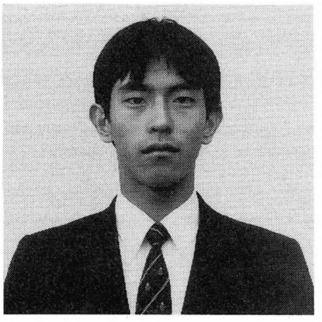
CONCRETE LIBRARY OF JSCE NO. 19, JUNE 1992

RESISTANCE TO FREEZING AND THAWING OF A HYBRID STRUCTURE COMPOSED OF STEEL AND HIGH-STRENGTH LIGHT-WEIGHT CONCRETE

(Rearrangement in English of papers in Concrete Research and Technology of Japan Concrete Institute, Vol.2, No.2, 1991)


Kazumi TAMURA

Hisao Teramoto

Kozo TAGAYA

SYNOPSIS

This paper describes the resistance to freezing and thawing of a sandwich-type hybrid structure consisting of steel and high-strength light-weight concrete, for utilization in arctic regions. In this study,the following tests were performed : A freezing and thawing test of high-strength light-weight concrete in the atmosphere ; compressive strength and punching shear tests with respect to the bond strength between steel and concrete ; and a loading test of the sandwich-type hybrid beam after freezing- and thawing-temperature cycles. In addition a new separate mixing method in which 2 parts of water and cement are mixed was tested, as the mixing method of high strength light-weight concrete. This method improved the resistance to freezing and thawing of high-strength light-weight concrete.

K.Tamura is a senior research engineer at Hiroshima Research and Development Center of Mitsubishi Heavy Industries. His research interests include separate mixing method for high-strength light-weight concrete and hybrid structures composed of steel plate and concrete. He is also a member of JSCE and JCI.

H.Teramoto is a research engineer at Hiroshima Research and Development Center of Mitsubishi Heavy Industries. His research interests include ultra fine particles produced from fly-ash for ultra high-strength concrete. He is also a member of JSCE and JCI.

K.Tagaya is a manager of construction engineering department in Headquarters of Mitsubishi Heavy Industries. He received his doctor of Engineering Degree in 1987 from Hiroshima University. His research interests include mass concrete and steel-concrete hybrid structure. He is also a member of JSCE, ISSMFE and JSSMFE.

1.INTRODUCTION

The recent studies on the resistance to freezing and thawing of high-strength light-weight concrete for offshore concrete structures to be used in extremely cold areas such as the Arctic Ocean have indicated its dependence to a large extent upon the water content of light-weight coarse aggregate before mixing. That is, the resistance to freezing and thawing to be required can be satisfied by maintaining the water content of light-weight coarse aggregate before mixing in a near oven-dry state.

Meanwhile, the resistance to freezing and thawing of a sandwich-type hybrid structure that is covered with steel plates over concrete is considered to be increased as compared with that of pure concrete only. However, almost no data have been available on the resistance to freezing and thawing of such a structure.

2. FREEZING AND THAWING TEST OF HIGH-STRENGTH LIGHT-WEIGHT CONCRETE (TEST 1)

2.1 Materials used

Cement : Ordinary Portland cement
Fine aggregate : Pit sand taken from Hiroshima Prefecture
Coarse aggregate : Non-granular-type artificial light-weight aggregate
Admixture : Silicafume (specific gravity : 2.2 ; specific surface area : 134,000 cm^2/g)
Chemical mixtures : Superplasticizer (β-naphthalin sulfonic acid) and air-entraining agent (natural resin)
Table 1 shows the physical properties of aggregates used.

Table 1. Physical properties of aggregate

Aggregate	Specific gravity		Absorption (%)		
	oven-dry	saturated surface dry	0.5 H	1 H	24 H *)
Fine agg.	2.49	2.55	—	—	2.12
Coarse agg.	1.30	1.41	7.40	8.75	11.9

*) time absorbing water (hour)

2.2 Mixing Procedure of Concrete

Two procedures were used to study their effects on the resistance of concrete to freezing and thawing, as shown in Fig. 1. Procedure " A " is the conventional mixing procedure. Procedure " B " is a separate mixing procedure different from the conventional one in which both water and cement are divided into two[1].

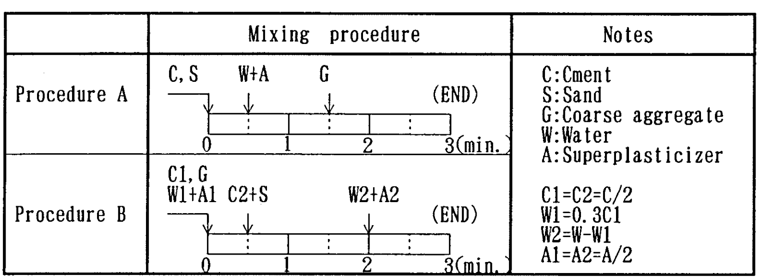


Fig.1 Mixing procedure of concrete

2.3 Test Piece and Test Method

The sandwich-type hybrid structures are covered with steel plates on both sides and considered to allow almost no water on their concrete surface to move. Therefore, the test specimens (100 x 100 x 400 mm(H)) were contained in thin rubber containers to cause no water movement and subjected to a freezing-thawing test in the atmosphere.

The temperature cycles were applied as specified in ASTM C666, Method " A "[2]. Concrete was cured in the atmosphere for 2 weeks after placing and subjected to the test. In the test, change in weight and dynamic modulus of elasticity were measured at each 30 cycles (by the transverse frequency method).

2.4 Test Cases and Mix Proportions

Sixteen test cases were determined considering the different water contents of light-weight coarse aggregates before mixing, the presence and amount of silicafume, and the different mixing procedures, as shown in Table 2.

The mix proportions were determined based on trial mixing by standardizing mix proportion of 30% of water cement ratio and 520 kg of cement content per unit volume of concrete. Silicafume of 10% of cement weight was added to aim at 18 cm of slump and 6% of air content.

Table 2. Test cases and mix proportions

<table>
<tr><th rowspan="2">Case</th><th rowspan="2">Mixing procedure</th><th rowspan="2">ω
(%)</th><th rowspan="2">W/C
(%)</th><th rowspan="2">Air content
(%)</th><th rowspan="2">S/a
(%)</th><th colspan="5">Unit content (kg/m³)</th><th colspan="2">Ad. (C*wt%)</th></tr>
<tr><th>W</th><th>C</th><th>Sand</th><th>G</th><th>Silica fume</th><th>Super-plasticizer</th><th>A.E. agent</th></tr>
<tr><td>AF0</td><td>A</td><td rowspan="4">0</td><td rowspan="4">30</td><td rowspan="4">6</td><td rowspan="4">37</td><td>156</td><td>520</td><td rowspan="2">570</td><td rowspan="4">507</td><td rowspan="2">0</td><td>2.0</td><td>0.18</td></tr>
<tr><td>BF0</td><td>B</td><td>78
78</td><td>260
260</td><td>1.7
1.7</td><td>—
0.15</td></tr>
<tr><td>AS0</td><td>A</td><td>156</td><td>520</td><td rowspan="2">510</td><td rowspan="2">52</td><td>2.2</td><td>0.23</td></tr>
<tr><td>BS0</td><td>B</td><td>78
78</td><td>260
260</td><td>2.0
2.0</td><td>—
0.21</td></tr>
<tr><td>AF11</td><td>A</td><td rowspan="4">11.2</td><td rowspan="4">30</td><td rowspan="4">6</td><td rowspan="4">37</td><td>156</td><td>520</td><td rowspan="2">570</td><td rowspan="4">563</td><td rowspan="2">0</td><td>1.5</td><td>0.15</td></tr>
<tr><td>BF11</td><td>B</td><td>78
78</td><td>260
260</td><td>1.3
1.3</td><td>—
0.13</td></tr>
<tr><td>AS11</td><td>A</td><td>156</td><td>520</td><td rowspan="2">510</td><td rowspan="2">52</td><td>1.8</td><td>0.23</td></tr>
<tr><td>BS11</td><td>B</td><td>78
78</td><td>260
260</td><td>1.7
1.7</td><td>—
0.21</td></tr>
<tr><td>AF26</td><td>A</td><td rowspan="4">26.1</td><td rowspan="4">30</td><td rowspan="4">6</td><td rowspan="4">37</td><td>156</td><td>520</td><td rowspan="2">570</td><td rowspan="4">639</td><td rowspan="2">0</td><td>1.6</td><td>0.12</td></tr>
<tr><td>BF26</td><td>B</td><td>78
78</td><td>260
260</td><td>1.2
1.2</td><td>—
0.10</td></tr>
<tr><td>AS26</td><td>A</td><td>156</td><td>520</td><td rowspan="2">510</td><td rowspan="2">52</td><td>1.7</td><td>0.23</td></tr>
<tr><td>BS26</td><td>B</td><td>78
78</td><td>260
260</td><td>1.6
1.6</td><td>—
0.21</td></tr>
<tr><td>AF20</td><td>A</td><td rowspan="2">19.9</td><td rowspan="2">30</td><td rowspan="2">6</td><td rowspan="2">37</td><td rowspan="2">156</td><td rowspan="2">520</td><td>570</td><td rowspan="2">608</td><td>0</td><td>1.4</td><td>0.12</td></tr>
<tr><td>AS20</td><td>A</td><td>510</td><td>52</td><td>1.5</td><td>0.23</td></tr>
<tr><td>AS26-15</td><td>A</td><td rowspan="2">26.1</td><td rowspan="2">30</td><td rowspan="2">6</td><td rowspan="2">37</td><td rowspan="2">156</td><td rowspan="2">520</td><td>483</td><td rowspan="2">639</td><td>78</td><td>2.3</td><td>0.28</td></tr>
<tr><td>AS26-20</td><td>A</td><td>454</td><td>104</td><td>2.8</td><td>0.35</td></tr>
</table>

Note 1) ω: water content of light-weight aggregate before mixing

2.5 Test Results and Discussion

(1) Physical Properties of Fresh Concrete and Compressive Strength

Table 3 shows the physical properties of fresh concrete and compressive strength, and Table 4 shows the average compressive strength in each series.

Both the slump and the air content nearly achieved their target values in spite of some dispersion.

The compressive strength was higher in the cases of silicafume included and also in the cases where the separate mixing procedure was used. Comparing between the AS and BS series with silicafume included, the compressive strength was higher by about 11% in the series where the separate mixing procedure was used.

Table 3. Properties of fresh concrete and compressive strength

Cases	Mixing procedure	Slump (cm)	Air (%)	Bulk density of air-dry state (kg/m^3)	σ_c (MPa) 7days	28days
AF0	A	18.1	6.8	1754	46.5	52.1
BF0	B	23.0	6.4	1744	43.6	51.8
AS0	A	18.5	5.9	1736	51.5	56.3
BS0	B	18.0	6.9	1750	56.1	65.1
AF11	A	16.0	6.4	1782	45.6	51.2
BF11	B	21.0	6.2	1791	44.2	51.7
AS11	A	20.5	6.8	1776	50.4	55.5
BS11	B	20.0	6.5	1786	55.3	61.3
AF26	A	21.3	6.3	1797	44.8	50.8
BF26	B	21.5	7.0	1780	46.1	52.3
AS26	A	18.7	6.0	1796	45.6	56.2
BS26	B	17.1	5.7	1799	52.2	59.3
AF20	A	24.6	6.9	1783	43.4	50.2
AS20	A	19.5	7.0	1785	44.5	54.4
AS26-15	A	21.0	5.2	1798	45.3	54.4
AS26-20	A	21.5	5.4	1793	46.4	57.6

Table 4. Mean compressive strength of concrete

Cases	σ_c (MPa) 7 days	28days
AF-series	45.1	51.1
BF-series	44.6	51.9
AS-series	48.1	55.6
BS-series	54.6	61.9

(2) Change in Weight

Fig. 2 shows the relation between the number of cycles of freezing and thawing and the change in weight. Generally, in the freezing and thawing test, the weight of the test specimen is changed due to scaling on the concrete surface during the test. However, this test performed in the atmosphere showed almost no damage to the test specimen causing nearly no changes in its weight. Instead, some change in the relative dynamic modulus of elasticity was observed, as described later.

(3) Relative Dynamic Modulus of Elasticity

The relation between the number of freezing and thawing and the relative dynamic modulus of elasticity is shown in Figs. 3 and 4. For the light-weight coarse aggregate before mixing, a water content of about 11% or less caused no change, while a water content of about 20% caused a rapid decrease in the relative dynamic modulus of elasticity. Such a decreasing tendency is more distinct in the cases where silicafume was not included.

The amount of silicafume inclusion was increased to 15% and 20% in AS26-15 and -20, which were compared with AS26 of 10% silicafume inclusion. There was almost no change observed between them. From this, the amount of silicafume to be added is considered appropriate at about 10% of cement weight.

Comparing the two mixing procedures, Procedure " B " showed a slower decrease in the relative dynamic modulus of elasticity than Procedure " A ".

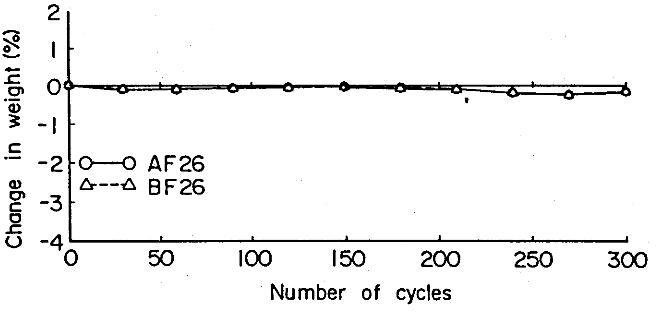


Fig.2 Relation between number of cycles and change in weight

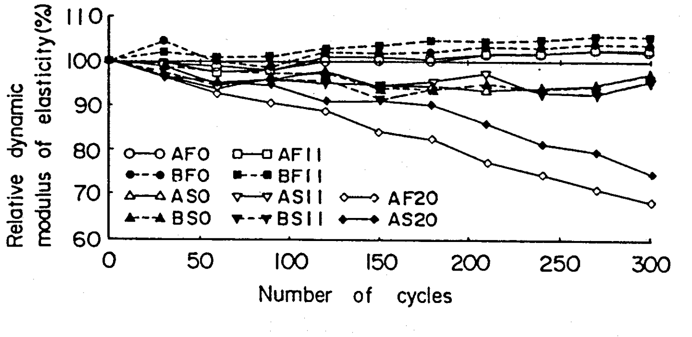


Fig.3 Relation between number of cycles and relative dynamic modulus of elasticity

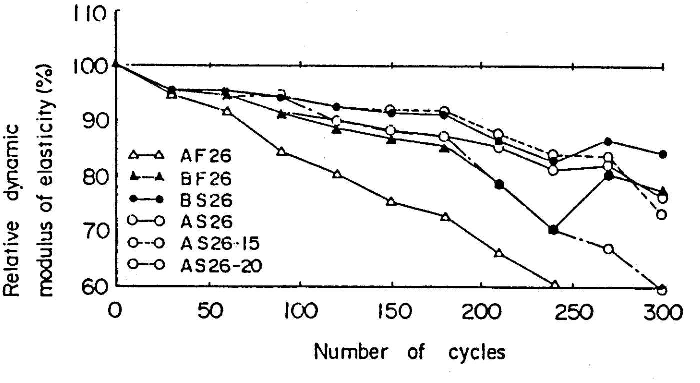


Fig.4 Relation between number of cycles and relative dynamic modulus of elasticity

(4) Durability Factor

Fig. 5 shows the relation between the water content of the light-weight coarse aggregate before mixing and the durability factor. The light-weight coarse aggregate with water content of about 11% or less before mixing showed very high durability regardless of the presence of silicafume. In the case of 26% water content, the cases of silicafume included showed a durability factor of about 76% much higher than about 48% in the cases of no silicafume included.

The cases by the separate mixing procedure (Procedure " B ") showed higher durability than those by the conventional mixing procedure (Procedure " A "). For the light-weight aggregate even with a water content of about 26%, the durability factor of Procedure " B " reached as high as about 80%.

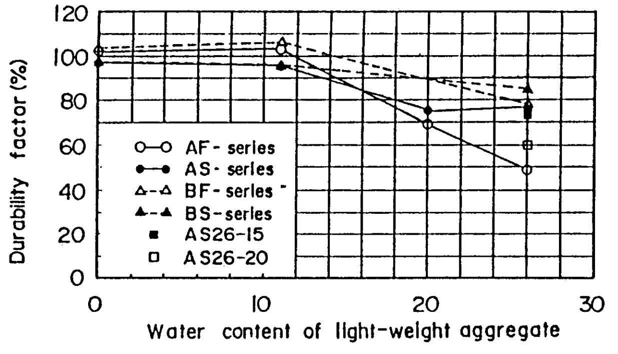


Fig.5 Relation between water content of light-weight aggregate and durability factor

3. COMPRESSION AND PUNCHING SHEAR TESTS ON FROST DAMAGED TEST PIECES (TEST 2)

3.1 Materials used

The materials used for high-strength light-weight concrete were the same as used in TEST 1.

3.2 Test Specimen and Test Method

(1) Compression Test

The test specimens were cylindrical (100mm ϕ x 200 mm(H)). They were prepared in the moulds with a heat insulating material (foamed polystyrene) of 10 mm in thickness set at the bottom of the moulds and another one set on top after placing concrete.

The test specimens were cured under 20 ℃ atmosphere, as they were in the moulds, for 2 weeks after placing the concrete, set in the freezing-thawing test apparatus and subjected to the cycles of freezing and thawing. The cycles of freezing and thawing were given in the same manner as in TEST 1 so that the central temperature cycles of a dummy concrete (100 x 100 x 400 mm) were in conformity with those as specified in ASTM C666 Method A.
After the specified number of temperature cycles had been completed, the test specimens were taken out of the freezing and thawing test apparatus, and removed from the form after the temperature of the test specimens reached room temperature. The end faces of the test specimens were polished and specimens were subjected to the compression test.

(2) Punching Shear Test

Test specimens were prepared by welding studs on both flanges of an H-shape and placing concrete from the top side, as shown in Fig.6.After curing in the atmosphere (20℃) for 2 weeks, the test specimens were set in the freezing-thawing test apparatus. At this time, the concrete surface had been covered completely with heat insulating material so as to apply the temperature cycles only on the steel surface. After completing the specified number of temperature cycles, the punching shear test was performed on the test specimen using a compression test machine.

3.3 Test Cases and Mix Proportions

Tables 5 and 6 show the test cases and the mixing proportions of high-strength light-weight concrete.

Tables 5. Test cases

Cases (series)		ω (%)	Number of cycles at test
Compression test	S0	0	0, 150
	S26	26	300
Punching shear test	S0	0	0, 300
	S26	26	

Table 6. Mix proportions of concrete

Cases (series)	Unit content (kg/m³)					Ad. (C*wt%)	
	W	C	S	G	Silica fume	Super-plasticizer	A. E. agent
S0	156	520	510	507	52	2.1	0.23
S26				639		1.7	

Note 1) W/C=30%, Sand percentage=37%, Air content=6% (common to all cases)

3.4 Test Results and Discussion Physical Properties of Fresh Concrete and Compressive Strength

Table 7 shows the physical properties of fresh concrete and the results of the compression test of the test specimens that had been cured in the atmosphere at 20 ℃. As shown in the table, the compressive strength of the S0 series is smaller than that of the S26 series because of the greater amount of air content in the former than in the latter.

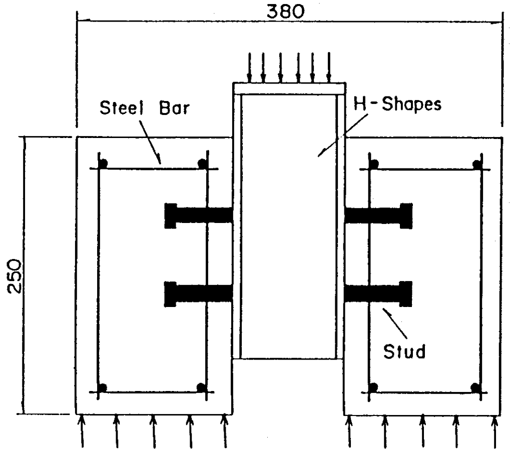


Fig.6 Specimen for punching shear test

Table 7. Properties of fresh concrete

Cases (series)	Slump (cm)	Air (%)	σ_c (MPa) 7 days	σ_c (MPa) 28days
S0	5.2	9.7	35.5	48.2
S26	24.4	6.1	41.9	56.3

(1) Relation between Number of Freezing-Thawing Cycles and Compressive Strength

Fig. 7 shows the relation between the number of freezing and thawing cycles and the compressive strength. In case of S0 series of 0% water content, the compressive strength increases as the number of freezing-thawing cycles increases. The reason for this is that the strength has increased with age of concrete because of little effect of freezing and thawing.

On the other hand,the S26 series shows a decrease in strength as the number of cycles increases. This is possibly because of concrete deterioration due to freezing and thawing.

(2) Relation between Number of Freezing-thawing Cycles and Shear Strength

Fig. 8 shows the relation between the number of freezing-thawing cycles and the shear strength. The shear strength is defined as the maximum load used in the punching shear test divided by the number of studs.

In case of the number of freezing-thawing cycles being zero in both SO and S26 series, the shear strength is determined by rupture of the stud welds. In the case of 300 cycles in the S26 series, the concrete was broken conically centering around 4 studs. That is, in the case of light-weight coarse aggregate with 0 % water content, no decrease in shear strength was observed even after applying the freezing-thawing cycles similar to that for the compressive strength. In the 26% cases, however, the shear strength was decreased greatly in a higher decrease ratio than that for the compressive strength. The reason for this is that internal fine cracks caused due to freezing and thawing had a greater effect on the shear (or tensile) strength than on the compressive strength of the concrete.

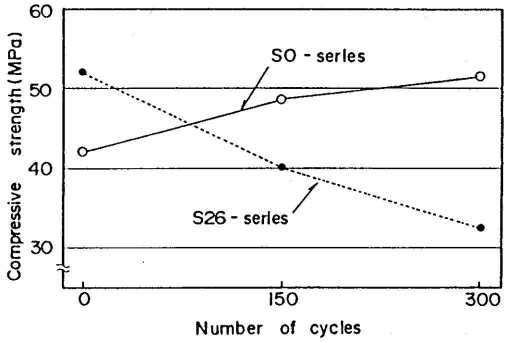


Fig.7 Relation between number of cycles and compressive strength

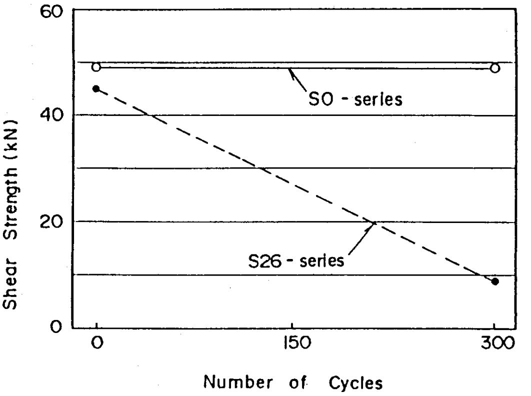


Fig.8 Relation between number of cycles and shear strength

4. LOADING TEST ON FROST DAMAGED HYBRID BEAMS (TEST 3)

4.1 Test Beams

Fig.9 shows the test specimens used. As shown, long studs were so arranged that they overlapped with each other in the middle part of the beam section and were also used as stirrup for the concrete.

4.2 Materials used

The materials for high-strength light-weight concrete used were the same as used in TEST 1. Steel plates of SS41 and studs of its equivalent were used. The mixing proportions used for the SO and S26 series were the same as for ASO and AS26 (Table 2), respectively. Tables 8 and 9 show the mechanical properties of the concrete and steel plate, respectively.

4.3 Test Cases

Table 10 shows the test cases.

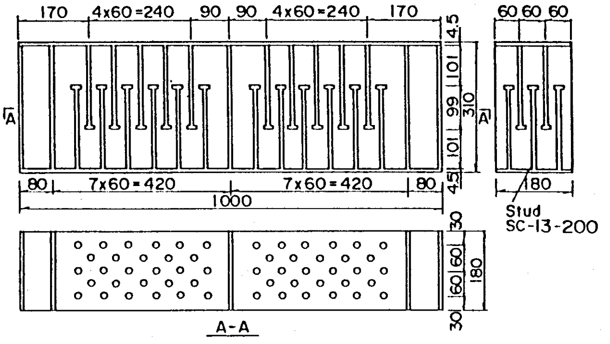


Fig.9 Dimension of beam specimen

Table 8. Properties of concrete *)

Cases (series)	Compressive strength (MPa)		Tensile strength (MPa)	Young's modulus (MPa)	Poisson's ratio
	7 days	28days	28days	28days	28days
S0	44.6	56.7	4.0	1.86×10^4	0.21
S26	50.6	53.0	3.3	1.82×10^4	0.20

*) Atmospheric curing (20 ℃)

Table 9. Properties of steel plate

Thickness (mm)	Yield stress (MPa)	Tensile strength (MPa)	Young's modulus (MPa)
4.5	292.9	385.7	2.1×10^5

4.4 Test Method

Test specimens were cured for 2 weeks in the atmosphere at 20 ℃ after placing concrete, set in the freezing-thawing test apparatus and subjected to the freezing-thawing cycles. The test specimens had been contained in a steel container (2.3 mm in wall thickness) with a gap of 2-3 mm between them, then the freezing-thawing temperature cycles were applied over the entire surface of the test specimens in the same manner as in TEST 1 and 2. The freezing-thawing temperature was controlled using a dummy concrete in the same manner as in TEST 2. The temperature cycles were applied to the test specimens so that those at the center of the dummy concrete were in conformity with those as specified in ASTM.

As shown in Table 10, 3 cases of 0, 150 and 300 freezing-thawing cycles were used. The test specimens of the 150-cycle case was removed from the freezing-thawing test apparatus when it completed 150 cycles and cured in the atmosphere (same for the 0-cycle test specimen) until the 300-cycle test specimen completed its given cycles, so that each case would provide the same age of concrete at the time of loading test.

In each test case, the test specimen was removed from the freezing-thawing test apparatus after completing the given freezing-thawing cycles and subjected to the loading test at room temperature.Loads were applied on the test specimen, as a simple beam (span : 0.84 m), using the the point loading method at the center of its span. The loads were controlled in steps with a hydraulic jack through a load cell.

4.5 Test Results and Discussion Temperature Cycles in Test Piece

Fig. 10 shows an example of the temperatures measured at the center of the dummy concrete and in the test specimen during application of the freezing-thawing temperature cycles. As shown, the temperature change in the central part of the test specimen is about 0 to -5 ℃ to that of the dummy concrete of +4 to -18 ℃, indicating little effect on freezing and thawing.

(1) Compressive Strength of Concrete at Loading Test

Table 11 shows the compressive strength of concrete at the loading test. The test specimens for compressive strength (100 mm ϕ x 200 mm(L)) that had been cured in the same manner as for the hybrid beam were subjected to the compression test at the same time of the loading test on the hybrid beam. As shown, the S0 series indicated almost no decrease in strength due to frost damage, while a decrease in strength of about 20% is observed in comparison between S26-0 and S26-300 cases in the S26 series.

Table 10. Test cases

Cases		Water content of lightweight agg. (%)	Number of cycles at test
S0-series	S0-0	0	0
	S0-150		1 5 0
	S0-300		3 0 0
S26-series	S26-0	2 6	0
	S26-150		1 5 0
	S26-300		3 0 0

Table 11. Compressive strength of concrete

Cases		Compressive strength (MPa)
S0-series	S0-0	57.1
	S0-150	56.3
	S0-300	56.0
S26-series	S26-0	53.4
	S26-150	53.0
	S26-300	43.3

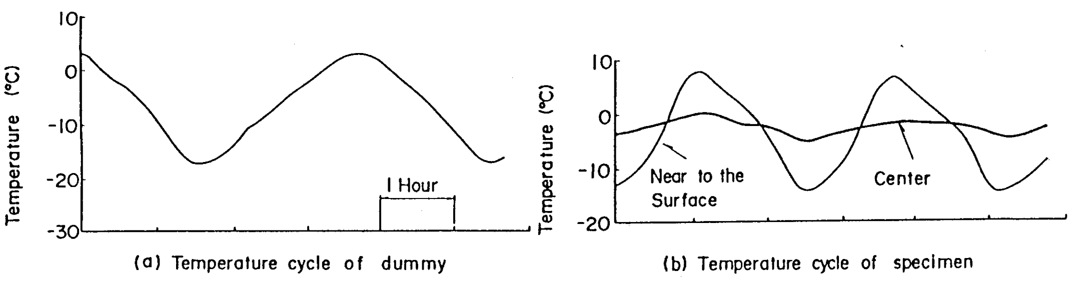


Fig.10 Temperature cycles of dummy and specimen

(2) Relation between Load and Deformation

Fig. 11 shows the relation between the load and the deformation at the center of the span. In Fig. 11(a), the S0 series indicated a tendency that the greater the number of freezing-thawing cycles, the higher the strength would become. One of the reasons for this is that, as shown in Table 11, although almost no decrease in compressive strength was observed, the freezing-thawing actions had caused fine cracks that decreased the so-called apparent stiffness to improve the deformation capacity.

In the S26 series, the S26-0 case where no freezing-thawing cycles had been applied, was found to have a higher strength. This is because of deterioration of concrete due to frost damage in S26-150 and -300 cases (Table 11). As shown in Table 11, the ultimate load that is decreased drastically due to frost damage has little effect on the load-deformation relation. The reason for this is that, whereas the ultimate load test specimen was secured with 60-mm studs only on the concrete surface that was liable to frost damage, the hybrid beam was secured with 200-mm studs deeper into the center of the concrete that was little liable to frost damage, and thereby reducing the effect of deterioration of surface concrete. The rough curves with abrupt drops of load, as observed in the Load-deformation relation in Fig. 11, may be due to slips of the studs in the shearing direction of the beam under the increasing load.

The S0 series resulted in higher strength than the S26 series although there was no clear difference.

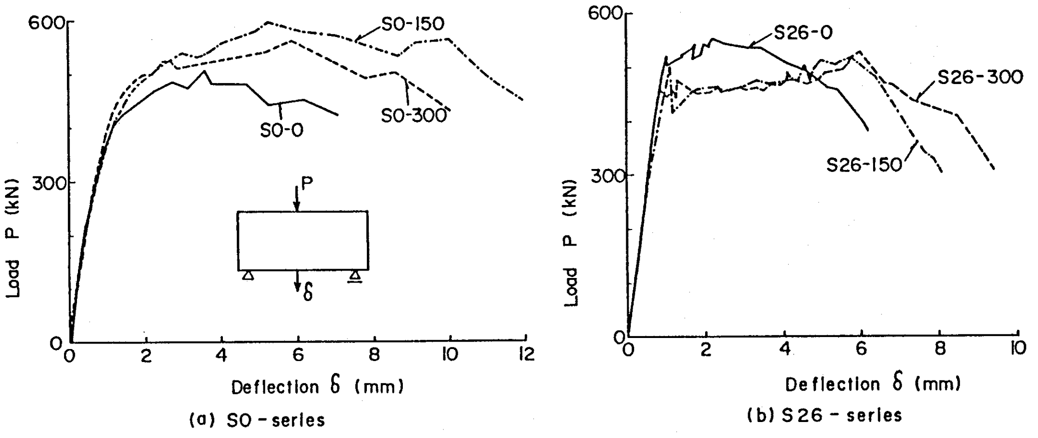


Fig.11 Relation between load and deflection

(3) Cracks in Concrete

In the S26-150 and -300 cases, cracks were caused by frost damage (Fig. 12). These cracks were about 0.05-0.2 mm in width, with no scaling phenomena. Other cases indicated no cracks due to frost damage. These cracks, independent from one another, are not considered to have a great effect on the beam strength. As described above, however, these cracks may make the apparent stiffness of the beam smaller to provide a sufficient possibility of improving the deformation capacity of the beam.

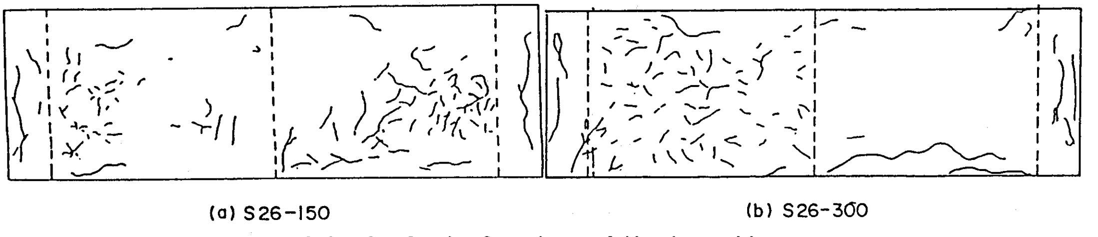


Fig. 12 Cracks due to freezing and thawing action

Fig. 13 shows examples of the characteristics of cracks in the test specimen at collapse under load in the loading test.The characteristics of cracks were somewhat different in each case, but not clearly defined. Bending cracks occurred near the middle of the span,and lamination, in the stiffener at about 250-300 kN, and shear cracks, at about 350-400 kN. These cracks grew and resulted in failure as the load was increased further.

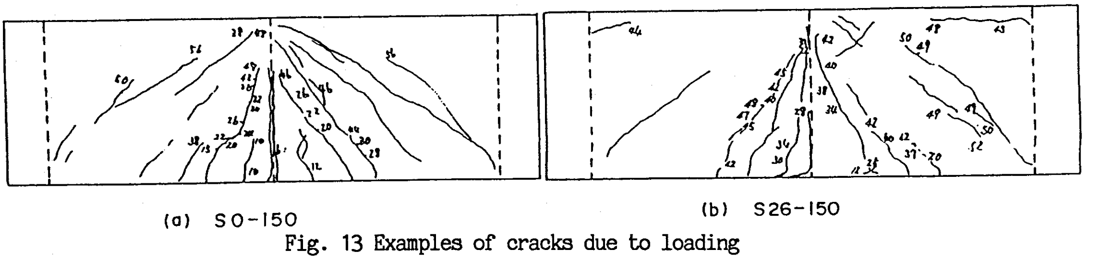


Fig. 13 Examples of cracks due to loading

6. CONCLUSIONS

In this study, the resistance to freezing and thawing of the sandwich-type hybrid structures made of steel and high-strength light-weight concrete was examined by performing various tests. The conclusions reached are, as follows :

(1) The high-strength light-weight concrete of about 30% of water-cement ratio, about 6% of air content, and about 11% or less of water content in light-weight coarse aggregate before mixing indicated high durability even in a rapid freezing and thawing test in the atmosphere according to ASTM C666 Method A. The high-strength light-weight concrete with silicafume, as an admixture, included by about 10% of the cement weight also indicated high durability even with light-weight coarse aggregate at about 20% of water content.

(2) The high-strength light-weight concrete (silicafume included) mixed by the new separate mixing method, in which both water and cement are divided into two parts each and mixed, satisfies the durability factor of 80% even with light-weight coarse aggregate at about 26% water content and is considered highly effective for improving the resistance to frost damage.

(3) The test specimen that had been given the freezing-thawing cycles in the case of 0% water content of light-weight coarse aggregate indicated almost no decrease in both compressive and shear strengths due to frost damage. However, the 26% case indicated decreases in the compressive and shear strengths by about 20% and about 80%, respectively. The reason for this is that frost damage has a greater effect of deterioration especially on the shear strength.

(4) The hybrid beam that had been given the freezing-thawing cycles in the case of 0% water content of light-weight coarse aggregate indicated a high strength even at the number of cycles of 300 and no decrease in the concrete strength due to frost damage. Even in the case of 26% water content of light-weight coarse aggregate, although deterioration of concrete due to frost damage caused some decrease in strength, the hybrid beam indicated a strength as high as that of the sound one not affected by frost damage.

(5) The long studs that were fixed in the central portion of the concrete not liable to the effect of freezing and thawing are considered effective against frost damage in comparison with the short studs.

In this report, the resistance to freezing and thawing of sandwich-type hybrid structures has been examined experimentally in accordance with the temperature cycles as specified in ASTM C666 Method A. Almost no data have so far been available on this type of resistance to freezing and thawing. In the future, it is considered necessary to accumulate the data by performing experiments and investigations of actual structures.

ACKNOWLEDGMENT

Last but not least, the authors wish to express their sincere appreciation to the Japanese Naval Architectural Research Association for valuable assistance to accomplish this study.

REFERENCES

[1] Tamura, k., Fujita, H., Tagaya, K., Ohba, K., "Study on Resistance of High-Strength Light-Weight Concrete to Freezing and Thawing," Proceeding of the Sixth International Offshore Mechanics and Arctic Engineering Symposium, Volume III, Mar. 1987, pp.185-191

[2] ASTM, Annual Book of ASTM Standards, Volume 04.02, 1984, pp.403-410