Review paper

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Determining the reactivity of concrete aggregates for Nuclear Power Plant concrete structures

Wyznaczanie reaktywności alkalicznej kruszywa do betonu przy budowie elektrowni jądrowej

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Abstract. The authors describe the additional requirements to ensure durability of concrete related to probability of corrosion due to alkali-silica reactivity of aggregates based on French Rules for Design and Construction of PWR nuclear civil works RCC-CW. Since these requirements are based both on European standards and the French experience they are not fully compatible with the conditions and requirements in other countries, including Poland. In the paper the RILEM methodology and assessment according to American ASTM standards are presented as well. The article is an introduction to the discussion on adapting to Polish conditions the guidelines for the reactivity assessment of aggregate for concrete resulting from RCC-CW.
Keywords: nuclear power plant, aggregates reactivity, internal corrosion of concrete.

Streszczenie. W artykule przedstawiono dodatkowe wymagania mające na celu zapewnienie trwałości betonu z uwagi na prawdopodobieństwo korozji wynikające z reaktywności alkalicznej kruszywa zgodnie z francuskimi wytycznymi do projektowania elektrowni jądrowej RCC-CW. W związku z tym, że wymagania te bazują zarówno na normach europejskich, jak i doświadczeniu francuskim, to nie są one całkowicie kompatybilne z warunkami i wymaganiami obowiązującymi w innych krajach, w tym w Polsce. W artykule przedstawiono także ocenę reaktywności zgodnie z RILEM oraz wg norm ASTM. Artykuł jest wstępem do dyskusji na temat dostosowania wytycznych dotyczących oceny reaktywności kruszyw do betonu wg RCC-CW do warunków polskich.
Słowa kluczowe: elektrownia jądrowa, reaktywność alkaliczna kruszywa, korozja wewnętrzna betonu.

Concerning durability of the NPP civil engineering concrete structures, according to RCC-CW [16], the main objectives are to:

- prevent internal disorders resulting from Alkali Silica Reaction (ASR) and Delayed Ettringite Formation (DEF);
- reduce and/or prevent cracking of concrete and corrosion of steel reinforcement and
- control creep of concrete.

Alkali-Aggregate Reactions (AAR) may involve siliceous aggregates (alkali-silica reactivity, ASR) or very rare carbonate aggregates (alkali-carbonate reactivity, ACR), and failure to take precautions may result in progressive deterioration of concrete structures. AAR are chemical reactions that occur between certain types of mineral in aggregates and the alkaline (Na+ and K+) and hydroxyl (OH-) ions present in the interstitial solution of cement paste in concrete. These dissolution reactions occur due to the high solubility in very alcaline solutions of certain amorphous, disordered or poorly crystallized forms of silica. This reaction leads to formation of a hygroscopic alkaline gel that absorbs water and expands, causing significant expansion and characteristic cracking of the concrete. The rate of expansion caused by AAR typically has been found to be 20 to 200 x 10^{-6} mm/mm per year [1], depending on the severity of the reaction and the degree of restraint. The expansion becomes detectable in about five to ten years after construction, and the most noticeable expansion may be detected in about 15 to 25 years.

The three prerequisites must be simultaneously fulfilled for AAR expansion to occur: high content of alkali in concrete (usually ≥ 3 kg/m^3), presence of reactive minerals in aggregate and sufficient moisture supply (at least 80%). If any one of these three conditions is not met, expansion due to AAR cannot occur. Other conditions, such as higher temperature, accelerate the speed of reaction. ASR involves a chemical reaction, and for the reaction to occur, the following components must be present: water, reactive silica, and a high concentration of hydroxyl ions – high pH [1]. Likewise, the concentration and distribution of these components and the ambient temperature have a significant influence on the rate and deleterious effect of the reaction. A concrete structure with ASR commonly exhibits widely differing signs of deterioration in different places. Concrete exposed to dry, interior environments without water normally does not develop cracking from ASR and the most vulnerable parts of a concrete structure are those exposed to a warm and humid environment [1].

In the absence of previous long-term experience EN 12620 [14] suggests to take one of the following precautions:

- limit the total alkali content of the concrete mix;
- use a cement with a low effective alkali content;
- use a non-reactive aggregate combination;
- limit the degree of saturation of the concrete with water.

When compliance with one of the above procedures is not possible the combination of aggregates and cement can be assessed using regulations applying at the place of use.

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Summaries of the specifications and recommendations in 12 european countries were published in 1995 in CEN Report CR1901.

Tests to evaluate potential alkali-silica reactivity of aggregates

Many test methods have been proposed for identifying potential reactivity of aggregate all over the world. These may be classified into three types:

• **petrographic examination** – identifying the types of minerals in aggregate or concrete section by observation using microscope or other aid by an experienced petrographers. This method can give suggestions as for whether the aggregate is potentially reactive or not. Because the uncertainties involved in the test, the method is generally used as a screening test as a part of an investigation.

• **chemical analyses** – used to identify potential reactivity of aggregate, for example, evaluation of aggregate reactivity by measuring the amount of dissolved silica and the reduction of alkalinity in the reaction alkali solution.

• **expansion tests** – mortar bars or concrete prisms are made using the aggregate to be investigated. There specimens are then put in to a specified condition and the expansion of the specimens are measured. Since at normal climate conditions the reaction will take at least a few years or even decades to complete, measures to accelerate the reaction are commonly adopted for such tests, so in such a condition the AAR and its expansion complete within a few months up to one year [4].

All the methods have their limitations. Some succeeds in identifying reactivity for certain aggregates whereas fails for others – so it is difficult to ascertain an aggregate is absolutely non-reactive. At the moment, the main issue is to be able quickly determine the reactivity of an unknown aggregate.

French methods for evaluating aggregates reactivity for NPP structures

The alkali content of aggregates shall be controlled in order to limit the total alkali content of the concrete [5]. The recommendations relating to protection against the alkali-reaction are contained in FD P 18-464 [5]. The classification regarding ASR shall be made by a specialized laboratory, in accordance with these recommendations and in accordance with: FD P 18-542 [6] and NF P 18-454 [8].

Each type of aggregate (and aggregate combination) proposed to be used in the concrete shall be classified as (Figure 1):

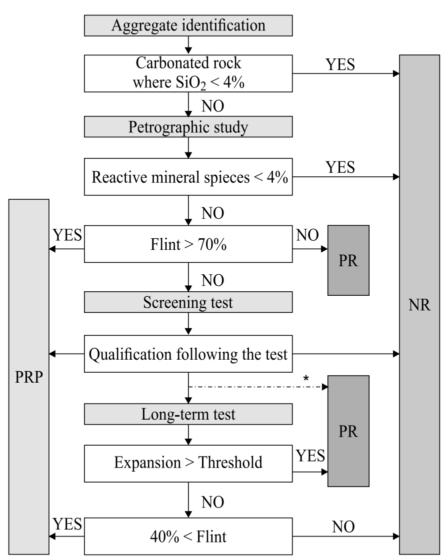
■ non-reactive (NR) – describes aggregates for hydraulic concretes which, whatever their conditions of use, will not cause alkali-reaction problems

■ potentially-reactive (PR) – aggregates likely, under certain conditions, to cause alkali-reaction problems;

■ potentially reactive with pessimum effect (PRP) – aggregates which, although rich in reactive silica, can be used with no risk of problems, provided that their use meets the conditions described in FD P 18-464 [5].

Nonqualified (NQ) aggregates shall not be used.

Screening test uses a greatly accelerated procedure capable of diagnosing, in less than one week, the reactivity of the alkalis in an aggregate which is NR, PR or PRP – reference method is accelerated autoclave test on mortar (5 days). Long-term test is a diagnosis procedure which, although accelerated in comparison with the reaction kinetics observed on constructions, is sufficiently close to actual conditions to take into account the effective sensitivity of the aggregates. Expansion test on concrete samples is taken at: 1, 2, 3, 4, 6 and 8 months.



*) If the PR qualification is considered to be sufficient, the procedure may be stopped

Fig. 1. Sequence of tests for identifying aggregates reactivity [2, 6]

Rys. 1. Kolejność oznaczeń reaktywności alkalicznej kruszyw [2, 6]

The prevention level (in accordance with [5]) respect to ASR shall be *level C* (where no risk of appearance of any damage is tolerable, such as exceptional constructions, nuclear power stations, prestige monuments, etc.). Aggregates shall be natural as defined in EN 12620 [15], at least comply with EN 12620 and with code B of NF P 18-545 section 10 [9] that calls for FD P 18-542 [6].

NR aggregates shall be used in principle. However, in consideration of the local deposits, the use of PR or PRP aggregates is permitted but in the case where the concrete mix contains at least one aggregate or mixture classified PR or PRP by a specialized laboratory, one of the following conditions shall be respected for thenominal concrete mix [16]:

■ where: Tm (Na_2O eq.) in the concrete mix is ≤ 1,4 kg/m^3, the nominal concrete mix is accepted;

■ where: 1,4 kg/m^3 ≤ Tm ≤ 2,5 kg/m^3, the concrete mix is accepted if the test for non-reactivity described in FD P 18-464 [5] is successful;

■ where the concrete mix includes a cement or binder with a slag content ≥ 60%, or a fly ash content ≥ 40%, or also where a ternary cement or binder have a fly ash and slag content such that [(amount of ash/40)+(amount of slag/60)] ≥ 1:

– if the active alkali content of the cement or binder is < 0,75% Na_2O eq. and Tm is ≤ 2,5 kg/m^3: no additional requirement;

– if Tm > 2,5 kg/m^3, the concrete mix is accepted if the test for non-reactivity described in FD P 18-464 [5] is successful.

Tm is the average active alkali content of the nominal concrete mix. It equals the sum of the active alkali introduced by each constituents (aggregates, cement, admixtures, etc.) in terms of the percentage of equivalent sodium oxide (%Na_2O eq. = 0,658%K_2O + %Na_2O).

The binder contributes to Tm on the basis of its alkali content averaged throughout one year. For long lasting works, the variation of active alkali content shall be measured at least every year. Where aggregates are deemed to be PR, the qualification test shall include a non-reactivity test of the nominal concrete mix. This test shall be carried out using aggregates which are representative of those to be used in production.

This non-reactivity test shall be carried out in accordance with NF P 18-454 [8], modified as follows:

– where the structure is situated on the coast (in a XS exposure environment) or exposed to alkalis (dosage of alkalis at 150% of the average quantity Tm);

– in all other cases, dosage of alkalis at 125% of the average quantity Tm;

– dimensional variations shall be measured throughout the test according to the time periods defined in NF P 18-454 [8].

The acceptance criteria shall be:

– in the case of a mix containing only CEM I: the expansion at 5 months was shall be less than 0.02%,

– for all other cements (and combinations) in the mix: the expansion at 9 months shall be less than 0.02% or less than 0.03% at one year.

The margins to the reaction triggering threshold shall be estimated on the basis of additional tests with alkali content higher than 150%.

Polish way for identifying aggregates reactivity

In Poland, assessment for determining the aggregates reactivity is based on two methods that are used for identifying aggregates reactivity (Figure 2):

● PN-B-06714-34:1991 [13] (standard withdrawn in 2012, without replacement) – determining the linear change as well as destructive changes in concrete bars (cracks, color changes, rash, spills, chipping).

● PN-B-06714-46:1992 [14] – carrying out the reaction of aggregates with sodium hydroxide and determination of the weight loss aggregates and determining the content of reactive silica (this method is the most common due to the very short testing time).

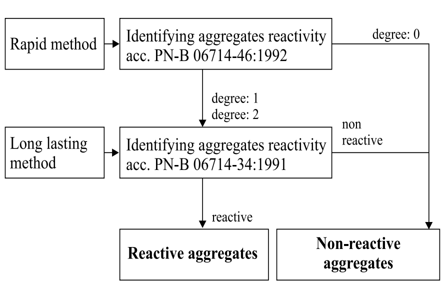


Fig. 2. Assessment scheme of aggregates reactivity in accordance to polish standards [7]
Rys. 2. Schemat oceny reaktywności kruszyw według norm polskich [7]

Used for initial (rapid) assessment of the national aggregates PN-B-06714-46 [14], allows only for coarse determination of the reactivity of aggregates. Test methods of aggregates reactivity in conditions similar to the exploitation (eg. PN-B-06714-34 [13]) providing more reliable results rely on long-term study of linear changes of concrete or mortar samples.

RILEM methodology

The new methodology, concern the new criteria of reactive aggregates evaluation was created by RILEM. A recommended scheme for the integrated use of these assessment procedures are illustrated in Figure 3.

RILEM proposed five methods (Table 1) for the alkali-aggregate reactivity (AAR) assessment of aggregates. Petrographical examination AAR-1 should be carried out in all cases. Ultra-accelerated methods are AAR-2, AAR-4 and AAR-5 – a specialised procedure for the assessment of carbonate aggregates.

ASTM methods

Currently, in addition to RILEM methods for the assessment of aggrega-

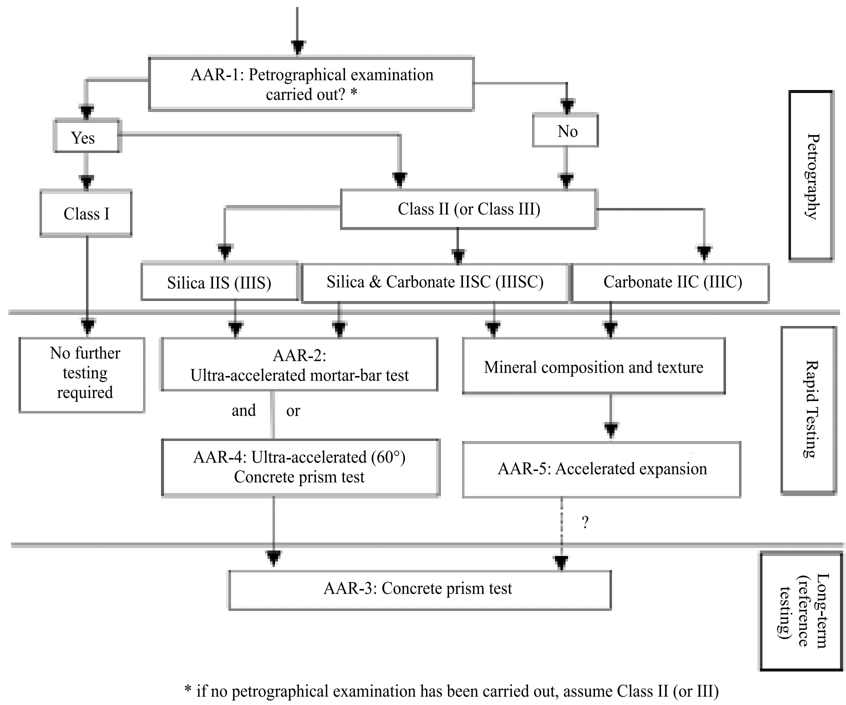


Fig. 3. Integrated assessment scheme by RILEM [17]
Rys. 3. Zintegrowany system oceny według RILEM [17]

Table 1. Outline of RILEM test methods [10]
Tabela 1. Przegląd metod badawczych RILEM [10]

Test method	Brief outline of method
RILEM AAR-1. Petrographic method	The reactivity of the aggregate is classified on the basis of its petrographic composition. Depending on the nature of the aggregate this can either be by hand separation, crushing and point counting under a microscope or by microscopic examination in thin section.
RILEM AAR-2. Accelerated mortar bar method	Mortar prisms made with the aggregate and a reference high alkali cement are stored in1M NaOH at 80°C and their expansion monitored over a 14 days period.
RILEM AAR-3. Concrete prism method	Accelerated expansion test for 12 months. Wrapperd concrete prisms made with the aggregate and a reference high alkali cement are stored in individual containers within a constant temperature room at 38°C and measured at 20°C.
RILEM AAR-4. Accelerated concrete prism method	Accelerated expansion test for 20 weeks. Wrapped concrete prisms made with the aggregate and a reference high alkali cement are stored in individual containers within a constant temperature room at 60°C and measured at 20°C.
RILEM AAR-5. Accelerated carbonate aggregate method	Rapid preliminary screening test for carbonate aggregate

tes reactivity, ASTM C1260, C1293, C295, C586, C1105, C1567 standards are used in Poland as well (Table 2).

Summary

Durability of concrete related to probability of corrosion due to reactivity of aggregates is, next to freeze-thaw resistance [12], another example where the special requirements from RCC-CW need to be adapted. It is because, there is no full compatibility between polish, RILEM and ASTM requirements and RCC-CW published by AFCEN – as it is based partially on French experience and French National Standards [11]. The RCC-CW code is aware of this issue so it adds that *„National standards and practices can replaces the French ones, provided that they are equivalent and accepted by ther Project”*. That's why a Project in Poland must be evaluated and adapted to the local Standards on a case by case basis, as it has recently been done in UK.

W artykule wykorzystano studium literaturowe wykonane w ramach projektu NGS-Concrete realizowanego w programie Lider IV (LIDER/033/639/L-4/12/NRDC/2013) finansowanego przez NCBiR. Artykuł powstał dzięki współpracy z Instytutem Techniki Budowlanej w ramach konsorcjum Pol-Nuclear BCC, którego działalność jest współfinansowana z pracy statutowej realizowanej na WIL PW w latach 2014-2016.

Table 2. American normative methods for identifying aggregates reactivity [2]
Tabela 2. Normy amerykańskie do oznaczania reaktywności kruszywa [2]

Name of the test	Period of the test	Comments
ASTM C227: Standard Test Method for Potential Alkali Reactivity of Cement Aggregate Combinations (Mortar-Bar Method)	Varies: first measurement at 14 days, then at 1, 2, 3, 4, 6, 9 and 12 months, then every 6 months	The test must not cause significant expansion of carbonated aggregates. Long test period. The expansion is not necessarily caused by the alkali reaction of the aggregate
ASTM C289: Determination of the silica alkali reactivity of aggregates (chemical method)	24 hours	Rapid results. Certain aggregates give low expansion, even if they have a high silica content. Not very reliable
ASTM C294: Natural mineral components of aggregates	Short period – as long as the visual examination takes	These descriptions are used to characterise the natural minerals forming the aggregates' sources
ASTM C295: Petrographic examination of the aggregates in the concrete	Short period – visual examination, not requiring long test periods	Generally includes an optical microscopy. May also include an X-ray, thermal or infra-red analysis - ASTM C294
ASTM C441: Effectiveness of mineral or slag additions in concrete expansion prevention due to silica alkali reaction	Varies: first measurement at 14 days, then at 1, 2, 3, 4, 5, 9 and 12 months, then every 6 months	Highly-reactive artificial aggregate, may not represent real aggregates Pyrex contains alkalis
ASTM C856: Petrographic examination of hardened concrete	Short period - including the preparation of the samples and the visual and microscopic examinations	Samples may be examined with a stereo microscope, a polarising microscope, a metallographic microscope and a scanning electron microscope
ASTM C856: Uranium acetate treatment procedure	Immediate results	Identifies small quantities of gel which may or may not cause expansion Opal, a natural aggregate, and carbonated paste may light up – the results must be interpreted accordingly. The tests may be supplemented by a petrographic examination and a physical test in order to determine the expansion of the concrete
ASTM C1260 Potential alkali reactivity of aggregates (mortar bar method)	16 days	More rapid alternative to ASTM C227. Used for aggregates reacting slowly or those whose expansion is delayed in relation to the reaction
ASTM C1293: Determination of Length Change of Concrete Due to Alkali-Silica Reaction (concrete prism test)	Varies: first measurements at 7 days, then 28 and 56 days, then at 3, 6, 9 and 12 months, then every 6 months	Requires a long test period to give significant results. To be used to supplement ASTM C227, C295, C289 and C1260
ASTM C1567: Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method)	16 days	More rapid alternative to ASTM C1293. Used for aggregates reacting slowly or those whose expansion is delayed in relation to the reaction

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