Construction and Building Materials 153 (2017) 728–739

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Stress-strain relationships and modulus of elasticity of rocks and of ordinary and high performance concretes

Wojciech Piasta [a,*], Jacek Góra [b], Waldemar Budzyński [b]

[a] Faculty of Civil Engineering and Architecture, Kielce University of Technology, Tysiaclecia PP 7, 25-314 Kielce, Poland
[b] Faculty of Civil Engineering and Architecture, Lublin University of Technology, Nadbystrzycka 40, 20-618 Lublin, Poland

HIGHLIGHTS

- Rare study of the rocks and concretes with aggregate of those rocks were carried out.
- Good strength properties of rocks do not guarantee good deformation properties of concretes.
- Elastic moduli of granite concretes were the lowest and of dolomite concretes the highest.
- A change in the type of aggregate may change the elastic modulus of concrete by 15 GPa.
- Results of elastic modulus of concrete tests were lower than the standard-based values.

ARTICLE INFO

Article history:
Received 21 February 2017
Received in revised form 3 June 2017
Accepted 22 July 2017

Keywords:
Rock
Aggregate
Mineral composition
Concrete
Elastic modulus
Stress-strain relationship

ABSTRACT

Simultaneous testing of rocks from which aggregate was derived (basalt, granite, dolomite, quartzite, gravel) and of 20 high-performance and ordinary concretes containing this aggregate revealed the factors that affect stress–strain properties of concrete. The mechanical property-related items addressed in this paper include rock mineral compositions and, excluding gravel, moduli of elasticity, stress–strain relationships, compressive strains at peak stress, and their compressive and splitting tensile strengths. The same parameters were determined for the concretes with the w/c ratio of 0.70, 0.58, 0.45 and 0.28, for which Poisson's ratios were additionally found. The tests demonstrated that the suitability of aggregates for different concrete applications can be best predicted through the mineral composition, elastic modulus and stress–strain response of rocks from which the aggregate was sourced, while the compressive strength of the rocks was found to be a secondary factor governing the elastic properties of the concretes. The best stress–strain qualities were observed in the dolomite and basalt concretes and the worst in the granite concrete. The results obtained for the concretes and the data reported in the literature indicate that the values of elastic moduli in EN 1992-1-1 may be overestimated.

1. Introduction

Improved mechanical properties of construction materials result in the decreased cross-sectional area of concrete members, thereby reducing their stiffness and increasing stresses at the cross section. Since, as a result, the members will be subject to larger deformations (deflection and cracking), the modulus of elasticity of concrete becomes a very important consideration.

Static modulus of elasticity of concrete in axial compression is typically applicable at stresses up to $0.33f_c$ [1] or $0.4f_c$ [2,3], that is, at the levels lower than the initiating stress level beyond which new microcracks form in the aggregate-cement paste interfacial transition zone (ITZ). Thus, elastic modulus characterizes the strain at a low stress value, when the continuity of the material between the paste and aggregate is maintained. Owing to limit state design with partial safety factors for materials and loads, real stresses in the majority of structural elements in existing structures do not exceed the initial stress, which is usually from $0.4f_c$ to $0.55f_c$, depending on the aggregate type and concrete strength. This suggests that the modulus will provide correct assessment of the effects that coarse aggregates have on deformations of structural members under typical conditions of use. These effects and the suitability of aggregate for use in reinforced or prestressed concrete elements will be predicted with more detail through the study of stress-strain relationships in concrete under instantaneous compressive loading. However, testing and data interpreta-

* Corresponding author.
E-mail addresses: wpiasta@tu.kielce.pl (W. Piasta), j.gora@pollub.pl (J. Góra), w.budzynski@pollub.pl (W. Budzyński).

http://dx.doi.org/10.1016/j.conbuildmat.2017.07.167
0950-0618/

tion will be much more difficult. In many cases, the deformation of members is a more important factor for the concrete structure in service than is its bearing capacity. Therefore, not concrete strength but elastic modulus (tested at low stress level) and stress-strain relationship (with stress varied from zero to peak level) are fundamental to all analysis with regard to the effect of aggregates on the performance of structures under loading.

From the scientific standpoint, the identification of primary factors determining the influence of particular aggregates on stress-strain properties of concrete is a key issue. Coarse aggregates constitute nearly half of the concrete mixture volume, thus the mechanical properties of the rock they have been derived from should also be investigated. The literature on mechanical properties of concrete containing various aggregate types rarely reports data from joint analysis of concrete and parent rocks. The effect of the rocks may be twofold: i) related to the mechanical properties of the rock and aggregates, and ii) related to the constituent mineral composition affecting the bond between aggregates and paste.

2. Literature review

Tests show that the influence of coarse aggregate type is greater on the deformation properties of concrete than on its compressive strength, both in ordinary concretes and in HPC [4–6], though some researchers associate this property only with the HPC [7,8]. However, the European standard EC2 [2] links the modulus of elasticity to the compressive strength class according to $E_{cm} = 22 (0.1f_{cm})^{0.3}$. For basalt aggregates the value should be increased by 20% and for limestone and sandstone aggregates, the value should be reduced by 10% and 30%, respectively. Reported research results indicate discrepancies between the standard-based and experimental values of the modulus of elasticity [9,10]. A large number of investigations found that concretes with popular granite aggregates had the elastic modulus significantly lower than that specified in the standard [7,9,11,12]. The standard does not mention a correction factor for granite. Moreover, information about the moduli of elasticity for concretes with quartzite aggregates is unclear, as crushed aggregates may affect the elastic modulus differently than natural gravel. Mosley et al. [13] claim that the values given apply to quartzite gravel. However, the mineral composition of the gravel used in practice is in fact regional. Since in addition to the compressive strength, the type of coarse aggregate has a substantial effect on the elastic modulus, it is necessary to carry out experimental studies for determining the influence of the most commonly used coarse aggregate types on the modulus of elasticity and to develop more adequate recommendations for the standards. The recommendations will be national in scope, considering the regional occurrence of rocks with defined characteristics.

Wu et al. [4], Beshr et al. [5], Uysal [14], and Beushausen and Dittmer [9] observed significant differences between the values of elastic modulus of concretes made with various types of coarse aggregates despite the same w/c ratio used. The modulus increased with increasing strength of concrete due to increased stiffness of the mortar and adhesion of the aggregate to the paste. Other researchers observed a significant effect of the type of coarse aggregate on stress-strain relationships in concrete [7,8,11]. According to Aitcin and Mehta [7] and Baalbaki et al. [8], the primary factors affecting the modulus of elasticity and stress-strain relationships in HPC are the properties and mineral composition of coarse aggregate. Results of tests for the effects of aggregate types on the deformation behaviour of ordinary and high-performance concretes rarely allow the test results for the parent rocks to be taken into account. Baalbaki et al. [8] were one of few research teams that used the results from modulus and deformation properties of rocks in the analysis of deformation of HPC containing silica fume.

The adhesion of aggregates to the cement paste and the resistance to cracking increase with decreasing w/c ratio, which is associated with the reduced width and porosity of the ITZ [15–18]. However, the microstructure of the ITZ and the aggregate-paste adhesion are also dependent on the surface roughness [19,20] and mineral composition of the aggregate. The roughness as well as some of the aggregate types may affect the microstructure of the interfacial paste adjacent to the aggregate grains [20]. A favourable effect on the microstructure of the interfacial transition zone and thus on the adhesion to the paste, is observed when carbonate aggregates (limestone and dolomite) are used [7,20–23].

3. Materials and methods

3.1. Aim and scope of the experiment

The aim of this study was to investigate and evaluate the effects of the mineral composition and mechanical properties of rocks on deformation properties of concretes containing aggregates derived from those rocks. The results from the tests for the properties and mineral composition of rocks were used to identify and explain the factors determining differences in stress-strain relationships and deformation properties of concretes. Various aggregate types were compared to see whether their effect on the deformation properties of ordinary and high-performance concretes was the same.

The experimental design had two variables – the type of rock from which the aggregates were derived as a qualitative variable and the w/c ratio as a quantitative variable. The tests were carried out on four rock types: basalt, granite, dolomite, quartzite and on a total of 20 concretes with four different w/c ratios and five aggregate types: crushed basalt, granite, dolomite and quartzite aggregates, and with natural gravel for reference.

The samples were tested for secant modulus, Poisson's ratio, stress-strain relationship, compressive strain at peak stress, strength characteristics of the rocks and concrete and mineral composition of the rocks.

3.2. Materials

Four types of rock were tested, along with concretes at different w/c ratios with crushed aggregates from the rocks under analysis. The test material was from Polish quarries that produce aggregates commonly used in concrete production. The rocks and aggregates were from the following deposits: basalt (Gracze quarry) of bulk specific gravity $\rho_a = 2.90$ kg/dm^3, granite (Graniczna quarry) of $\rho_a = 2.65$ kg/dm^3, dolomite (Laskowa quarry) of $\rho_a = 2.83$ kg/dm^3, quartzite (Wiśniówka quarry) of $\rho_a = 2.65$ kg/dm^3 and gravel (Suwałki quarry) of $\rho_a = 2.65$ kg/dm^3. Concretes with gravel were made for comparison purposes. To avoid the effect of different grading, all the aggregate mixes were composed of fractions 2–4, 4–8, 8–16 mm of each aggregate type, allowing for different bulk densities of the coarse aggregates so that the content of particular fractions in the concretes having the same w/c ratio was the same by volume. The concretes were produced with washed natural quartz sand (Suwałki quarry). The particle size gradation of the fine and coarse aggregates is shown in Table 1.

All the mixtures were made with Portland cement CEM I 42,5 R. The chemical composition of the cement clinker is presented in Table 2. Physical properties of cement are shown in Table 3.

No mineral admixtures were added. In the mixtures with w/c = 0.45 and w/c = 0.28, superplasticizers (a mixture of polycarboxylic ether and calcium lignosulphonate) were used for similar mix consistency. To compare the mixtures with the same w/c ratios, the cement paste volume in 1 m^3 of the mixture was the same in all the mixtures. In this way, the amount of cement, water and sand in the mixtures with the same w/c ratios was held constant. The volume of coarse aggregate in the mixtures was also maintained at the same level.

The mixtures were batched in the testing at w/c ratios of 0.70, 0.58, 0.45 and 0.28. The mixture proportions are listed in Tables 4–7. The following concrete mixture designations were used: BC – the mixture with basalt aggregates, GRC – the mixture with granite aggregates, DC – the mixture with dolomite aggregates, QC – the mixture with quartzite aggregates, and GC – the mixture with gravel aggregates. The consistency index of the mixtures, measured by the slump test, was 10 ± 2 cm.

3.3. Methods

3.3.1. Testing of rocks and aggregates

The testing material was derived from the quarries producing crushed aggregates used in the concrete mixtures under analysis. The mineralogy of the rocks was identified by X-ray diffraction (XRD) analysis. Selected characteristics of the