- Technical Paper -

A STUDY ON SHEAR STRENGTH OF CONCRETE UNDER DIRECT SHEAR TEST

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ABSTRACT

The results of double shear tests are reported on lightweight aggregate (LWA) and normal weight concretes. A linear relationship between shear strength and compressive strength was obtained for both types of concrete. It has been found that shear strength has direct relationship with surface roughness of a sheared section. Surface roughness of LWA concrete section was lower than that of normal weight concrete. Some aspects of failure mechanism were discussed.
Keywords: Shear strength, double-shear test, lightweight concrete, surface roughness

1. INTRODUCTION

Shear strength of a material is often used to cover several concepts such as 1) strength against pure shear, 2) shear stress required for failure without normal stress, 3) shear diagram on solid interface depending on normal stress, 4) Mohr's stress envelop [1]. According to Everling [2] shear strength τ can be defined as the breaking shear force T applied to an imposed surface A supporting no normal force, that is τ=T/A.

Shear strength has been the subject of many controversies and debates since the beginning of the 20th century [3]. The problem is that the pure shear failure mode (mode II) of concrete, which is needed for modeling of the shear phenomenon, is envisaged but not yet can be realized. At the laboratory scale, attempt to realize mode II crack propagation often fail because tensile mode (mode I) growth takes over. Concrete material is weak in tension and comparatively stronger in shear. Under shear loading, stress concentration near shearing edges of specimen occurred, this is the reason of present of tensile stress causing mode I crack propagation before mode II growth.

Some shear testing methods have been proposed and applied to concrete. Fig.1 shows specimen geometries and loading configurations of these methods. Fig.1(a) indicates the situation of pure shear stress along a crack, which is envisaged by testing, but no device yet can create this condition. Fig.1(b) is loading configuration proposed by

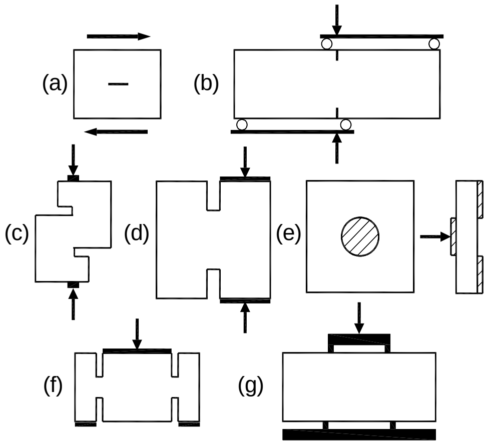

Figure1 Different test configurations

Iosipescu [4]. This single shear test geometry looks very attractive. Bazant and Pfeiffer [5] claimed to achieve mode II using this method. The results and interpretations were rather controversial. After Ingreffea and Panthaki [6], and Schlangen [7] came to the conclusion that mode I is the governing mode of this test. This test is also not reliable because cracks often start from the two middle loading points and the damaged section is different from the tested section [8]. Fig.1(c) and 1(d) show two types of indirect single shear test. Finite element analyses have shown that the push-off specimen in Fig.1(c) has tensile stress exist at the crack tips, that is a mixed stress condition. Reinhardt et al. [9] reported that the test in Fig.1(d) yields pure mode II. However, later Prisco and Ferrara [10] raised doubt about this conclusion and showed that the testing method is

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also mixed mode. Fig.1(e) is the punch-through shear test. Shear strength and damage condition of specimen obtained by this test are very much depend on specimen size and loading part size[8]. Fig.1(f) is double-shear test for cylinder specimen proposed by Luong [1]. Obviously this test yields a mixed mode result because of the existence of bending stress. Finally, Fig.1(g) is double shear test for a beam specimen. This testing method is very suitable for measuring shear strength [8]. One of the good points of this test is that the damaged section very often coincided with the test section. The test geometry is comparatively easy and loading is also simple. The test, however also yields the mixed mode result.

Concrete shear strength is of practical interest. For example, Uomoto and Minematsu [8] pointed out that the NATM (New Austrian Tunneling Method) required knowledge of shear strength of concrete. Joints between dissimilar media under shear forces or normal forces parallel to existing cracks are also cases where shear strength is needed.

Based on the ground of the aforementioned studies, the present work has two main objectives. The first is obtaining shear strength of different types of LWA and normal weight concretes. And the second is to find out the relation between shear strength and roughness of a sheared section. Double shear test in figure 1(g) was selected as a testing method for the experimental study.

2. TEST PROGRAMS

2.1 Detail of Tested Specimens

The experimental work consisted of four types of concretes. Table 1 shows different types of concrete together with Water/Cement (W/C) ratio and quantity of specimens for each series of tests. There are 12 series of tests. Each series has 12 specimens and the total number of specimens is 144. Shear test specimen was a concrete beam with dimensions 10×10×40cm. In addition, for each series of tests, there were three standard cylinder specimens for compressive strength and Young's modulus tests. All specimens were cast and cured in water under standard room temperature for 28 days.

Table 1 Detail of beam specimens

Series name	W/C (%)	Qtt. (unit)	Description
NSNG-1	86	12	Normal weight concrete.
NSNG-2	58	12	
NSNG-3	43	12	
NSLG-1	86	12	LWA concrete of normal fine and LW coarse aggregates
NSLG-2	58	12	
NSLG-3	43	12	
LSNG-1	86	12	LWA concrete of LW fine and normal coarse aggregates
LSNG-2	58	12	
LSNG-3	43	12	
LSLG-1	86	12	LWA concrete of LW fine and coarse aggregates
LSLG-2	58	12	
LSLG-3	43	12	

2.2 Materials and Concrete Mix Proportions

Materials used for concrete mixture are presented in Table 2. LWA used in this study were made from expanded shale with density 1.9g/cm^3 and 1.58g/cm^3 for fine and coarse aggregates respectively. The selection of mix proportions for concrete specimens is presented in Table 3. In order to find out an influence of W/C ratios to shear strength of concrete, three ratios 86%, 58% and 43% were selected for each type of concrete.This aims to have concrete compressive strengths of 20, 40 and 60N/mm^2 respectively for normal concrete. In the case of LWA concretes, however lower compressive strength is expected due to the fact that lightweight aggregate was saturated before mixing [11].

2.3 Test Arrangement and Procedure

Photo 1 shows loading arrangement of the double-shear test. A beam specimen was symmetrically positioned within a shear device. The shear device consists of two parts, a base and a top part. The outer

Table 2 Materials for concrete mixture

Name	Symbol	Type	Notes
Cement	C	Ordinary Portland cement	Density 3.16(g/cm^3)
Fine aggregate	S_N S_L	Natural sand Lightweight	Dry density 2.60(g/cm^3) Dry density 1.90(g/cm^3), absorption 20.2%
Coarse aggregate	G_N G_L	Natural crushed rock Lightweight	Dry density 2.63(g/cm^3) Dry density 1.58(g/cm^3), absorption 28.9%
Admixture	LS	Lime stone powder	Density 2.70(g/cm^3)
Admixture	SP	Superplasticizer	-
	AF	Antifoam agent	-
	VI	Viscosity improver	-

Table 3 Concrete mix proportions

Series name	W/C (%)	s/a (%)	Weight per unit volume (kg/m^3)										G_{max} (mm)
			W	C	LS	S_N	S_L	G_N	G_L	SP	AF	VI	
NSNG-1	86			192	162					2.667			
NSNG-2	58	48	165	287	81	892	-	977	-	3.810	0.381	1.143	
NSNG-3	43			381	0					4.953			
NSLG-1	86			192	162					1.143			
NSLG-2	58	48	165	287	81	892	-	-	587	2.286	0.381	1.143	
NSLG-3	43			381	0					3.429			15
LSNG-1	86			192	162					0.762			
LSNG-2	58	48	165	287	81	-	652	977	-	1.524	0.381	1.143	
LSNG-3	43			381	0					2.286			
LSLG-1	86			192	162					0.762			
LSLG-2	58	48	165	287	81	-	652	-	587	1.905	0.381	1.143	
LSLG-3	43			381	0					3.048			

* Gmax denotes maximum size of corase aggregate

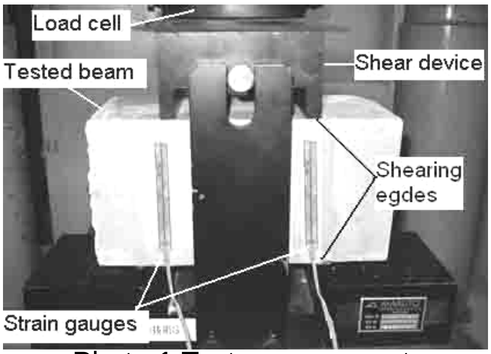


Photo 1 Test arrangement

surface of shearing edges of the top part is coincided with the inner surface of shearing edges of the base. The intersection of this surface and the beam is the tested section that is the section used to calculate shear strength. Along two tested sections there were strain gauges glued on the surface of the beam. These gauges were used to monitor and adjust eccentric loading. Monotonic, force-controled loading was applied with speed of increment of shear stress of 0.1N/mm^2 per second.

3. TEST RESULTS AND DISCUSION

3.1 Failure of Beams

Failure of all beams was brittle. At first load increased without any sight of cracks. Then near the peak load, visible cracks were seen followed by sudden brake of specimen into pieces. The failure process of concrete beams under shear was proposed by Kaneko and Mihashi [12]. At the first stage of loading, multiple micro-cracks occurred on the local principle stress trajectories, which form a shear fracture zone along tested section. These micro-cracks distributed evenly along the fractured zone with certain inclined angle. This stage is stable. With further shear loading micro-cracks rotated following the principle stress axis under mode I condition, they tend collapse on each other. Crushing failure of the compression struts between cracks occurred as the result of further increase of shear loading, leading to macroscopic strain softening. After this stage macroscopic cracks can be seen and failure mechanism transferred into the contact mechanism that is interlocking. The interlocking phenomenon is associated with surface roughness and strength of aggregates. Interlocking mechanism of low compressive strength concrete was found ineffective. Eye-observation of damaged sections of these specimens showed that coarse aggregates were almost intact, so a possible reason for the inefficient interlocking is because of low cement paste strength. In this case sliding due to shear loading occurred along weak plane within cement pastes.

3.2 Damage Patterns

Damaged specimens were divided into two groups, namely succeeded and failed. Shown in Fig.2 are typical crack patterns of specimens. About 25% of specimens had crack pattern as shown in Fig.2(a), where crack run along the line, connecting top and bottom shearing edges (ideal crack). About 50% of specimens had crack pattern as shown in Fig.2(b). In these specimens crack started from one shearing edge and ended some where in the inner side of opposite shearing edge (good crack). Specimens with ideal and good crack patterns belong to succeeded group. They were selected for further analysis. The remained specimens had unfavorable crack pattern, where cracks were curvy or inclined in certain angle like the one shown in Fig.3(c). They failed the test and were not used for further analysis because the area of damaged section of these specimens is very much deviated from calculated area, which yields unreliable results.

Table 4 Test results

Series name	f_c' (N/mm^2)	E_c (kN/mm^2)	τ_c (N/mm^2)	ρ (Ton/m^3)
NSNG-1	20.68	27.24	4.15	2.3
NSNG-2	40.99	28.98	5.50	2.3
NSNG-3	65.35	30.91	8.41	2.4
NSLG-1	16.18	20.25	3.54	2.0
NSLG-2	33.31	19.06	4.99	2.0
NSLG-3	45.24	21.30	6.31	2.0
LSNG-1	14.91	18.65	3.11	2.1
LSNG-2	26.22	21.54	4.70	2.1
LSNG-3	42.56	22.68	6.40	2.1
LSLG-1	14.04	11.29	3.44	1.6
LSLG-2	27.90	14.46	4.81	1.6
LSLG-3	38.17	15.30	5.64	1.8

3.3 Concrete Strength

(1) Compressive strength

Experimetal results of compressive strength, Young's modulus and shear strength together with density of each type of concrete are shown in Table 4. Compressive strength and Young's modulus were obtained from average strength of 3 cylinders. Normal weight concrete gained expected compressive strength with slight over-strength for the 43% w/c ratio, while LWA concrete had 15% to 30% lower compressive strength compared to that of normal concrete.

(2) Shear strength vs. compressive strength

Fig.3 shows plots of shear strength versus compressive strength for all selected specimens. Variation of shear strength has a tendency to increase with increment of compressive strength. This variation may depend on coarse aggregate distribution density in a sheared section for high strength concrete. Relation between shear strength and compressive strength was established by fitting all data points using least-square linear regression analysis. The resulting straight line is shown in Fig.3. Coefficient of determination of the approximation is 0.65. Shear strength can be expressed by formula:

$$\tau_c = 0.1 f_c' + 2.03 \qquad (1)$$

where,

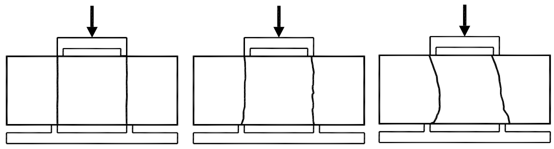
τ_c : shear strength (N/mm^2)

f_c': compressive strength (N/mm^2)

Formula (1) predicted shear strength of LWA concrete specimens tested by Azuma et al. [13] with only 6% of maximum error and shear strength of normal concrete specimens tested by Uomoto and Minematsu [8] with no more than 15% of error.

(3) Influence of W/C ratio

Fig.4 shows relation between W/C ratio and average shear strength.Decrease W/C ratio resulted



(a) Ideal (b) Good (c) Failed

Figure 2 Damage patterns

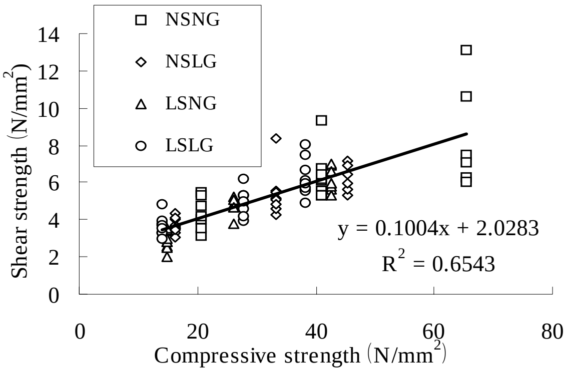


Figure 3 Shear strength and compressive strength relation

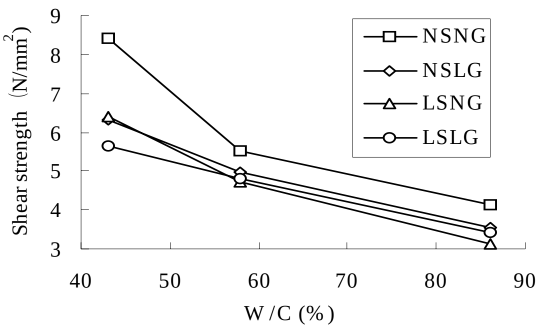
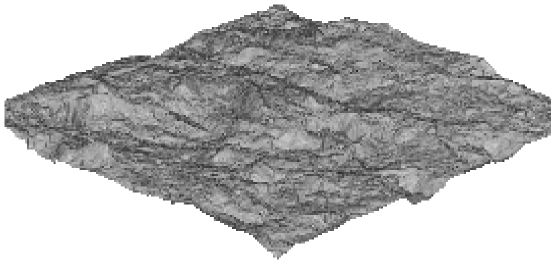


Figure 4 Relation between shear strength and w/c ratio

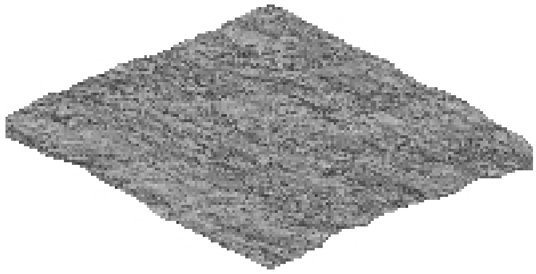
in increase of shear strength.When W/C ratio was higher than 0.6, both LWA and normal concrete had the same rate of strength increment. Shear strength of normal concrete was about 1.2 to 1.3 times higher than that of other LWA concretes. When W/C ratio was less than 0.6 shear strength of concrete increased more sharply. NSLG and LSNG showed the same rate of increment which was higher than that LSLG concrete. Normal concrete improved its strength significantly.

4. SURFACE ROUGHNESS

Crack width and surface roughness are two main factors governing the shear resistance by interlocking mechanism of RC beams. Hoang and Nielsen [14] suggested using roughness as a factor to evaluate the effect of cracking in their model to predict shear strength of RC beam using plasticity approach. This section describes the technique to measure surface roughness of sheared sections and



(a) LSNG-3



(b) NSLG-3

Figure 5 Computer images of sheared sections

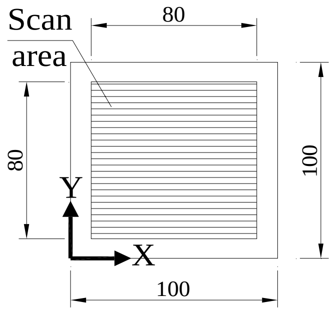


Figure 6 Scan area

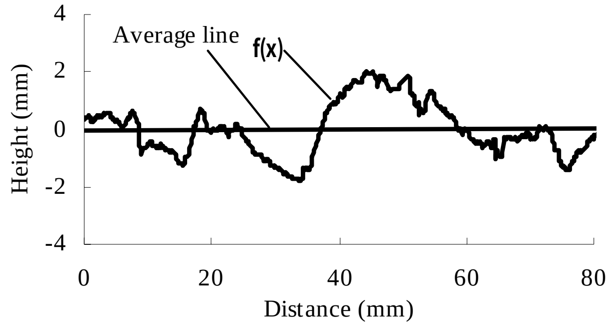


Figure 7 Surface at scanned line

later discusses its relation with concrete strength.

(1) Surface scan and roughness calculation

Surface of a tested section of specimens was scanned using the needle 3D scanner (Roland Pix-4). The scan pitch was 0.1 mm. Fig.6 shows the scan area of a section. The scanner's needle moved in straight lines along x direction to get three coordinates (x,y and z) of each point. For the selected resolution there were 801points for each scan line and there were 801 such lines in y direction. Output coordinates were used for imaging sections surface. Fig.5 shows examples of images created by CAD program using scanned coordinates. It is easy to recognize differences in roughness of these sections.

Coordinate data later used as an input for calculation of surface roughness. Average roughness R_a defined in JIS B 0610 standard was used. R_a is average value of height or depth of mountains or valleys in the waveform of concrete surface. This index could give us a link between effectiveness of interlocking mechanism due to roughness and crack size in beam shear, which will be discussed later. The calculation technique is decribed hereafter.

First, points with x and z coordinates for a scan line were plotted out. Fig.7 shows waveform of surface at scan line. Then, using least-square method the average line was drawn for the wave. Total area bounded by the wave and average line divided by length of average line is the roughness of surface at the scan line which can be written by the following formula:

$$R_a = \frac{1}{L}\int_L |f(x)|dx \qquad (2)$$

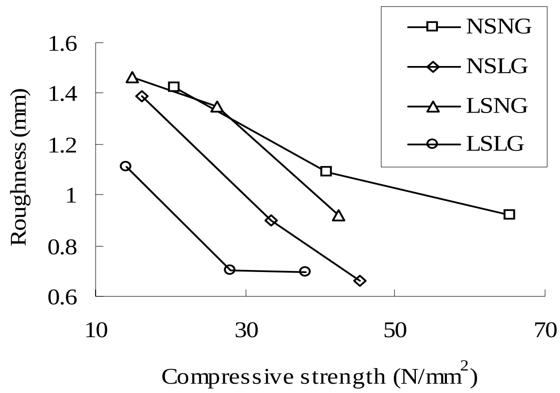


Figure 8 Roughness vs. compressive strength

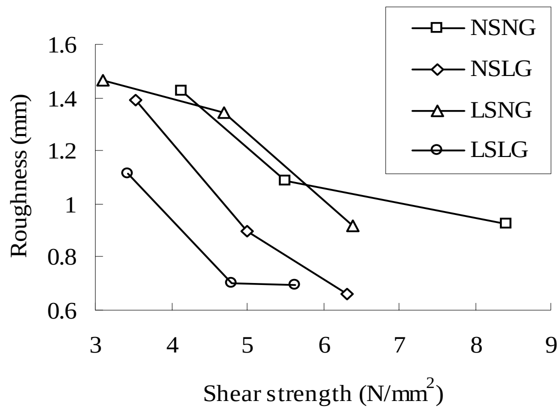


Figure 9 Roughness vs. shear strength

Average roughness of all 801 scanned lines for each sample is the roughness of the whole section.

(2) Roughness versus concrete strength

Fig.8 show relation between roughness and compressive strength. When strength is low, roughness is high. This means few coarse aggregates damaged because roughness is mainly contributed by the existence of non-damaged coarse aggregate on a surface. As concrete strength increases, roughness decreases quickly. LSLG had the lowest roughness. When strength higher than 30N/mm^2, there is no further roughness decrease in LSLG specimen. Thus almost all of coarse aggregates were damaged. This fact was confirmed by visual inspection. NSLG had higher roughness than that of LSLG when strength of concrete in a range between 20 N/mm^2 to 40 N/mm^2, however for higher strength its roughness is as low as LSLG roughness. LSNG had shear strength quite closed to normal weight concrete. In general, NSNG had the highest surface roughness.

The aggregate interlocking mechanism can only be effective if two surfaces of a crack closed to each other. It is possible to think R_a simply as average height or depth of the mountain or valley in the waveform concrete surface. If so when the distance between two crack surfaces, i.e. crack width, is larger than Ra the interlocking mechanism will lose its effectiveness. It can be seen from Fig.9 that in order to gain, for example 5N/mm^2 LSLG concrete required crack size of no more than 0.7mm, whereas NSNG concrete could gain the same strength with crack size up to 1.2mm. From the above discussion, it is possible to conclude that the reason of shear strength reduction in LWA reinforced concrete beam is because its low crack surface roughness. Limitation of crack width, by prestressing forces for example, could improve shear strength of LWA concrete.

5. CONCLUSIONS

Experimental work on LWA and normal concretes shear strength has been conducted using double shear testing method. The following conclusions can be drawn from the study:

(1) Model for shear and compressive strength relationship was established for all types of concrete.
(2) Shear strength increased when W/C ratio decreased. The rate of increment was significant when W/C ratio smaller than 60%. Of the same W/C ratio normal concrete shear strength was higher than LWA concrete about 20% to 30%.
(3) The source of shear strength reduction in LWA concrete is because of its low roughness. NSNG concrete had the highest average roughness follow by LSNG concrete, which had very closed roughness to that of NSNG concrete. Roughness of NSLG concrete was intermediate value between roughness of NSNG and the lowest roughness value belong to LSLG concrete. Limit crack size could improve shear strength of LWA concrete.

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REFERENCES

[1] M.P. Luong: Fracture Testing of Concrete and Rock Materials, Nuclear Engineering and Design, Vol.133, pp.83-95, May 1990.
[2] G. Everling: Comment up on the Definition of Shear Strength, International Journal of Mechanics, Mining science, Vol.1, pp.145-154, 1964.
[3] K.S Rebeiz : Shear Strength Prediction for Concrete Members, Journal of Structural Engineering, Vol.125, No.3, pp.301-308, March 1999.
[4] N. Iosipescu and A. Negotia: A new Method for Determining the the Pure Shearing Strength of Concrete, Concrete, Vol.3, No.2, Feb.1969
[5] Z.P. Bazant and P.A. Pfeiffer: Shear Fracture Tests of Concrete, Material and Structures, RILEM, Vol.19, pp.111-121, 1986.
[6] A.R. Ingraffea and M.J. Panthaki: Analysis of Shear Fracture Test of Concrete Beams, U.S.-Japan Seminar on Finite Element Analysis of Reinforced Concrete Structure, pp.71-91, May 1985.
[7] E. Schlangen: Experimental and Numerical Analysis of Fracture Process in Concrete, HERON, Vol.38, No.2, 1993.
[8] K. Uomoto and T. Minematsu: Fundamental Study on Testing Method for Shear Strength of Concrete, Concrete Engineering, Vol.23, No.3, pp.17-18, March 1985.
[9] H.W. Rehardt, J. Ozbonlt, Xu and A. Dingku: Shear of structural concrete members and pure shear mode II testing, Advanced Cement Based Material, Vol.5, pp.75-85, 1997.
[10] M. Prisco and L. Ferrara: On the Evaluation of mode II Fracture Energy in High Strength Concrete, Computational Modelling of Concrete Structures, pp.409-418, Apr.1998
[11] A.M. Neville: Properties of Concrete, Addison Wesley Longman, pp.760, 1995.
[12] Y. Kaneko and H. Mihashi: Mechanical Model for Direct Shear Failure of Concrete, Journal of Structural and Construction Eng., AIJ, No.535, pp.101-109, Sep. 2000.
[13] Y. Azuma, K. Iso and K. Okubo:Experimental Study on Shear Strength of Concrete, Concrete Engineering, Vol.1,pp.13-16, 1979.