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Properties and durability of coarse igneous rock aggregates and concretes

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HIGHLIGHTS

- Crushing strength is helpful at assessing frost durability of igneous rock aggregate.
- Igneous rock aggregate with weathered minerals is freeze-thaw and alkali sensitive.
- Strained quartz was the alkali reactive phase in granodiorite; chalcedony in basalt.
- Alkali nepheline basalt showed best properties and durability.

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ABSTRACT

Direct tests allowed determining properties of coarse igneous rock aggregates in comparison with gravel along with freeze-thaw resistance and susceptibility to alkali-aggregate reaction. The relationship between the properties and durability of the aggregates and concretes was evaluated taking into account the results from microstructural analyses. Granodiorite, basalt and gravel were sensitive to alkali-silica reaction due to the presence of strained quartz, chalcedony and opal, respectively. The resistance of the aggregate to freezing and thawing was demonstrated to agree with the values of crushing resistance and the lowest contents of pores with diameters unsafe in terms of the freeze-thaw resistance.

1. Introduction

Concrete structures exposed to severe environment require the applied concrete to be not only of good mechanical properties but also of high durability. In moderate and subarctic climate zones and wet conditions, the durability of concrete is strongly dependent on the resistance of coarse aggregate to freezing and thawing. In wet environments, the durability of structures is also related to the aggregate sensitivity to detrimental internal physical and chemical processes as for instance the alkaline pore solution present in the cement paste [1].

The structure of igneous rock capillary porosity is different from that of the majority of sedimentary rocks. The system and structure of pore spaces in igneous rocks are more random and attributed to their genesis. Occasionally, minerals with capillary porosity may occur locally due to their partial weathering. A characteristic arrangement of microcracks or a tendency towards their formation due to the microstructure and mineral composition may be important factors for the properties of many igneous rocks, and thus in part, aggregates. In addition to the pores, primary microcracks may contribute to the flow of water, as may the aggregate grains mechanically induced during the aggregate production process. The formation of new microcracks in the grains has been confirmed in the studies which demonstrated an increase in water absorption and reduction in bulk density of aggregates even up to about 10% relative to the rock raw material [2–4]. Uncontrolled microcracks form when the rocks, after being crushed during extraction, are fragmented several times in a production process until an adequate particle fraction is obtained.

The authors of this paper suggest that analyses and evaluations predicting the freeze-thaw durability of igneous rock aggregate should also allow for its resistance to cracking under mechanical

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load. This parameter is dependent on the mineral content, mineral microstructure and microcracks in the aggregate, not only on the pore size distribution and porosity, which usually, though not in the case of these rocks, may play a dominant role.

Ukrainian igneous rock aggregates have been readily exported and used in some European countries in the past few years. To evaluate their suitability, our detailed studies were performed of the properties and durability of these aggregates, including their application to concrete. The outcome of the studies should indentify the igneous rock aggregates that are suitable for the use at a broader level, also in the structures exposed to severe environments.

2. Literature survey

Limiting the considerations about the freeze-thaw resistance of igneous rock aggregate to the porosity-dependent degree to which the water fills the pores or to water absorption level, even when the pore size distribution is taken into account, may be insufficient, as the effect of the rock matrix strength, dependent on its mineral composition, mineral structure and, in part, the microcracks, is neglected. Cyclic freezing and thawing makes the occurring stresses exceed the strength limit of the rock material leading to grain cracking – the final effect of freeze-thaw damage. This fact is used by standard testing methods for the resistance of aggregate to freezing and thawing [5,6]. Martinez-Martinez et al. [7] observed rock microstructures and reported that during the cycles of freezing and thawing, localized damage to the structure is initiated "as inter-particle-mickrocracking". Then the propagation of this local mickrocracking is stopped for a number of cycles. During the stable period, isolated microcracks appear from where new ones nucleate and grow. When a critical threshold is exceeded, microcracks turn into cracks and grow rapidly, causing ultimate failure of rock after a few cycles [7]. Huge mineral and structural diversity of rocks hinders proposing an universal scheme and rules of cracking during freeze-thaw deterioration. There are opinions that freeze-thaw durability of rocks is not related to their origin, composition or mineral content, crystal size or water absorption level [8].

The deterioration of concrete in the structure may be caused not only by external actions (loads, temperature and chemical attack) but also by internal physical and chemical processes, in which the share of the environment is negligible. These deleterious processes include alkali-aggregate reaction (AAR) due to the influence of alkali present in the concrete pore solution on certain phases in the aggregate. The reaction occurs when the air relative humidity exceeds 80%. The cement clinker is the main alkali source, but they can also come from the aggregate, for example, from granite [9], or from the external environment. The alkali-silica reaction (ASR) product is a calcium-alkali-silicate-hydrate (C-N(K)-S-H) gel or an alkali-silicate-hydrate (N(K)-S-H) [10] gel, which is precipitated in the aggregate-cement paste interfacial transition zone, paste microcracks or aggregate microcracks. By absorbing water and swelling, the gel induces internal stresses that cause expansion and micro- and macrocracking in the paste, which gradually propagates in the concrete across the entire structural element.

From the structural standpoint, AAR and microcracks, which extend into cracks and increase the transport of mass in concrete, can be a serious problem, as they open access for air and water or an aggressive agent to the steel reinforcement thus accelerating rebar corrosion substantially. Concrete mechanical properties worsen with progressing AAR. Ahmed et al. [11] and Giaccio et al. [12] reported a significant drop in the tensile strength of concrete containing reactive aggregate in the early stage of ASR, even though no noticeable reduction in compressive strength of concrete was observed at that time. At that ASR stage, elastic strains increase in concrete along with gel formation and first microcrack formation, reducing the static modulus of elasticity of concrete [11–13].

AAR was observed in various elements of bridges and marine structures. The reaction was first identified by Stanton [14] in the concrete element of a bridge. Lukschová et al. [15] reported concrete defects in 13 bridges due to the swelling of the ASR gel product. The bridge concrete was produced with coarse basalt, granite and diorite aggregates. The gel formed as a result of the reaction with the grains of quartzite, monomineral quartz or greywacke present in fine aggregates. The basalt, granite and diorite aggregates did not react with alkali [15]. Shayan and Lancucki [16] reported ASR of the apparently non-reactive granite aggregate slowly progressing in the concrete of the bridge. Fifteen years after construction first microcracks appeared with alkali silicate gel formed in the cracks around the granite aggregate particles detected after 36 years. Sibbik and Page [17] also observed a slow deterioration of concrete with granite aggregate. Ponce and Batic [18] think that many granite and granodiorite aggregates can be classified as aggregates reacting very slowly and showing no signs of ASR in standard tests. This slow reaction can be associated with the presence of cryptocrystalline or strained quartz in granite.

Basalt as the extrusive rock containing no quartz or minor quantities of quartz is recommended as the aggregate nonreactive to alkalis. However, some basalts can be reactive. Katayama et al. [19] showed that when the SiO_2 content in the chemical composition of basalt exceeds 50%, it might be suspected to be potentially reactive to alkalis, nearly as reactive as andesite aggregate. Tiecher et al. [20] found that the amount of silica in volcanic rocks used to produce aggregates was the critical quantity for predicting their reactivity to alkalis. The reactivity is attributed to amorphous volcanic glass present in the interstices between the grains of the matrix. This material is crypto-microcrystalline and made up of quartz, silica, apatite and hematite [20].

ASR may affect various sedimentary but also plutonic and volcanic rocks including granite and basalt, which are apparently nonreactive. But in the case of igneous rocks, ASR proceeds very slowly due to their tightness and the special forms of silica. Therefore the aggregates from this rock material require reliable and long-term tests, as the majority of the aggregates react slowly.

3. Materials and methods

3.1. Aim and scope of the experiment

The aim of this study was to investigate and evaluate the properties of coarse crushed aggregates derived from igneous rocks, plutonic and volcanic, used for constructing concrete structures exposed to severe environments. The same investigations were conducted with the postglacial gravel for comparison. The evaluation included the use of direct test methods for aggregate characteristics and for the properties of concretes formed with these aggregates. In addition to mechanical properties of the concrete and aggregate, the properties responsible for the durability of structures in severe climatic conditions were also studied. To explain the differences between the performance of individual aggregate types and concretes, the results of the tests and microstructural analyses are presented in the paper.

3.2. Materials

The tests were performed on five types of crushed aggregate derived from igneous rocks and, for comparison, one type of gravel aggregate, along with six concretes made with these aggregates. Three aggregate types came from western Ukraine – basalt from Iwaniczi (Buk), granite from Vyrivs'kyi karier (GRuk) and