- Technical Paper -

DEF-INDUCED ANISOTROPY AND EXPANSIVE ENERGY OF CONCRETE UNDER UNI-AXIAL RESTRAINT

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ABSTRACT

This study investigates the anisotropic expansion of concrete affected by Delayed Ettringite Formation (DEF) under uniaxial restraint conditions. Utilizing a device designed to impose varying levels of restraint, the research examines concrete samples with rebar ratios of 0%, 0.75%, 1.34%, and 2.10%. The anisotropic characteristics of expansive behavior was also evaluated, and the study uniquely employs expansive energy as a key metric to analyze the expansive potential, providing valuable insights into the influence of uniaxial restraint on DEF-affected concrete.

Keywords: delayed ettringite formation, uni-axial restraint, anisotropic expansion, expansive energy

1. INTRODUCTION

Delayed Ettringite Formation (DEF) is a deterioration that occurs in hardened concrete structures, characterized by the growth of ettringite, leading to expansion, and cracking of concrete, and affecting durability and serviceability of structures [1]. The combinations of cement and high-temperature curing can usually be considered as the reasons for leading to DEF. Alkali Silica Reaction (ASR) is also well known as a kind of concrete deterioration due to internal expansion. The microscope mechanisms of expansion due to DEF and ASR are different from each other, however, the expansion due to ASR or DEF under stress-free condition can be considered as isotropy. Both can lead to some degradation problems of concrete such as cracking of concrete and deterioration of mechanical properties of concrete. The internal and external restraints have been proven to be effective in suppressing expansion induced by ASR. Some researchers have experimentally investigated how the restraint works on expansion and cracking of concrete under several restraint forms and levels [2,3]. The anisotropy of swelling due to restraint on DEF-affected concrete was also well-studied. However, many researchers have pointed out that no “expansion transfer”, which is sometimes suggested for ASR, occurs in the DEF case. Volumetric expansion would be an important parameter to quantitatively assess the anisotropic expansion due to DEF.

Until now, there have been fewer studies on anisotropic expansive models on concrete affected by DEF under uni-axial restraint. The expansive energy was well studied in the field of expansive agent. And it shares a similar chemical mechanism with DEF. It may be feasible to apply on restrained DEF case and predict the final expansive behavior under uniaxial restraint by considering the expansion energies involved. Up to now there is no such study regarding expansive energy in restrained concrete affected by DEF according to the author's knowledge. This paper mainly discussed the anisotropic swelling phenomenon and the expansive energy of concrete degraded by DEF under different levels of uniaxial restraint.

2. RESEARCH DETAILS

2.1 Materials

Table 1 shows the mixture proportion of this study, the water to cement ratio was set to 0.5 and the water content is 174kg/m^3. High early strength Portland cement (Type Ⅲ Portland cement / JIS R 5210:2009), in which SO_3 contents were 3.06% of the mass of cement, was employed. The K_2SO_4 at a dose of 7.27 kg/m^3 was added into the concrete as a liquid form, which increases sulfate content to 4.0% of the mass of cement, to accelerate the DEF process. Non-reactive fine and coarse aggregates were used to avoid ASR expansion.

2.2 Loading Method

Experiment was performed on prismatic specimens (100×100×400 mm) under restraint devices and cylindrical specimens (ϕ100 × 200 mm). Fig. 1 shows the specimen with uni-axial restraint device.

Table 1 Mixture of concrete (kg/m^3)

Component	
Cement	348
Water	174
Fine aggregate	777
Coarse aggregate	963
K_2SO_4	7.27

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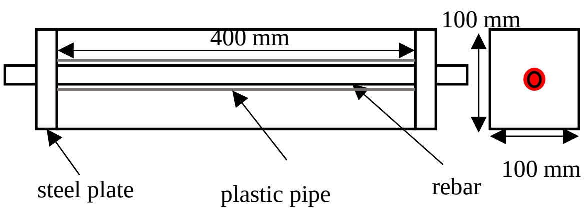


Fig.1 Outline of rectangular specimens

The restraint device consists of rebar and two steel plates with a thickness of 10 mm. The steel plates and rebar are well welded together to form the restraint system to completely avoid steel plate displacement during expansion. A PVC pipe of 26mm diameter was used to cover the rebar throughout the expansion experiment so that the rebar cannot contact the concrete directly. This will exclude the interaction between the rebar and the concrete. Three kinds of reinforcement, D10, D13, and D16, were used in this study to investigate the effect on anisotropic expansion. The reinforcement ratio to the concrete section except the area of the PVC pipe (As/Ac) are 0.75%, 1.34%, and 2.10% respectively. It is noted that the concrete directly contacts with steel plates at both ends which might affect transverse expansion there.

3, 2, 3 and 2 prismatic specimens were prepared corresponding D10, D13, and D16 and stress-free specimens to evaluate the effect of different levels of restraint. The cylindrical specimens were used to evaluate the stress-free expansion and mechanical properties in this study.

2.3 Curing condition

In this study, hot water curing was conducted for the initial heat curing process. In 8 hours after casting, all specimens were cured in their mold, covered with plastic film and placed in a room where maintain humidity of 60%, 20 degree Celsius. This step was crucial to ensure the concrete attained sufficient strength to prevent damage when demolding. And then all specimens were demolded and transferred to a sink equipped with automatic temperature control. The history of temperature obtained from a sensor placed inside concrete was shown in Fig. 2: increase the temperature from approximately 30℃ to 80℃ in 2 hours, and maintain for 12 h, and then gradually reduce it back to 20°C in 24 hours. Following this, all specimens were relocated to a water-filled container. No special treatment to avoid corrosion was implemented to the restraint devices. All specimens have always been kept together to ensure the prismatic and cylindrical specimens meet the same condition.

2.4 Expansion measurement

Expansion measurements were carried out with an extensometer between stainless steel studs. The measurement range of the extensometer is 100 ± 5 mm. In this study, the width of prismatic specimens is 100mm, was nearly equal to the measurement range. This led to the transverse strain is difficult to measure directly because it was not possible to glue the studs within only 100mm. Thus, two other measurements were made

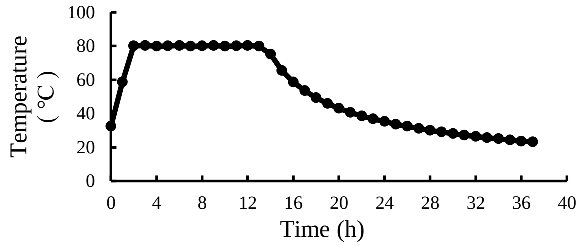


Fig. 2 History of high-temperature curing

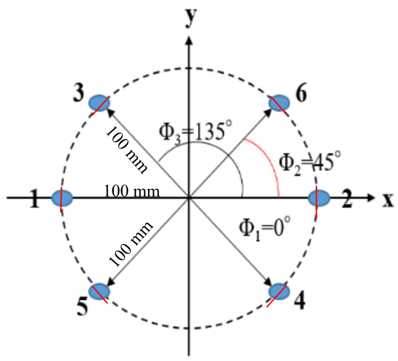


Fig. 3 Arrangement of measurement studs

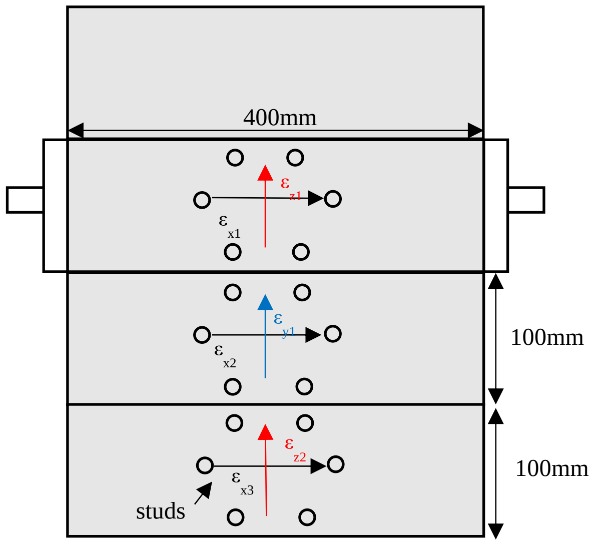


Fig. 4 Studs groups

except the longitudinal direction, one along the direction forming angle of 45° with the longitudinal direction and another one forming the angle of 135°, which is shown in Fig. 3. This arrangement of studs was also used in the experimental study of Thiebaut [4]. The transverse expansion strain could be assessed by the concept of the strain rosette using the expansion strain along three directions with this type of stud arrangement. It is important to note that the transverse expansion strain is a calculated value derived from three separate strains. When considering this value, it is crucial to account for potential errors in calculation and the impact of forming angles. The studs glued on the central region of 3 surfaces of prismatic specimens, the outline of the studs group is shown in Fig.4. In this study, the transverse strain encompasses ε_{z1}, ε_{z2}, and ε_{y1}, which calculated from three surface. The longitudinal strain is strain from directly measured strain on the surface 1, 2 and 3.

3. RESULTS

3.1 Stress free expansion

The stress-free expansions were measured from the cylindrical and prismatic specimens. The relationship between expansion and aging time is illustrated in Fig. 5, which combined the results of the cylindrical specimens and prismatic specimens. Figure 5 shows the average longitudinal and transverse strains for stress-free expansion of prismatic specimens. The error bar presents the standard deviation. In this figure, the mean value obtained from the three cylindrical specimens is also incorporated as a reference. The longitudinal and transverse strains of each prismatic specimen are the mean values of the measured strain explained before and calculated by Eq. 1.

$$\varepsilon_{lg} = \frac{\varepsilon_{x1} + \varepsilon_{x2} + \varepsilon_{x3}}{3}$$
$$\varepsilon_{tr} = \frac{\varepsilon_{z1} + \varepsilon_{z2} + \varepsilon_{y1}}{3} \qquad (1)$$

In this figure, the blue and orange lines represent the longitudinal and transverse expansion under stress-free condition. These two lines are developing almost in same, which illustrates the DEF-induced expansion can be considered as isotropic. Moreover, the stress-free expansion of prismatic specimens tends to be roughly the same as cylinders. The final expansion is marginally greater than those of the cylinders, which are 5500μ and mean value of cylinders is 4700μ. The curing condition for prismatic and cylinders is the same.

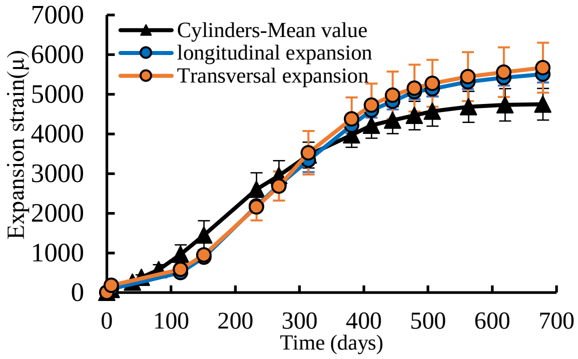


Fig. 5 Stress-free expansion

3.2 Expansion under restraint

The expansive behavior in the longitudinal direction looks significantly influenced by the restraint, as demonstrated in Fig. 6(a). In the figure, square markers indicate the longitudinal expansion of stress-free specimens. Triangle markers represent the expansion strain under D16 restraint, rhombus markers denote the strain under D13 restraint, and circle markers correspond to the longitudinal expansion strain of D10 restrained specimens. The final longitudinal expansion for the restrained concrete, correspond to D10, D13, and D16, was 1900μ, 1500μ, and 1100μ, respectively. This represents a decrease of 65%, 72%, and 80% in comparison to the free expansion in the longitudinal direction. The findings indicate that the expansion of concrete is significantly impacted by the application of restraint. The trend of reduction in comparison to the free expansion suggests that the degree of restraint play a crucial role in determining the extent of concrete expansion.

The transverse expansion, as shown in Fig. 6(b), which was considerably less than free expansion in the transverse direction. The different markers in different colors represents the same meaning with Fig. 6(a). It shows a reduction of 15–32% regardless of the degree of restraint. At the 679 day the average transverse strains for specimens under D10, D13, and D16 restraints were 4300μ, 4800μ, and 3900μ, respectively. In this experiment, the concrete was in direct contact with steel plates at both ends. A possible explanation for this diminished expansion could be the influence of friction between the steel plates used for restraint and the concrete specimen, which could affect the transverse expansion. A similar result was obtained by a literature [4]. In that test, a reduction ranging from 20% to 32% in transverse expansion was observed under different levels of restraint, compared to the stress-free expansion. The levels of restraint in that test are 0.75%, 1.5%, 2.56% and 5.98%. However, the restraint levels for this experiment are 0.75%, 1.34%, and 2.10%. The analysis and comparison were conducted for a stable phase of expansion.

4. DISCUSSIONS

4.1 Anisotropy of expansion

Figure 7 illustrates the relationship between

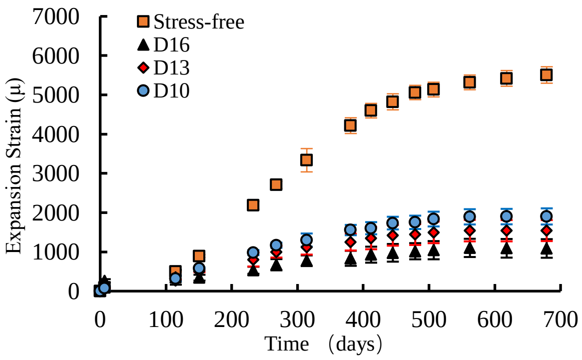


Fig. 6 (a) Longitudinal expansion

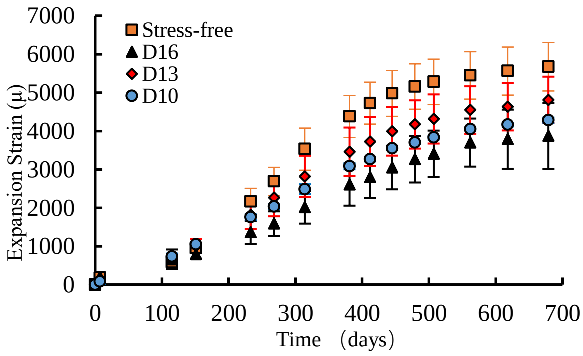


Fig. 6 (b) Transverse expansion

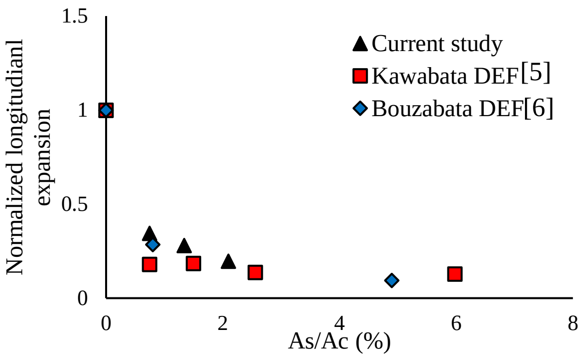


Fig. 7 Expansive behavior under restraint

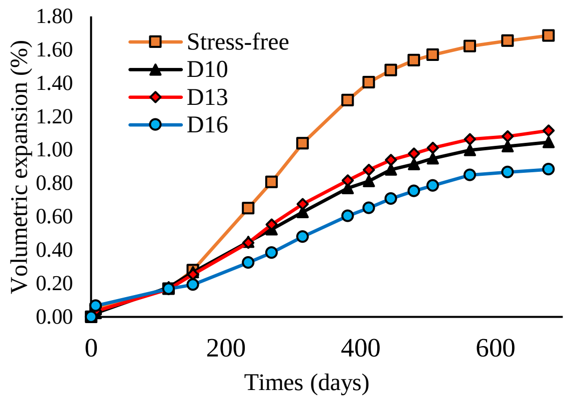


Fig. 9 Volumetric expansion

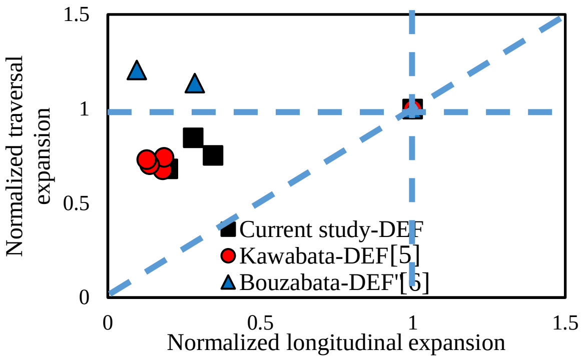


Fig. 8(a) Anisotropic expansion in DEF cases

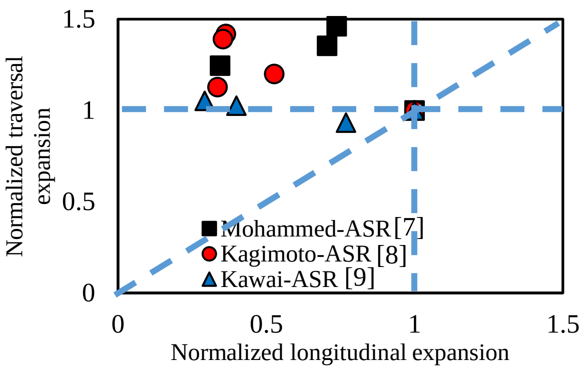


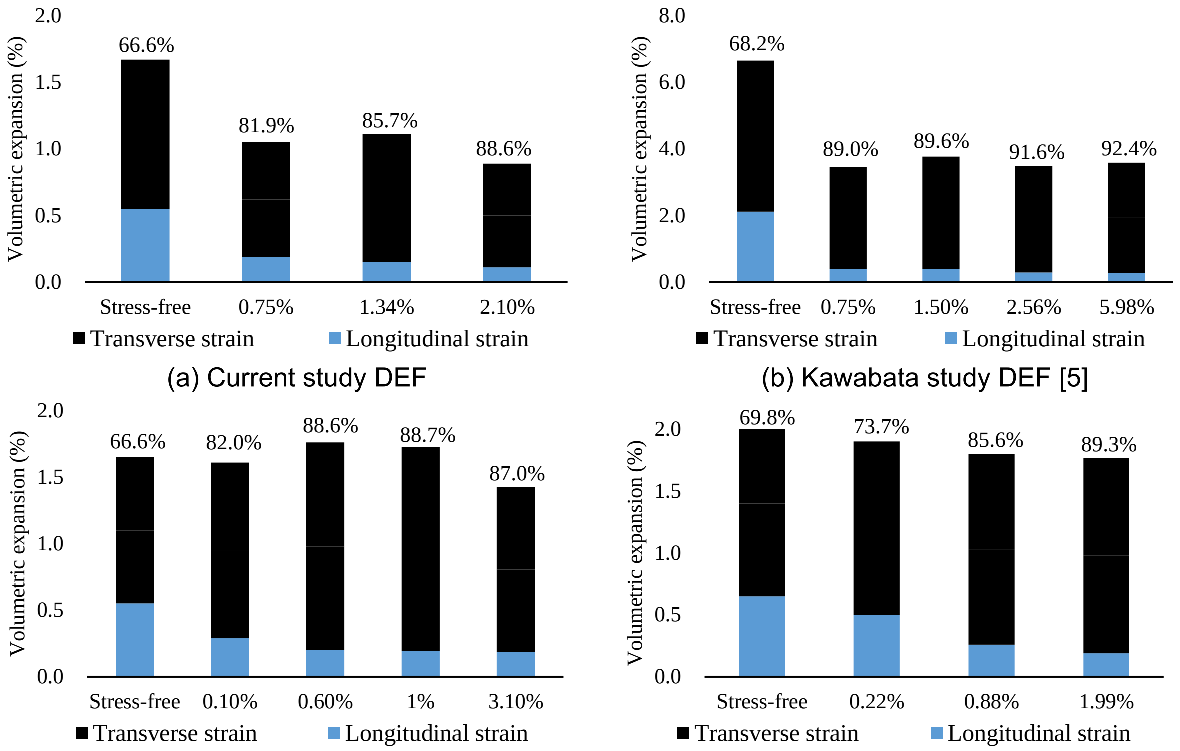
Fig. 8(b) Anisotropic expansion in ASR cases

normalized expansion strain in the longitudinal direction and rebar ratio under uni-axial restraint condition. The x-axis represents the rebar ratio, while the y-axis displays the expansion strain, normalized by the strain observed in longitudinal direction under stress-free expansion conditions. In this figure, various markers signify different studies. Black triangle shows the results of current study, while square markers in red color denotes the study of Kawabata. Rhombus-shaped markers in blue colors illustrates the result of Bouzabata. All studies focus on the DEF case. In the figure, all longitudinal expansion decreased as As/Ac increased in the current study and reference. We could observe a rapid decline and gradual stabilization. A significant effect on longitudinal expansion induced by DEF due to the application of longitudinal restraint is evident.

Figure 8 demonstrates the correlation between normalized longitudinal expansion and normalized transverse expansion. Here, 'normalized' refers to the expansion under various levels of restraint, with each value normalized by the corresponding stress-free expansion in the same direction. Markers in different colors represent results obtained from this study and other research. From this representation, it is observable that the anisotropy, or the directional difference in expansion behavior due to the anisotropic restraint, varies significantly between the ASR and DEF cases. The Fig.8 (a) presents the DEF cases, while Fig.8 (b) focus on the ASR cases. The longitudinal expansion induced by both ASR and DEF under restraint is significantly reduced. However, in the DEF cases, a slight reduction in expansion is observed in the transverse direction. Conversely, in the ASR cases, a noticeable increase in expansion along the unrestrained direction can be seen from Fig.8(b). This observed phenomenon, especially in DEF-affected concrete, could be attributed to the absence of "expansion transfer" in a uniaxially restrained environment. This suggests that the uniaxial restraint significantly influence the expansive behavior, resulting in different anisotropic patterns in the DEF and ASR cases.

4.2 Volumetric expansion

The volumetric expansion is calculated that combines both transverse and longitudinal expansion strains, represented as the sum of longitudinal and 2 times of transverse expansion strains. The result is expressed in percentage. As indicated in Fig. 9, the uni-restraint results in a decrease in volumetric strain compared to stress-free prismatic specimens. For stress-free specimens, the volumetric strain reaches 1.68% after 679 days of immersion. However, with uniaxial restraint, this strain reduces to 1.12% and 1.05% for the D13 and D10 restrained specimens, respectively, indicating decreases of approximately 33.3% and 37.5%. For specimens restrained with D16, the volumetric strain further declines to 0.88%, representing a decrease of about 47.6%. The observation from Fig.9 illustrates that even a small level of applied restraint can significantly influence the volumetric expansion of concrete. This is particularly noteworthy given that expansion due to DEF is typically considered to be of a much larger magnitude compared to that induced by ASR. However, it is important to note that the phenomenon of expansion



(a) Current study DEF (b) Kawabata study DEF [5]

(c) Kagimoto study ASR [8] (d) Kawai study ASR [9]

Fig.10 The volumetric expansion

transfer does not need to be considered in the case of DEF. As a result, despite the expansion occur due to DEF, the volumetric expansion behavior of concrete structures affected by DEF under restraint can be maintained at a relatively safe level.

Figure 10 illustrates the volumetric expansion and ratio of expansion along transverse and longitudinal directions for each rebar ratio, comparing findings from this study with those calculated from other research. The black portion of each bar indicates the contribution of transverse expansion to the overall volume expansion, and the numbers represent the proportion, while the blue portion represents the contribution made by longitudinal expansion. It should be attention that Fig.10 (a) and (b) are related to DEF, while Fig.10 (c) and (d) focus on ASR case. In the DEF cases, a notable reduction in expansion was observed when restraint was applied. However, a slight decrease and increase can be noted in the ASR cases. This aspect highlights the unique expansive behaviors in ASR and DEF cases. Fig.11 shows the volumetric expansion normalized by it under stress-free expansion with As/Ac increased. Regarding the volume expansion caused by ASR, it is noted that although there is an initial decrease in volume expansion under small level of restraint, this volumetric expansion tends to stabilize or increase as the levels of restraint intensifies. This behavior suggests that the ASR-induced volume expansion is somewhat unrelated to the restraints. Conversely, in cases of DEF, a different pattern emerges, characterized by a clear reduction occur when restraint was applied and a continual decrease in volumetric expansion. This contrast illustrates the distinct responses of ASR and DEF under uni-axial restrained condition.

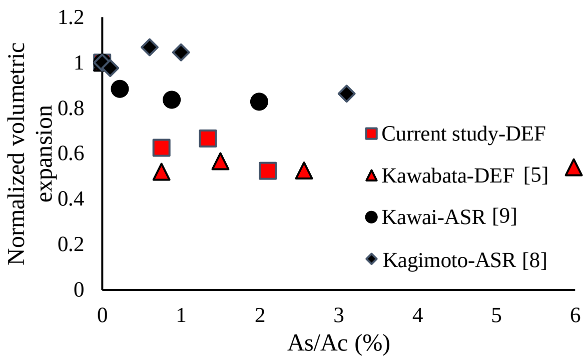


Fig. 11 Normalized volumetric expansion under restraint

4.3 Expansive energy

Expansion energy was introduced at a very early stage of research on application of expansion agent in Japan. The mechanism of expansive agent is quite similar with DEF. Thus, this research aims to evaluate the expansive energy of DEF from different levels of uni-axial restraint. Specifically, the expansive energy of concrete, when assessed uni-axial restraint condition was calculated using a defined formula [10].

$$U = \frac{\rho \cdot Es \cdot \varepsilon^2}{2} \tag{2}$$

where,

ρ : rebar ratio

E_s : Modulus of elasticity of reinforcement

This approach enables a detailed comparison and understanding of the expansive behavior of concrete under varied testing methodologies and conditions.

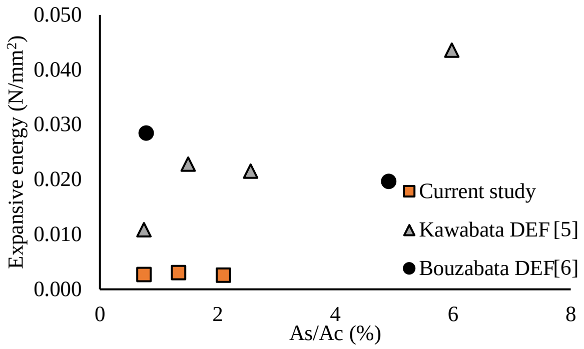


Fig. 12 Expansive energy

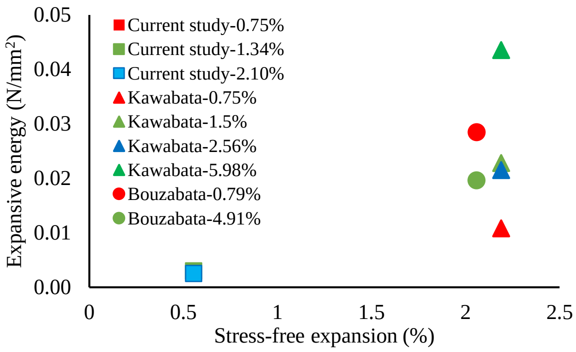


Fig. 13 Relationship between stress-free expansion and expansive energy

Figure 12 illustrates the calculated expansive energy of current study and some other researchers' expansive energy by calculated with their results. We assume the Young's modulus of reinforcement is 200 GPa for all calculation. The gray triangles represent the expansive energy in this study, and orange square markers show the results calculated from Dr. Kawabata's result, similarly black circle markers illustrate the ones of Dr. Bouzabata's result. The expansive energy calculated in the current study are relatively similar, range from 0.0025 N/mm^2 to 0.0030 N/mm^2, and the correlation between expansive energy and rebar ratio cannot be observed. The calculated expansive energy reaches 0.028 N/mm^2 when rebar ratio is 0.79% and the expansive energy further decline to 0.020 N/mm^2 with rebar ratio increased to 4.91. Fig.13 shows the relationship between stress-free expansion strain of each concrete and expansive energy. It is observable that the expansive energy calculated from the experiment shows scattering to some extent but remain at a relatively similar level with it under stress-free expansion, which indicating that this phenomenon is independent of the restraint. The stress-free expansion is governed by expansive potential which is related with specific components: the content of sulfates, aluminates, alkali concentrations, and the initial high-temperature curing because the expansion is solely attributed to the formation of new ettringite.

5 CONCLUSIONS

We discussed the anisotropic expansive behavior of concrete affected by delayed ettringite formation under uni-axial restraint. The conclusion can be made as followings:

(1) The DEF-induced expansion under stress-free condition is isotropic. However, the expansion shows anisotropy even if a small restraint exists. Uniaxial restraint significantly influences the expansive behavior especially change the anisotropy as restraint levels increased.

(2) The anisotropy of DEF shows a different trend compared to one of ASR. Some decrease in expansion along unrestrained direction was obtained for DEF, however some increase for ASR. The volumetric expansion decreased even if under uni-axil restraint in DEF.

(3) The expansive energy has some relationship with the stress-free expansion, which is one of index of the expansive potential. It might depend on some index such as content of sulfate and initial high temperature curing history.

ACKNOWLEDGEMENT

The authors acknowledge the efforts of students in Composite Materials and Structures Laboratory and the financial supports by JSPS KAKENHI (20K04650).

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