INSTITUTE OF FUNDAMENTAL TECHNOLOGICAL RESEARCH
POLISH ACADEMY OF SCIENCES

BRITTLE MATRIX COMPOSITES

10

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A.M. BRANDT,
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PREFACE

These Proceedings include a collection of papers presented during the 10th International Symposium on Brittle Matrix Composites (BMC-10), which was held October 15-17, 2012 in Warsaw, Poland.

This Symposium is the tenth in the series that dates back to EUROMECH 204 Colloquium on Brittle Matrix Composites, which was held in Jabłonna, Poland in November 1985. This meeting was later renamed BMC-1. Three years later (September 1988), the Second Symposium (BMC-2) was organized in Cedzyna, also in Poland. This was followed by a series of triennial Symposia, each held in Staszic Palace in Warsaw, Poland. In each case, the Institute of Fundamental Technological Research (IFTR) of the Polish Academy of Sciences served as the host. The BMC Symposia provide a forum which encourages and enhances cross-disciplinary collaboration and exchange of knowledge. Since the beginning, the BMC Symposia have created an environment where researchers from many countries of the world gather once every three years to share their latest research findings and to learn first-hand about the development in composite research in various regions of the world. The BMC Symposia have not only earned a reputation for high quality technical content and focused collegial discussions but also for superb social activities.

The objective of this series of Symposia is to bring together researchers in the broad field of different composites that behave (or may behave under certain conditions) like brittle materials. These include materials with cement, ceramic and polymer matrixes. While their intended applications can be quite different, these composites share many similar characteristics. In the years since the first Symposium there has been continuous growth in research and applications of less-traditional materials, many of which have moved from the laboratory settings to field applications. The BMC series of conference proceedings offers an excellent opportunity to learn about these developments. Examples of topics covered during the symposia include:

- aggregate-binder composites (concretes, fiber concretes, polymer concretes),
- sintered materials (ceramics), and
- other composites with brittle matrices.

In addition, the symposia papers frequently focus on various approaches to material engineering problems are presented in the papers, including:

- mechanical properties, strength, toughness and rheology,
- analysis of materials structure and microstructure,
- various degradation effects, crack propagation and control,
- development of new test methods,
- computation methods and manufacturing processes,
- durability assessment of materials and structures, and
- applications of new materials and their behavior in structures.

The present volume of the BMC-10 Proceedings should prove useful to experienced researchers and to students entering this field as a helpful reference. The included papers have been selected on the basis of a two-stage peer review process. The volume contains 38 papers prepared by 87 authors from 17 countries. To a great extent this set of papers represents the latest advancements in the field of Brittle Matrix Composites, including works on applications of different kinds of fibers in cement matrix, various test techniques used for evaluation of concrete and ceramics, durability and repair of structures, analytical methods and other new problems in composites.

Particular thanks are due to the authors of the articles in this volume for their readiness to present the results of their outstanding investigations in the form of original contributions. Grateful thanks are extended to members of the International Advisory Board for their significant help in reviewing the papers and in solving problems encountered during the organizational stages.

It is with great sadness that we acknowledge the loss of our friend Professor Alain Vautrin from St. Etienne (France) who served as a member of the International Advisory Panel since the BMC-1 in 1985 and participated at several Symposia; he died in 2011.

Notable new elements of this 10th Symposium (with respect to the past meetings) include:
- increased participation of young researchers, many of whom will bring their papers to be presented and discussed for the first time;
- expansion of the International Advisory Panel to include several countries that were not represented previously;
- inclusion of several new research topics and new test methods.

All these three characteristics prove that the basic concept of this series of symposia is still valid and may be developed in the future.

The efforts and creative attitude of the local Organizing Committee during preparations for this event is highly appreciated. Without their dedicated work it would not have been possible to publish this volume in time for the start of the Symposium. The support of the Institute of Fundamental Technological Research of the Polish Academy of Sciences was essential for organization of this Symposium, as well as previous Symposia. The scientific sponsorship of RILEM is also acknowledged with gratitude.

We sincerely hope that this volume, along with the nine previously published in this series, will prove useful to those involved with the development of science and technology in the field of composite materials.

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KEYNOTE PAPER

EFFECTS OF MECHANICAL PROPERTIES OF ASR DAMAGED CONCRETE ON STRUCTURAL DESIGN

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ABSTRACT

The paper reports on an experimental investigation of concrete with three slow reacting aggregates (greywacke, quartz-porphyrite, crushed gravel). The specimens were stored in a fog room at 40°C for 560 days. The compressive strength, the tensile strength, the static modulus of elasticity, and the dynamic modulus of elasticity were measured at certain intervals. The results show how these mechanical properties are affected by the alkali-silica reaction (ASR). It turned out that the dynamic modulus of elasticity cannot be used for the prediction of deterioration due to ASR. However, when the compressive and tensile strengths and the static modulus of elasticity have been determined a re-evaluation of an ASR affected structure can be performed.

Keywords
Aggregate, alkali-silica reaction, concrete, durability, mechanical properties

INTRODUCTION

There are many concrete structures which suffer from alkali-silica reaction (ASR) due to the reaction of certain types of aggregate. The aggregates can be fast reacting such as opal, chalcedony, flint, chert, or they can be slow reacting such as greywacke, quartzite, granite, quartz-porphyrite, rhyolite, and others. The reaction starts with sufficient supply of alkalis in aqueous environment. Fast reacting aggregates have been investigated very thoroughly whereas slow reacting aggregates need more investigations. The treacherous feature of slow reacting aggregates is that the damage may manifest itself only after 15 to 20 years and that the testing of aggregates is sometimes ambiguous. That is why the research on this subject has been carried out. Frequently, the expansion behavior is of main interest. However, as soon as existing structures have to be evaluated more information on mechanical properties is necessary. The design engineer should know the strength of the deteriorated material and the modulus of elasticity, sometimes also the creep behavior. A literature review has been presented in [1].

However, the mineralogical composition of rocks varies strongly from place to place. That is why three slow reacting aggregates from Germany have been investigated. In this study the expansion, the tensile and compressive strength, and the modulus of elasticity have been measured during the exposure in a fog room at 40°C for 560 days. The results will be reported and discussed with respect to structural design.

TESTING PROGRAM

Overview

The testing program considered three concrete mixes with one binder and three types of aggregates which were supposed to be slow reacting with respect to ASR reaction. The slow reacting aggregates have been selected because this type of aggregates causes severe problems in Germany in the last years [2] and not much is known about the ASR degradation. Exposure tests were carried out for 560 days. The expansion was measured as well as the dynamic and static modulus of elasticity, the compressive strength and the tensile strength. The specimens were inspected visually with regard to the extent of cracking.

Specimens and exposure condition

Beams with the dimensions of 100 mm x 100 mm x 500 mm (volume/surface ratio = 23 mm) are used for the determination of the expansion and of the dynamic elastic modulus with the resonance frequency method (Grindo Sonic device). Cubes of 300 mm edge length are cast for the visual inspection of crack formation. Cylinders with 300 mm height and 150 mm diameter (volume/surface ratio = 30 mm) are tested in compression for the modulus of elasticity and in splitting to get the tensile strength. Cubes with 150 mm edge length (volume/surface ratio = 25 mm) serve for the determination of the compressive strength. All specimen shapes and sizes follow the German guideline [3].

The specimens were stored after casting at 20°C and 95 % RH for one day. Thereafter they were placed in a fog room at (40 ± 2.0)°C for 560 days. Measurements of the expansion and the dynamic modulus of elasticity were taken at 2, 7, 28, 35, 70, 140, 280, and 560 days. At the same dates, the specimens were visually inspected. Compressive strength, tensile strength, and the static modulus of elasticity were determined at 35, 70, 140, 280, and 560 days.

Materials

The crushed aggregates were greywacke (GW), quartz-porphyrite (QP) and crushed gravel (from boulders) from the Upper Rhine valley (UR). The composition of the aggregates has been described elsewhere [4, 5]. The binder was a Portland cement CEM I 32.5 R [6] with 1.51 % K_2O and 0.25 % Na_2O which makes the Na_2O equivalent 1.24 % by mass.

The three concrete mixes are the same except the type of aggregate. The cement content is 400 kg/m^3, the water-cement ratio amounts to 0.45, and the grading curve follows almost the Fuller curve with a maximum grain size of 16 mm according to DIN 1045-2 [7]. 30 % by vol. of the aggregates consist of non-reactive sand up to 2 mm grain size while 40 % with grain size 2-8 mm and 30 % of grain size 8-16 mm stem from the reactive rocks.

RESULTS

Expansion and dynamic modulus of elasticity

The mean expansion and the dynamic modulus of elasticity of three beams are plotted in the following graphs as function of exposure time. Fig. 1 shows the measurements on the concrete with greywacke aggregate.

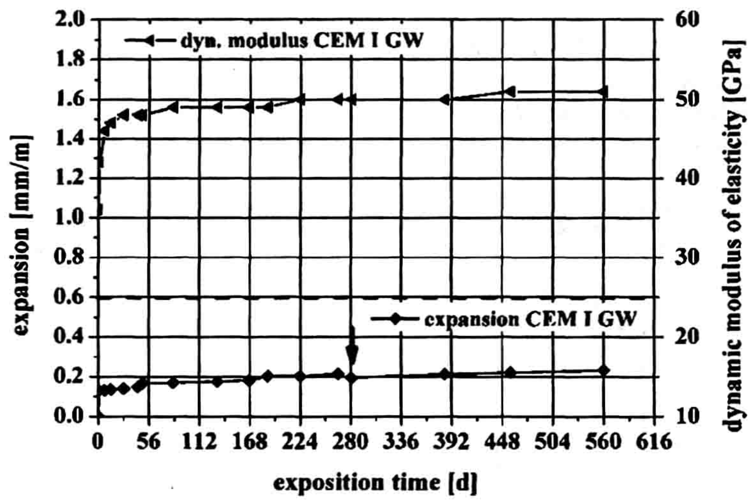

Fig. 1. Expansion and dynamic modulus of elasticity of greywacke concrete

The arrow marks the time when a crack with ≥ 0.2 mm width appeared at the edge of the 300 mm cube. This happened at 280 days storage. The expansion is small and reaches 0.2 mm/m after 560 days. There are two criteria for alkali sensitive aggregates according to DAfStb Guideline [3]:one is the expansion of the beam which should not be more than 0.6 mm/m after 9 months, the other is the edge cracking of the cube. The first is fulfilled, the second is not. That means the greywacke has to be considered reactive. The lines of the dynamic modulus of elasticity show a steep increase during the first 28 days which is the result of the continuing hydration. Thereafter, only a small increase can be seen. The curves are rather smooth and do not show any discontinuities.

Fig. 2 shows an analogous graph for the concretes made of quartz-porphyrite aggregates. The expansion of the concrete reaches the critical mark of 0.6 mm/m after 280 days and increases up to 0.75 mm/m after 560 days. It shows also a crack ≥ 0.2 mm after 224 days.

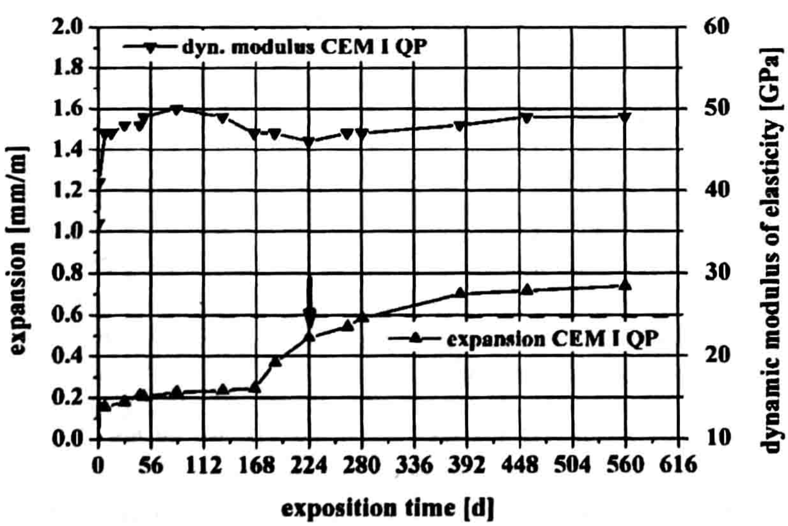

Fig. 2. Expansion and dynamic modulus of elasticity of quartz-porphyrite concrete

Fig. 3 gives the results for the crushed gravel concretes. The expansion curve of the concrete shows a slow increase up to 140 days, then a steep increase up to 224 days and after it stays constant. Cracking occurs after 168 days. The dynamic modulus of elasticity of the concrete shows some reverse sign of the expansion curve since it decays when the expansion increases strongly.

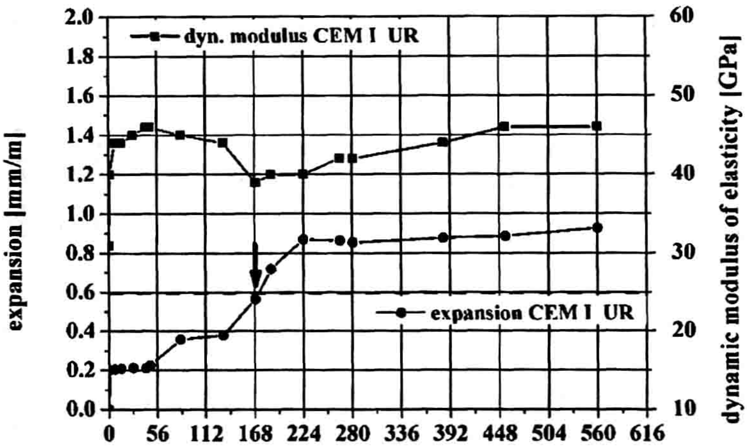

Fig. 3. Expansion and dynamic modulus of elasticity of crushed gravel concrete

Strength and static modulus of elasticity

The compressive strength is determined on 150 mm cubes, whereas the tensile strength is gained on cylinders by splitting and the static modulus of elasticity is measured by compression of cylinders. All values are the mean of three specimens. Fig. 4 shows the results of the concretes with greywacke aggregates. The values of the tensile strength and the static modulus of elasticity are normalized with respect to the averaged measured value after 35 days of fog room storage at 40°C ($f_{ctm,35d}$and $E_{cm,35d}$, resp.). The compressive strength is plotted in absolute numbers in order not to mix up the lines. It can be seen that the modulus of elasticity of the concrete stays constant up to 140 days and then drops to 50 % after 560 days.

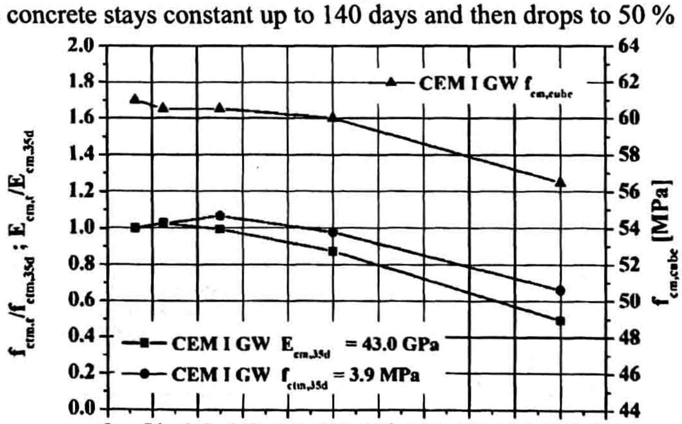

Fig. 4. Normalized tensile strength and static modulus of elasticity of greywacke concrete on the left ordinate, compressive strength at the right ordinate

The tensile strength increases a little up to 140 days and then decays to 67 %. The compressive strength of concrete is reduced by 5 MPa after 560 days.

Fig. 5 shows the results with quartz-porphyrite concrete. Tensile strength and modulus of elasticity of the concrete decrease by 32 and 54 %, resp., after 560 days.The compressive strength of the concrete is reduced by 2 MPa after 560 days.

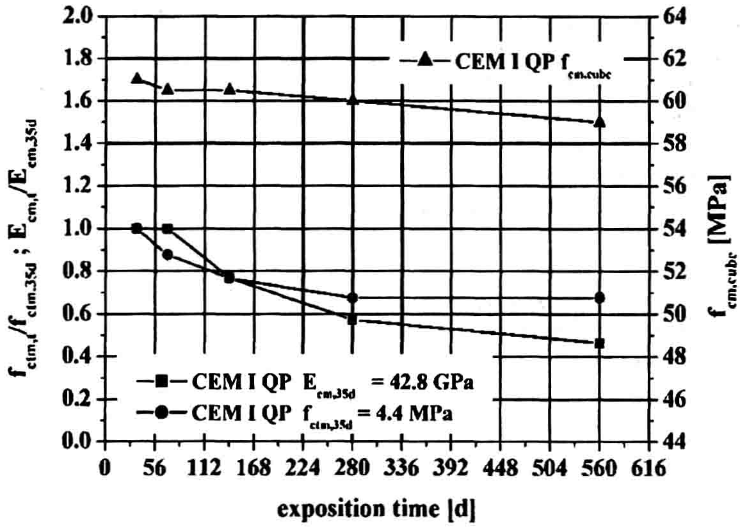

Fig. 5. Normalized tensile strength and static modulus of elasticity of quartz-porphyrite concrete on the left ordinate, compressive strength at the right ordinate

Finally, the results of the crushed gravel concrete are presented in Fig. 6. The decay of the modulus of elasticity of the concrete is very obvious during the first 140 days. After that time it stays constant. The same applies for the tensile strength. The compressive strength of the concrete is reduced by 3 MPa.

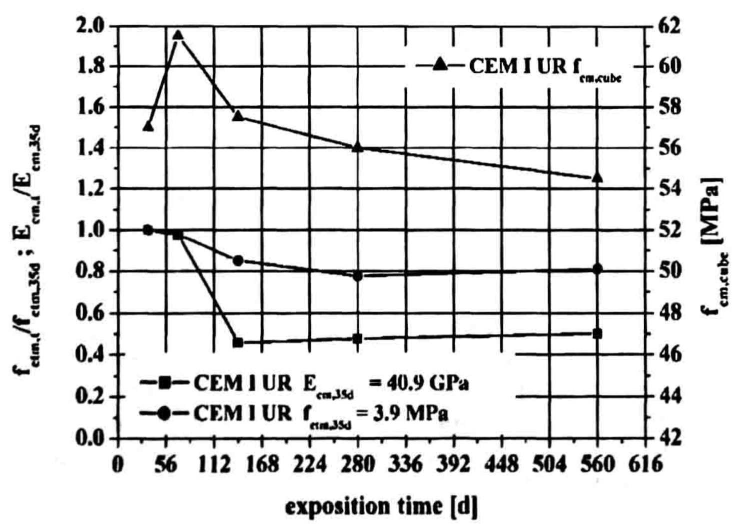

Fig. 6. Normalized tensile strength and static modulus of elasticity of crushed gravel concrete on the left ordinate, compressive strength at the right ordinate

DISCUSSION

Compressive strength

As Figs. 4 to 6 indicate the compressive strength is the least affected by the ASR. The slow reacting rocks become cracked due to reaction of the alkalis with the rock minerals. Greywacke showed in the pristine state veins of pyrite and calcite which were dissolved during the exposure. Veins in quartz-porphyrite were originally filled with chlorite and hematite which was also dissolved during the exposure [4]. The dissolution creates open cracks in the grains which are compressed at compressive loading, however, the compressive strength does not suffer much from such a degradation process. The strength loss of the greywacke concrete with amounts to about 7 % after 560 days, the one of quartz-porphyrite concrete is 2 %, and the one of crushed gravel is 4 %.

Tensile strength

When the grains have got cracks due to the dissolution of cementing substances an important component of the concrete is weakened. Opposite to compressive loading tensile loading causes an opening and propagation of the crack. Figs. 4 to 6 show the relation between tensile strength and exposure time. The concrete with greywacke aggregate lost 33 % of tensile strength, with quartz-porphyrite 32 %, and with crushed gravel 21 %. Comparing the strength losses at compressive and tensile loading the loss at the latter loading is 3 to 5 times higher. The observation that the tensile strength is much more affected by ASR than the compressive strength has been made at structures in service several times before [8], however, the observations were not made on slow reacting aggregates.

Modulus of elasticity

The modulus of elasticity has been measured dynamically and statically. Figs. 1 to 3 show the dynamic modulus of elasticity as function of exposure time whereas Figs. 4 to 6 contain the static modulus of elasticity in normalized form. The dynamic modulus of greywacke concrete seems not to be affected by the exposure, also quartz-porphyrite concrete seems unaffected. The dynamic modulus of crushed gravel concrete shows a decay of 20 % in the course of exposure but recovers later again. This result means that the dynamic modulus of elasticity is not very sensitive to the alkali reaction and is therefore not a good indicator for ASR. The reason for this fact is the type of loading which is, from a mechanical point of view, negligibly low and the mass and geometry of the concrete specimen plays an important role in the test. One can also assume that ettringite crystals grow into the cracks and increase the stiffness but, to a lesser amount, the strength.

In contrast to the measurement of the dynamic modulus of elasticity, the static modulus of elasticity is determined from the stress-strain diagram between 5 and 30 % of the compressive strength, i.e. at a much higher stress level. Cracks in the aggregate grains are compressed and therefore the static modulus could decrease with the exposure time since the dissolution process is progressing. Figs. 4 to 6 show how the static modulus develops during 560 days of storage in the fog room. With CEM I as a binder, the static modulus of greywacke concrete diminishes by 51 %, of quartz-porphyrite concrete by 54 %, and of crushed gravel concrete by 50 %. The comparison between the two moduli of elasticity is made by dividing the static modulus by the dynamic modulus for the exposure time between 35 and 560 days. The results are plotted in Fig. 7 for the concretes tested.