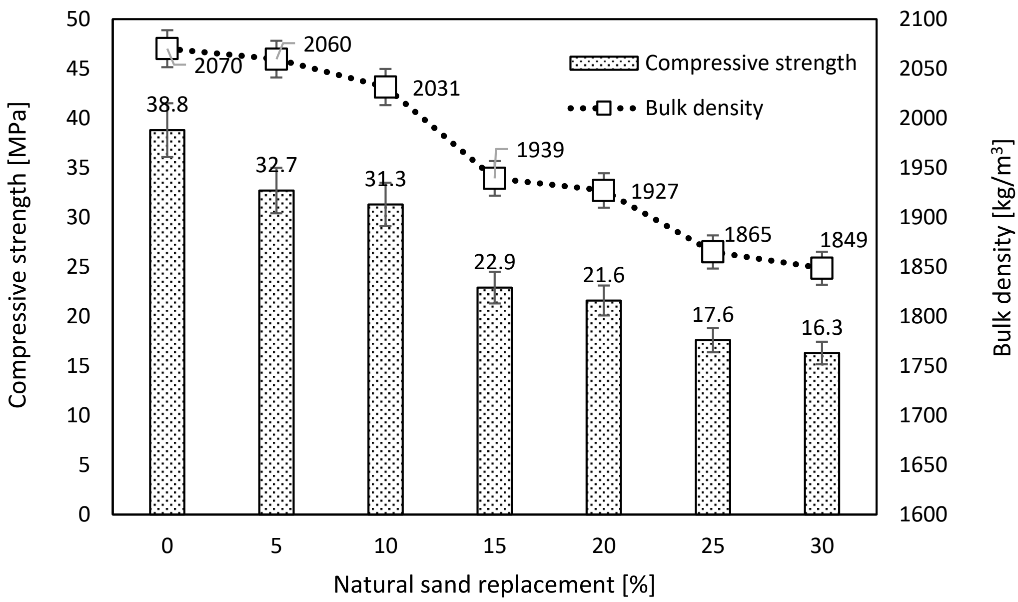

Figure 5. Compressive strength and bulk density after 28 days.

The gradual decrease of mechanical properties with an increasing amount of cable waste was well documented on the record of flexural tests carried out after 28 days, Figure 6. There was obvious decay of the modulus of elasticity and change of deformation behavior.

Mixtures with a higher amount of cable waste exhibited significant softening. Respectively, the brittle character of the rupture attained on the control mixture was reduced. Thus, the incorporation of cable waste had a similar effect as the use of fibers. The partial flexural-hardening effect of plastic waste was mentioned by Azhdarpour et al. [31]. These results indicated good cohesion of cable waste with cement paste. Such behavior was described during the utilization of rubber scraps.

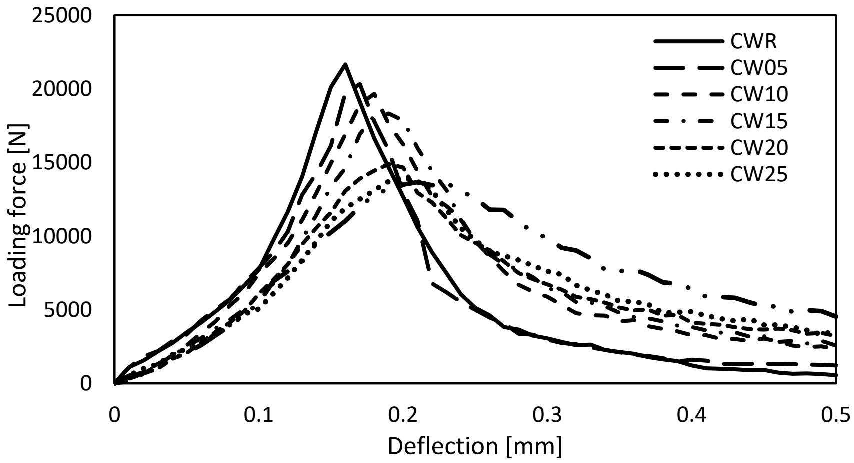

Figure 6. The records of flexural tests after 28 days.

The freeze-thaw resistance of cement-based screeds was a crucial technical parameter, which was required for practical use [26]. The gradual deterioration of specimens subjected to freeze-thaw cycling monitored by non-destructive testing NDT is shown in Figure 7. Studied mixtures exhibited the gradual reduction of the modulus of elasticity with increasing content of cable waste before freezing-thawing, which was caused by the reduced bulk density. Alongside, NDT measurement signalized slightly reduced freeze-thaw resistance; control mixture without cable waste reached decay after 50 cycles about 10.2%, CW30 with 30% of cable waste then 15.2%. However, results obtained from destructive testing have relevance for the determination of final freeze-thaw resistance, thus flexural strength, Figure 8.

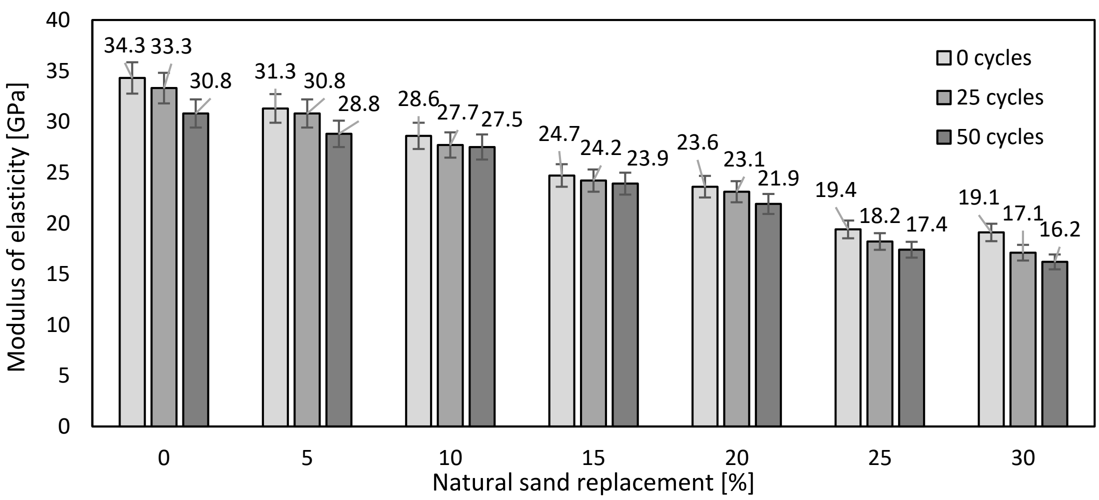

Figure 7. Dynamic modulus of elasticity during freezing-thawing.

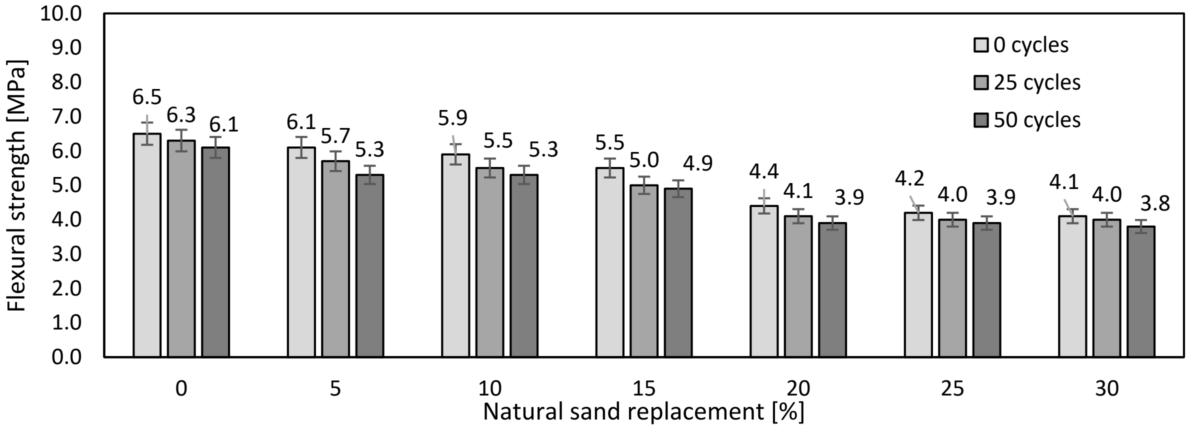

Figure 8. Flexural strength during freezing-thawing.

The results of destructive testing correspond well with the results determined in terms of NDT. Thus, all studied mixtures exhibited slight decay of flexural strength during freeze-thaw cycling. As in the NDT case, the destructive method confirmed the decreasing trend of freeze-thaw resistance with an increasing amount of cable waste. The coefficient of freeze-thaw resistance of the reference mixture was 0.94 after 50 cycles; the lowest value, 0.89, exhibited mixtures incorporating 15 and 20% of cable waste. However, mixtures containing the highest replacement by cable waste exhibited a coefficient of freeze-thaw resistance of just about 0.93, which produced a nearly similar value as the reference mixture free of the studied waste material. On the other hand, screeds exhibiting the coefficient of freeze-thaw resistance higher than 0.85 could be assessed as resistant to freezing–thawing [32]. Thus, all studied mixtures passed the required limit. It can be concluded that utilization had no significant negative impact on the freeze-thaw resistance, thus the coefficient of freeze-thaw resistance was similar.

The utilization of cable waste as natural sand replacement predominantly caused the decay of all studied material properties of cement-based screeds that were expectable due to the worse technical properties of studied waste material. Similar results were reported by a number of authors, who replaced natural aggregate with plastic waste material. On the other hand, the main aim of the performed program was the determination of freeze-thaw resistance. Although there were lower mechanical properties with the increasing amount of cable waste, all studied mixtures exhibited a nearly similar coefficient of freeze-thaw resistance after 50 cycles. The effect of the incorporation of cable waste on the properties of studied screeds is depicted in Figure 9.

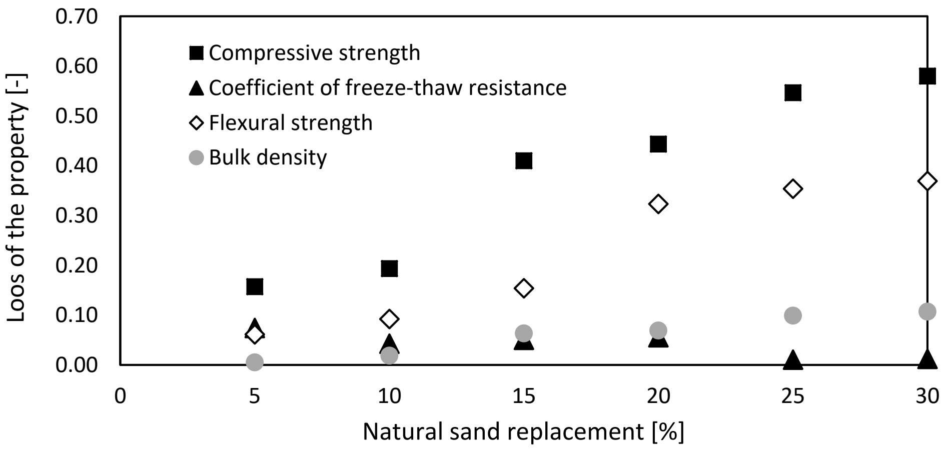

Figure 9. The loss of compressive strength and freeze-thaw resistance.

Bulk density, compressive strength, and flexural strength dropped with the increasing level of the replacement, however, the freeze-thaw resistance tended to be in the control mixture. Thus, an increasing amount of cable waste does not reduce the durability performance in terms of freeze-thaw resistance. This is very important because the enhancement of sufficient freeze-thaw resistance is attained in practice with the increase of the cement content, respectively, by increasing the strength class, even though higher compressive strength is not required with respect to the nature of the use. Quite problematic would be the utilization for the production of structural concrete because the studied solution cannot pass the requirements for aggregate for concrete, and in addition, the reduced values of modulus of elasticity are problematic with respect to the final deformation and probable significantly higher creep. On the other hand, the advantage of the utilization of cable waste grit lies in the production of cement-cement screeds of low strength classes, which exhibit sufficient freeze-thaw resistance allowing application in the exterior for various underlying beds. These screeds belong to the very frequently used building materials, and incorporation of waste material could bring interesting savings in natural resources.

4. Conclusions

The performed experimental program dealt with the utilization of crushed cable waste as a partial replacement of natural siliceous sand in cement-based screeds. Attention was paid to the response of hardened composites to freezing–thawing. The attained results can be summarized as follows:

- Utilization of cable waste has a significant air-entraining effect on the fresh mixture,
- The bulk density and mechanical properties of hardened screed have been reduced proportionally to the amount of the cable waste,
- Freeze-thaw resistance of hardened screeds have been similar or slightly better with an increasing amount of cable waste in comparison with the control mixture,
- The content of cable waste controls the mechanical properties of hardened screeds without loss of freeze-thaw resistance.

The studied waste material seems to be prospective for utilization in cement-based screeds because its addition contributes to air-entraining, which ensures resistance to freezing-thawing. Although there was confirmation of the ability to replace natural sand, the contribution of the studied waste material to that would be relatively low with respect to the extremely high global demands for natural sand. Hence, future research will be focused on milled powder prepared from grit as an alternative air-entraining additive to dry-ready mix screeds. In general, crushed cable waste is a prospective material, which could be successfully used in the building industry.

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