

Importance of petrographic diagnosis and a proposal of comprehensive management flow of concrete structures for alkali-aggregate reaction

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Abstract

The purpose of diagnosis of alkali-aggregate reaction (AAR) by the structure administrator is to know the structural soundness in the future. Therefore, it is important to know not only whether AAR will occur in the future but also to evaluate the soundness of the structure by examining the cause of the AAR, predicting the future expansion, and predicting the performance after the expansion. Japan's Nuclear Regulation Authority (NRA) has conducted a project to study a comprehensive AAR assessment flow as part of its response to high aging of nuclear facilities. Based on the results of this project, a comprehensive management flow is proposed that combines the procedures for diagnosis and evaluation of AAR. At the request of the structure administrator, diagnosis is often conducted by field observation and then cores are taken for petrographic diagnosis. However, taking cores means damaging the structure, and its necessity should be carefully considered. In addition, even if the cause of the AAR is found after core sampling and petrographic diagnosis, there is no reliable method to inhibit the ASR progress. Therefore, in the stage of minor deterioration, it is desirable to continue the inspection after investigating the history of aggregates and concrete mixtures based on the deterioration cases of surrounding structures and considering the risk of AAR. For those with significant deterioration, even if diagnosis using established methods is performed, the reality is that control measures are trial and error, and we have no choice but to work with experts over a long period of time. In this current situation, this paper will summarize the basics useful for diagnosis. First, is the reasons why the expansion behavior does not agree between laboratory and exposure. Next, points that are often overlooked in petrographic observations to analyze the reaction conditions are presented. In addition, the difficulty of residual expansibility testing of cores will be pointed out.

Keywords: *Diagnosis; prognosis; appraisal; reliable accelerating test; residual expansion; petrographic observation*

1. INTRODUCTION

Various detailed methods for diagnosis, prediction, and appraisal of alkali-aggregate reaction (AAR*), which are necessary for structural management, are described in RILEM AAR-6.1 [1], STAR RILEM TC 259-ISR [2], and the textbook Alkali-Aggregate Reaction in Concrete [3]. All the main points of them as shown in Figure 1.1, have been explained and do not need to be explained here again. However, there is a gap between the various stakeholders in the AAR, such as geologists, concrete engineers, and structure managers, in the way they think about individual information in management. Geological research**) is extremely effective in elucidating the causative materials and the mechanisms that cause expansion of AAR. However, considering the meaning in structural management rather than research, the quality of petrographic diagnosis**) is highly dependent on the skills of engineers, and general engineers cannot understand the terms related to petrographic diagnosis and geological research, nor can they verify its validity. Although many methods for the construction and maintenance of concrete structures have been standardized, AAR diagnosis is dependent on the individual who performs it, making it difficult to standardize structural management based on it. In addition, the ability to perform AAR diagnosis means understanding all deterioration mechanisms of concrete and being able to discriminate between them. AAR diagnosis also requires knowledge of the evaluation method of

aggregates and AAR control measures in the background of the construction of the structure. Therefore, petrographic diagnosis of AAR should not be limited to identification of reactive minerals and observation of reaction products, but in reality, it is often only important to determine whether a structure is AAR or not, rather than considering various viewpoints. Thus, the procedures developed by researchers who are mainly involved in geological studies may be difficult to apply to field engineers who are generally specialized in concrete engineering. Furthermore, it is inappropriate from the perspective of social organizations for those responsible for the management of concrete structures to act on the opinions of individuals who are not responsible for the management of structures, no matter how advanced and superior they may be, in order to fulfill their legal management responsibilities.

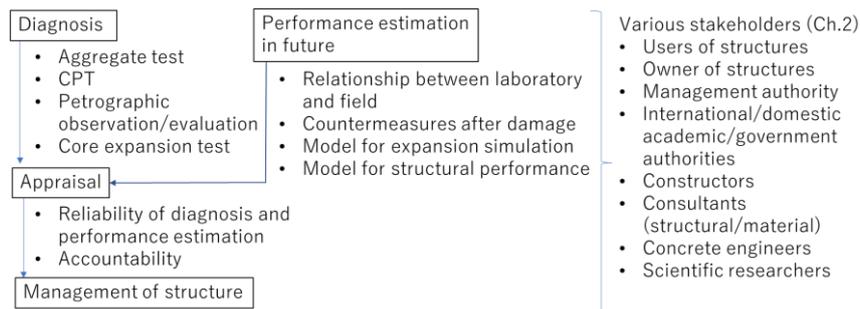


Figure 1.1: Structure of management from diagnosis and various stakeholder

The authors, who are non-experts with regard to petrographic diagnostics, have been involved in AAR research from the standpoint of materials science, with the support of experts in the field. In the process, we have heard various opinions from geologists, petrographers, concrete engineers, and structural managers related to AAR [4]. In addition to the aforementioned books, this paper points out the following issues that should be considered in the future, based on the authors' experience.

- ✓ Awareness of the various engineers involved in AAR diagnosis
- ✓ Limitations of aggregate testing and the importance and challenges of mixture testing
- ✓ Uncertainty of concrete prism test (CPT)
- ✓ Comparison between laboratory and real environment
- ✓ Issues in petrographic diagnosis
- ✓ The need for predictive models
- ✓ Challenges of accelerated curing of cores

This paper presents these case studies and then proposes a comprehensive management flow for AAR of concrete facilities. The Nuclear Regulatory Authority in Japan conducted a study on the long-term soundness assessment of concrete structures by alkali-aggregate reaction as a project for the advancement of aging technology assessment of nuclear facilities [5]. In this project, the Japan Nuclear Energy Safety Organization (JNES) applied the aging technology evaluation method for AAR of concrete for nuclear facilities [6], which was proposed by JNES with reference to RILEM and ASTM, to Japanese aggregates, and reviewed the method for soundness evaluation of nuclear facilities. This paper presents the results of this project.

*) The essence of AAR is the reaction of silica in aggregate, the alkali-silica reaction (ASR) [7]. However, reactive silica alone does not determine the expansion, but its presence in the aggregate determines the degradation. Therefore, in this paper, the term ASR is used when referring to the reaction of silica and AAR when referring to the reaction of aggregate.

**) Petrographic diagnosis is based on polarized light microscopy and certain other procedures. On the other hand, the research on the mechanism of AAR should be called geological research, considering various related information with petrological diagnosis. From this point of view, a distinction is made between petrographic diagnostics and geological researches. Detailed geological explanations can be found in reference [2].

2. AWARENESS OF THE ENGINEERS INVOLVED IN AAR DIAGNOSIS

2.1 Questionnaire Survey in Japan

2.1.1 Various positions

There are various positions of people involved in AAR, with different objectives, levels of consideration and perspectives. They include: 1) researchers who study AAR mechanisms from a geological point of view, 2) researchers who model expansion and deformation based on reaction mechanisms, as well as structural performance, 3) consultants who evaluate aggregate reactivity and potential expansion of concrete, provide petrographic descriptions, diagnose degradation, and predict expansion, 4) academic experts who prepare guidelines for concrete producers and managers, and 5) orderers of construction of structures and maintainers of structures. Even in the same position, there are differences in viewpoints: 1) research and countermeasures based on local experience, and 2) research and creation of criteria for universal AAR reaction mechanisms common to the whole world. Since concrete works reflect regional characteristics and aggregate is not a commercial material distributed worldwide except in the coastal areas, AAR research tends to be rooted in regional experiences. In addition, of course, the scope of consideration differs according to the interests of individual stakeholders. While common guidelines are required for the construction and maintenance of concrete structures, the creation of guidelines is a matter of balancing cutting-edge academic research with mature technologies that can be implemented in the field. In the case of serious AAR deterioration, the reality is that the field of management, starting with diagnosis, has become research itself. Once guidelines are created, they become rules, and even if there are inappropriate aspects, they are not easily changed because they are judged based on the overall interests of society as a whole. As an industrial standard, the EN standard is considered to be in accordance with the ISO standard in the EU, but it is unreasonable for the AAR to reflect the geological conditions in Europe, and the related standards of the AAR should be universal, taking into account the geological conditions of the world.

2.1.2 Survey Results

With this understanding of the background, JCI-TC 115 FS "Technical Committee on Diagnosis of ASR-affected structures" conducted a survey on the awareness of concrete engineers regarding AAR-affected concrete structures [8] on the following three points, and 361 responses were obtained.

Awareness of control measures for newly constructed structures

Awareness of diagnostic techniques related to AAR

Experience in the diagnosis of structures deteriorated by AAR

About one-third of the respondents belonged to government agencies and one-third to consultants. About half of the respondents were qualified persons related to concrete technology in Japan. 20% of the respondents had more than 6 times of experience in AAR diagnosis.

According to the results of the questionnaire, 64% of the respondents thought that the control measures on new structures was effective or generally effective. 12% of the respondents answered that it was not effective or not very effective. Those who answered not effective considered the testing method of aggregates, the total alkali content limit, and the replacement ratio of SCMs to be issues. When asked whether the risk of AAR should be reduced even at the initial cost, although there is still a risk of AAR even with the implementation of control measures, about half of the respondents answered that elaborate measures are necessary for important structures, and about a quarter answered that exceptional cases are unavoidable.

Regarding AAR diagnosis, the respondents were asked about the difficulty of diagnosis. More than half of the inexperienced respondents answered that it was difficult, while about three-fourths of those with more experience answered that it was easy. Those who had experience in the diagnosis of deteriorated structures were asked about the diagnosis of AAR deterioration, and when asked about the stage at which they recognized the possibility of AAR, 30% of the respondents answered periodic inspection, 15% answered detailed inspection, and 10% answered routine inspection. As a result, almost all of the structures where the possibility of AAR was identified were judged to have AAR or a combination of AAR and other deterioration. The most common rationale for the diagnosis was appearance features, combined with accelerated expansion of the core and confirmation of ASR gel in the core.

We asked questions about the usefulness and implementation of various diagnostic techniques and analyzed the correlation between them. As shown in Figure 2.1, those with more experience naturally performed more of what they considered useful. In the case of those with little experience, there was no difference in the usefulness of the various methods, but the items performed were generally the same as those with experience, suggesting that those with little experience may not understand the significance of the various methods, but may be following the advice of experts.

The most common method was the thin-section observation, and other methods were elastic modulus techniques, residual expansion test, peripheral investigation, and gel observation by SEM. Those that were neither useful nor performed were observation with uranyl acetate, mortar bar test, chemical method, and gel analysis of the surface. The major difference between those with and without experience was in the implementation of the chemical method. Aggregate was taken out from the core and the reactivity was evaluated by the chemical method. Although experts do not perform this method because they consider it meaningless, it is estimated that the chemical method is the most commonly used method to determine the reactivity of aggregate in Japan, and it may be performed in some cases with little experience.

Based on the results of the above survey, it is estimated that field engineers are struggling with AAR diagnosis and are unable to determine the usefulness of conducting AAR diagnosis because it is generally expensive. Although detailed diagnostic techniques are now available, there is no reliable way to control the progress of AAR even if they are diagnosed. Of course, the results of AAR diagnosis and the accumulation of experience are useful for new construction, but it does not mean that managers of existing structures can invest in new structures with consideration. Furthermore, managers and owners of structures often do not disclose the diagnosis results because the diagnostic result of AAR reduces the asset value of the structure. A social mechanism is necessary to collect case studies of AAR diagnosis.

In the following, the current status and issues of various basic technologies surrounding petrographic diagnosis and management of structures will be explained, assuming that various stakeholders read this paper.

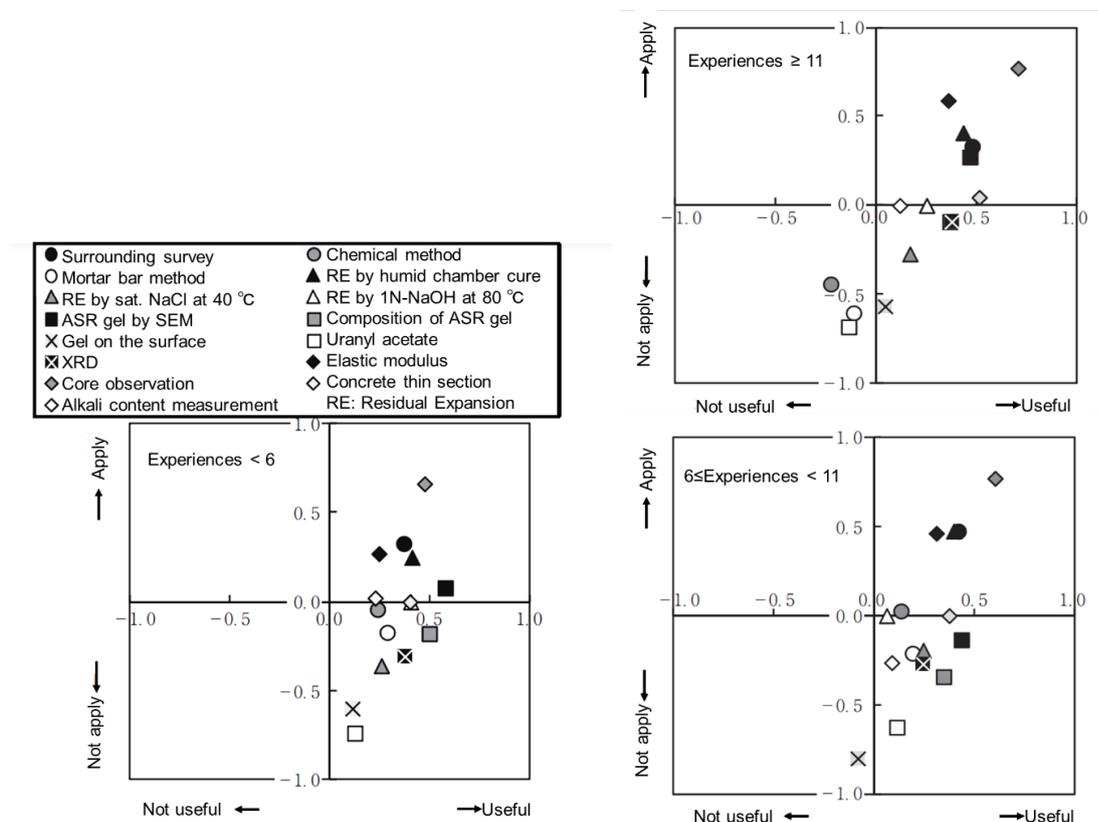


Figure 2.1: Effectiveness and actual application of various methods for AAR diagnosis [8]

2.2 Discrepancy between Petrographic Diagnosis and Performance Prediction of Structures

In current petrographic diagnosis, the damage state of concrete is generally determined from the cracks that occur in the aggregate or paste. Such diagnosis is mainly performed from the viewpoint of materials. On the other hand, it is very important to consider the mechanical point of view in evaluating the performance of structures. There is a large discrepancy between petrographic diagnosis, which is the diagnosis of concrete deterioration, and performance evaluation and prediction of structures.

The structural engineer needs to know whether the structure with AAR will meet the performance requirements at present or in the future, and if not, when it will not meet the requirements. In order to evaluate the performance of current structures, it is necessary to estimate not only the mechanical properties of concrete (strength, Young's modulus, etc.), but also the expansion strain caused by AAR, and perform structural analysis. In order to predict the performance of the structure when AAR develops in the future, it is necessary to consider the changes in the mechanical properties of concrete as well as the future expansion behavior. However, since AAR is strongly affected by environmental conditions (temperature and humidity), the degree of AAR is often different even for the same structure, as shown in Figure 2.2. The scale at which the performance evaluation of a structure is required is on the order of several to several tens of meters, whereas the scale for petrological diagnosis is often a few centimetres. Therefore, how to utilize the local information obtained by petrological diagnosis for the performance evaluation of structural scales is a major issue, but it has not been sufficiently discussed so far.

The performance of structures, such as safety and usability, is strongly influenced by the balance between the mechanical properties of the concrete and the reinforcing bars, where AAR alters the mechanical properties by causing (micro)cracks in the concrete and AAR expansion becomes anisotropic under stress. Although stress-induced anisotropy is controversial, predicting expansion behavior under stress is still a difficult problem. In particular, the effects of creep as well as AAR expansion must be properly considered for predicting the deformation of structures as show in Figure 2.3.

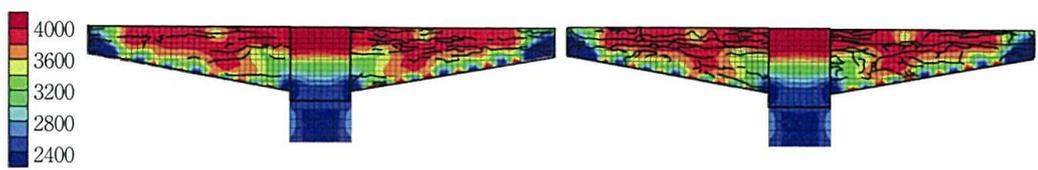


Figure 2.2: Simulated AAR expansion and actual crack patterns Contour plots show simulated expansion strain and black lines indicate cracks above 0.5 mm observed in the structure [9].

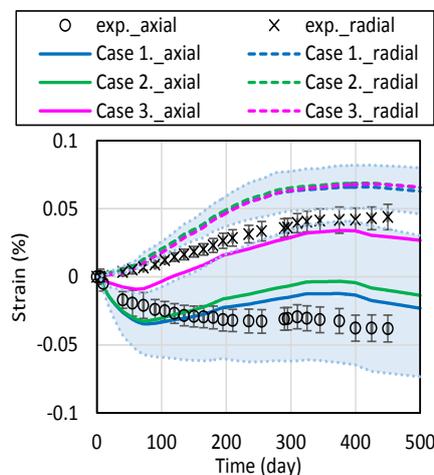


Figure 2.3: Simulated AAR expansion of concrete jacketed with 3mm steel ring under 10 MPa loading [10, 11]. Case 1: full analysis (w/ creep and damage), Case 2: analysis w/o considering damage, and Case 3: analysis w/o considering creep.

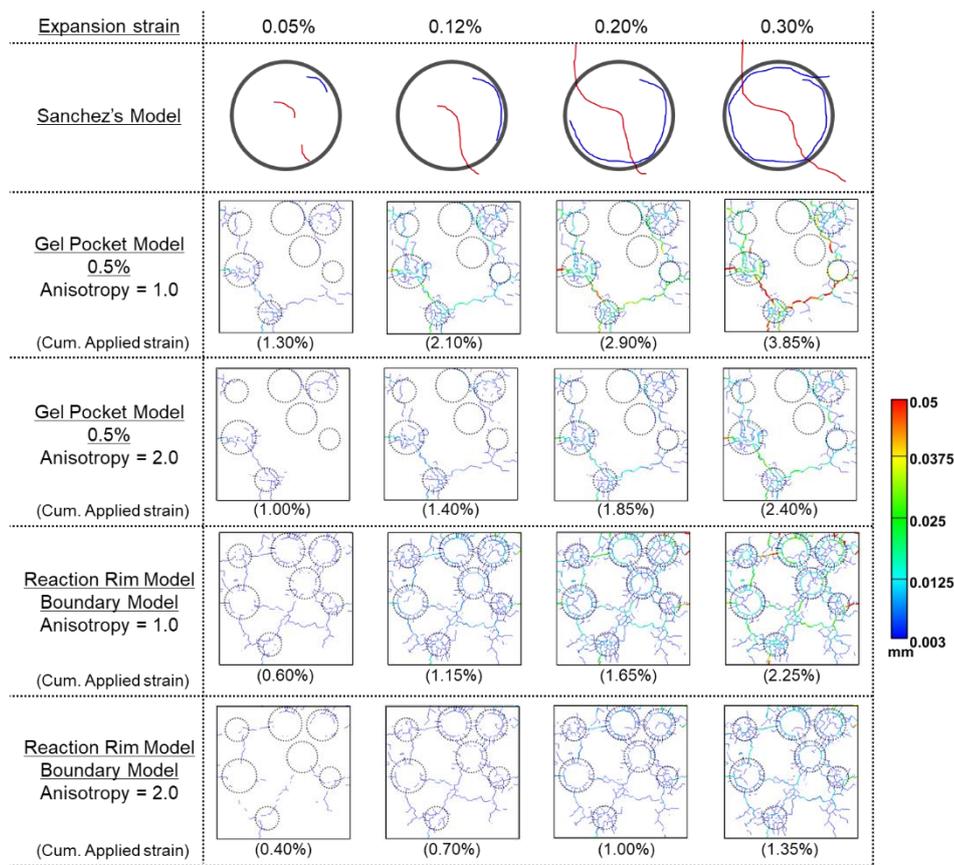


Figure 2.4: Simulated crack patterns in comparison with the experimental observations. For the Sanchez model, red and blue lines represent 'sharp crack' and 'onion skin crack', respectively [14]. Expansion sites are randomly distributed in the modeled aggregate in Gel pocket Model whilst expansion sites are localized at the 2 mm inside from the aggregate surface in Reaction Rim Model. In the case of the Gel Pocket Model, the crack pattern corresponds to sharp cracking, whereas for the Reaction Rim Model, the crack pattern corresponds to onion skin cracking.

Recent mesoscale analysis has shown that the cracking behavior varies greatly depending on the spatial distribution of expansion sites. Microscopic observation shows cracks inside the aggregate, which can be roughly classified into onion skin cracks (cracks along the aggregate-paste interface) and sharp cracks (cracks through the aggregate) [12]. The difference in the crack patterns depends on the spatial distribution of expansion sites, which varies greatly depending on the rock type of the reactive aggregate as shown in Figure 2.4. Such differences in crack patterns are extremely important in terms of performance evaluation of concrete structures. The difference in the crack pattern is directly related to the anisotropy of the mechanical properties of concrete under stress. It has been suggested that the expansion anisotropy of concrete under stress may also be affected by the spatial distribution of expansion sites [13]. In other words, in order to understand the stress anisotropy of macroscopic AAR expansion of concrete, it is necessary to better understand the spatial distribution of expansion sites of aggregates. In addition, the phenomenon is extremely complex because the stress anisotropy, which varies among aggregate rock types, also affects the anisotropy of the mechanical properties of the concrete itself. Therefore, it is necessary to understand what kind of information is needed from the viewpoint of performance evaluation and prediction of the structure at the time the core is taken from the structure. In particular, the cover concrete from which the core is taken is relatively weakly restrained, which is different from the characteristics of the core concrete inside than the reinforcement, which is important from the viewpoint of the performance of the structure.

Thus, there is a large discrepancy between the information obtained in petrographic diagnosis and the information to be obtained in performance evaluation and prediction of structures, and the diagnosis is not made with an understanding of both. However, the spatial information (width, length, distribution, etc.) of microcracks in concrete is an extremely important issue for understanding the physical properties

of concrete, which is necessary for evaluating the performance of structures. In order to link the scale of micro-cracks observed in petrographic diagnosis with the scale of structural behavior evaluation, multi-scale methods are essential. For example, Dunant has developed a mesoscale analysis in the order of cm (AMIE), and a multi-scale model based on it using a homogenization method has been proposed by Gallyamov et al [14]. Such a method will be one of the useful methods to link micro petrographic diagnosis and macro structural performance assessment.

3. AGGREGATE TESTING AND MIXTURE TESTING

3.1 Meaning and Limitations of Aggregate Testing

When considering the risk of future AAR of existing structures, the implementation of harmless aggregates and suppression measures may be used as a basis. Therefore, it is necessary to understand the meaning and limitations of aggregate testing in AAR diagnosis. The ideal AAR measure is the use of harmless aggregates. At present, based on local experience, certain aggregates can be considered harmless. However, this is a judgment based on experience, and we do not know if it is harmless under conditions beyond experience. For example, it is not possible to determine from experience the soundness of a biological shield wall of a nuclear reactor under massive conditions and maximum temperature of 60 degrees Celsius. It is also possible that an aggregate that is considered harmless in one location may become more reactive when transported to another location (common in the coastal areas and in island countries) and mixed with another aggregate. The only exception would be high-purity carbonate rocks, which contain negligible amounts of potentially reactive quartz.

In terms of the relationship between the behavior in the real environment and the test in the laboratory, unfortunately, the Japanese criterion relies on the expansion by the JIS A 1146:2017 mortar bar method (similar to ASTM C227-10), not on field experience, and the criterion is not updated even though exceptions have been reported in the field. In order to build the Shinkansen viaducts, JR East has established the criteria more stringent [15], but this has not led to an essential solution. This may be due to the fact that chemical methods, which are easy to implement, are already widely used in Japan, and that the main reactive aggregates are volcanic rocks and chert, which are highly reactive and for which chemical methods have some effectiveness. Even if the chemical method is not effective for the reactive aggregates that are a problem in North America, it has a certain significance in Japan.

However, when various mixture proportions, environments in use, and periods of time are considered, there is a limit to aggregate testing, since various pessimum phenomena are known, as described in Section 3.4. If an aggregate is judged to be harmful in the aggregate test, the total alkali content may be suppressed to 3.0 kg/m^3 as a measure to control AAR, and SCMs may be required to be added, but in the case of pessimum proportion, the usual measures may be insufficient. It is not only the limitation of aggregate testing, but also the limitation of AAR suppression measures. When this happens, mixture testing becomes necessary. For example, there are so-called "performance tests" such as RILEM AAR-10 and 11 [16,17] to determine the alkali threshold for expansion, and there are also methods to predict expansion by fitting the expansion behavior to some mathematical formula based on various considerations [18]. However, it is also mentioned in Section 3.4 that the alkali threshold cannot be easily obtained depending on the type of aggregate. If this is the case, in the actual construction of structures, in order to predict what kind of expansion behavior a certain mixture of concrete will have in the actual environment, multiple levels of mixture tests with varying total alkali content and temperature are conducted, and based on these tests, it is determined whether or not the expansion can be controlled to an acceptable level during the service life. It may be necessary to manage this process in conjunction with monitoring. Therefore, it will require a reasonable amount of time and effort, and can only be applied to important structures that are worth it. In such a case, it would be appropriate for a review committee of the structure owners to be formed to discuss the measures with experts. For other general structures, under the current level of research, prescribed design may be suitable compared to performance design.

3.2 Necessity of Mixture Testing

3.2 Necessity of Compounding Tests

The limitation of the aggregate test is that the AAR is not a mere chemical reaction, but rather a complex of changes in the microstructure resulting from the chemical reaction that causes the expansion.

Therefore, various mechanisms of action are ignored by crushing the aggregate or other means to make the situation different from the real usage. The expansion mechanism is not merely a particle size dependency or a pessimum proportion phenomenon, but a complex one in which the effects of increasing total alkali content and temperature appear in the form of different expansion at different ages. In fact, when concrete of the same composition is cured at different temperatures, the microstructure of deterioration due to ASR will be different, resulting in different expansion behavior [19]. However, when predicting the expansion rate, it is necessary to determine the temperature dependency of the constant used in the function, assuming that the expansion behavior is fitted to some function. However, excessive changes in the conditions will change the expansion mechanism. Therefore, unfortunately, it must be said that it is impossible to predict the future using a simple CPT, considering the principle of AAR expansion.

3.3 Uncertainty of CPT

3.3.1 Uncertainty factors

CPT is a more realistic test than aggregate testing. Nevertheless, there are still uncertainties in terms of correspondence with actual structures. The factors are listed below.

- Change in expansion mechanism due to accelerated temperature: Although the reaction is accelerated by increasing the temperature, the degraded structure formed by the ASR gel changes with the actual environment, and the expansion may become smaller even though the ASR progresses. There is also a problem for the long test period if temperature is suppressed in reasonable value.
- Concept of total alkali content: There is a concept that the total alkali content in CPT should simulate the maximum value considering the variation of materials in the field. On the other hand, there are cases where a larger amount of alkali hydroxide, etc. is added from the viewpoint of accelerating expansion. As in the case of increasing temperature, if the total alkali amount becomes too large, the viscosity of ASR gel may decrease and the expansion mechanism may change.
- Alkali leaching: Alkali may be lost from the concrete prism during the test for various reasons.
- Moisture supply: Since ASR is a reaction between highly concentrated alkaline solution and silica, the presence of liquid water is necessary, but sealed containers filled with water do not always meet the conditions of sufficient moisture supply.
- Heterogeneity of aggregates: Aggregates with high reactivity exhibit pessimum proportion, but if the amount of the coarse aggregate becomes pessimum at 5%, it is difficult to make the aggregates uniformly present even in a 10x10x40 cm square column. In addition, if a wide variety of rock types, such as river gravel and glacial sediments, are mixed in, and some of them are expansive rocks, there is still the issue of uniformity of the test specimens. Normally, three test specimens are prepared, but the variation of each specimen increases and the test accuracy decreases. It is not easy to prepare larger test specimens from the viewpoint of handling, and it is desirable to increase the number of test specimens.

3.3.2 Reproducibility of accelerated conditions: alkali leaching and water supply

In RILEM AAR-10 and 11, the measurement procedure was modified to minimize alkali leaching and drying during the measurement. In terms of moisture supply to the specimen, moisture supply in a high humidity environment and liquid water supply are not necessarily equivalent. Therefore, alkaline wrapping (AW), which actively and stably supplies liquid water, was proposed as RILEM AAR-13 [20]. In AAR-13, concrete prisms are packed with water-retaining material containing water with the same alkalinity as the pore water in concrete, and then covered with plastic film. This prevents the migration of alkali from the concrete prism while realizing sufficient water supply. A measurement example is shown in Figure 3.1 [21]. The aggregates are early-expansive andesite (TO) and late-expansive hornfels (WI). RILEM AAR-4 was used as the reference and the results were compared with and without the application of AW. As shown in Figure 3.1, the initial expansion of TO was faster without AW but reached saturation, while the expansion of WI was stagnant without AW but continued to expand gradually with AW for a long time. The mass change showed that without AW, the mass increased or decreased slightly,

but with AW it increased over time. When the water at the bottom of the container was measured, alkali was detected without AW, but not with AW, indicating that alkali leaching was suppressed.

CPT usually involves increasing the temperature or the amount of alkali to accelerate the reaction. As mentioned earlier, alkali leaching suppression and sufficient water supply can also be AW. Therefore, it is thought that an acceleration factor can be considered [22]. However, it is assumed that the AAR-induced expansion mechanism occurring in the field is simply accelerated in the test. Unfortunately, as will be discussed in Section 3.5, the existence of various pessimum phenomena makes long-term prediction by simple extrapolation fraught with uncertainty. Nevertheless, if data on the correlation between real-field expansion and CPT, which is reproducible and can continue to promote under constant conditions over a long period of time, are accumulated, the promotion multiplier may be useful for future predictions with a certain degree of accuracy.

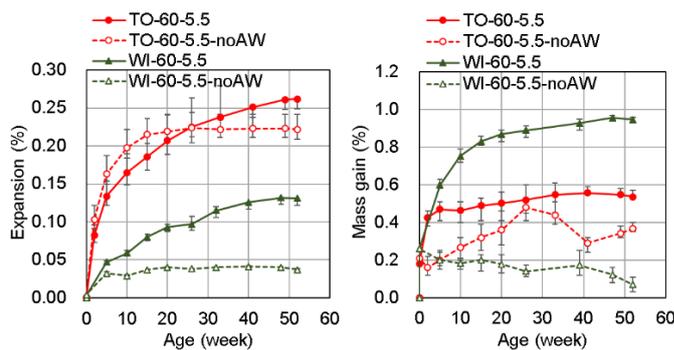


Figure 3.1: Effects of AW on RILEM AAR-4 [21]

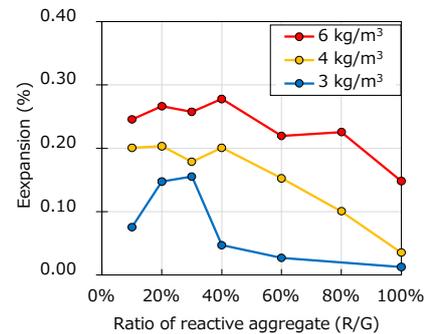


Figure 3.2: Pessimum of mixture proportion. Cure at 40 °C for 1 year.

3.4 Various Pessimum Phenomena

3.4.1 Kinds of pessimum phenomena

In the AAR, the pessimum phenomenon generally means that when a less reactive aggregate is mixed with a more reactive aggregate in concrete or mortar, the maximum expansion occurs at a lower percentage of the highly reactive aggregate rather than 100% [23]. The pessimum percentage varies depending on the degree of reactivity of the aggregates to be combined, and when non-reactive aggregates are mixed with highly reactive aggregates, the higher the reactivity of the highly reactive aggregate, the lower the pessimum percentage. However, the phenomenon of maximum expansion is not only caused by the mixing conditions of the aggregate, but also by other factors. For example, aggregate particle size, specimen size, total alkali content, humidity, and the age of the specimen are not simply proportional to the expansion.

These pessimum phenomena indicate the limitation of the application of aggregate testing, but at the same time, they also indicate the limitation of CPT. Each of the factors mentioned above affects the specific surface area of the aggregate, the rate of consumption of alkali in the porewater, the composition of the alkali-silica gel produced, and the mechanical conditions such as damage and restraint. In other words, the mechanism of the pessimum phenomenon is difficult to explain uniquely because of the interaction of complex chemical and physical phenomena. In AAR diagnosis, it is necessary to examine the cause of AAR expansion based on the understanding of these circumstances. The following is an example of the detection of various pessimum phenomena using various aggregates by AW-CPT, which minimizes the effect of alkali leaching from the specimen.

3.4.2 Pessimum proportion

Aggregate particles containing highly reactive minerals can cause harmful cracking even in small amounts (e.g., 5%). Since the pessimum proportion is thought to be determined by balancing the reactive area of the aggregate with the alkali concentration in pore solution, the pessimum proportion can vary depending on the age of the evaluation and the total alkali content. Figure 3.2 shows the results of the expansion test of concrete made from andesite containing highly reactive opal. The total alkali content was 6, 4, and 3 kg/m³, and the data were obtained at 40 °C acceleration at 1 year of age. For

all alkali contents, about 30% of the mixture is pessimum. Therefore, there is a risk of overlooking the pessimum if the reactivity is evaluated only for concrete using 100% of this aggregate. In addition, even if the alkali amount is kept to 3.0 kg/m^3 , the concrete will expand by about 0.15% when used with pessimum, which may cause unexpected damage to the concrete.

3.4.3 Pessimum temperature

The higher the temperature, the faster the chemical process of silica dissolution in the aggregate. However, the higher the temperature, the less viscous the alkali-silica gel becomes and the more likely it is to flow out of the specimen through cracks. The damage pattern in the aggregate also differs depending on the temperature. Therefore, the tendency of expansion obtained from the laboratory test is not necessarily linked to the one in the real environment, and it should be understood that it varies depending on the temperature.

Figure 3.3 shows the expansion by CPT using different aggregates against temperature. In the case of shist as shown in Figure 3.3 left, the lower temperature, the less expansion was observed. However, in Figure 3.3 right, reactive chert containing chalcedony showed strange behavior. In early ages, the more expansion was observed at the higher temperature. But in longer ages, the relationship became reverse. The pessimum temperature changes with age of evaluation.

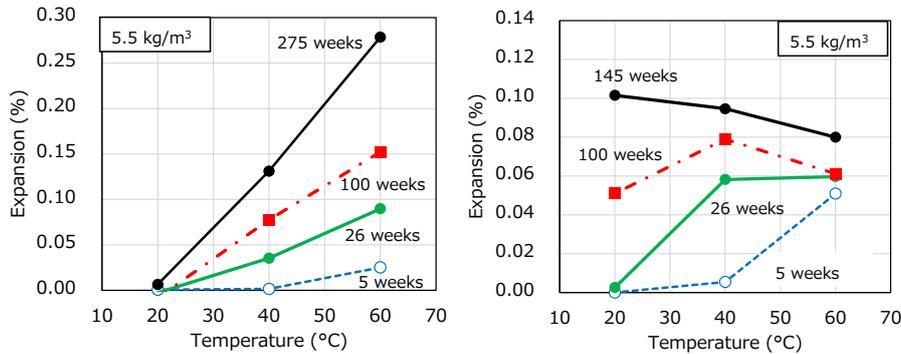


Figure 3.3: Expansion and temperature at difference ages (left: sandy-shist, right: chert)

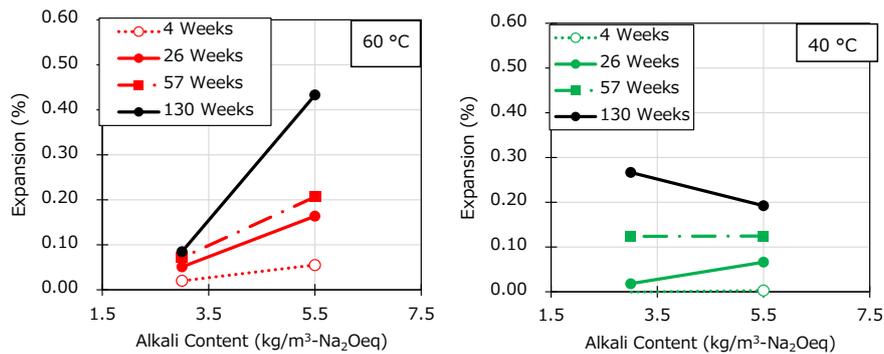


Figure 3.4: Expansion by AW-CPT and alkali content at different ages (Norwegian mylonite)

3.4.4 Pessimum alkali content

Figure 3.4 shows an example of AW-CPT with total alkali content as a parameter, showing different expansion trends depending on the age of the specimens and at different temperatures. The aggregate examined was Norwegian mylonite, which has micro/cryptocrystalline quartz as a reactive mineral.

It can be seen that the level of 3.0 kg/m^3 alkali content expands significantly at $40 \text{ }^\circ\text{C}$ at longer age, and reaches 0.27 % at 130 weeks, surpassing that of high alkali content, indicating that the pessimum of alkali content varies with age of evaluation. From the test results at $60 \text{ }^\circ\text{C}$, expansion is limited at the 3.0 kg/m^3 of alkali content. So, it seems as if ASR can be suppressed by taking measures to keep the

total amount of alkali below 3.0 kg/m^3 , but this claim cannot be said to be correct, considering the trend at 40°C . It should be noted that the method of excessively increasing the alkali concentration in order to simply evaluate the expansion of concrete has the risk of overlooking such a phenomenon.

4. COMPARISON BETWEEN LABORATORY AND REAL ENVIRONMENT

4.1 Causes of Disagreement

Comparisons between CPT results and the expansion behavior of specimens of a certain size exposed or in real structures have been made in various situations. Most of the results do not agree with each other [24]. As mentioned in Chapter 3, CPT has the problems of alkali leaching and insufficient water supply, and AW was introduced as one of the methods to solve these problems.

However, the results of AW-CPT are not always directly proportional to the results of exposure. As explained in Section 4.2, the expansion rate due to CPT at different temperatures is complicated by the age of the material. The higher temperature may not result in a higher expansion rate for all ages, which affects which age of CPT is compared to the expansion rate at exposure.

Rainfall, or humidity, may also have an effect, but testing for the effect of humidity on AAR expansion is not straightforward: to measure AAR expansion, a test specimen three times the size of the aggregate dimension is required, but even if, for example, a 1-inch cross-sectional bar is placed in an environment with controlled external humidity, the humidity inside the test specimen will not be reached to equilibrium in a short time. Studies of the humidity dependence of AAR expansion have controlled the environmental humidity, but not the humidity inside the specimen. Measurements on thin specimens have shown that they do not expand unless they are in at least 95% relative humidity and almost water saturated [25]. Therefore, it may be better to simply assume that the moisture supply comes from rainfall and consider the sum of the number of days of rainfall and the number of days it takes for the rainfall to dry, as described in section 4.3, rather than the effect of humidity itself.

4.2 Alkali Leaching in Field

When the reactivity of ASR is experimentally evaluated by CPT or mortar bar method, alkali metals are gradually leached from the surface of the specimen during the acceleration period, and the alkali concentration is lower than the design alkali concentration, resulting in the underestimation of the long-term expansion [26]. This alkali leaching is noticeable in accelerated tests with high temperature and high ambient humidity, but it is not a problem limited to indoor tests. Even in an outdoor environment, alkali leaching due to rainfall can affect expansion in the long run.

In this section, the results of outdoor exposure tests of concrete with different dimensions using two different formulations are presented. Two types of reactive aggregates were used: andesite (NT), which contains opal and cristobalite and is highly reactive, and sandy schist (EH), which contains cryptocrystalline quartz and is relatively less reactive. The unit water content was 160 kg/m^3 , the W/C was 50%, and the fine aggregate was non-reactive limestone crushed sand. The reactive aggregate was used as coarse aggregate and the concrete with NT aggregate was mixed with limestone at 30% which is the pessimum proportion. The total alkali content was adjusted with NaOH to be 3.0 kg/m^3 for those using NT aggregate and 5.5 kg/m^3 for those using EH aggregate. Two types of test specimens with different dimensions were produced for each mix: a large block of $40 \times 40 \times 60 \text{ cm}$ and three cylinders of $10 \times 35 \text{ cm}$ diameter. The fabrication was done in the same place on the same day. The length variation of each surface was measured for the blocks, and the longitudinal length variation was measured for the cylinders. The measurement was done by the contact gauge method with a base length of 20 cm and embedded reference points.

The exposure sites are shown in Figure 4.1. Okinawa (O) is warm with daily mean temperature in the range of $30\text{--}20^\circ\text{C}$ with 2000 mm of annual rainfall. Fukuoka (F) has large seasonal temperature fluctuations, with an annual mean temperature of 17°C and annual rainfall is 1800 mm. Monbetsu (M) has a daily mean temperature below 5°C for half the year, averaging about 20°C in summer, an annual mean of about 7°C and annual rainfall is 800 mm. Precipitation is about 120-140 days per year at all sites.



Figure 4.1: Exposure

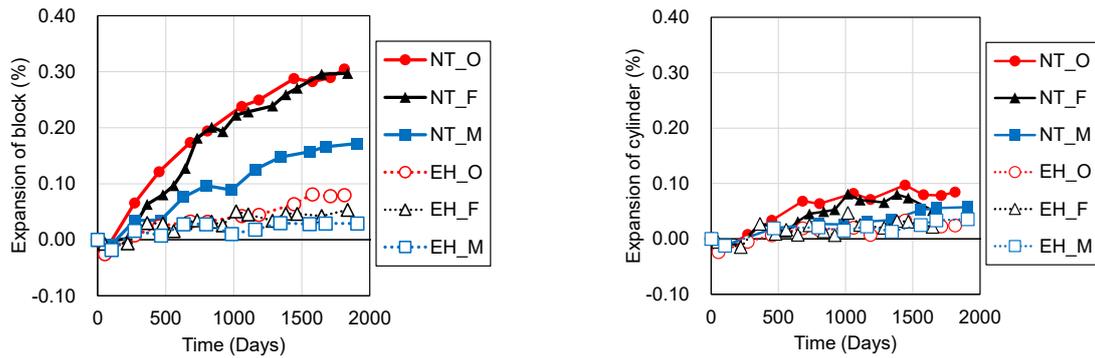


Figure 4.2. Expansions of blocks (left) and cylinders (right).

Legend indicates aggregate type (N or EH) and exposure site (O, F, or M)

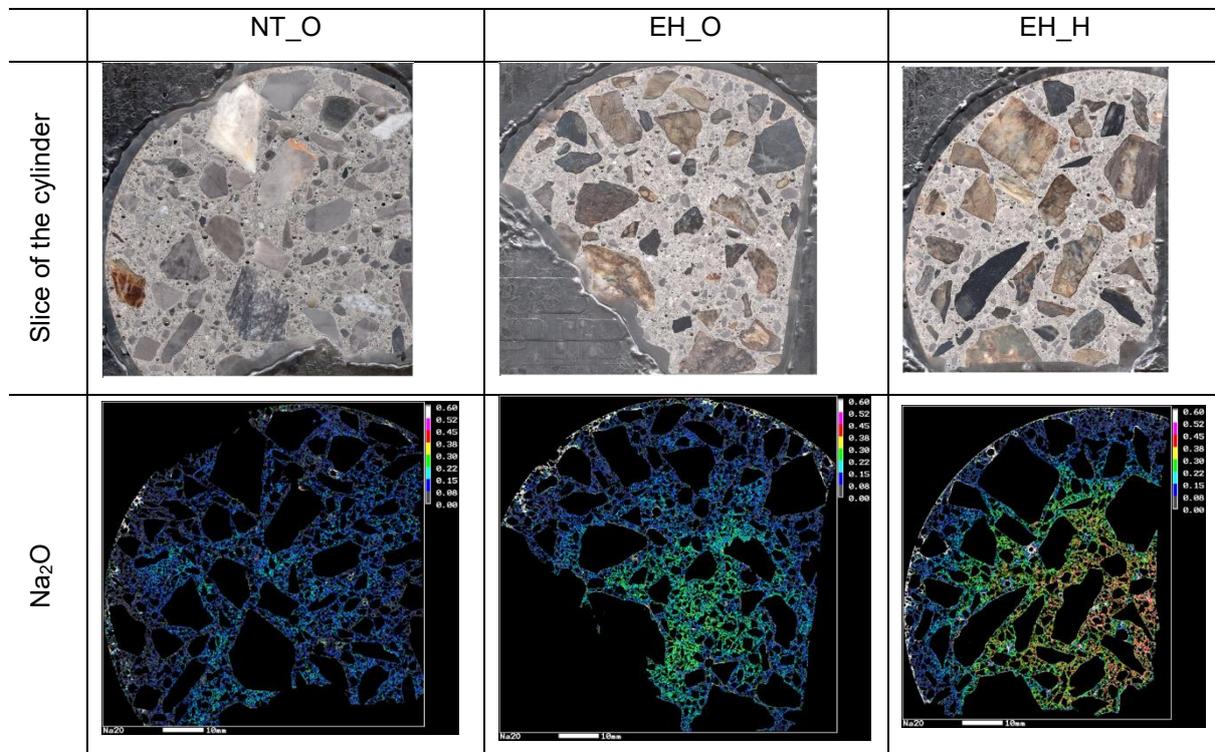


Figure 4.3: Na distribution in cylinder cross section at 1200 days

Figure 4.2 left shows the expansion behavior of the block and Figure 4.2 right shows the expansion behavior of the cylindrical specimen. The thermal expansion was cancelled assuming the coefficient of linear expansion is $10 \times 10^{-6} / ^\circ\text{C}$. Overall, the expansion of the cylinders was lower than that of the blocks. As for the concrete with N-aggregate, the expansion tendency of the block specimen continued even after about 2000 days of exposure, while the expansion of the cylinder specimen almost stopped after about 800 days of exposure. It was confirmed that the magnitude of the expansion rate and the duration of the reaction progress differed depending on the size.

Since the effect of alkali leaching was inferred as the cause of the above, the distribution of Na concentration in the cross-section of some levels of cylindrical specimens was measured by EPMA at 1200 days of exposure. As a result, a gradient of alkali concentration from the center to the surface of the specimen was observed as shown in Figure 4.3. When the dissolution depth is 2 cm or 5 cm, the apparent diffusion coefficients are $2.0 \times 10^{-13} \text{ m}^2/\text{s}$ and $1.2 \times 10^{-12} \text{ m}^2/\text{s}$, respectively. Even for the same concrete, the rate of alkali leaching differed depending on the exposure site, and leaching was more advanced in Okinawa, where the temperature and precipitation were higher, than in Monbetsu. In the

case of the NT aggregate cylinder, which started to expand and crack at an early stage, the Na concentration had already decreased to the extent that the concentration gradient in the cross section could not be seen clearly at 1200 days, supporting the fact that ASR was stopped by alkali leaching from the surface of the specimen.

The smaller the specimen size, the more it is affected by the decrease in alkali concentration due to alkali leaching, so the amount of expansion is lower than that of a specimen with a larger size, and the reaction converges earlier. In addition, in high temperature and high rainfall environments, where the reaction is more accelerated, alkali transport is easier and solution diffusion is easier through the cracks that occur, which may accelerate alkali leaching. Therefore, the rate of alkali leaching in outdoor exposure is affected by the size, setting environment, presence or absence of damage to the concrete, etc. In this case study, the exposure period was 1200 days (3.3 years), but after 10 years, the depth of leaching would increase from 2-5 cm in 3.3 years to 5-12 cm in 10 years, and the range of influence would increase even in larger specimens. Even in the outdoor exposure test, which is a reliable method for investigation of concrete expansion, alkali leaching affects the expansion behavior, so it is necessary to plan and evaluate with this in mind.

If concrete expands by AAR, map cracks typical of AAR should not be generated if it expands uniformly. It is thought that many open cracks are observed because the external expansion is smaller than the internal expansion. If this is the case, then the smaller expansion of the external concrete could be due to this alkali leaching.

4.3 Predicting the Expansions of Exposed Blocks Based on CPT Results by Modeling

4.3.1 Expansion prediction based on the dissolution speed of aggregate

It was shown that it is not easy to predict the expansion in the real environment simply by CPT from various pessimum phenomena. On the other hand, using the UFO model [27], the authors showed that the dissolution rate of crushed aggregate can reproduce the expansion behavior of the specimen considering the pessimum proportion phenomenon to some extent [28]. However, the model also contains several factors that can only be determined by experience. In particular, the decrease in the expansion coefficient at high temperatures also introduced a relaxation term in the expansion coefficient. Although a certain amount of progress has been made in reproducing the phenomena with models that consider the reaction mechanism in detail, there are still many unclear points. If this is the case, it is effective to predict the future by assuming some expansion pattern, fitting the expansion behavior to it, and obtaining constants that determine the expansion pattern. In this paper, we introduce a case study of reproducing the expansion behavior under exposure conditions from CPT based on such a model.

The feature of the UFO model referred to by the authors is that the rate of ASR progression is expressed by the diffusion of alkali into the aggregate, and by reflecting the effect of pore solution alkali concentration, various types of pessimum phenomena can be considered to some extent. The general calculation flow of this model is as follows: First, the diffusion depth of alkali metal into spherical aggregate, or the reaction rate of aggregate particles, is calculated according to Fick's diffusion equation. Then, the reaction rate is multiplied by the amount of aggregate to obtain the amount of reaction product, and the expansion rate is calculated by multiplying this by the conversion factor. At the same time, the decrease in alkali concentration proportional to the reaction is calculated, and the expansion rate is calculated over time until the reaction stops when the alkali concentration drops below a certain threshold.

In this model, the parameters that determine the reaction process are obtained from dissolution experiments of crushed reactive aggregate. However, two other parameters are used for the conversion to expansion, and their values can only be obtained by fitting with the measured expansion data. One is a term that takes into account the amount of the generated gel that does not contribute to the expansion pressure by filling the voids, etc., and the other is a constant that converts the amount of the generated gel to the expansion rate. The former is set to match the start of the expansion of the measured data, and the latter is set to match the initial slope of the expansion curve (expansion speed). Since this model was developed for accelerated tests using mortar bars that are assumed to be constantly wet, it does not satisfactorily consider humidity conditions. Therefore, how to set these fitting coefficients and how to incorporate the effect of rainfall are important to predict the long-term ASR expansion behavior in real environment.

In an attempt to predict expansion under real conditions on a laboratory test basis, the expansion behavior of a concrete block of dimensions 40x40x60 cm of the same material exposed outdoors in Fukuoka (average temperature 17°C) was calculated based on coefficients obtained by fitting from CPT expansion data [29]. The reactive aggregate was chert containing chalcedony, and the experimental factors were temperature and alkali content in CPT. The experimental results and model fitting results are shown in Figure 4.4. For the calculation in the real environment, the same coefficients were used except for the fitting parameters mentioned above, and the fitting parameters were selected from the values obtained in the CPT reproduction for the closest environment. As for the effect of moisture, calculations were carried out under the condition that the reaction would proceed for three days after rainfall. Figure 4.5 shows the calculation results of expansion rate and pH change of pore solution. The start time of expansion and the degree of expansion for an alkali amount of 5.5 kg/m³ were reproduced accurately. In terms of the predicted change in alkali concentration, both alkali content conditions still maintain the concentration at which the reaction proceeds, so it can be inferred that the expansion will continue in the future in terms of alkali concentration. Under the condition of total alkali concentration of 3.0 kg/m³, the expansion rate of concrete blocks measured is small, but according to the prediction, it will expand in the future.

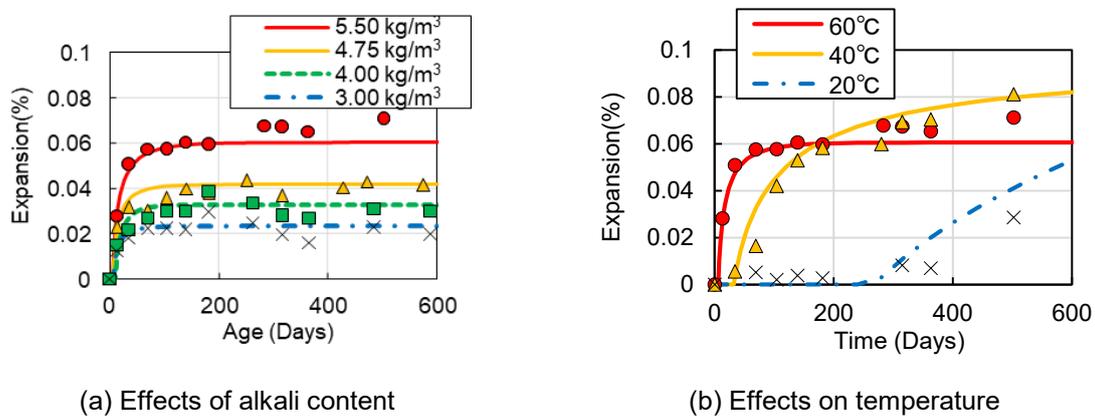


Figure 4.4: Expansions by CPT (dots) and fitted lines by a model for chert aggregate [29]

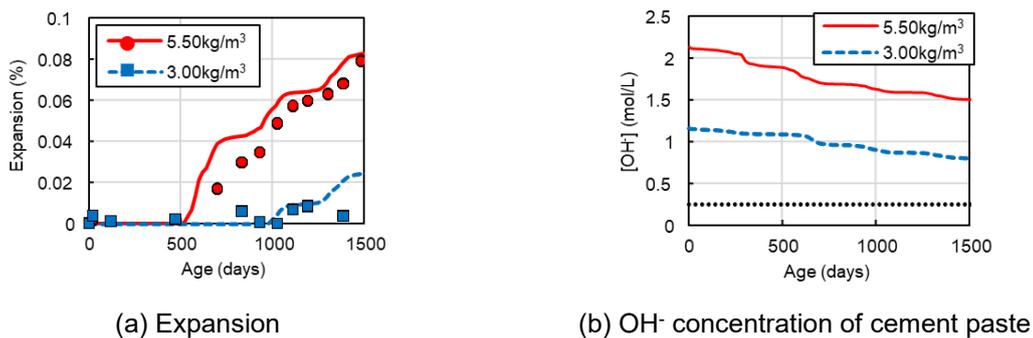


Figure 4.5: Field expansions (dots in left) and estimated expansions (lines in the left) and simulated OH⁻ concentration [29]

4.3.2 Expansion prediction based on the direct fitting for AW-CPT

The above prediction is based on the dissolution characteristics of the aggregate, fitted to the expansion behavior of CPT, and the reaction is converted to expansion by a certain model. It is possible to reproduce the exposure test without considering the reaction mechanism. The authors determined the parameters by fitting the AW-CPT results to Brunetaud's equation, and simulated the expansion behavior of blocks of the same mix installed at three different locations in Japan with different environments by applying the effects of temperature and humidity [30]. The reactive aggregate was NT

aggregate and AW-CPT was performed at 20°C and 40°C with dimensions of 75×75×250 mm. Details of the exposure tests are given in 4.2.

Brunetaud's equation can easily express the macroscopic expansion behavior by setting the amount of long-term expansion and each time constant, as shown in Equation (1) below. This model can trace the long-term gradual increase of expansion behavior by multiplying the S-curve Larive's equation by a correction term by fitting. Furthermore, the model is suitable for the analysis of structures that require a large amount of computation because of its relatively simple equation form.

$$\varepsilon_t = \varepsilon_\infty \frac{1 - \exp\left(-\frac{t}{\tau_C}\right)}{1 + \exp\left\{-\frac{(t - \tau_L)}{\tau_C}\right\}} \left(1 - \frac{\phi}{t + \delta}\right), \quad (1)$$

where t is time (day), ε_t is the expansion at time t (%), ε_∞ is the asymptotic final expansion (%), τ_C is the characteristic time (day), τ_L is the latency time (day), and ϕ and δ are experimental constants (days).

Figure 4.6 shows the results of AW-CPT and the fitting situation by the model. By fitting the AW-CPT results at each temperature, the temperature dependence of each parameter in Equation (1) is determined by the Arrhenius law shown in Equation (2).

$$\frac{X(T_1)}{X(T_2)} = \exp\left[\frac{U_X}{R} \left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right] \quad (2)$$

where X and U_X denote each parameter and its activation energy, respectively, R is 8.314 J/(K·mol), T_1 is the temperature (K) of the desired environment, and T_2 is the temperature (K) of the laboratory (313 K in this study).

Furthermore, for each parameter, the effect of moisture was defined according to Equations (3) and (4) below.

$$\varepsilon_{\infty}(s) = \varepsilon_{\infty}(100\%) \left(\frac{(s - s_{\infty, \varepsilon})^+}{1 - s_{\infty, \varepsilon}}\right)^{m_{\varepsilon}} \quad (3)$$

$$\tau_{C, L}(s) = \tau_{C, L}(100\%) \left(\frac{(s - s_{\infty, \tau_{C, L}})^+}{1 - s_{\infty, \tau_{C, L}}}\right)^{m_{\tau_{C, L}}} \quad (4)$$

where $s_{\infty, x}$ is the threshold saturation degree of parameter x below which no expansion occurs, and m_x is the nonlinearity parameter of x .

Here, the effect of humidity inside the block was incorporated by solving the nonlinear moisture diffusion model by Bazant et al. and considering the moisture transfer due to rainfall.

Figure 4.7 shows the comparison between the measured and modeled expansion rates of the outdoor exposed blocks. It can be seen that the differences in expansion behavior due to different environments observed in the experiments can be reproduced by numerical simulations in which the parameters and their temperature dependence are determined by AW-CPT and rainfall is modeled.

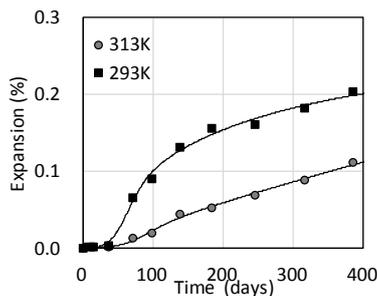


Figure 4.6: Expansion of concrete prism tested by AW-CPT [30]

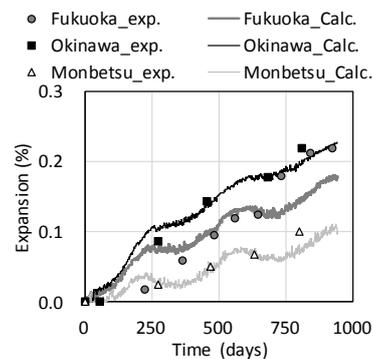


Figure 4.7: Simulated expansion of concrete blocks based on AW-CPT results [30]

5. CHALLENGES IN PETROGRAPHIC DIAGNOSIS

5.1 Description and Cause Estimation

In petrography, the constituent minerals and those texture of a rock are identified by polarized light microscopy, chemical composition, XRD, etc., and together with the microstructure, the rock type is determined. Detailed advanced methods are already available in the literature [31-33], and it is believed that AAR can be described with a certain accuracy by experienced engineers. In the case of AARs, however, we need to observe something different from what is required in general petrology: the detection of substances and textures that are of particular importance in AAR.

- ✓ Silica minerals as reaction sources (tridymite, cristobalite, opal-CT, opal-A, acidic volcanic glass, crypto/micro-crystalline quartz, chalcedony, etc.)
- ✓ Viscously deforming amorphous material (ASR gel)
- ✓ Rosette-like crystal aggregates of ASR gels
- ✓ Cracks associated with AAR

These descriptions are not easy for ordinary petrographers, because they need to understand in which rock types the reactive minerals associated with the AAR are found before making observations. However, petrographers are not always familiar with AARs. There is also a lack of consensus on the petrographic observations related to AARs. Aside from beginners who cannot identify minerals, even experts can make mistakes. It was once believed that ACR was unique and different from ASR, but it is only recently that it has been widely accepted that the reaction of dolomite with dedolomitization is not the cause of the expansion, but the overlooked fine quartz is the essential substance [34]. There is also not necessarily consensus on whether fine-grained quartz is reactive or not. It is often assumed that perfectly crystalline rocks do not react even in the presence of quartz, but the reaction may proceed from grain boundaries, and this cannot be determined simply by looking at a thin section. Furthermore, crypto/microcrystalline quartz is important for ASR, but it is difficult to identify cryptocrystalline quartz by polarized light microscopy, and SEM/EDS/EBSD is necessary. ASR gel is highly viscous and slowly exudes from reactive aggregates when cores are taken from AAR-damaged structures and the surface is covered with a plastic film. If a thin section is prepared without knowing its existence, there is a possibility to observe a specimen in which the ASR gel has fallen out, and proper estimation of the cause may not be possible. Thus, petrographic diagnosis sometimes induces errors. Geology is a discipline that reconstructs the background mechanism of the formation of a particular texture by combining observation results and relevant physicochemical knowledge, and is not a discipline in which the formation mechanism of a phenomenon is simply inferred from the results of polarized light microscopy or SEM/EDS analysis. For example, Figure 5.1 shows the results of SEM/EDS analysis of AAR-expanded concrete [35], and what do you think? The lower right corner is andesite, and the cracks started from the interior of it and continued through the cement paste to the limestone in the upper left corner. It is a geological research to consider the background for the formation of this texture.

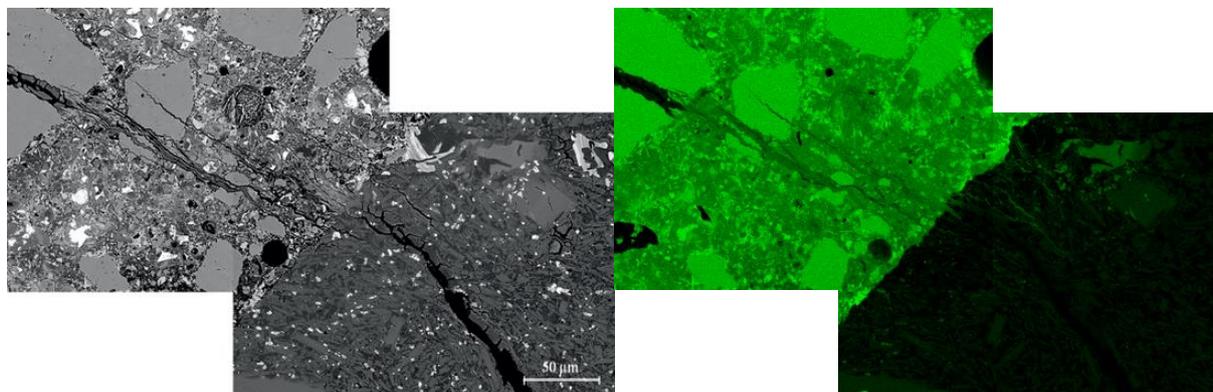


Figure 5.1: Damaged texture of concrete by AAR after AW-CPT. Left: back scattered electron image, right: EDS mapping of Ca [34]

After making these observations, we conclude that the expansion of this specimen is an AAR caused by andesite, but we analyze smaller parts of the specimen after making wider observations. For example, observations to determine the location of concrete cores in the field, surface scanning of the collected concrete cores, and whole photographs of polished thin sections. In the thin section stage, there is an opinion that larger thin sections where a wider area can be observed are preferable. However, it is difficult to produce large polished thin sections of 5 cm square, for example, at the recommended thickness of 15 μm [34], so it is difficult to determine small minerals that cause AAR. For the observation of small minerals and reactive textures, the use of SEM/EDS in combination with polarized light microscopy is recommended. A normal thin slice is about 2 cm square, but in order to obtain the above analysis results, about 10 pieces should be observed. The area that can be observed with a polarized light microscope or SEM is even smaller. Recently, it has become possible to combine more than 1,000 images, and an area of several centimeters square can be observed on a display at 500x with continuous magnification. On the basis of such observations over a wide to minute range, a typical degraded texture is conceptualized in the mind of the analyst, a mechanism is constructed on that basis, and as a result, only the image of the location that typically shows that mechanism is posted in the report. However, from the outside, the process of this consideration is difficult to understand. As a non-specialist, the manager of the structure cannot understand the validity of the results of diagnosis. In order to ensure the reliability of AAR diagnosis and to invest in economically rational diagnosis, it will be necessary to be able to seek a second opinion as in the case of medical treatment.

Table 5.1: Chemical composition of aggregates (mass%)

	LOI	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	MnO	Total
NT	4.92	63.31	14.06	5.38	4.58	0.98	0.06	3.94	1.39	0.64	0.19	0.2	94.73
NW	1.65	63.54	16.08	4.64	5.26	2.06	0.00	3.58	1.86	0.51	0.11	0.08	97.72

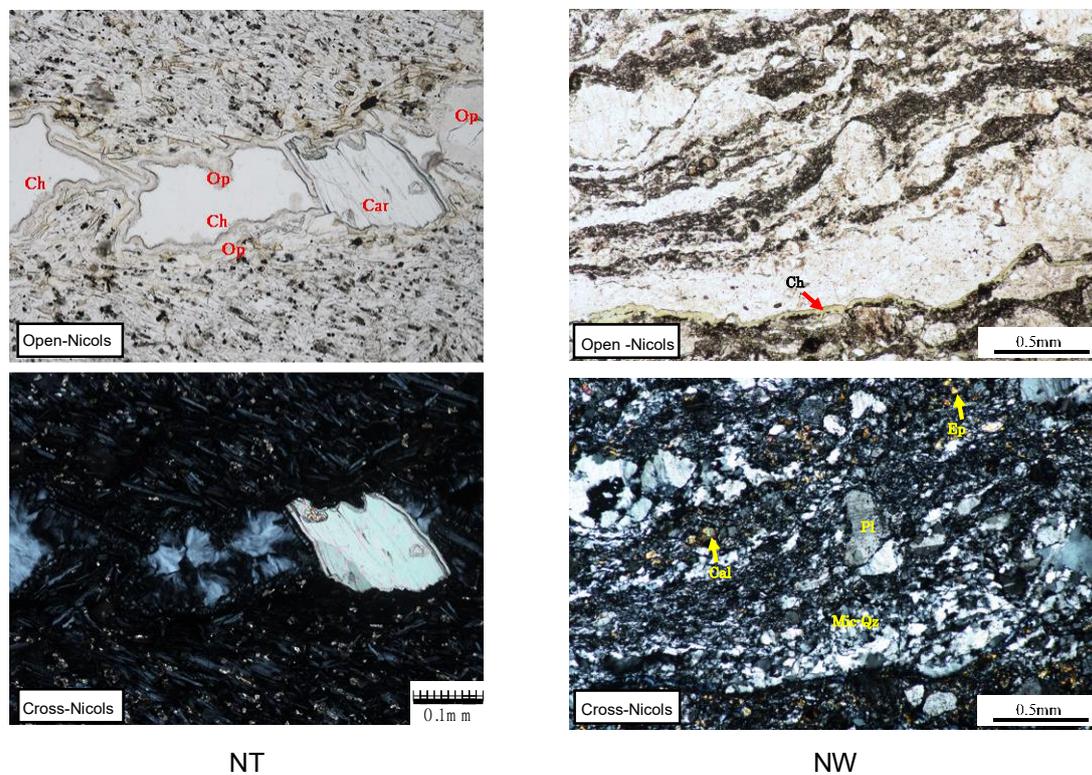


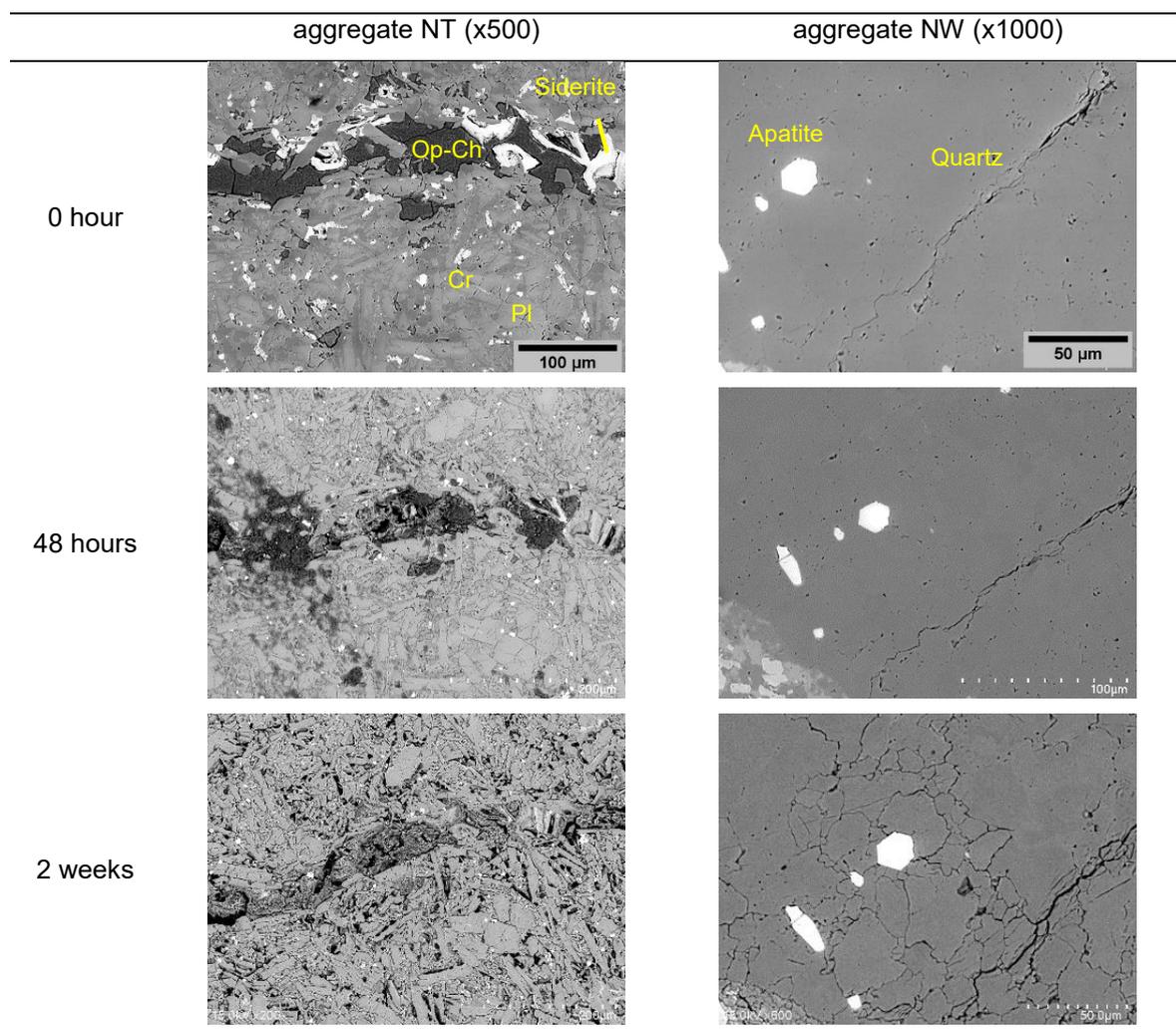
Figure 5.2: Micrographs of thin sections of reactive aggregates from Japan (NT) and Norway (NW)
 Ch: chalcedony, Op: opal, Car: carbonate, Ch: chlorite, Ep: epidote, Pl: plagioclase, Cal: calcite, Mic-Qz: microcrystalline-quartz

5.2 Example of reactive silica

Aggregate reacts differently to alkali depending on the petrographic characteristics such as the form and amount of silica contained and the microstructure, and the way the migration path of alkali metal ions and gel formed inside the aggregate develops also differs depending on the characteristics of the rock. There are also reports of cases where the site of the reaction was captured from analysis of samples from real deteriorated structures [36].

Here, we present two examples of dissolution of reactive silica with widely different properties. Those are example of actual application in structures and serious degradations have been reported. One is andesite (NT) from Northeast Japan and the other is mylonite (NW) from Opphaug, Norway. Table 5.1 shows the chemical compositions of the two aggregates. Those are similar. Figure 5.2 shows polarized light micrographs of the two aggregates. NT was suffered alteration and a large amount of cristobalite was also observed in the matrix with veins composed of opal and chalcedony. In NW, a large quantity of microcrystalline quartz suggesting recrystallization.

In order to directly observe the reaction of silica, the evolution of dissolution traces upon contact with alkaline solution was visually observed using a scanning electron microscope (SEM). Polished pieces were prepared from each aggregate and immersed in a 1.0 mol/L NaOH solution at 60 °C for a specified time. After removal from alkaline solution, the surface was rinsed with distilled water and dried in a desiccator, and the dissolution of the cross section was observed by low vacuum SEM. After observation, the specimens were immersed in the alkaline solution again.



Op: Opal, Ch: Chalcedony, Cr: Cristobalite (darker-gray), Pl: Plagioclase (lighter-gray).

Figure 5.3 BEI of dissolved texture of aggregates NT and NW

Figure 5.3 shows the results of cross-sectional observation of the aggregates by back scattering electron image (BEI) before immersion, 48 hours immersion and 2 weeks immersion. In the case of NT, the opal veins dissolved first, followed by the dissolution of cristobalite in the matrix. At 48 hours, the alkali silica gel dissolved from the vein was observed at the surface as massive materials of low density. At 2 weeks, many pits after cristobalite were observed in a wide range of matrix. On the other hand, the appearance of the quartz phase of NW was almost unchanged in a short time, but the grain boundaries of quartz became clearly visible at 2 weeks. Diffusion through the grain boundaries is expected to be dominant, and the formation rate of alkali-silica gel may change with contact with the alkaline solution.

NT is an extremely reactive early-expansive aggregate, which dissolves opal and chalcedony within a short time, followed by dissolution of cristobalite. The reactivity can be easily determined by polarized light microscopy. On the other hand, in NW, although the presence of microcrystalline quartz can be identified by polarized light microscopy, it is the grain boundaries rather than the particles themselves that react. Therefore, polarized light microscopy will point out only the possibility of reactivity by micro quartz. Although the large quartz particles themselves are unlikely to dissolve, there is a possibility that there is silica that binds the particles together, and the reactivity of that silica is likely to be high.

The above observations are related to the specimen cross-section, and it is possible that in concrete, the relatively porous NT will allow the alkaline solution to easily penetrate into the aggregate and produce ASR gel from the inside, whereas the relatively dense NWs will react in such a way that the grain boundaries expand from the surface [37].

5.3 SCMs

Polarized light microscopy and SEM observations will detect the presence of fly ash (FA) and blast furnace slag particles in the cement paste, if present. In general, both SCMs are considered to have suppression effect on ASR and when the existence of them are recognized in damaged concrete by AAR, one may feel questionable the reason even in the case of SCMs blended. Both SCMs and reactive silica in aggregates are pozzolanic materials, and which one is more reactive determines the occurrence of AAR suppression [39].

SCMs generally have an AAR suppression effect, but the effect strongly depends on the properties of SCMs. The fundamental mechanism of those suppression effects is in the formation of C-S-H with lower Ca/Si ratio and alkali metals adsorption on it. Therefore the effectiveness of SCMs depends on the chemical composition and reactivity. Since Class F FA have different particle size, glass content, and glass chemical composition, it is natural that the same AAR suppression effect cannot be obtained even with the same amount of addition of the FA in the same category. When Al also reacts, it is incorporated into C-S-H with alkali metals as C-(N,K)-A-S-H, which results in alkali metal fixation, and the pH of the liquid phase decreases as shown in Figure 5.4 [40]. This lowering of the liquid phase pH is the essence of the effect of SCMs, and the effect can be estimated as a decrease in the total amount of alkali, as shown in Figure 5.5 [40].

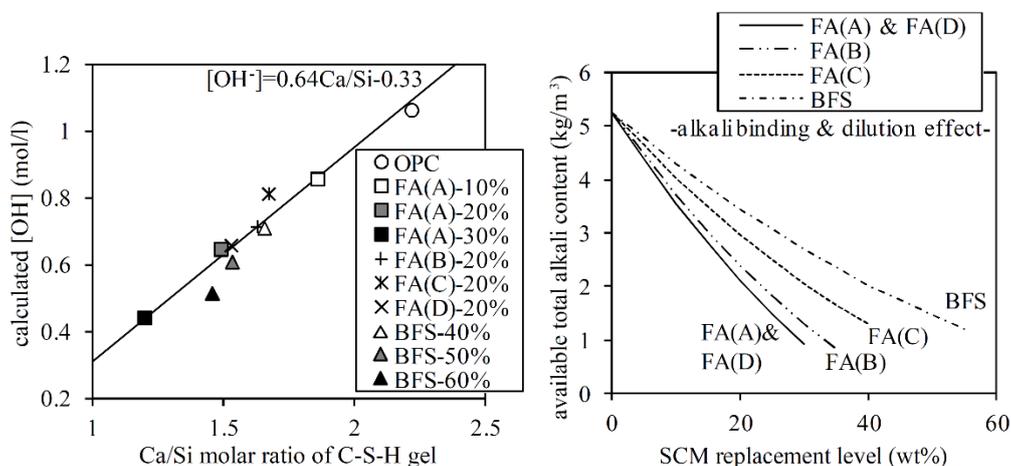


Figure 5.4: Formation of C-S-H with lower Ca/Si ratio by FA and [OH⁻] (left) and SCM level and alkali reducing effect (right) [40]

The FA identified in the petrographic diagnosis is the remainder of the reaction. Figure 5.5 shows the expansion rate of chalcedony-containing chert coarse aggregate after accelerated curing at 38 °C and 60 °C by AW-CPT with two levels of total alkali. The effect of the addition of siliceous FA with a Blaine specific surface area of 4060 cm²/g and a 28-day activity index of 89 was also investigated; although FA had a suppressive effect, it showed a tendency to expand at both 38 °C and 60 °C at a total alkali content of 5.5 kg/m³. Even if the total amount of alkali was 3.0 kg/m³, it showed a tendency to expand at 60°C. In the long term, 15% replacement of this FA may cause expansion. Thus, even with the addition of FA, AAR expansion cannot necessarily be controlled if the amount of alkali is large. Therefore, it is necessary to estimate the total amount of alkali as well in petrographic diagnosis. In old structures in the bay area, the origin of alkali is not limited to cement, but may also come from sea sand [38], and alkali may also come from anti-freezing agents in cold regions.

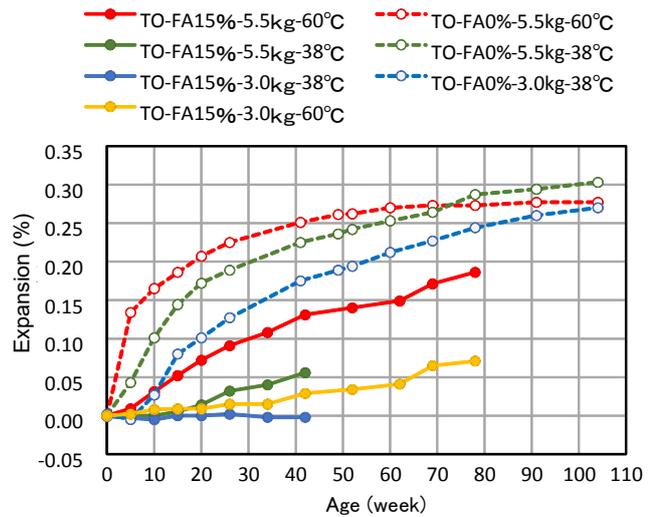


Figure 5.5: Adding effect of fly ash on the expansion of reactive andesite in the pessimum proportion [5]

5.4 Estimation of alkali content

In the diagnosis of AAR, it is also important to estimate the total amount of alkali in the concrete to determine the cause. This is because AAR is unlikely to occur if the initial total alkali content is small even if it is reactive aggregate. A method for estimating the amount of alkali has been proposed by Katayama (Katayama method) [6, 41, 42]. This method was actually applied to the AW-CPT specimen whose history was known, and the estimation accuracy was verified.

The size of the CPT is 75x75x250 mm. The aggregates were early-reactive andesite (TO) with 30% of coarse aggregate, late expansion hornfels (WI) with 100% of coarse aggregate, and non-reactive high purity limestone (IO). Ordinary Portland cement (OPC) was used as cement; a level of 15% replacement of OPC with siliceous fly ash was also done in the TO level. The curing temperature was 38°C or 60°C. A total of 14 cores with a diameter of 48 mm were taken for alkali content estimation. The cores were taken at various ages with different stages of expansion reaction ranging from 5 to 80 weeks.

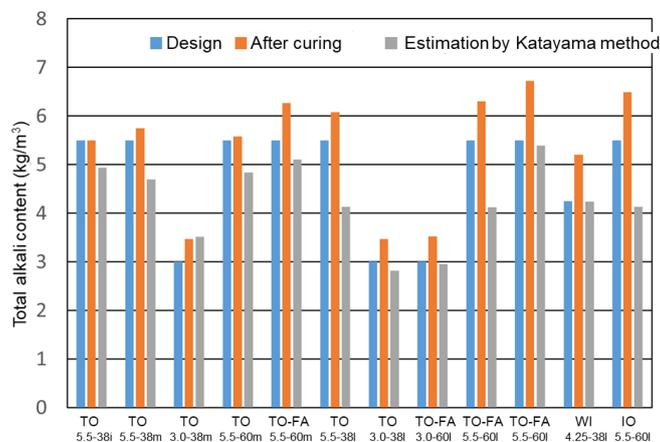


Figure 5.6 Estimated total alkali contents in various experimental conditions [5]

Abbreviation of sample name: four numbers indicate total alkali content - stored temperature and the last letter means the stage of expansion of initial, middle, and late. 55-38i means 5.5 kg/m³-total alkalis, stored at 38 °C and initial stage. TO: andesite, WI: hornfels, IO: limestone, FA: fly ash.

AW was applied to prevent alkali leaching during the test. Since the amount of alkali in the wrapping affects the amount of alkali in the concrete, the alkali in the wrapping at the time of core collection was determined by chemical analysis and the amount of alkali in the concrete was corrected. For the alkali balance calculation, the alkali from the cement and the alkali from the aggregate were considered. Alkali from cement was done by analyzing the composition of unreacted clinker minerals by SEM/EDS and by considering the amount of alkali sulfate. Alkali from aggregate was determined by grinding the core, separating it into coarse aggregate and mortar, and measuring the water-soluble alkali of each.

The results of the total alkali measurement are shown in Figure 5.6, and it can be seen that the total alkali content in the concrete tends to increase with AW. The estimated alkali content is underestimated in many cases. This indicates that the alkali in the ASR gel may not be measured by hot water extraction.

In the test, the alkali metal concentration in the pore water was also measured by compressive extraction of the core taken from the same specimen. The results are shown in Figure 5.7. For the non-reactive IO aggregate with a total alkali content of 5.5 kg/m^3 , the highest alkali metal concentration was 900 mM. In other experimental conditions, alkali concentration was decreased and alkali fixation was considered by aggregate or ASR gel. When the specimens of TO aggregate with 5.5 kg/m^3 total alkali content were cured at 30°C , the alkali concentration changed from 670 mM in the initial stage to 570 mM in the middle stage. It can also be observed that the alkali metal concentration was reduced by the addition of FA.

As described above, it was possible to estimate the initial total alkali content in concrete with a certain accuracy, which is important for the diagnosis of AAR, but there was a possibility of some underestimation probably due to the fixation of alkali metal ions by ASR gel formation. The measurement of alkali metal ion concentration in pore water from the collected cores may be an indicator to evaluate the possibility of continuing the AAR in the future.

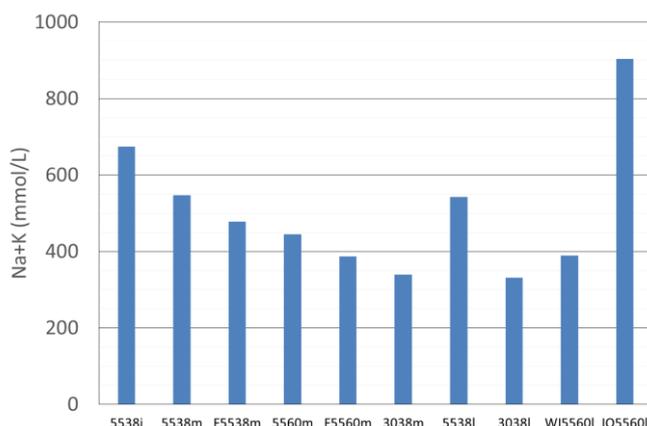


Figure 5.7: Alkali concentration extracted by pressure squeezing from cores [5]

5.5 Challenges in Accelerated Expansion Testing of Cores

Many attempts have been made to predict long-term AAR expansion behavior or final expansion by taking cores from concrete and performing some kind of accelerated expansion, and there is a comprehensive review of the results, including how they are used [43]. Comparison of core expansion with that of the original structure has also been performed. Here, cores were taken from 65 cm square cubic wet accelerated cured blocks with known history, accelerated cured by three different methods, and the results are presented to show the challenges of predicting expansion.

Two types of aggregates were used: early expansive andesite (TO) as a pessimum proportion with 30% of coarse aggregate and late expansive hornfels (WI) with 100% of coarse aggregate. High purity limestone was used as non-reactive fine aggregate and coarse aggregate. Ordinary Portland cement was used, with a water cement ratio of 50%, a unit water volume of 160 kg/m^3 , and an air volume of 4.5%. The total amount of alkali was set at 3.0 and 5.5 kg/m^3 for TO and 5.5 kg/m^3 for WI. In the following, the name of the specimen is given as TO_5.5 (TO aggregate with a total alkali content of 5.5 kg/m^3), etc., using the aggregate type and total alkali content as indicators. For curing of the specimens, after

casting, the casting surface was covered with plastic film and stored indoors for two weeks. After that, the specimens were packed with a water-holding paper containing water and plastic film, and accelerated curing was carried out in a stainless steel curing tank set at 38°C with water in the bottom. The expansion rate was measured using a contact gauge with a distance of 20 cm between the test points. The installation of the test specimens is shown in Figure 5.8.



(a) Placing of block in a humid chamber



(b) Placed concrete blocks

Figure 5.8 Curing of concrete blocks in humid chambers [5]

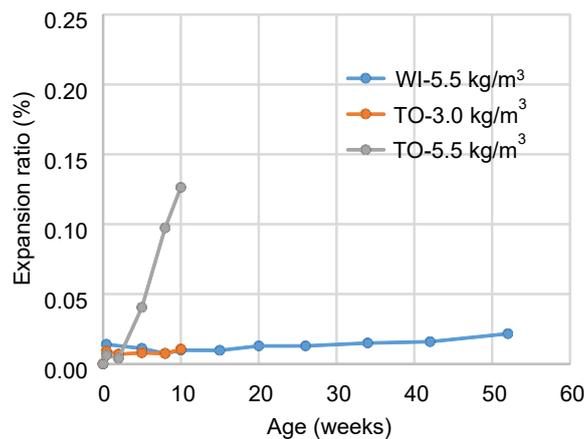


Figure 5.9: Expansion behaviours of concrete blocks [5]

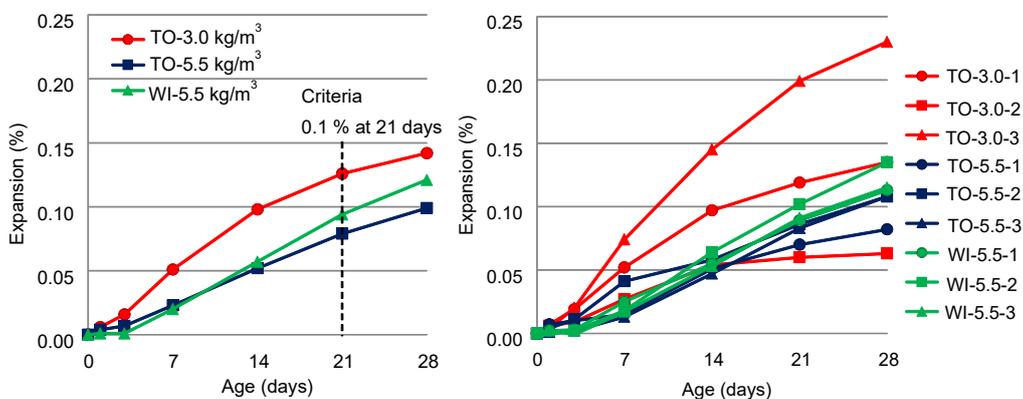


Figure 5.10: Average expansion behaviors of cores in 1M-NaOH solution at 80 °C. Left: average of 3 cores, right: individual cores [5]

Figure 5.9 shows the change in expansion rate of the unconfined specimens. For the other levels, no significant expansion was observed. As the saturated expansion coefficient of this concrete is 0.2-0.3% in AW-CPT, cores were taken at the age of 10 weeks to investigate the residual expansion from the expansion process. 52-week-old cores were taken for WI_5.5 because of its late expansive and the time required for expansion.

Figure 5.10 shows the change in expansion rate of the accelerated expansion test using Katayama's method of curing 5 cm diameter cores in 1 M NaOH solution at 80°C [43]. The average value of Figure 5.10 left shows the expansion behavior including TO-3.0 and WI-5.5, which did not show expansion in the block. In the original paper [43], the criterion was 0.1% at 21 days of age, but TO-5.5 showed the least expansion at 0.08%. In this test, three cores were used, and the expansion of each core is shown in Figure 5.10 right. the variation of the expansion of each of the three cores in TO-3.3 is large, which may be due to the small size of the specimen in concrete with a small percentage of reactive aggregate.

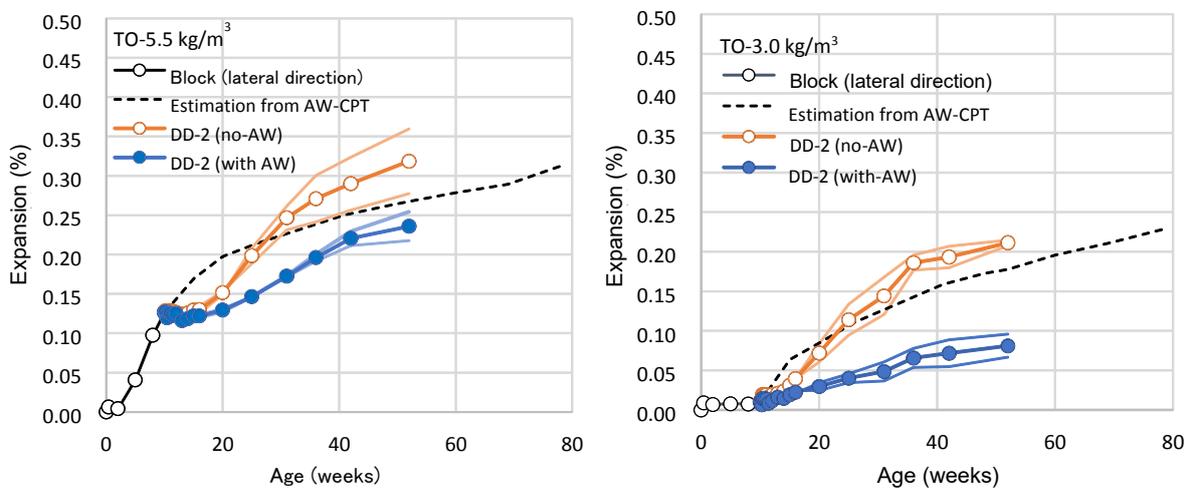


Figure 5.11: Expansion behaviours of cores stored in a humid chamber with/without AW [5]

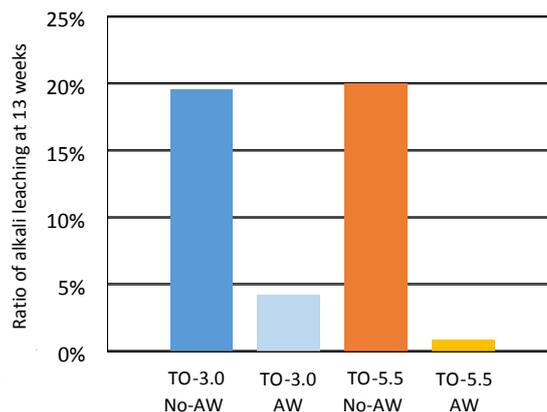


Figure 5.12: Alkali leaching of cores after storage in a humid chamber with/without AW [5]

Figure 5.11 shows the expansion behavior of TO-3.0 and TO5.5 in AW-CPT at 38°C, which was performed separately on the same concrete, and the expansion behavior of 10 cm diameter cores cured in a wet air environment at 38°C [45]. The curing was done level by level in a different closed container with water at the bottom. The tests were conducted with and without AW cores. Characteristically, the expansion was stagnant for about 5 weeks after the cores were taken, and then it started. Independent of the total alkali content, the expansion was smaller in the case of AW. The general trends of measurement were similar to those of AW-CPT conducted separately.

Figure 5.12 shows the results of measuring the amount of alkali leached from the water at the bottom of the container after the test was completed. Without AW, 20 % of total alkali was leached regardless of the total alkali content but by AW, the leaching was suppressed lower than 4 %.

The less accelerated expansion of the core is thought to be due to the fact that the core extraction results in the cutting of coarse aggregate with a maximum dimension of 20 mm, and the ASR gel accumulated in the aggregate is lost from the system without contributing to the expansion. This may be the reason why it takes several weeks after core collection before the core shows expansion again. Alkali leaching also occurred during curing in the wet air environment. It is not clear why the expansion rate is greater without AW, but it is possible that there was enough water in the core without AW, since the accelerated expansion was performed on a core taken from a concrete block that was completely wet in this test. This may be the reason why the expansion rate became smaller in AW. The fact that AW made it easier for the ASR gel to flow out of the cut aggregate on the surface of the specimen may be the reason why the expansion rate became smaller with AW.

6. COMPREHENSIVE MANAGEMENT FLOW OF CONCRETE STRUCTURES RELATED TO AAR

6.1 Limitations of Diagnosis

Various suppression measures have been proposed [46], but unfortunately nothing is certain. As a new idea, the carbonation of cement paste not only decreases the alkalinity of pore water, but also adsorbs alkali metal ions as shown in Figure 4.3 by ion exchange [47], and this reaction can be actively used to reduce the alkali concentration in concrete pores, which may suppress AAR [48]. When fully carbonated, all Al becomes IV-coordinated and becomes amorphous aluminosilicate, which is considered as a geopolymer, equimolar amount of alkali is adsorbed with the contained Al. 5.5 mass% of Al_2O_3 in OPC means that 3.3 mass% is fixed by Na_2O . Using this property, consider a hypothetical situation in which a concrete structure is drilled and carbonated from there. 1cm hole is drilled in a 20cm square cross section, and the hole is forcibly carbonated with highly concentrated CO_2 gas up to 5cm from the hole. Assume that the alkali concentration of the original cement is 1.8%, the unit cement volume is 300 kg/m^3 , the water-cement ratio is 50% (total alkali volume 5.4 kg/m^3), and the carbonated paste contains 3.3% alkali metal concentration. The concentration of alkali metals in the carbonated paste reduces the alkali concentration in the cement to 1.0% (total alkali content 3.1 kg/m^3). This is equivalent to the effect of adding about 15% siliceous FA.

As long as there is no certainty about the suppression effect, the meaning of diagnosis using cores must be said to be limited. It is doubtful that it is meaningful to conduct a detailed diagnosis of all piers of a bridge constructed at the same time. Furthermore, the performance of concrete structures deteriorates when cores are taken. Therefore, from the standpoint of concrete structure management, core extraction should be avoided as much as possible.

If the deterioration is significant both in appearance and in displacement measurement, it is desirable to take cores for future prediction. This is because it is necessary to inspect the load bearing capacity of the structure and also to consider the replacement of the structure itself. Even in this case, core collection should be kept to a minimum. The purpose is to collect information for management purposes, not for AAR studies.

6.2 A Proposed Diagnostic Flow

A diagnostic flow combining the above ideas and various technologies was proposed in the aforementioned project. The flow is shown in Figure 6.1.

If the deformation is minor, A. Simple evaluation route shall be taken, and the scope shall be (1) daily inspection, (2) investigation of existing records, and (3) field survey. If there are clear alterations, B. Normal evaluation route should be taken. After A, (4) visual observation of the core (development photograph, stereomicroscope observation, fluorescence method for microcracks detection) should be conducted to clarify the possibility of ASR. At this point, instead of proceeding to petrographic diagnosis, accelerated expansion tests and porewater analysis of the core were conducted to investigate the possibility of future swelling, with the option of taking countermeasures without detailed investigation. In

addition, only when degradation is significant and detailed information is required, the C. Detailed evaluation route is used. After B, (5) petrographic evaluation (naked eye and stereomicroscope) → (6) petrographic evaluation (thin section scanner, polarized light microscopy observation, powder X-ray diffraction) → (7) rock types and compositional quantification → (8) ASR gel observation and compositional analysis (SEM observation/EDS analysis) → (9) Evaluation of the cause of ASR and the degree of damage to identify the cause of AAR, to take countermeasures, and to provide reference data for future new construction.

6.3 A Proposal of Management Flow

Figure 6.1 shows the ASR diagnosis, but the prediction of expansion after diagnosis and the appraisal of the effect on structural performance are important for the management of structures. A proposal to this flow is shown in Figure 6.2. The flow on the left side of the figure starts with periodic inspection, followed by deformation and environmental monitoring, deterioration diagnosis by detailed inspection including mechanical and petrographic diagnosis, and then future prediction, structural performance evaluation, and future soundness evaluation. There are individual test methods and evaluation methods used in this process, and these are still under study. The methods and the factors to be considered in the methods are shown on the right side of Figure 6.2. It is necessary to conduct reliable experiments to compare expansion in the laboratory and in the real environment, accelerated tests using cores from the structure, future predictions based on the expansion mechanism using ASR based on these tests, separate experiments and numerical analysis for expansion and structural performance in the structure, and advanced technology for numerical calculations that take into account expansion prediction and the effect on structural performance at the same time. In addition, advanced technology for numerical calculations that simultaneously consider expansion prediction and its effect on structural performance is needed.

7. SUMMARY

This review paper summarizes the current issues in the management of structures related to AAR from the viewpoint of various stakeholders. The management of structures related to AAR involves the steps of AAR diagnosis, expansion prediction, structural performance evaluation, and comprehensive judgment, and involves various engineers. First, a questionnaire survey was conducted among various engineers involved in AAR diagnosis, and it was found that the current AAR control measures are generally considered effective, that more precise measures are required for important structures, that AAR diagnosis is not difficult for specialists, and that petrographic diagnosis and residual expansion tests are often conducted. The gap between petrographic diagnosis and prediction of structural performance was also pointed out.

The individual techniques are described in detail in several recent books. Although reactive aggregates are the root cause of AAR, there is a limit to testing aggregates alone, and it is necessary to test them as concrete. It was shown that even the concrete prism test can be a performance test only after taking into account alkali leaching, inadequate water supply, and various pessimum phenomena, due to the inherent uncertainty of the test method.

In order to estimate the behavior in the real environment from the results of laboratory tests, in addition to the effects of temperature and rainfall, alkali leaching from the concrete surface needs to be taken into account. Then, individual information necessary for general engineers to interpret the results of petrographic diagnosis was summarized. Examples of observation of the dissolution of reactive silica, the concept of the suppression effect of SCMs, an example of confirming the accuracy of alkali balance estimation, and the challenges of accelerated expansion testing of cores are discussed.

Finally, a comprehensive management flow for the AAR of concrete in nuclear facilities in Japan is presented. In the diagnostic flow, visual inspection should be continued and core sampling is not recommended as long as no significant deterioration is observed, because there are no reliable measures for structures with deteriorated AAR, damage to structures by core sampling should be avoided whenever possible, and petrographic diagnosis is expensive. In addition to this diagnostic flow, a comprehensive management flow was proposed by combining it with elemental technologies such as future prediction of expansion by accelerated expansion testing of cores, alkali content estimation, and structural performance evaluation.

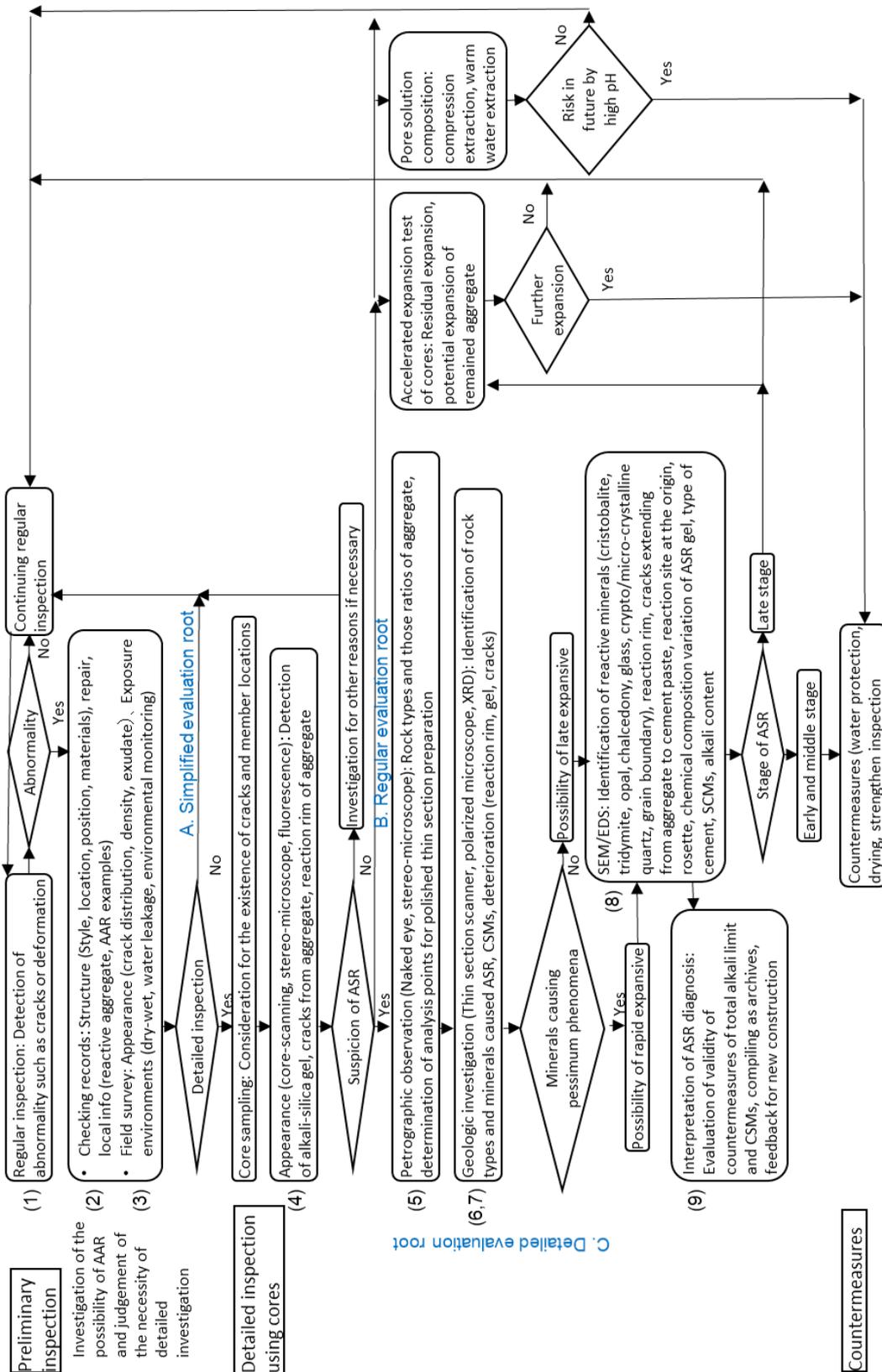


Figure 6.1: Proposed flow of AAR diagnosis (modified from [5])

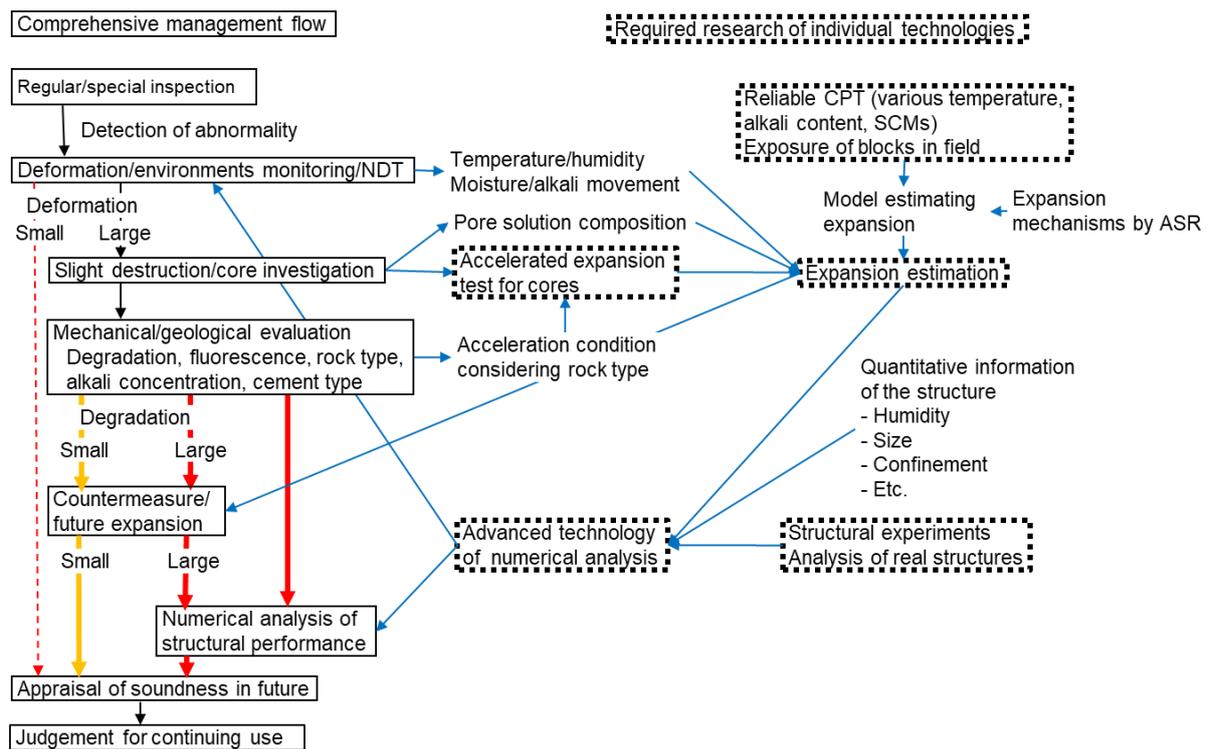


Figure 6.2: Proposed flow for structural management (modified from [5])

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