AGING MANAGEMENT OF NUCLEAR POWER PLANTS IN JAPAN WITH RESPECT TO THE ALKALI–SILICA REACTION

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Abstract

Aging management of concrete structures in existing nuclear power plants with respect to the alkali–silica reaction (ASR) is a challenge in Japan. The Nuclear Regulation Authority (NRA) has been organizing a project on advanced integrity evaluation technology for aging management of structures. In this paper, the activities of a working group studying the ASR are introduced. ASR management does not only mean identification or diagnosis of ASR but also includes performance evaluation of structures in order to judge whether the structure can maintain its performance during a required period. The NRA has a pivotal role in evaluating applications provided by utility companies for aging management of nuclear power plants (NPP). However, in Japan, the available countermeasures for ASRs are intended for general civil structures and architectural buildings, and there is insufficient experience and data related to evaluation systems for NPPs, which require high-level safety and multi-functions, such as shielding performance, pipe and cable supporting performance, and seismic performance. In particular, regarding slow-reactive aggregates, which have been under focus recently, quantitative data are scarce and evaluation methods and countermeasures have not been established. Therefore, in the current project, before discussing aging management, the alkali reactivity of typical Japanese reactive aggregates are first evaluated using various Japanese and international test methods and a reasonable procedure for evaluating the alkali reactivity of aggregate or concrete mixtures is investigated. Next, methods for ASR diagnosis are verified. Simultaneously, concrete expansion estimation and performance evaluation within the scope of aging management are discussed, and target research topics are outlined for establishing an effective evaluation system for NPP concrete structures at risk of ASR-induced damage.

Keywords: nuclear power, ageing management, alkali reactivity, performance test, future estimation

1 INTRODUCTION

Alkali–silica reaction (ASR) in the concrete structures of nuclear power plants (NPP) has been gathering great interest worldwide. However, because ASR depends on the properties of the local aggregate type, countermeasures for ASR should be investigated with regards to local materials and conditions. Andesite and cherts are believed to be the major reactive rock types in Japan. Since ASR countermeasures were introduced in Japan in 1989, a classical methodology based on a chemical method JIS A 1145 (modified ASTM C289) and an established mortar bar test (MBT) JIS A 1146 (modified ASTM C227) with a total alkali limit of 3.0 kg/m^3 have been used.

However, this simple methodology was recently pointed to be ineffective in Japan by a technical committee of Japan Concrete Institute (JCI) [1]. ASR damages were found for non-reactive aggregate by the chemical method or MBT or in concrete having alkali content less than 3.0 kg/m^3.

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Therefore, a new methodology is under discussion not only for new construction but also for aging management of concrete structures in nuclear power plants from the viewpoint of ASR, because conventional construction regulations do not address ASR.

For activities such as life extension or license renewal from 40 years to another 20 years, integrity assessment on ASR is required. For this purpose, several projects have been implemented worldwide. These are called as OECD/NEA/CSNI [2], RILEM TC 259-ISR [3], and the French ODOBA [4]. These programs aim to obtain the required results in a relatively short period of a few years. This paper discusses and summarizes the target parameters to be analyzed for establishing a ASR aging management system that can be implemented in Japan.

Integrity assessment is not simply material testing or petrographic diagnosis but a comprehensive evaluation of a system regarding its performance in each function for a designed period, such as shielding or seismic performance. This paper does not deal with an experimental or analytical study but is instead a discussion of a holistic system of ASR management and an in-depth analysis of its various aspects. The French Institute of Science and Technology for Transport, Spatial Planning, Development and Networks [5] and the US Federal Highway Administration [6] have established ASR management systems for existing structures. The established methodology for aging management for general concrete structures can form excellent guidelines. However, the main difference between nuclear power plants and general civil structures is the presence of inaccessible concrete members in the former, which increases the difficulties of core sampling. In addition, nuclear power plants have intrinsic characteristics such as large cross-sections, continuous high-temperature environments, and denser reinforcements, and a lack of alkali supply from the environment.

Based on this background, the Japanese Nuclear Regulation Authority (NRA) has commenced a study on ASR as a part of a project targeting advanced integrity evaluation technology related to aging management; this study comprises a working group of specialists from academia [7]. The present paper first reviews the background of ASR countermeasures in Japan. Next, various material testing methods, ASR-induced expansion potential, and a holistic performance evaluation method including ASR diagnosis, a core accelerated expansion test, modelling, and monitoring are described. Finally, as a framework for this activity, the design of the study is summarized with the help of several test results for various rock types for better understanding of the importance of this new approach.

2 BACKGROUND OF JAPANESE ASR COUNTERMEASURES

2.1 History of ASR regulations

In Japan, ASR and chloride attacks came to be recognized as a serious problem in early 1980s. After intensive research [8], ASR countermeasures were established in 1989 by Japanese Industrial Standards (JIS). One countermeasure should be selected from the followings: use of "harmless" aggregated judged by two alkali reactivity tests mentioned above; limiting the total alkali content less than 3.0 kg/m^3; use of blended cement such as blast furnace slag cement and fly ash cement. Because andesite of relatively young geological age and cherts from the Jurassic period were the major reactive rock types in Japan, these methodologies worked effectively, and incidences of ASR-induced damage reduced remarkably, with the reduction of alkali content in cement as cement kiln systems could be renewed in a timely manner, thus providing greater efficiency. However, ASR research activities declined thereafter and the effectiveness of ASR countermeasures has not been reviewed considerably. From the current advanced knowledge, it is reasonable that serious ASR-induced damages due to compositional pessimum effects or by slow-reactive aggregates still occur even after its establishment.

Since the establishment of the JIS methodology, it has been adopted as JASS 5N "Reinforced Concrete Work for Nuclear Power Plant Facilities" with an additional test, T603, "Test method for reactivity of concrete". T603 was considered the most advanced test method that can determine the alkali expansion threshold as a performance factor of a concrete mix by considering the compositional pessimum effects. However, for the present-day specification of a mix, the use of half a year as the period for judgement may be too short and the alkali content may be too low for slow-reactive aggregates. Because certain amounts of alkali such as 1.2, 1.8, or 2.4 kg/m^3 were added to a concrete mix and alkali content in cement decreased after 1986, the acceleration condition of T603 has been decreased in the present conditions. In fact, in the establishment of the JIS methodology, variations in aggregate quality, compositional pessimum effects on different alkali contents, alkali content dependence of expansion, temperature pessimum, and alkali leaching were considered; however, in the application to real concrete structures, these might only be considered to be minimum requirements might be considered. However, many of them were considered in T603.

Although the JASS 5N regulation is accepted as a kind of law, certain exceptions can be considered for industrial standards when they are established. Through recent academic activities in the JCI [1], a significant number of exceptions have been reported and many Japanese concrete engineers have recognized the imperfectness of traditional methodology. ASTM C1260 and ASTM C1293 have been developed after recognizing the limitations of the old methods based on MBT [9]. Recently, Australia revised their ASR evaluation method based on their long-term experiences [9]. However, activities related to modification of the methodology considering real commercial products are limited in Japan, except for minor changes in threshold values adopted by Japan Railway East [10].

2.2 Integrity evaluation of nuclear power plants in Japan

Here, the situation of integrity evaluation with regard to the aging of NPP in Japan is addressed. Before the Fukushima Daiichi accident, the Japanese government had been examining NPPs to evaluate their integrity after an operation period of 30 years and every 10 years subsequently. This process, called "Plant Life Management (PLM)," requires data on the integrity of structures in both present and future conditions [11,12]. To evaluate concrete structures in the PLM, two deterioration phenomena were chosen—reduction in concrete strength and reduction in shielding performance. The following are the factors that adversely affect the concrete strength by considering environmental conditions and materials used in reactor buildings: elevated temperature, irradiation, carbonation, alkali–silica reaction, and machine vibration.

After the accident, a new nuclear reactor regulation law came into force on July 8th, 2013, and an approval system for the extension of the operation period of NPPs was introduced by the NRA. In general, a 40-year operation period is allowed for every NPP, but the extension of this period to a maximum of 20 years is allowed only after the facility passes a special inspection, which involves evaluation of ASR risk for the reactor building, control building, and water intake channel. Around the same time, the Japan Nuclear Energy Safety Organization (JNES, became a part of the NRA) published a technical document [13] describing an ASR countermeasure for new constructions and ASR diagnosis based on understandings of the limitations of the existing methodology.

For ASR diagnosis, the processes of identification of ASR by petrographic observation and of alkali budget evaluation, as shown in Figure 1, were introduced [14]. These processes will be helpful for improving ASR countermeasures for new constructions and can be a basis for diagnosis of existing structures. However, for existing structures, even if ASR-induced symptoms or damage levels are identified using such an advanced diagnosis process, it is difficult to judge whether a nuclear facility is safe for an extended period of 20 years. The performance test T603 of JASS 5N allows for a certain level of alkali reaction of aggregates if it does not affect the concrete's properties. However, this approach contradicts the JNES report, which introduced a diagnosis method by petrographic observation, which can evaluate the damage state of concrete but cannot estimate future risk. Therefore, a new, holistic approach is required. Thus, from 2014, the NRA commenced a new project on the ASR aging management of nuclear power facilities at least for three years [7].

3 AGING MANAGEMENT OF CONCRETE STRUCTURES IN NPP

3.1 Aggregate reactivity test

To develop a new methodology, a critical comparison of various test methods from the viewpoint of NPP is important, with specific focus on the application of the method for estimating the possibility of concrete structure expansion. Various testing methods for the alkali reactivity of aggregates are summarized in Table 1 and their characteristics are listed below. Since there are considerable variations of aggregate characteristics in a quarry, it is important to clarify the effect of them on test results.

Chemical method: This is effective for rapid-expansive but may not for slow-reactive aggregates.

Mortar bar method: This is effective for rapid-expansive aggregates but may not for slow-reactive aggregates and pessimum phenomena of rapid-expansive aggregates if special attention is not paid.

Aggregate-mortar tests: All aggregate tests are ineffective in the case of size pessimum effects of certain types of aggregates such as chert containing chalcedony.

Concrete prism test (CPT): This is the most reliable laboratory test and may be applicable as a performance test for estimation of expansion of structures in future. However, especially at 60 °C, alkali leaching is serious. At 38 or 40 °C, problems related to varying moisture supply at different alkali contents occur because of the different relative humidity in equilibrium. The conventional CPT shows less expansion compared to field exposure of large blocks.

Exposure of large blocks: This method is considered much better than the CPT as it covers various effects such as alkali leaching, aggregate size, specimen size, wet/dry cycles, aging effects of cement paste, especially for fly ash, reinforcement, and so on. However, it is time consuming and difficult to evaluate the effects of environmental condition.

Field experiences: This is the most reliable and indispensable method to determine threshold values for judging the reactivity of aggregates. This method is also time consuming and required sufficient experiences and the applicable environments are limited.

3.2 ASR-induced expansion potential and aging effects of ASR on the performance of a concrete member

Tests for reactivity of aggregates are used to evaluate the possibility of ASR-induced expansion of a structure. Expansion of real structures may not necessarily occur even if the aggregate is found to be reactive. In Figure 2, the relationship between representative factors causing ASR and aging effects is summarized. The ASR-induced expansion potential of concrete is determined from parameters such as the aggregate characteristics, the alkali content of the concrete, and the mix proportions, such as aggregate size, composition of different types of aggregates, cement type, and replacement level and quality of supplemental cementitious materials (SCMs). The degree of expansion of a structure will be affected by environmental conditions, including temperature, humidity/water supply, and their history, as well as alkali supply from deicing salt or marine salt. It is also affected by the specifications of the structural member, such as its dimension with respect to the intrinsic moisture supply, confinements with rebars, and a combined system with other members.

This situation calls for a model that estimates ASR-induced expansion in future by considering a significant number of these parameters and correlating the effects of the parameters. Therefore, detailed understanding of not only the aggregate characteristics, including petrographic characteristics, but also the reaction mechanisms is required from both chemical and mechanical perspectives.

3.3 Position of performance estimation in a holistic ASR integrity evaluation system

The goal of this study is to propose guidelines for integrity evaluation of ASR in concrete structures in NPP, which will enable future safety and performance assessment based on data obtained from existing structures. For this purpose, we must first recognize the required subjects to be investigated. Traditionally, researchers in material field have worked in order to detect the reactivity of aggregate, while structural engineers have mainly worked on simulations of structures damaged by ASR, *e.g.*, RILEM TC 259-ISR [3]. For NPP, only a few cases consider the total deformation of the entire system, such as the long-term challenges faced by Hydro Quebec [15]. RILEM TC 258-AAA [16] is currently discussing a performance test of job mix in addition to aggregate tests. This new approach should be understood in a holistic ASR integrity evaluation system, as shown in Figure 3.

In general, concrete plants are subjected to periodic visual inspection, and when abnormalities such as cracks or deformations are detected, their progression is monitored continually. In this case, it is important to recognize crack density and pattern, whose variation trend may depend on the confinement conditions. However, minor cracks may not necessarily mean limited ASR. To detect the progression of an abnormality or for a special inspection, concrete cores are usually sampled and subjected to petrographic observation/analysis. When ASR is detected, regardless of the degree of damage, the causes of the damage will be investigated, as described in Figure 1.

Furthermore, when ASR is judged to be still ongoing, an estimation of future concrete expansion is required to assess the integrity of the facility in a required service life. For this purpose, accelerated-expansion tests of cores are performed, in addition to mechanical tests such as those for strength or elasticity in many cases. With knowledge of the correlation of core expansion and mechanical behavior or using certain constitutive models, the performance of structural members is estimated. From the estimation results, a secondary evaluation for integrity assessment of NPP is performed.

3.4 Challenges

In a case of intensive damages that occurred in a nuclear power facility in Japan [17], a core expansion test and monitoring had been conducted. The aggregate used in this facility was a typically reactive andesite. Core expansion tests did not reveal expansion. Although the elastic modulus of the concrete decreased, the compressive strength was still sufficient for the structure. Twenty-two years of monitoring showed a transition in the expansion behavior, from the structure undergoing expansion to becoming stable or rather to show slightly shrinking behaviors approximately 6 years after the first detection of an abnormality in the basement of the power generation turbine, 5 years after construction. Given the stable state of the deformation, continuous use of this facility was permitted.

However, in nuclear power plants, there are inaccessible members, such as the pedestal of the reactor or the supporting walls of various ducts, exposed to high temperature and temperature–humidity gradients that may cause alkali movement and concentration at some positions. For the concrete of a nuclear power facility, temperature elevates not because of the acceleration condition but due to real-world environmental exposure. Expansion behaviors need to be estimated at elevated temperatures from samples taken from parts that are accessible. In Table 2, characteristic challenges in ASR evaluation for concrete structures in nuclear power plants are summarized.

For the evaluation of effects of ASR damage on the structural performance, the behavior of existing concrete that may contain reactive aggregates must be estimated. Therefore, an aggregate test alone is insufficient, and a performance test of concrete is also required. In general, it is difficult to obtain the same aggregate samples from structures used in plants and so the core samples must be used to evaluate the behavior of future expansion. The core accelerated-expansion test procedure is described in the JCI standard DD-2, where ϕ10L20-cm cores are sampled and stored in a humidity chamber, with a relative humidity of more than 95% and a temperature of 40 ºC, for half a year. However, the procedure has certain problems related to insufficient moisture supply and alkali leaching, as well as difficulties in converting the test results to the expansion behavior in real structures. Therefore, the test protocol must be modified significantly.

Depending on the characteristics of the concrete member in a facility, the effect of concrete expansion on its performance will differ. Therefore, the mechanical behavior of the member after expansion must also be estimated. Because of the use of dense reinforcement in nuclear power plants, the effect of ASR may be limited but quantitative estimation is indispensable.

4 STUDY DESIGN

In this chapter, to establish a holistic ASR evaluation system for integrity assessment, the procedures required for addressing each of the challenges described in the previous sections are outlined and their positions in the system are shown in Figure 3.

Aggregate selection: Selection of the aggregate is one of the most difficult steps in the study of ASR. In this project, five types of aggregates were selected mainly on the basis of field experiences. An additional two aggregates were referred from a previous study [18]. Table 3 presents a comparison of results from various reactivity test methods. Hereafter abbreviations indicate their origins of place. Andesites TO, SI, and TN and chert YT are typical reactive aggregates, and they are evaluated as being reactive by traditional test methods of JIS. However, for slow-reactive aggregates containing cryptocrystalline quartz, such as sandstone WI, hornfels HE, and green schist GK, both JIS methods failed to detect the reactivity status. There are examples of real structural damages showing HE and GK although their alkali contents in concrete have not been made clear. Therefore, the JIS methods are clearly insufficient for slow-reactive aggregates. Therefore, results of these concrete evaluation tests made during construction cannot be applied in a safety assessment of the facility in the future.

Alkali wrapping: Because many factors affect concrete expansion, an aggregate test is difficult to apply for expansion estimation, and a test of the concrete mix may be the only solution. In this procedure, the effects of temperature, alkali content, and moisture content need to be determined. Because the conventional CPT has problems in controlling alkali content and moisture supply, an alkali wrapping (AW) method has been proposed [19]. The concept of AW proposed in previous studies [has been modified. Even if the concrete prism is exposed in a specially designed sealed container in order to avoid direct contact with water dropping from the top cover or due to moisture leakage, alkali leaching and drying may still vary depending on temperature and alkali content. From the viewpoint of an aggregate reactivity test, the conventional CPT may be acceptable because the threshold values of expansion for judging reactivity are determined through field experience. However, to apply the obtained results to a qualitative estimation of concrete expansion, controlling the alkali and moisture contents in the concrete is crucial. One possible solution is to wrap the concrete with a cloth containing water or an alkaline solution. Wet wrapping is effective at avoiding drying and providing a constant water supply, but alkali leaching can be a problem. On the other hand, alkali wrapping may result in an increase in the concrete's alkali content. This problem can be avoided by controlling the alkali concentration in wrapping cloth. After verification of the effectiveness of AW for the CPT, the final procedure is the core accelerated expansion test.

Precise effects of temperature and alkali contents: As explained in the previous section, the effects of temperature and alkali content are not factors of acceleration but are indispensable parameters for estimating the expansion of concrete members in nuclear power plants. Although some studies have investigated the effects of temperature [20,21], new series of experiments considering alkali leaching and drying are required [22].Important findings from these AW-CPT experiments are the dependence of expansion behavior on the temperature, alkali content, and aggregate type in the concrete. Although the details are not described here, it is worth noting that, in some cases, either alkali dependence for the expansion is not noted or a lower alkali content results in less expansion. The effects of alkali leaching and drying are thus clarified, and we can now discuss the fundamental mechanism of this expansion behavior of concrete.

Humidity gradient: There have been several studies on humidity effects [23]. In this project, for a preliminary test, a 65–cm concrete block wrapped differently depending on the position was prepared and cured in a humidity chamber, as shown in Figure 4. Reactive andesite TO was used as 30 mass% of the coarse aggregate with non-reactive pure limestone. The alkali content was 5.5 kg/m^3. The bottom one-third of the block was covered with a wet mat, the middle portion was covered with a plastic thin film, and the top one-third was kept open, as illustrated in Figure 5 (left). Even in the humidity chamber, where moisture content is expected to be saturated at 38 ºC, some variations in the expansion ratio are observed, owing to the differences in moisture control, as shown in Figure 5 (right). The upper open portion receives a relatively lower moisture supply and hence shows relatively less expansion and cracking. The effect of moisture supply was modeled in the following step. Importantly, significant differences in expansion were observed even at almost 100% relative humidity.

Reinforcement effects: Reinforcement effects have been discussed [24]. Here, a preliminary test was conducted by placing reinforcements in the block described earlier. The reinforcement ratios in horizontal and vertical directions were 0.8% and 2.4%, respectively. For this experiment, all surfaces of the concrete block were covered by a plastic thin film. For comparison, another block without reinforcements was also analyzed. At 10 weeks, the block without reinforcements exhibited an expansion of 0.13%. In the less reinforced direction (*i.e.*, 0.8%), the expansion was 0.20%, while in the more reinforced direction (*i.e.*, 2.4%) it was 0.06%. In the block without reinforcement, expansions in different directions varied, with the vertical expansion almost double that of the horizontal expansion. This behavior will be numerically analyzed in the subsequent step.

ASR diagnosis to understand the expansion mechanism of CPT: As described in Ref. [22], because of the complex concrete expansion behavior, which depends on temperature and alkali content, a detailed analysis of the mechanisms is required using various techniques. One impressive method is fluorescence detection using uranyl acetate [25]. In general, uranyl acetate a substance related to nuclear fuels and its handling is widely restricted. However, recently, it was proposed that a standard solution of general elemental measurement, XSTC-331, includes 10 ppm uranyl can be used without restriction for alkali silica gel (ASG) detection [26]. With some modifications, detailed observations were made [27]. At higher temperatures, such as 60 ºC, a greater amount of ASG is expected to be generated, while the amount detected by the fluorescence method was less than the amount at 40 ºC. This deviation has not yet been explained. If the amount of ASG does not control the expansion, then another mechanism should exist, such as topo-chemical reaction and an expansion generation mechanism in the microtexture. In any case, possible candidates affecting expansion are ASG formation speed, ASG viscosity, aggregate microtexture, and ion exchange speed between the alkalis in ASG and the Ca in cement paste. Therefore, petrographic observations and SEM/EDS analysis using polished thin sections are currently in progress.

Core-accelerated expansion: Since AW is indispensable, even in the case of CPT, the effects of wrapping in various ways are currently being investigated. From a demolished bridge deck affected by ASR, cores are being sampled and the expansion is accelerated in different ways. Meanwhile, cores are also being drilled from the concrete block shown in Figure 4, and another series of core-accelerated expansion tests are ongoing. The cores are stored in a humidity chamber according to the traditional method, or are wrapped with a thin plastic film, wet cloth, or alkaline solution–dipped cloth. Based on the results, a new standard procedure for the core-accelerated expansion test may be recommended by a technical committee for ASR assessment at the JCI (chaired by Dr. K. Yamada).

Field exposure: As discussed in the WP2 for "Performance testing; Laboratory vs. field; Exposure site", chaired by Prof. B. Fournier of RILEM TC 258-AAA (chaired by Prof. B. Wigum) [16], there are significant differences between a CPT in a laboratory and a field exposure test. There is a great deal of comparison data and new trials will be carried out, but there have been few detailed analyses of the causes of the differences. As discussed in this paper, a quantitative evaluation of expansion based on CPTs has been difficult. The new procedure will provide quantitative data and the results will be discussed elsewhere based on further tests using specimens of different sizes and different exposure conditions. Various effects can be expected to be revealed, such as intrinsic dimension effects with various causes, including surface effects of aggregate localization, temperature, and moisture supply history; wetting/drying cycles; and cracking. For analyzing the mechanisms underlying such effects, alkali leaching and reaction texture will be analyzed. Such experiments are currently under preparation in Japan and have either already been conducted or are under preparation in various locations around the world.

Estimation of expansion of exposed block based on CPT: A series of experiments involve CPTs at various temperatures and alkali contents has been reported [22], and another involving a field exposure test of a 40 × 40 × 60 cm^3 block with various alkali and fly ash contents for almost 5 years is in currently progress. Based on the results of the CPT experiment, the expansion behavior of exposed blocks was reproduced and meteorological data at the place of exposure were obtained and described [28]. In that study, alkali content, hourly temperature changes, and daily precipitation were considered. The analysis indicates that, in the exposure of a block of the abovementioned size, moisture supply plays an important role in expansion. However, the range of simulation is limited and dimension effects may appear after the simulation period. The experiment is being continued under new exposure conditions, including cold conditions in Hokkaido with an annual average temperature of 7 °C, moderate conditions in Kyushu with an average temperature of 17 °C, and hot conditions in Okinawa with an average temperature of 22 °C.

Numerical modeling for performance simulation of a concrete structure with ASR-induced damage: Concrete technologies in Japan can typically be divided into civil engineering and architecture of buildings and architecture related to NPP. ASR-induced damages are usually considered evident in civil structures. Although ASR-induced damages in structures in NPP cannot be less than those in civil structures, the number of reports is limited, perhaps for social reasons. Consequently, research activities on ASR in such structures have been much less than those in civil engineering. Numerical modeling of structures damaged by ASR is an active field of research in civil engineering [29] and is one of the major topics of the active "Technical Committee on Performance-Based Design and Maintenance Scenarios for Controlling ASR Deterioration" of the JCI. Therefore, collaboration with both research fields is required, and contributions from the JCI in addressing these challenges would be valuable. To verify the results of numerical modeling in addition to an evaluation of the progress of degradation, continuous effective monitoring or non-destructive tests are indispensable and will also be discussed.

5 CONCLUSIONS

To evaluate the integrity of concrete structures relating to nuclear power plants from the viewpoint of the alkali–silica reaction, a holistic evaluation system is required. This is not simply an aggregate reactivity test or petrographic diagnosis but instead an expansion estimation based on limited information and a performance evaluation under various environmental and structural conditions. Nuclear power plants have characteristic features such as members subjected to high-temperature conditions, large cross-sections, dense reinforcements, and parts inaccessible for sampling.

As a challenging project organized by Japan's Nuclear Regulation Authority, various subjects required for the evaluation system were highlighted and the ongoing processes of the project were outlined, as follows:

1) Preparation and characterization of various types of aggregate;
2) Development of alkali wrapping for an appropriate concrete prism test (CPT) to avoid alkali leaching and drying;
3) Clarification of the precise effects of temperature and alkali content;
4) Consideration of humidity gradients;
5) Effects of reinforcement on expansion;
6) Petrographic diagnosis of reaction and analysis of expansion mechanisms;
7) Development of a reasonable core-accelerated expansion test procedure;
8) Comparison between CPT and field exposure tests for understanding the mechanism underlying the differences;
9) Estimation of expansion based on a CPT and environmental conditions; and
10) Numerical modeling and a monitoring plan.

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TABLE 1: Test methods for alkali reactivity of aggregates or concrete and their characteristics.[30]

Test	Characteristics
Field experiences	Long-term experience. Most reliable but applicable environmental conditions and terms are limited
Concrete test: Useful for both aggregates and concrete mixes	
Exposure of large specimens	Long time required. Alkali leaching and applicable environments are limited.
CPT at 38 (AAR-3, ASTM C1293) or 40 °C (T603)	Most reliable as laboratory test and able to evaluate the effects of SCMs. AAR-3 has problems retaining moisture and alkali. Test period of T603 is too short (0.5 y).
CPT at 60 ºC (AAR-4)	Shorter period (20 weeks). Alkali leaching is a serious problem.
Aggregate tests: Every test has some limitations. Special attention has to be paid for compositional and size pessimum effects.	
Accelerated mortar bar test (AAR-2, ASTM C1260)	Test period is short at 2 weeks. Severe test as many aggregates is evaluated as reactive. AMBT may overlook size pessimum effects.
Mortar bar test	Suitable for rapid-expansive but not slow-expansive aggregates.
Chemical method	Suitable for rapid- but not slow-expansive aggregates

TABLE 2: Characteristic challenges in ASR evaluation for concrete structures in nuclear power facilities.

Performance test	Factors that need to be considered
Pessimum effects	Type of aggregate, aggregate composition, particle size, temperature, alkali content, concrete dimensions
Environmental conditions	Temperature, humidity, temperature–humidity gradient, continuous or cyclic condition of temperature and humidity, movement and local concentration of alkalis
Controlled conditions	Alkali leaching from specimens, drying
Core acceleration	Alkali leaching from specimens, drying
Evaluation simulation	**Factors that need to be considered**
Expansion	Empirical or theoretical expansion mechanism from chemical reactions and micro-mechanics, utilization of core accelerated-expansion test but limited possibility of core sampling
Mechanical behavior	Effect of reinforcement, creep
Criteria	Different performance requirements and limits for each member

TABLE 3: Comparison of reactivity test results by various test methods.[31,except TN,YT,LS]

Test methods	Aggregate type							
	Rapid expansive			Slow reactive				No reactive
	TO	SI	TN	WI	HE	GK	YT	LS
Origin	Hokkaido	Hokuriku	Tohoku	Kanto	Shikoku	Kyushu	Chubu	Kyushu
Petrography/ reactive minerals	Andesite/ crist, v-glass	Andesite/ crist., v-glass	Andesite/ opal, crist., v-glass	Sandstone/ crypt-qz	Hornfels/ crypt-qz	Green schist/ crypt-qz	Chert/ chalcedony, crypt-qz	High purity limestone/ no
Damages in structures	Yes	Yes	Yes	Unknown	Yes	Yes	Yes	No
JIS chemical	Harmful	Harmful	Harmful	Harmful	Harmless	Harmless	Harmful	Harmless
JIS mortar bar	Harmful	Harmful	Harmful	Harmless	Harmless	Harmless	Harmful	Harmless
RILEM AAR-2	Harmful	Harmful	Harmful	Harmful	Harmful	Harmful	Harmful	Harmless
RILEM AAR-3 AW	Harmful	Harmful	Harmful	Harmful	Harmful	On going	Harmful	Harmless
RILEM AAR-4 AW	Harmful	Harmful	Harmful	Harmful	Harmful	Harmful	Harmful	Harmless
RILEM AAR-4	Harmful	—	Harmful	Harmful	—	—	Harmful	Harmless

Crist: cristobalite, tri: tridymite, v-glass: volcanic glass, crypt-qz: cryptocrystalline quartz.

Stage 1: Investigation of the possibility of ASR by preliminary tests
Preliminary survey
-> Daily checking: cracks, abnormality
-> Records survey
-> Field survey: External appearance, exposure condition, judgement of further survey
->Core sampling planning
Stage 2: Detection of ASR by material testing
Detailed survey of cores
-> External appearance observation: Aggregate composition, gel detection
-> Identification of ASR: if yes, then tests for determining whether rapid or slow;* if no, then other tests if required.
*-> Petrographic evaluation
-> Evaluation of the progress of ASR and core accelerated-expansion tests
-> SEM/EDS analysis of gel
-> Identification of the cause of ASR
Stage 3: Feedback to ASR countermeasures
Construction under countermeasures: if yes, then conduct detailed analysis;* if no, then perform confirmation test, if necessary.
*-> Investigation of alkali budget and effectiveness of SCMs
-> General interpretation and feedback to ASR countermeasures

FIGURE 1: ASR diagnosis process proposed by the NRA (2014) (taken from [14]).

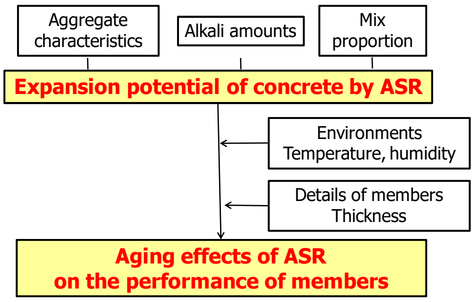

FIGURE 2: Factors causing ASR and aging effects.[30]

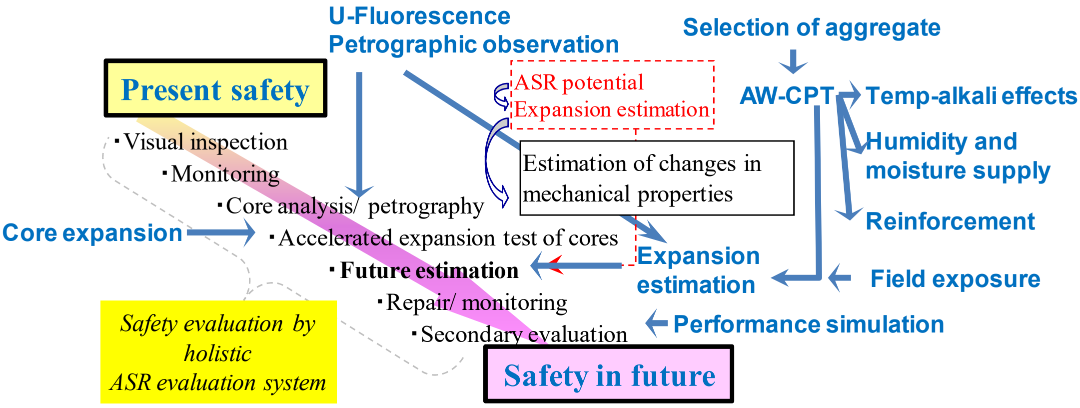

FIGURE 3: Holistic ASR evaluation system required for integrity assessment and the positions of procedures for addressing challenges in the holistic ASR evaluation system. [30]

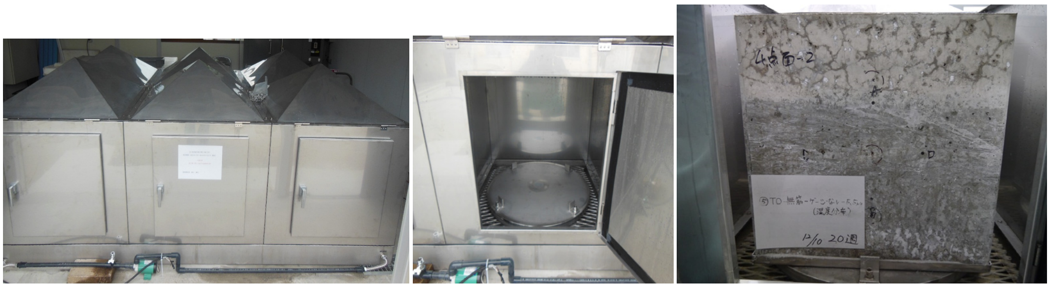

FIGURE 4: Block exposure test. [30]

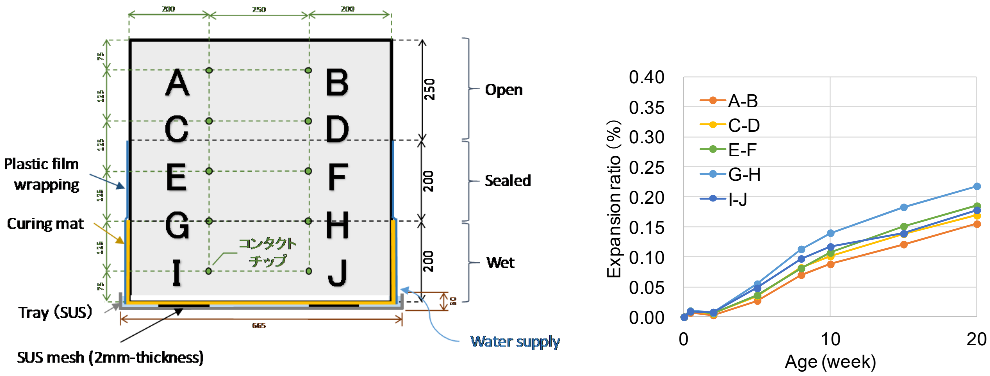

FIGURE 5: Moisture control of a block specimen (left) and expansion variation (right). [30]