SHEAR STRENGTH OF PC BEAMS WITH HIGH STRENGTH LIGHTWEIGHT AGGREGATE CONCRETE

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This paper reports on the shear strength of PC beams with high strength lightweight aggregate concrete. Shear cracking strength of RC beams with lightweight coarse aggregate and lightweight sand is remarkably smaller than that with normal weight concrete. Usage of lightweight aggregate also reduces concrete contribution for shear strength after shear cracking. Shear cracking strength and ultimate shear strength of concrete increased with the amount of prestressing force. The type of aggregate seemed to have no influence on the amount of increment of shear cracking strength by prestressing.

Keywords: Lightweight aggregate, High-strength concrete, Prestressed concrete, Shear

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1. INTRODUCTION

The quality of artificial lightweight aggregates has recently been greatly improved, and it is now possible to produce lightweight concrete featuring excellent durability and higher compressive strength[1]. Lightweight concrete was developed to overcome one of the major disadvantages of concrete as a structural material; its very large dead weight. It is expected to promote reduction of the energy used to construct concrete structures.

Lightweight concrete generally has a smaller Young's modulus and smaller tensile strength than ordinary normal-weight concrete of the same compressive strength. The fact that lightweight concrete is characterized by smaller tensile strength indicates that careful consideration is essential in evaluating safety margins against failure associated with tensile stress. A shear strength reduction factor is introduced in most design codes for structural concrete to reflect the empirical finding of reduced strength.

Our study focuses on superstructure members built using prestressed concrete (PC) and investigates their shear strength characteristics; PC beam members are selected as they can enjoy great benefits from reduction in weight. The weight of PC members can also be reduced by using a smaller sectional area; this is possible while reducing the weight of the concrete if concrete strength can be improved. In this study, high-strength concrete featuring a compressive strength of 60 MPa is used. This is the upper limit of the design standard strength for ordinary cast-in-situ PC members for highway structures.

2. REVIEW OF LITERATURE ON SHEAR STRENGTH OF LIGHTWEIGHT CONCRETE MEMBERS

According to the Standard Specifications for Concrete Structures (Japan Society of Civil Engineers, revised 2002), the shear capacity of lightweight concrete members containing both lightweight fine and coarse aggregates should be reduced by 30% from that for normal-weight aggregate concrete members. The specifications limit the types of lightweight aggregate that should be used, specifically including those categorized as Strength Class 3 or 4 as defined by JIS A 5002. However, even if lightweight aggregate products are properly used as given in these specifications, the physical characteristics of the concrete may of course vary depending on the precise characteristics of the aggregates used and the mix proportion, as well as the blending conditions of the lightweight aggregates. For this reason, the authors do not feel it is necessarily correct to introduce a constant shear strength reduction ratio.

Past investigations have evaluated shear strength reduction ratios on the basis of the physical properties of lightweight concrete. There have been many reports of loading tests with lightweight concrete RC specimens using no shear reinforcing bars, yielding the reduction in shear cracking strength as compared with normal-weight aggregate[2]-[7]. The parameters used to evaluate shear cracking reduction ratios include concrete density and the ratio of tensile strength to that of concrete made using normal-weight aggregate. For instance, Reference 2 reveals that it is possible to estimate shear cracking strength with an appropriate safety margin by substituting the tensile strength of the lightweight concrete into the tensile strength term for normal concrete in the equation that gives the shear cracking strength of normal concrete. Reference 3 verifies the validity of the shear cracking strength equation based on the concrete density specified in the revised version of the Euro Code. Reference 4 proposes a new shear strength correction factor based on concrete density. Reference 5 proposes a correction method using the brittleness factor of concrete. Reference 6 examines the shear cracking strength of lightweight concrete in the field of construction, and offers shear cracking strength reduction ratios according to concrete density. Reference 7 reports that the shear cracking strength of lightweight concrete is about 70% that of ordinary concrete, and identifies the causes of this reduction as reduced tensile strength and shear friction.

The results of these studies verify that the method given in the current standards, specifically reducing the shear cracking strength by 30%, ensures adequate safety. However, by taking concrete density as a new index, it seems feasible to estimate the shear cracking strength of lightweight concrete in terms of the characteristics of the concrete itself, not in terms of aggregate characteristics. Still, it should be noted that many of the specimens used in the reported loading tests had a compressive strength of less than 40 MPa, and there is a lack of experimental data for high-strength concrete of about 60 MPa. This illuminates a need to verify the performance of concrete members when high-strength lightweight concrete is used.

Although the shear cracking strength of PC members made using lightweight aggregate has not been studied as often as that of RC members, there have been some investigations over the past few years[8]-[10]. These reports indicate that prestressing causes a significant improvement in shear cracking strength, and they share the common observation that shear cracking strength is underestimated when the prestressing effect is taken into account simply by multiplying the prestress effect by a correction factor taking decompression moment as a parameter.

For concrete members made using normal-weight aggregate, shear bearing capacity is evaluated by the modified truss theory. This assumes that the shear force borne by the concrete after shear cracking remains equal to that at the time of shear cracking. Although the reduction in shear cracking strength is taken into account in design when using lightweight concrete, the modified truss theory treats lightweight concrete as equal to normal-weight concrete. Since tensile failure is a brittle phenomenon in lightweight concrete, it is considered necessary to judge whether this treatment is applicable to lightweight concrete. Reference 11 shows that, after loading tests on lightweight concrete RC members, there is less shear force due to the arch mechanism than in the case of normal concrete. This observation indicates that the use of lightweight aggregate has a certain impact on the shear resistance mechanism beyond shear cracking. There have been few studies of the shear resistance of lightweight concrete members beyond shear cracking, so it is necessary to review the suitability of the modified truss theory.

Taking into account this research background, we study the influence of lightweight aggregates on the shear strength of a PC member made using high-strength lightweight concrete, the increase in shear cracking strength resulting from prestressing, and the behavior beyond shear cracking.

3. LOADING TEST

3.1 Outline of loading test

The specimens consisted of 12 beam members with differing combinations of aggregate (4 types) and varying levels of prestress (3 levels).

3.2 Materials and prestressing

The water-cement ratio of the concrete was determined so as to achieve a compressive strength of 60 MPa for all specimens. The lightweight aggregates were artificial aggregates consisting of granulated expansive shale. The density and water absorption ratio of these aggregates are shown in Table 1. The four different concrete mixing conditions are shown in Table 2. Four mixes were used: (N) lightweight fine and coarse aggregates plus normal weight aggregate; (L1) lightweight fine aggregate only; (L2) lightweight coarse aggregate only; and (L3) lightweight fine and coarse aggregates. Normal weight aggregates were surface-dry during mixing, but lightweight aggregates were almost completely dry when used. Thus, in anticipation of the lightweight aggregates absorbing water during mixing, additional water was added to compensate. The term ΔW in Table 2 is the amount of correctional water added to the mixing water. The correctional water volume is not included in the calculation of water-cement ratio. Workability of the concrete upon mixing was set to a slump of about 20 cm so as to ensure easy casting and prevent separation of materials.

Table 1 Physical properties of lightweight aggregates

Type of aggregate	Lightweight fine aggregate	Lightweight coarse aggregate
Absolute dry density	1.63	1.30
24-hour water absorption	16.4	8.8
Grading	Not more than 5 mm	5mm-15mm

Table 2 Specified mix proportions of concrete

Mix of specimen	W/C (%)	s/a (%)	Air (%)	Unit content (kg/m^3) W	C	S	G	ΔW
N	41	45	3	160	390	805	992	0
L1	40	50	3	160	400	*570*	898	57
L2	32	50	3	160	500	849	*423*	17
L3	29	50	3	160	517	*547*	*426*	72

Italic: lightweight aggregate

Table 3 Results of tensile strength tests on PC tendon and rebar

PC steel strand wire (SWPR7B)	Tensile Strength (MPa)	At 0.2% permanent elongation Stress (MPa)	Strain($*10^{-6}$)	Young's modulus (GPa)
	1872	1848	10770	211
Shear reinforcement (D6)	Tensile Strength (MPa)	At yield Stress (MPa)	Strain($*10^{-6}$)	Young's modulus (GPa)
	518	323	1825	177

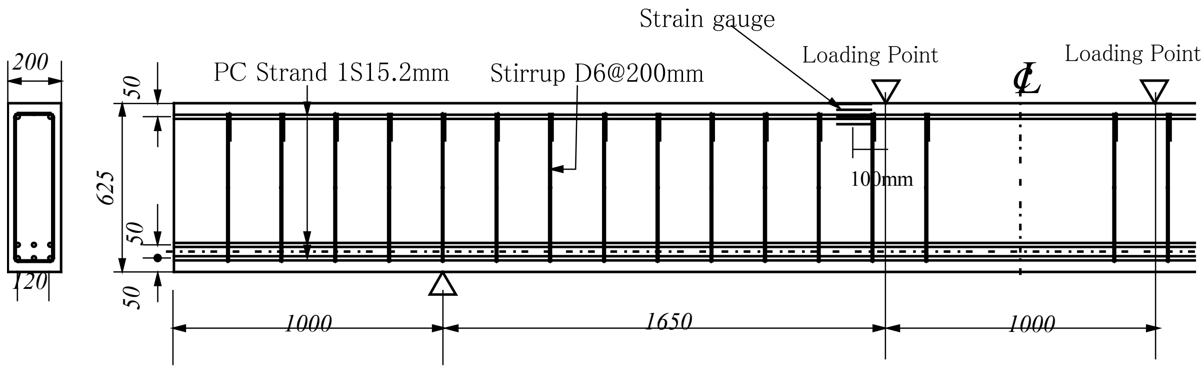

Fig.1 Dimensions of beam specimens

Fig.1 gives details of the PC beam specimens. All specimens had a shear span ratio of 3. Prestress was introduced by the pretension method using PC tendons of SWPR7B1 15.2 mm stranded wire. The shear reinforcing bars used in the specimens were D6 at an interval of 20 cm. **Table 3** shows the results of the strength tests carried out on the types of steel used. Four concrete strain gauges were attached; one at a point 100 mm from the loading point and at an interval of 25 mm as shown in **Fig. 1**.

The target value of compressive stress induced at the lower extreme fiber of the section by prestressing (the "prestressing level") was set at 8 MPa or 16 MPa. Stress at the upper extreme fiber of the section was set at 0, thereby setting up a triangular stress distribution. In addition to these specimens, specimens with no prestressing were also tested. **Table 4** lists the specimens prepared in this way.

Table 4 Details of specimens

Specimen No.	Type of aggregate		Prestress level (MPa)	No. of Specimen	Type of aggregate		Prestress level (MPa)
	Fine	Coarse			Fine	Coarse	
N-0	Normal	Normal	0	L2-0	Normal	Lightweight	0
N-8			8	L2-8			8
N-16			16	L2-16			16
L1-0	Lightweight	Normal	0	L3-0	Lightweight	Lightweight	0
L1-8			8	L3-8			8
L1-16			16	L3-16			16

Table 5 List of test results

Specimen number	N-0	N-8	N-16	L1-0	L1-8	L1-16	L2-0	L2-8	L2-16	L3-0	L3-8	L3-16
Compressive strength (MPa)*1	61.0	58.8	61.9	62.5	61.2	59.2	65.9	60.3	60.3	65.8	65.0	63.5
Tensile strength (MPa)*1	4.24	4.14	3.75	3.19	3.42	3.65	2.81	2.75	3.13	2.04	2.13	1.95
Bending strength (MPa)*1	5.09	5.52	5.80	4.95	4.25	3.99	3.29	3.60	3.53	2.18	2.36	2.28
Young's modulus (GPa)*1	31.9	33.2	32.3	27.8	27.3	27.1	24.9	24.8	24.4	20.9	20.5	19.5
Concrete density (g/cm3)*1	2.37	2.38	2.38	2.10	2.10	2.12	1.91	1.91	1.96	1.71	1.70	1.69
Stress at lower edge (MPa)	0.0	8.4	15.4	0.0	8.5	16.4	0.0	8.0	16.0	0.0	8.1	15.5
Bending cracking load (kN)	50	210	360	40	190	360	40	180	340	30	170	340
Shear cracking load (kN)	221	530	670	210	460	640	190	470	660	110	390	640
Shear reinforcing bar yield load (kN)*2	300	610	-*3	320	480	-*3	220	470	-*3	170	451	-*3
Mode of failure*4	ST	ST	BC	ST	ST	BC	ST	ST	BC	ST	ST	SC
Ultimate load (kN)	488	828	880	522	665	846	428	663	800	442	659	786

Note *1: Values are those measured on the day of the loading test under curing conditions identical to those for the PC beams.
Note *2: This value indicates the load at which any one of the shear reinforcing bars under strain measurement reached the yield point.
Note *3: Specimen failed before yielding of the shear reinforcing bars.
Note *4: ST: shear failure accompanied by yielding of shear reinforcing bars; SC: shear failure without yielding of shear reinforcing bars; and BC: bending compression failure

3.3 Test results

Table 5 shows the results, including the physical properties of the concrete as measured at the age of the loading test. Compressive strength and Young's modulus were measured with cylindrical specimens measuring 10 cm in diameter and 20 cm in height; tensile strength with cylindrical specimens 15 cm in diameter and 20 cm in height; and bending strength with prismatic specimens measuring 10 cm x 10 cm x 40 cm. Compressive strength was very close to the target value regardless of mixing conditions.

Prestressing was applied to the normal-weight aggregate concrete specimens at the age of three days and to lightweight aggregate specimens at the age of four days. From the strain distribution of the PC steel bars at prestressing time, the transfer length at the member edges was found to be less than 60 cm for all specimens, meaning that all beam specimens had adequate transfer length.

Calculated values of the load at which bending cracking occurred are compared with the measured values in **Fig. 2**. These calculated values were obtained for the moment when the calculated stress in the lower extreme fiber of the section at the center of the span became equal to the splitting tensile strength of the concrete. The calculated values correspond well with the actually measured bending cracking load, which is good evidence that the specified level of prestressing was achieved.

After bending cracking, all specimens went on to suffer shear cracking as the load increased. Loading continued beyond cracking, and specimens failed when the upper extreme fiber of the section underwent crushing. For all specimens with a prestress level of 16 MPa, concrete crushing took place before shear yielding of the reinforcing bars.

The ultimate bending load was calculated based on the hypothesis that the plane remains plane by using the stress-strain relationship of the concrete and PC steel obtained from materials strength tests. The ultimate limit state was judged as the point when the calculated value of concrete compressive stress at the upper extreme fiber of the section reaches the compressive strength obtained from the cylindrical specimens. In the calculation of ultimate bending load, concrete stress reached the compressive strength before the tensile strain of the PC steel reached a level of tensile strain corresponding to 0.2% eternal elongation, and all specimens are estimated to have failed by crushing of the concrete. The calculated ultimate bending load was compared with the failure load of the specimens in the loading test so as to understand the failure mode of the specimens. The ratio of these two values was adopted as the basic parameter for determining failure mode for two main reasons: (1) the expected mode of bending failure for all specimens was compression failure of the concrete without yielding of the PC steel and (2) observation of failed specimens revealed that, because specimens failed through concrete crushing, simple observation of the failure point did not allow easy judgment as to whether failure was shear compression failure or bending compression failure. **Fig.3** shows the ratio of failure load in the test to calculated ultimate bending load. The measured failure load of specimens with zero prestressing is far

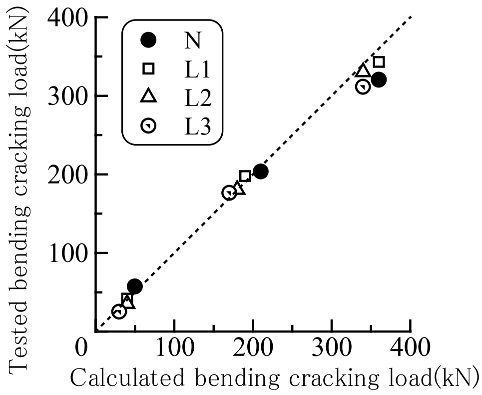

Fig.2 Bending cracking load

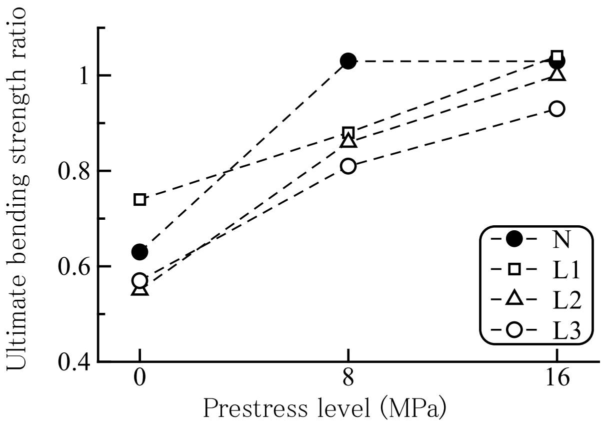

Fig. 3 Ratio of measured value of failure load to calculated value of ultimate bending load

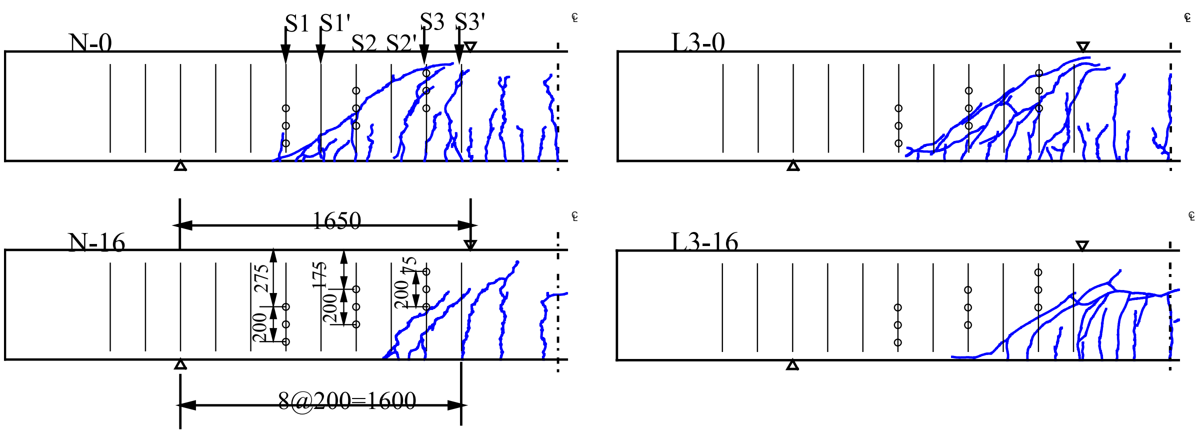

Fig.4 Strain measuring points on shear reinforcing bars and crack pattern (unit: mm)

below the calculated ultimate load regardless of the type of aggregate, indicating that shear failure occurred. The calculated ultimate bending strength of specimens with a prestressing level of 8 MPa is almost equal to the measured failure strength of specimens using normal-weight aggregate, indicating that failure mode was bending. But in the case of the specimens with lightweight aggregate, failure strength is smaller than the calculated ultimate bending load, indicating that shear failure occurred. The failure strength of specimens with a prestress level of 16 MPa is almost equal to the calculated value of ultimate bending strength except in the case of L3 specimens, indicating that bending failure was the failure mode. In the case of the L3 specimens, the actual failure load was about 90% of the calculated ultimate bending strength, indicating that bending failure did not necessarily occur. **Fig.4** shows the observed cracking pattern for N and L3 specimens.

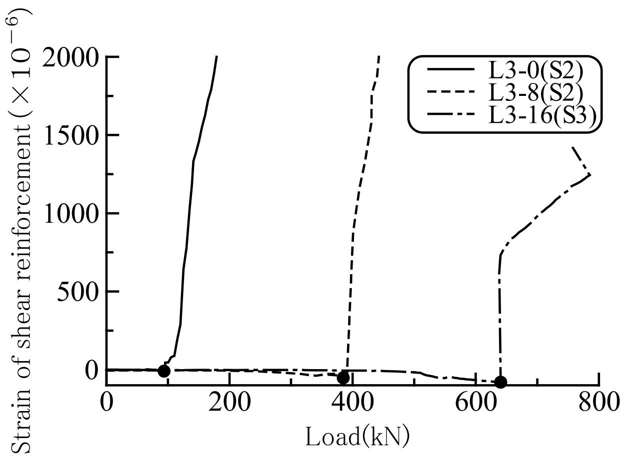

Fig.5 Example of measurement results of load and shear reinforcing bar strain

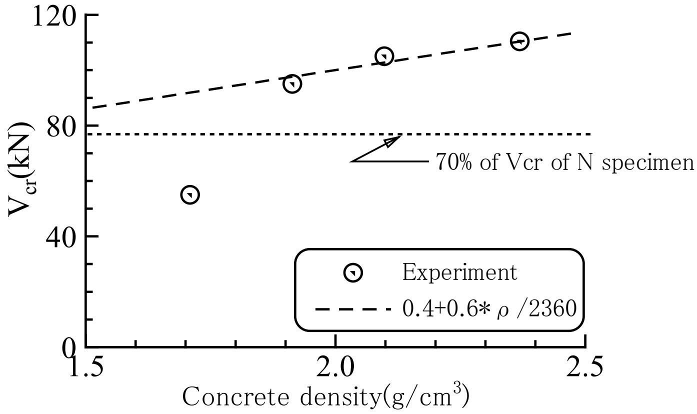

Fig.6 Relationship between concrete density and shear cracking strength (no prestressing)

4. DISCUSSION

4.1 Influence of aggregate type and prestressing level on shear cracking strength

Here the influence of aggregate type on the shear cracking strength of specimens without prestress is reviewed. Shear cracking is judged to have occurred when the tensile strain of the strain gauge attached to the shear reinforcing bars suddenly rises as the load is increased. **Fig.4** shows the strain gauge attachment points on the shear reinforcing bars and the locations of shear cracking. These strain measuring points on the shear reinforcing bars are indicated by circles in **Fig. 4**. These measuring points were the same for all specimens. **Fig.5** shows an example of the relationship between imposed load and the measured strain of shear reinforcing bars, with ● indicating the load at which shear cracking occurred. **Fig.6** indicates the relationship between concrete density (ρ) and shearing force at the moment of shear cracking (Vcr). Shear cracking strength declines as the concrete density is reduced.

L3 specimens exhibited a greater reduction in shear cracking strength than N specimens. This reduced shear cracking strength is much smaller than 70% of the shear cracking strength of normal weight aggregate concrete.

The next step is a study to determine whether the shear cracking strength specified in the revised Euro Code is compatible with the shear cracking strength reduction factor obtained by this loading test. To do this, the density of the normal-weight concrete, which serves as the reference, needs to be set at 2,400 kg/m³. Since the density of the normal-weight concrete used in this study was 2,360 kg/m³, an adjustment was made. Then we obtained the equation to evaluate shear cracking reduction factor as 0.4 + 0.6 * ρ/2360 where ρ is the density of light-weight concrete in kg/m³. The broken line in **Fig. 6** means shear cracking strength

Table 6 Brittleness factors of various concretes

Reference	Brittleness number
2	7.1～12.2
12	11.6～19.9
11	11.2～23.2
5	9.3～23.2
4	10.6～22.4
3	13.6～20.5
This experiment	N (15.0), L1 (17.9), L2 (21.6), L3 (31.8)

calculated with using the equation. The shear cracking strength for the L1 and L2 specimens falls in an almost linear relationship with the Euro Code reduction curve; this means that evaluation is possible on the basis of concrete density regardless of whether lightweight aggregate is used as the fine or coarse aggregate. For the L3 specimens, the shear cracking strength falls far below the Euro Code curve, indicating that evaluation based on concrete density is not appropriate in every case.

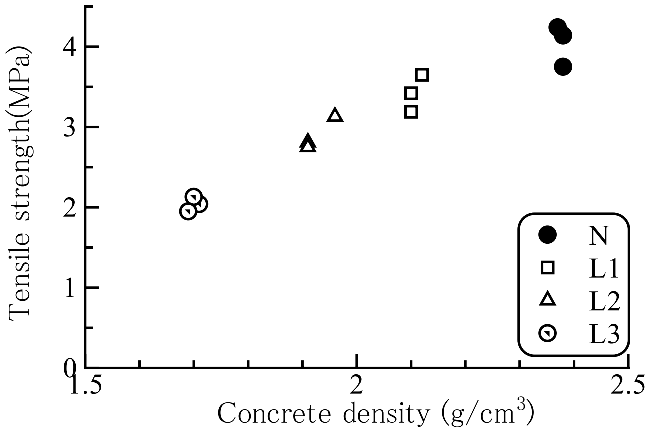

Fig.7 Relationship between concrete density and tensile strength

One of the reasons for the smaller-than-expected shear cracking strength of the L3 specimens is that their tensile strength is very low. **Fig.7** shows the relationship between concrete density and tensile strength. The tensile strength of the concrete in the L3 specimens is only about 50% that of the concrete used for the N specimens. **Table 6** shows the brittleness factor range (= compressive strength/tensile strength) of concrete used in previous studies focusing on the reduction in shear cracking strength of lightweight concrete members, and also the brittleness factors of the concrete used in this experiment. Whereas L1 and L2 specimens had similar values to past studies, the brittleness of L3 specimens was relatively high. Since the number of specimens tested was limited, these results alone are not enough to draw clear conclusions, but at least they suggest that when high-strength lightweight concrete with a very high brittleness factor is used, the shear cracking strength may be much lower than anticipated.

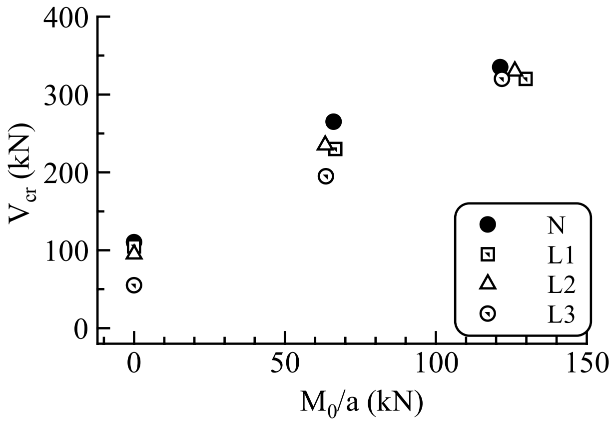

Fig.8 Relationship between prestressing level and shear cracking strength

The next subject of this study is the influence of prestressing on shear cracking load. **Fig.8** shows the relationship between Vcr and shear force, or the decompression moment produced in a specimen by prestressing (Mo) divided by the shear span (a). Some researchers have noted that the influence of prestressing on shear cracking strength differs according to the distribution of prestressing in the section[13], but that an almost linear relationship between Mo/a and shear cracking strength is obtained if PC members with stress distributed in a triangular pattern are compared. This is the case in our test. So, assuming Vcr is expressed as a linear function of Mo/a, we calculated the constant of proportionality and obtained values of 1.87 (N), 1.66 (L1), 1.86 (L2), and 2.17 (L3). This means there is no correlation between the type of aggregate and the value of the constant of proportionality. Considering this result, it is presumed that using lightweight aggregate will not affect the degree of increase in shear cracking strength achieved by prestressing.

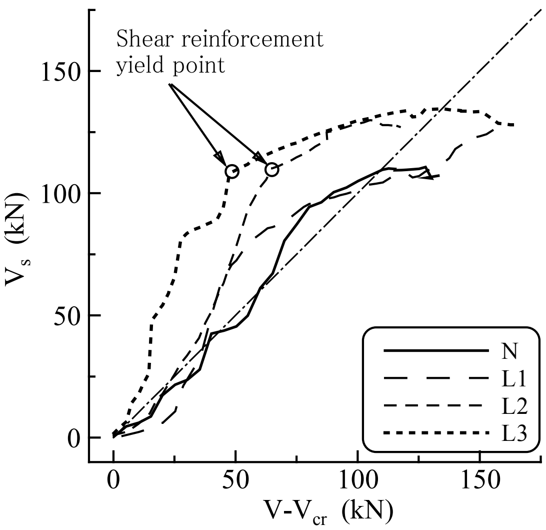

Fig.9 Relationship between V-Vcr and Vs (no prestressing)

4.2 Shear force borne by concrete after shear cracking

The shear force Vs borne by the shear reinforcement was calculated using the strain measurements taken from strain gauges attached to the steel bars. The stress-strain relationship for the steel used here was obtained from the tensile tests on the reinforcing bars, and the post-yield strain hardening area was also considered in the stress evaluation. The maximum tensile stress obtained for each strain measuring point was adopted for each of the shear reinforcing bars, S1, S2, and S3.

Fig.9 shows Vs for the case of no prestress. The shear force V acting on the member minus the shear force Vcr at the time of shear cracking is plotted on the x-axis.
If the shear force borne by the concrete were to remain at Vcr after shear cracking and, therefore, any excess shear force beyond that is sustained only by the shear reinforcement, the relationship between Vs and V-Vcr should fall on a straight line at an angle of 45° in Fig. 9. In the test results, the relationship is close to the 45° line for the N specimens, but for other specimens the slope is greater than 45°. This indicates that Vc, the shear force borne by the concrete, falls after shear cracking and that this reduction was compensated for by the shear reinforcement. The results for the L1 and L2 specimens fall somewhere between the results for the N and L3 specimens. Given this result, it should be noted that Vs for L2, made using lightweight coarse aggregate, increased more than that for L1, which means decrease of

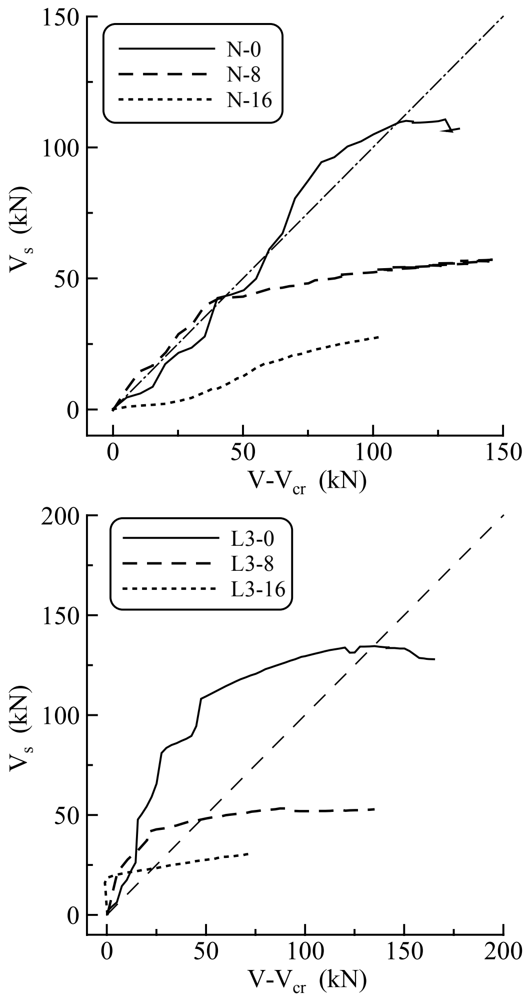

Fig.10 Relationship between V-Vcr and Vs (upper: N sample; lower: L3 sample)

Vc for L2 is more significant than for L1. As clearly indicated by these results, the shear cracking load of specimens with no prestress varies with the type of aggregate used, and after shear cracking Vc also varies widely depending on the type of aggregate used. This presumably occurs because, when lightweight aggregate is used, the transmission of stress through the crack surface suddenly decreases because the shear crack penetrates the aggregate to form a flat, smooth crack surface. A significant release of tensile stress occurs at this point. In other words, it seems to indicate that in RC members using high-strength lightweight concrete, the shear force borne by the concrete after shear cracking does not necessarily remain constant and that it is inappropriate to apply the modified truss analogy.

Table 7 Vcu calculation

Specimen	Vcu (kN)
N-0	134
L1-0	135
L2-0	86
L3-0	92

However, as the measurement results for the L3-0 specimen indicate, even after all shear reinforcement yields and the rise in Vs slows, the load continued to increase. That is to say, although Vc temporarily decrease with propagating shear crack, Vc begins to rise again after the shear reinforcement yields. Presumably this occurs because an arch mechanism forms after shear cracking. **Fig.10** shows calculated values of Vs after shear cracking for different levels of prestress in N and L3 specimens. For the N specimens, the increase in Vs after shear cracking matches the rise in shear force and the tensile force borne by the shear reinforcement did not exceed the modified truss analogy. Even for prestressed L3 specimens, Vs rises sharply after shear cracking, indicating a temporary decline in Vc. As the amount of prestress is increased, however, Vs becomes smaller.

Even with prestressing, a sudden sharp rise in Vs inevitably accompanies a temporary reduction in Vc after shear cracking. But with greater prestressing, Vs itself becomes smaller, which means that the influence of a temporary drop in Vc is reduced.

4.3 Shear force borne by concrete at shear compression failure

Table 7 shows measurements of shear force (Vcu) borne by the concrete at the time of compression failure for specimens with no prestressing. This shows that Vcu is lower for the L2 and L3 specimens made using lightweight aggregate, whereas the L1 specimens made using lightweight aggregate only as the fine aggregate produced a value of Vcu almost the same as that for the N specimens made using normal-weight aggregate.

In prestressed members, as shown by the progress of cracking in **Fig. 4**, shear cracks penetrate less into the compressive region of the concrete. Based on the axial compression strain distribution of the concrete, as measured by strain gauges attached to the compression side, the position of the neutral axis was calculated as shown in **Fig. 11.** When the prestress is 0 MPa, the measured position of the neutral axis is far below the analytical value, indicating that the compression region shrinks as shear cracking progresses. On the contrary, when the prestress is 16 MPa, the measured neutral axis is close to the analytical position and shear cracking has almost no influence on the position of the neutral axis. When the prestress is 8 MPa, the result depends on the type of aggregate; the two neutral axis positions are close for N specimens

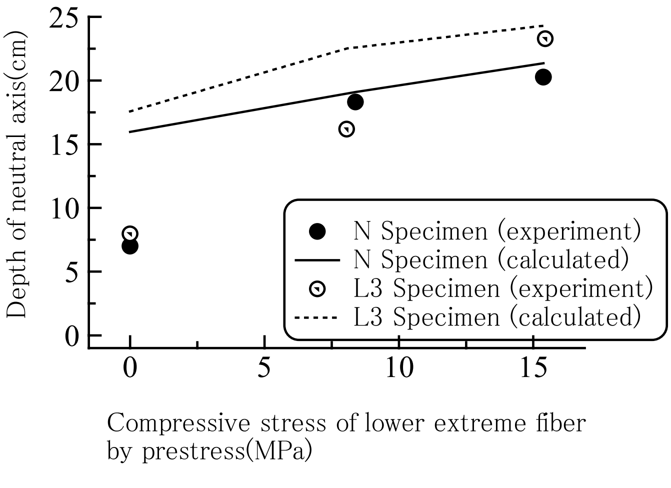

Fig.11 Depth of neutral axis of N and L3 specimens

made using normal-weight aggregate, while for the L3 specimens the calculated position is below the measured one.

The relationship between the compressive force of concrete at the section upon shear failure and Vcu was studied. The compressive force was calculated as follows. Assuming that the compressive strain of the upper extreme fiber of the concrete section is equal to the strain at the time of maximum stress, as obtained in compressive strength tests, and that the strain is linearly distributed from the position of the neutral axis to the compression edge of the section, the compression resultant was calculated from the stress-strain relationship of the concrete. **Fig.12** illustrates the relationship between Vcu and compression resultant at the time of failure. As indicated by the figure, the relationship is almost linear regardless of aggregate type. That is to say, prestressing restricts the rise of the neutral axis accompanying the progress of shear cracking and causes a larger axial compressive force to act on the concrete than when no prestress is introduced, eventually resulting in an increase in shear force borne by the concrete. The fact that the axial compressive force acting on the concrete is almost linearly proportional to the shear force is understood to indicate that the inclination of the compression strut in the arch mechanism formed by the concrete is constant regardless of the type of aggregate.

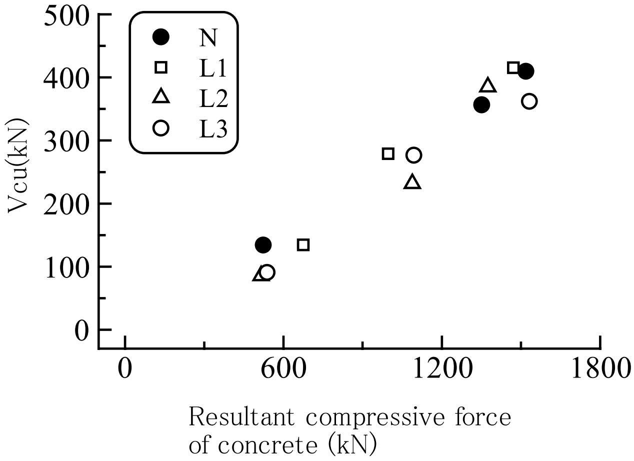

Fig.12 Relationship between Vcu and resultant force of concrete

A simplified method of calculating Vcu for a prestressed member is proposed. This method is based on the shear capacity equation corresponding to RC deep beams as reported in reference 14. The reported equation is modified to add an introduced compressive force term so as to take into account the influence of prestressing. Compressive stress introduced to the concrete by prestressing produces a triangular distribution pattern with zero stress at the upper extreme fiber of the section, and the centroid is located at 2/3h (h is the height of the beam section) from the upper edge of the section. The angle formed by the straight line connecting the centroid and the loading point to the member axis is θ; this is regarded as the tilt angle of the compression strut. Then, the effect of the compression resultant Co introduced into the concrete by prestressing is added, as shown in the following equation:

$$V_{cu} = v_{cu} \cdot bd + C_0 \cdot \tan\theta \qquad (1)$$

$$v_{cu} = \frac{0.24 \cdot \left(f'_c\right)^{2/3}\left(1+\sqrt{p_t}\right)\left(1+3.33r/d\right)}{1+\left(a/d\right)^2} \qquad (2)$$

where f'c: compressive strength (MPa) of the concrete; p_t: tensile steel ratio (%); r: width of the loading plate (m); d: effective height (m); a: shear span (m); and b: width of section (m). In this experiment, pt = 0.76%, r = 0.1 m, and a/d = 3. Specimens whose mode of failure appeared to be bending compression failure, N-8, N-16, L1-16, and L2-16, were excluded from the comparison. When lightweight aggregate was used, the value of vcu obtained from Equation (2) was reduced to 70%.

The experimental results for Vcu/bd and the results obtained using the simplified calculation method proposed above are shown in **Fig. 13**. Note that reference 15 as cited in the legend is a report on loading tests of 14 PC members with no shear reinforcement (with normal weight aggregate, compressive strength of 40.6 to 92.0 Mpa, and a/d = 3), while reference 16 is a report on loading tests of PC members using high-strength fly ash artificial aggregate (compressive strength: 56.2 to 84.9 MPa; a/d = 2.5 to 3.5). Because reference 16 does not indicate the width of the loading plate, a range is plotted, for r = 0 to 10 cm. As these results indicate, calculated values of Vcu/bd are smaller than the experimental values, and the ratio is roughly in the range 1.0 to 1.3. Since the calculation method yields results on the safe side, it is possible to say, roughly speaking, that the shear force borne by the concrete at shear compression failure of a prestressed beam with a rectangular section can be estimated. Even when lightweight aggregate is used, it is confirmed that this calculation method yields appropriate results.

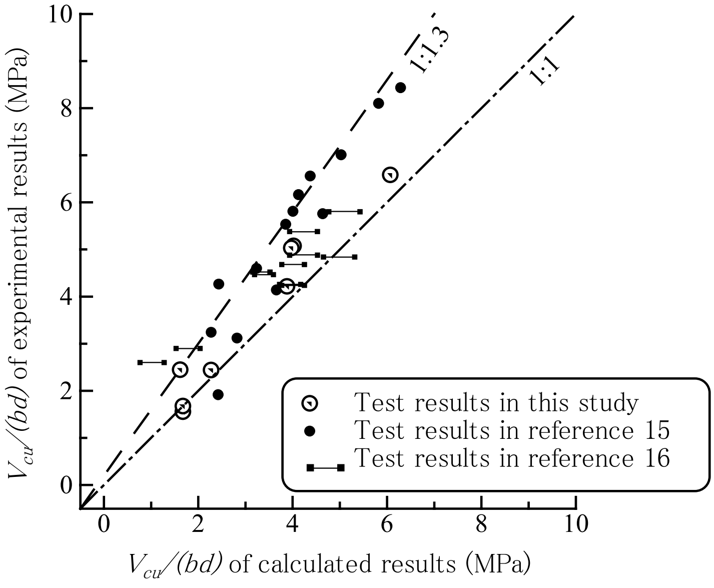

Fig.13 Comparison of Vcu/(bd)

For all specimens subjected to the loading test reported here, the prestress distribution was triangular. In future, it will be necessary to check whether Equation (1) is suitable in cases where the prestress distribution is not triangular. Changes in the amount of shear reinforcement could affect the shear force borne by the concrete on the compression side 17), so it will also be necessary to verify the influence of shear reinforcement.

5. CONCLUSIONS

A series of experiments was carried out on PC members made of high-strength lightweight concrete, and the results can be summarized as follows:

(1) The shear cracking strength of RC beam members made using high-strength lightweight concrete is lower than that of similar specimens using normal-weight aggregate. In particular, when a lightweight material is used as both the fine and coarse aggregate, shear cracking strength appears to be even lower than estimated by the conventional equation. One of the reasons for this is that the high-strength lightweight concrete used in these tests has a larger brittleness factor than typical lightweight concretes used in past loading tests. Therefore, if the brittleness factor of a lightweight concrete is outside the range investigated in past experiments, it is possible that the shear cracking reduction factor typically used for lightweight concrete members may not be applicable.

(2) The increase in shear cracking strength obtained by prestressing is not related to the type of aggregate. That is to say, there is no need to consider an adjustment to the shear cracking strength increment obtained by prestressing just because lightweight aggregate is used.

(3) The shear force borne by the concrete after shear cracking falls temporarily and sharply in the case of lightweight concrete members. In particular, for high-strength concrete made using a lightweight material for both the fine and coarse aggregate, it is sometimes inappropriate to assume that the contribution made by the concrete remains constant after shear cracking.

(4) The shear force borne by the shear reinforcement increases after shear cracking, but thereafter an arch mechanism is formed and contribution of the concrete begins to increase again. It is confirmed that the shear force borne by the concrete at shear compression failure tends to be lower when lightweight coarse aggregate is used.

(5) The shear force borne by the concrete at shear compression failure increases in proportion to the prestressing force, regardless of the type of aggregate.

(6) This increment may be calculated simply from the compressive force introduced by prestressing and its centroid regardless of the type of aggregate used. Some deviation between this simple calculation and experiment is observed, with the calculation yielding values between about 1.0 and 1.3 times the experimental values. It will be necessary to improve the accuracy of this calculation in future work.

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