- Technical Paper -

Impacts of Delayed Ettringite Formation on Expansive behavior and Shear Capacity of RC beams

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ABSTRACT

This study investigated on the deformation of RC beams due to Delayed Ettringite Formation (DEF) and their shear capacity degradation. RC beams with different reinforcement ratio, 1.14% and 2.03%, were tested. Because of the rebar restraint, anisotropic DEF swelling phenomenon in RC beams occurred so that warping deformation was observed, and its warping level was related to reinforcement ratio. And as a result of flexural-shear tests, significant decrease of shear capacity was observed, and these results provided insights into structural performances of DEF damaged RC beams.

Keywords: delayed ettringite formation, restraint of rebar, warping deformation, diagonal shear failure

1. INTRODUCTION

Delayed Ettringite Formation (DEF) is an endogenous chemical reaction occurring in structures, leading to expansion of concrete itself and affect durability and serviceability of structures [1]. Alkali Silica Reaction (ASR) is also well known as a kind of concrete deterioration due to internal expansion. As DEF and ASR show similar phenomenon in terms of swelling of concrete, they are often collectively called as Internal Swelling Reactions (ISR). Although the mechanisms of swelling of DEF and ASR are different with each other [2], some aspects occurred in concrete is similar, such as crack initiation and deterioration of mechanical properties of concrete. Some researchers have pointed out that DEF has usually more serious impacts on mechanical properties than ASR because the magnitude of DEF expansion is larger than ASR one [3]. Moreover, DEF expansion come directly from a cement hydrate so that the gaps occurred between mortal and aggregate, and they would lead durability problems [4].

Many researchers have already studied the mechanism of DEF expansion [5] as well as ASR one. For ASR, expansion decreased due to the restraint such as reinforcement and the effects have been investigated in past three decades [6]. However, only few researchers have discussed the effect of restraint on DEF expansion.

For RC structures, the location of reinforcement can be considered as a kind of inhomogeneous restraint and their impacts often result in unexpected deformation. Moreover, these deteriorated structures sometimes had been worried about safety problems. Then, many researchers have conducted the structural experiments for RC members deteriorated by ASR, and their performances have been clarified to some extent. However, for DEF, fewer studies on structural aspects were performed. However, the effect on the structure's mechanical properties due to only the deterioration of DEF was unknown.

This paper aims to investigate on the deformation of RC beams due to DEF swelling and its impact on structural performances of deteriorated RC beams. In this study, DEF induced expansion was measured and flexural-shear loading tests were conducted for two RC beams with different reinforcement ratio and their results were discussed.

2. EXPERIMENTAL DETAILS

2.1 Specimens

In addition to investigating the mechanical properties of the concrete affected by DEF, it is important to assess on the structural performance of the DEF-deteriorated structures. Two types of RC beams with D10 and D13 of longitudinal steel reinforcements were prepared. The size of the beam is that 100mm of width, 150mm of height and 800mm of length. The reinforcing bars were arranged at bottom side to keep 20mm of cover thickness so that their reinforcement ratio become 1.14% and 2.03%, respectively for D10 and D13. These specimens were named D10 and D13 DEF beam and D10 and D13 NC beam.

The 3 cylindrical specimens with Φ100×200 mm for each concrete were also casted for studying the mechanical properties and free expansion amount. These specimens were named DEF 1-3 and NC 1-3, respectively.

2.2 Materials

Experiments were performed on the concrete with a water/cement radio of 0.4 and a cement content of 425 kg/m^3 as shown in Table 1. High early strength Portland Cement (Type III Portland Cement / JIS R 5210:2009), in which SO_3 contents was 3.06% of mass of cement,

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was used in this study. K_2SO_4 at a dose of 4.25kg/m^3 of concrete was added into the concrete as a powder form, which increase SO_3 contents to 3.5% of mass of cement, to accelerate the DEF process.

The specimens without K_2SO_4 addition were casted to highlight the difference of structural performance degradation between the sound RC beams and RC beams affected by DEF.

2.3 Curing and storage conditions

All specimens were casted in metal molds. After casting, they were covered by watertight plastic film and cured in a room with the room-temperature environment for 8 hours, and then all specimens were demolded and moved into a thermostatic sink filled with water to begin the heat treat presented in Fig.1: an increase from 25°C to 80°C in 2 hours, a sustained heating at 80°C for 13 hours then a decrease from 80°C to 25°C in 9 hours. All specimens placed in the full water thermostatic sink to prevent the drying in early age and the possibility of uneven heating. After cooling, the specimens were placed in the full-water container to prevent drying in the early age for 7 days, and then the specimens were moved to dry condition in a room keeping at 20°C and 60% RH for 141 days. After that, all specimens began to cure in the water. Such long terms duration of storage in the air, may result in the large initial cracks due to drying shrinkage created, providing precipitation sites for delayed ettringite.

2.4 Measurement

Expansions of RC beams were measured on the surface of concrete. Measurement was performed with an extensometer between stainless steel studs stuck on the specimens affected by DEF. The precision of the measurement devices was 0.001 mm. The expansion was then calculated by dividing the change in length by the gauge length. Expansive strains were measured in a longitudinal direction at upper, middle and bottom positions, and one in a vertical direction. The abbreviated names are "L-U", "L-M", "L-B" and "V". In order to understand the influence of different parts of the warping, the 12 measured range were divided into three regions: left, middle and right as shown in Fig.2. Fig2(b) present the specific measured ranges of one region. To reduce the influence of human error, each measurement range was measured 10 times and the mean value and standard deviation were calculated. All specimens were placed in the same container filled with water of 20°C. In this study, the water in the container was replenished immediately after measuring the length change to prevent shrinkage cracks caused by water loss.

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

Component	
Cement	425
Water	170
Fine aggregate	707
Coarse aggregate	976
K_2SO_4	4.25

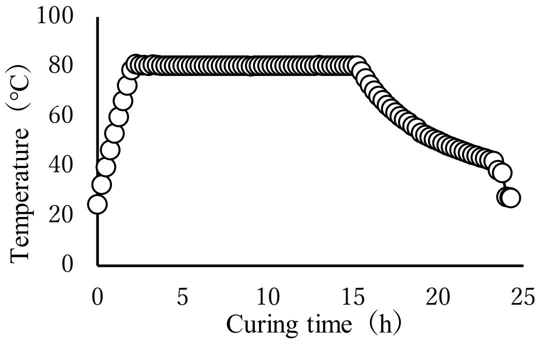


Fig.1 Temperature history

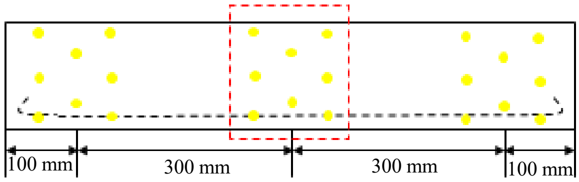


Fig.2(a) Measurement studs

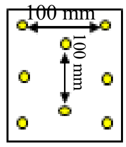


Fig.2(b) Studs group

Fig.2 Arrangement of studs of measured regions

3. EXPANSION

3.1 Expansion of concrete

Fig.3 indicates the expansion behavior of cylindrical specimens. It demonstrated the relationship between expansion development and time of concrete affected by DEF without any influence. This expansion strain of cylindrical specimens can be generally seen as stress-free expansion strain. The expansion strain of three cylindrical specimens were 3.02%, 2.89% and 3.09% respectively. In general, this relationship can be considered as the expansion potential of this batch of concrete.

Fig.4 shows the expansion strain in the vertical direction of RC beams and cylinder specimens. Generally in the RC beams specimen, only the position of "V" which is perpendicular to the restraint direction can regard as ignoring the effects of restraint. Thus, the expansion strain can be seen as stress-free expansion of RC beams. In the Fig.4, the blue line presents the mean stress-free expansion strain measured in three regions of D10 RC beam. Similar to the blue line, the red one indicates the average free strain of the D13 RC beam. The final expansion strain was 2.40% and 2.31% for D10 and D13 specimens, respectively. And the mean final free expansion of cylindrical specimens was 3.00% showed as black line in the Fig.4. Due to the difference in the dimension of specimens, the expansion strain of RC beams was slightly less than it in the cylinder specimens. Some researchers [2] pointed out the dimension differences may lead to the effect of water absorption and alkali leaching which are key factor of DEF expansion.

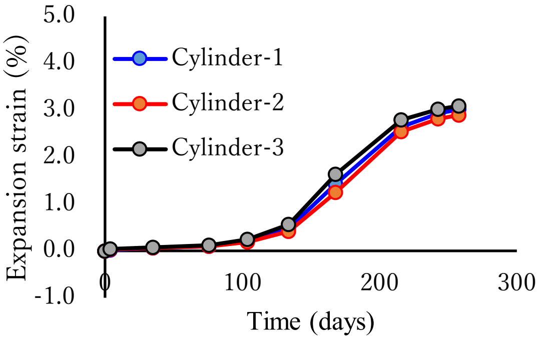


Fig.3 Expansion strain of cylinder specimens

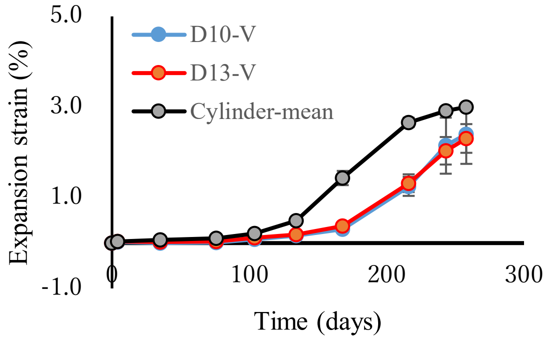
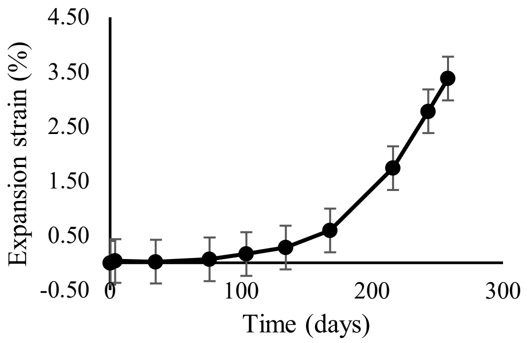


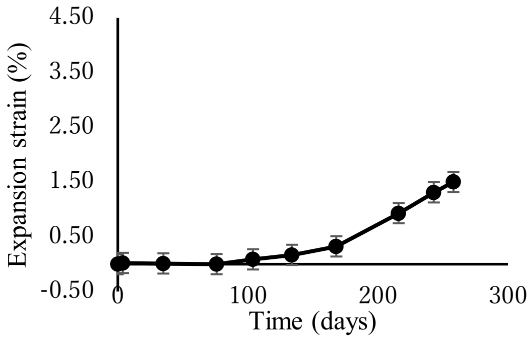
Fig.4 Comparison of expansion strain

As described in section 2.4, another 9 positions in the longitudinal direction were measured and the results were calculated to the mean and were indicated in Fig.5 and Fig.6. The error bar in these figures represented the standard deviation. For D10 specimens, the final expansion of longitudinal direction at the bottom position was 0.24%, and the final expansion of longitudinal direction at the middle position was 1.50%.

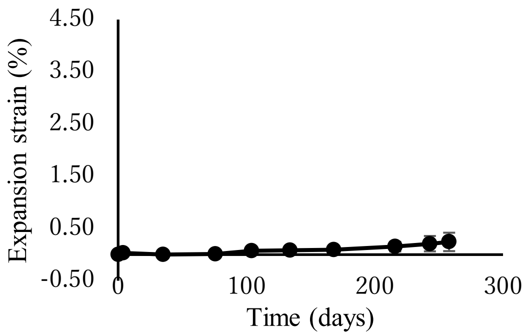
Whilst, for D13 specimens, the final expansion of longitudinal direction at the bottom position was only 0.40% at 258 days, the final expansion of longitudinal direction at the middle position was 1.42%. Longitudinal



(a) Upper side in the longitudinal direction

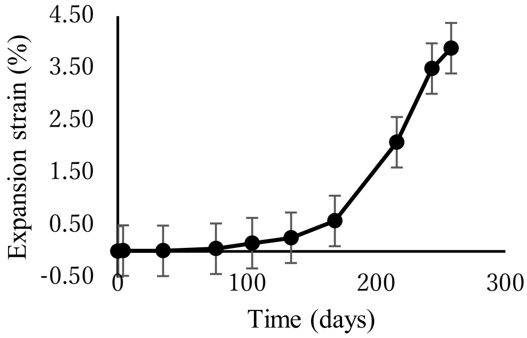


(b) Middle side in the longitudinal direction

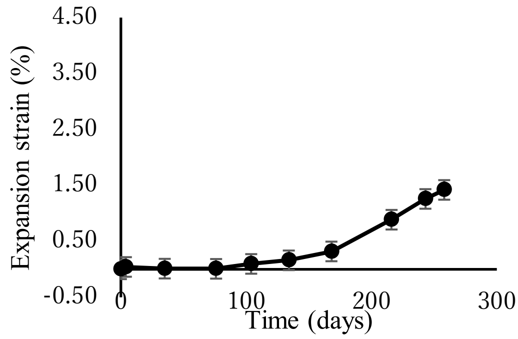


(c) Bottom side in the longitudinal

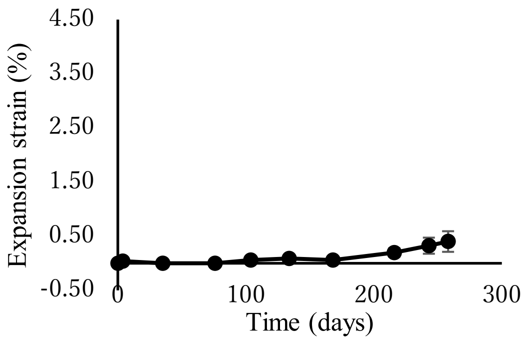
Fig.5 Expansion of D10 specimen in the three longitudinal positions



(a) Upper side in the longitudinal direction



(b) Middle side in the longitudinal direction



(c) Bottom side in the longitudinal

Fig.6 Expansion of D13 specimen in the three longitudinal positions expansion of at upper position in D10 and D13 specimens are 3.38% and 3.89% respectively. Compared to the stress-free expansion, vertical strain, of RC beams, the longitudinal expansion at the bottom position drastically decreased due to the rebar restrained. It shows a large effect on expansion in the restrained position

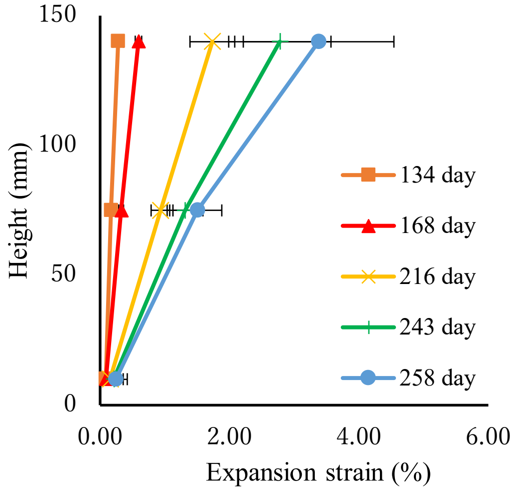
From the figures, similar effect on expansion strain occurred, regardless of the diameter of reinforcement used. It can be observed the expansion amount at the upper position is significantly bigger than other position. The expansion amount of upper position of D13 specimen is 3.89%, which is greater than same position of D10 specimens, which is 3.38%. The increment in the result of expansion strain at the upper position because of an increment in the reinforcement from 1.14% to 2.03%. Note some researchers have pointed out that more expansion can be generally observed in the direction parallel to the casting direction. However, those influences couldn't be cleared in this study. The higher restraint near the rebar in the beam, the smaller expanded, but unexpected larger expansion occurred apart from the rebar due to the anisotropy arrangement of reinforcement. Note that the different amount of expansion between D10 and D13, that is, larger expansion in D13 might occur due to the variation of internal swelling attributed to material origin.

3.2 Warping deformation

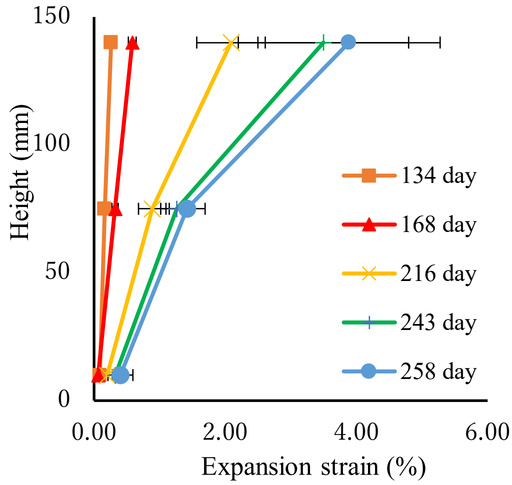
As the results illustrated in previous section, warping deformation occurred in RC beams affected by DEF. More detailed discussion shows in this section. The Fig.7 indicates the relationship between expansion strain to different position at specific days for D10 and D13 RC beams. The orange line represented the relationship between strain and height at 134 days, the red one presented it at 168 days, yellow one were 216 days, green one were 243 days and blue one were 258 days for two cases. The error bars indicated the standard deviation. For RC beams affected by DEF, the orange, red and lines illustrate a linear relationship between expansions strain and different positions. However, the relationship cannot always remain linear, which showed the dominance of warping deformation for anisotropic swelling. Rebar ratio was increased from 1.14% to 2.03%, the tendency of warping deformation was becoming more serious. And the RC beams also warp deformed earlier. The D10 RC beam met the warping deformation from 243 days but D13 met it form 216 days. The high restraint, the unexpected larger expansion occurred due to the anisotropy arrangement of reinforcement.

3.3 Crack pattern

The surface crack patterns were observed before loading test are shown in Fig.8. After measuring the final expansion strain, all glued studs were removed to obtain the crack pattern. No matter which specimens can observe the map cracking occurred. Both specimens appear the clear crack at the location where reinforcement were arranged at the bottom side. However, the difference is that the cracks in D13 specimen are more coherent while the cracks in D10 specimen are more independent. In other words, the cracks are more densely distributed in D13 specimen. The surface damage is more serious. Other researchers pointed out the higher the restraint, the higher concrete damage on the affected concrete. Crack pattern is also a key to help to study the effect of restraint and anisotropic swelling.

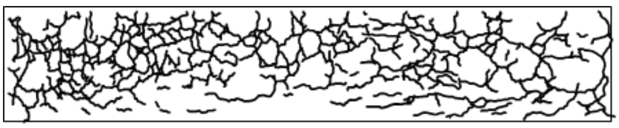


(a) D10

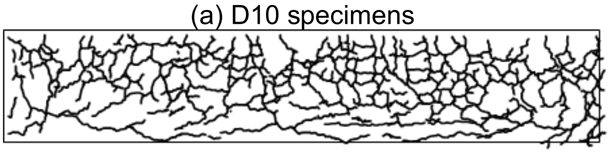


(b) D13

Fig.7 Expansion strain to different height on two specimens



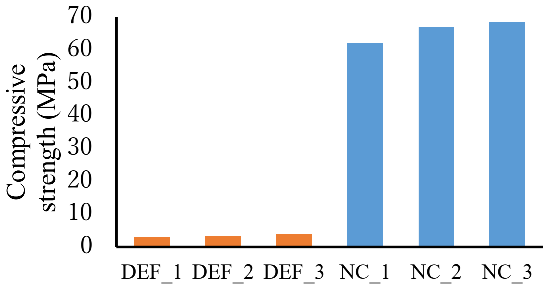
(a) D10 specimens



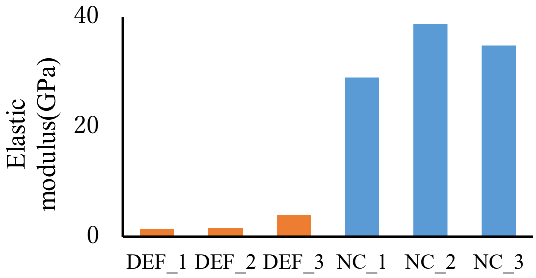
(b) D13 specimens

Fig. 8 Surface crack pattern of two specimens

Fig.9 Crack pattern of DEF-2



(a) Compressive strength



(b) Elastic modulus

Fig.10 Mechanical properties of cylinder specimens affected by DEF and normal concrete

4. LOADING TEST

4.1 Mechanical properties

Fig.9 shows the surface crack pattern of cylindrical specimens DEF-2. From the picture, the serious expansion could been observed. Fig.10 compares the compressive strength and elastic modulus of cylindrical specimens affected by DEF (DEF 1-3) and normal concrete (NC 1-3). Both DEF cylinder specimens and NC specimens had been subjected the high temperature treatment and cured in the same condition and same container as described in 2.3. This batch of concrete, there is no any additional K_2SO_4, which can be considered as sound specimens. As shown in the figure, the strength of the specimens cured at high temperature with the addition of K_2SO_4 was significantly lower than that of the sound specimens. The compressive strength of the deteriorated specimens were only 5% of the strength of the NC specimens, while the elastic modulus of elasticity decreased by about 93% compared to NC specimens. The mechanical properties of the specimens significantly decreased due to the expansion caused by DEF.

4.2 Flexural-Shear test

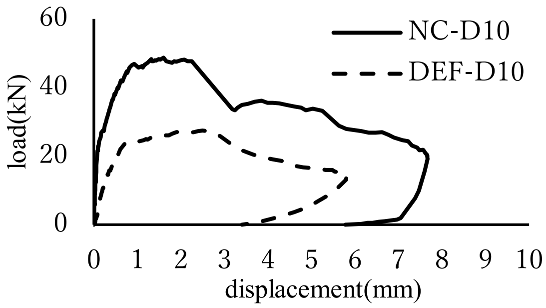
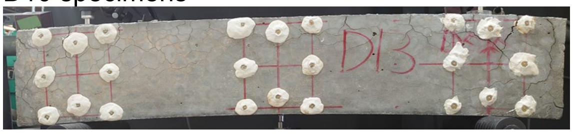
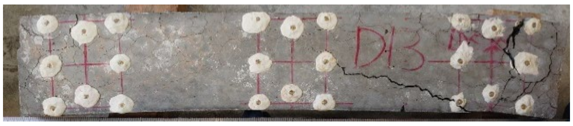


Fig.11 Relationship with displacement and load of D10 specimens



(a) D10 before loading test



(b) D10 after loading test

Fig.12 Crack pattern before and after loading test

The loading was carried out using a three-point bending test with a shear span of 300 mm, that is shear span to effective depth ratio was 2.40 for D10 and 2.43 for D13, respectively. Assuming the compressive strength of 60 MPa, the calculated strengths for D10 specimen were 47.6 kN for flexural failure and 45.9 kN for diagonal shear failure. The value of D13 specimen were 73.1 kN for flexural failure and 55.0 kN for diagonal shear failure.

The figure about relationship with displacement and load on D10 reinforcement arranged RC beams was shown in Fig.11. When loading at 26.9, the first peak was encounter, the displacement gradually increased but no longer able to support much load. When the load reach at 27.4kN, which is close to the calculative flexural failure. Similar trend was found in the D10 NC beam, when load reached at 48.7kN, no much load can't be applied. The initial slope of loading for DEF beams is 34.6kN/mm, which decreased by 36% of 54.0kN/mm for NC beams.

The crack developments before and after bending test for D10 RC beam affected DEF was shown in Fig.12. What should be mentioned is after flexural shear test, the beams were cut off and the diameter of rebar was confirmed. The surface of the beam written D13 is D10 specimen Before loading test, there had been, a significant crack occurred at upper part of the right side's span. After loading test started, this crack developed quickly to the part of right side span eventually. And meanwhile a diagonal crack was also observed in the right span, the diagonal crack propagated and opened, resulting in a rapid decrease in load and reaching the final stage when loading at only 27.4 kN. For reference NC RC beam, a diagonal crack occurred in the left span and the load decreased. The load was increased again until at 48.7 kN, the load decrease quickly, which means that final stage had reached. It is thought that shear failure was reached on both DEF RC

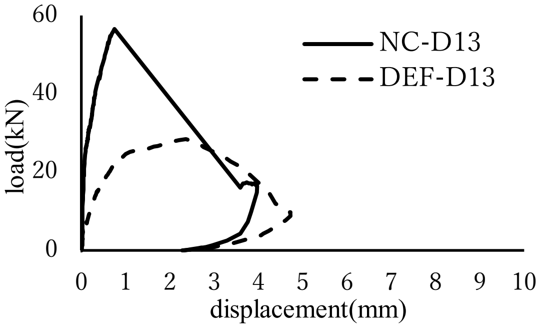
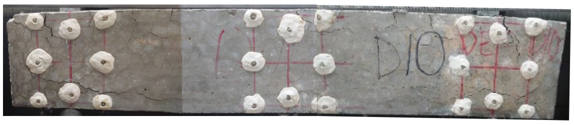


Fig.13 Relationship with displacement and load of D13 specimens

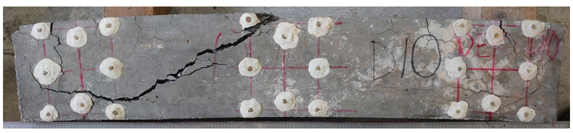
beam and NC RC beam. The relationship of displacement and stress for D13 RC beams was shown in Fig.13. The D13 DEF beam applied load at 28.4kN, which is closed to 30.2kN, the calculative flexural failure, the beam met the peak load, and displacement of beam can gradually increase. For D13 NC beam, when load reached at 56.5, then beam came the final stage, whose load is almost 2 times as much as D13 beam affected by DEF. The initial slope of loading stage was also affected by DEF, which showed 82.7 kN/mm for NC beams but only 24.0 kN/mm remained on the beam affected by DEF.

The picture of crack before and after bending test for D13 RC beam affected by DEF were compared in Fig.14. A visible crack can be observed at the upper position of two sides. When the test began, a crack developed quickly from the loading position to pivot position, it was an obvious shear failure. Only the difference is the concrete of upper middle position was broken due to compression. It was assumed the D13 NC RC beam was also reached shear failure.

After flexural test, two prism specimens (approximately 100×100×100 mm) were cut from each of D10 and D13 specimens. The Fig.15 shows the compressive strength of prism specimens cut from RC beams. The strength of prism specimens cut from NC beams were significantly smaller than mean value of NC cylinder specimens, which is 65.9MPa. It might be attributed to some damages due to flexural test although the prism specimens were cut from outside of support of loading test. In contrast, the strength of prism specimens cut from DEF beams were larger than cylinders affected by DEF. When 10 MPa of compressive strength was assumed, the calculated strengths of diagonal shear failure for D10 and D13 become 25.2MPa and 30.2MPa, respectively. These values are closed to the load obtained from flexural-shear test.



(a) D13 before loading test



(b) D13 after loading test

Fig.14 Crack pattern before and after loading test

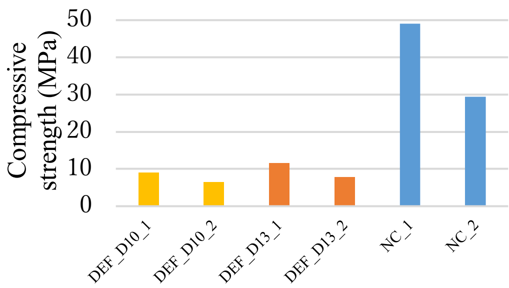


Fig.15 Compressive strength of prism specimens drilled from RC beams after flexural test

5. CONCLUSION

This RC beams dedicated experiment primarily investigates the effect of restraint on the expansion of concrete and the degradation of structural performance in concrete deteriorated by DEF. Base on the result of expansion and loading test, several conclusions can be made:

1. Expansion can be significantly affected by restraint even if serious expansion of DEF occurred. In the RC beams, the reinforcement arrangement would cause the warping deformation depending on their reinforcement ratio.
2. The shear capacity of DEF deteriorated RC beams drastically decreases and become almost half or one-third of that for sound specimen. The initial slope in the relationship of displacement and load would change due to deterioration of mechanical properties of concrete and wrap deformation.

ACKNOWLEDGEMENT

This work was supported by JSPS KAKENHI (20K04650).

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