Size Effect on Plastic Deformation Behavior of Plain and Confined Concretes under Compression

中心圧縮を受けるプレーンおよびコンファインドコンクリートの塑性変形挙動における寸法効果

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The purpose of the present study is to examine the effect of the specimen size and the aggregate size on the inelastic stress-strain behavior of both plain and confined concrete. The following statements can be drawn from the study.

1) It can be concluded that the behavior of the microconcrete in which the maximum size of coarse aggregate is reduced in proportion to the size of specimen may be more ductile than the concrete in actual structural members.

2) The behavior of confined concrete becomes more brittle with increasing size of specimen regardless of the spacing of hoops.

1. INTRODUCTION

Small scaled specimens are usually used for the test of Reinforced Concrete (RC) structures and members, because of the easiness of conducting experiments [1,2]. However, it is considered that there exists the effect of the size of a specimen on the strength and deformation properties of concrete [3,4]. To eliminate the size effect, microconcrete in which the size of aggregates is reduced in proportion to the size of a specimen is often used for the small scaled specimen[5,6]. It is, however, still questionable whether or not the size effect can be completely eliminated by using the microconcrete.

Little experimental data is available concerning the size effect on the stress-strain behavior of plain and confined concretes, while a lot of data exist concerning the size effect on the compressive strength of plain concrete[7,8,9,10]. The purpose of the present study is to examine the effect of the specimen size and the aggregate size on the inelastic stress-strain behavior of both plain and confined concretes.

2. SIZE EFFECT OF PLAIN CONCRETE

2.1 Outline of experiment

The details of plain concrete specimens are shown in Table 1. The test variables include the sectional shape of a specimen (circle and square), the size of a specimen (prisms: bxbx3b, b=4.5, 5.6, 7.3, 9.7, 12.5, 15.0cm; cylinder: height(h)/diameter(d)=2; d=7.5, 10, 15cm), the maximum size of aggregate (ϕa=5, 10, 20, 25, 30mm), and water-cement ratio (W/C=45, 60, 70%). The number of specimens prepared for each combination of variables was 20, and the total number was 1800. Cylinders were cast vertically, prisms

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were cast horizontally.

Ordinary Portland cement, river sand (maximum size: 5mm), and river gravel (size range: 5∿30mm) were used for the fabrication of mortar and concrete. Slump was designed to be 15cm. All the specimens were stripped at the age of 3 days, and then cured in a room at a temperature of 20 ± 2°C and a relative humidity of 75±10% until the tests. The tests were carried out at the age of 6 weeks.

The specimens were loaded under the constant strain rate of about $1\text{x}10^{-3}$/min. up to the specified longitudinal strain(ε) of $10\text{x}10^{-3}$ by using a high rigidity compressive testing machine. The longitudinal strain was measured by a couple of deformation transducers (measurement lengths were 2b for prisms and (h-2)cm for cylinders).

2.2 Test results and discussion

(1) Compressive strength

Figures 1 and 2 show the effect of the specimen size on the compressive strength(Fc) of prisms and cylinders, respectively. It is shown in these figures that i) the size effect of prisms and cylinders on the compressive strength is quite similar, i.e., the compressive strength increases with increasing specimen size (for the same maximum size of aggregate (φa)), and ii) the compressive strength decreases with increasing value of φa for the same size

Table 1 Detailes of plain concrete specimens

Size of prism	Size of cylinder	Water-cement ratio	Maximum size of aggregate
b×b×h (h=3b) (cm)	d※×h (h=2d) (cm)	W/C (%)	φa (mm)
4.5× 4.5×13.5 5.6× 5.6×16.8	φ7.5×15	45	15, 25
7.3× 7.3×21.9 9.7× 9.7×29.1	φ10 ×20	60	Mortar 10, 15, 20, 25, 30
12.5×12.5×37.5 15.0×15.0×45.0	φ15× 30	70	15, 25

※ d: diameter

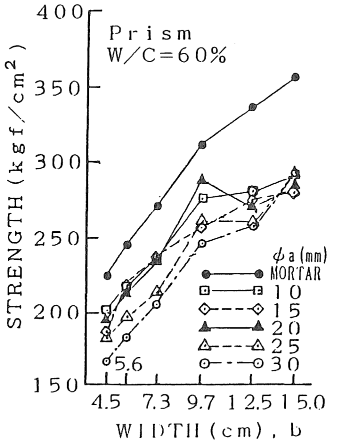


Fig.1 Compressive strength of plain concrete versus section width of specimen (prism)

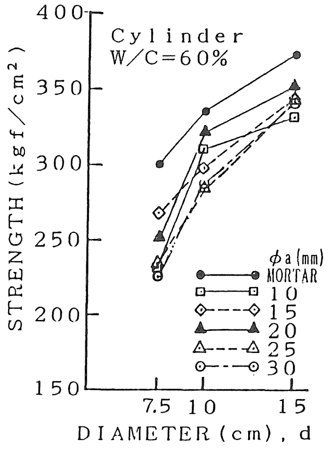


Fig.2 Compressive strength of plain concrete versus section diameter of specimen (cylinder)

of specimen. Note that all the specimens were cured in air.

Tanigawa et al.[9] reported, based on their test results, that the size effect in the compressive strength of concrete could be expressed by the product of the coefficient representing the effect in the compressive strength of mortar matrix and the other coefficient representing the effect of d/ϕa ratio (where, d: diameter of specimen, ϕa: maximum size of aggregate), i.e. the effect of geometrical heterogeneity. According to their proposed model reflecting the above findings, the compressive strength of concrete increases with the increase in the size of specimen for the value of d/ϕa smaller than about 8, and decreases with the increase in the size of specimen for the value of d/ϕa greater than about 8. In the tests conducted by Tanigawa et al., the specimens were cured in the room at a relative humidity of 90±5%.

Morita et al.[10] conducted an experiment on the size effect of concrete using various sizes of cylindrical specimens (d=1.25∿15cm) and coarse aggregates (ϕa=2.5∿10mm). In their tests, it was found that the compressive strength of concrete was constant or increased with the increase in the size of specimen for the constant value of ϕa (where, d/ϕa=5∿60). Those specimens were cured in water and tested in dry condition.

In the present experiment, the compressive strength of both mortar (d/ϕa=9∿30) and concrete (d/ϕa=1.5∿15) specimens increase with the increase in the size of specimen regardless of the value of d/ϕa. This tendency is different from the test results obtained by Tanigawa et al., and is similar to the results obtained by Morita et al., in spite of the fact that the curing conditions of concretes by the authors and Morita et al. are different.

Further experimental investigation is required for the effects of curing and testing conditions on the size effect, which are considered to affect the hydration of cement and drying shrinkage

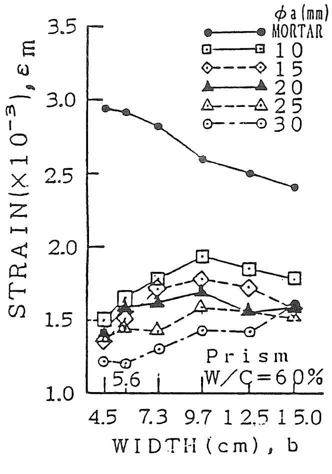


Fig.3 Strain(ε_m) at maximum compressive stress of plain concrete versus section widthof specimen (prism)

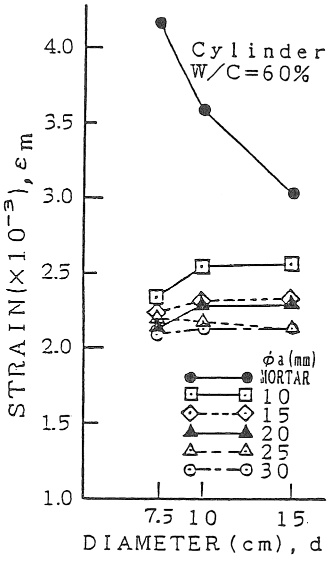


Fig.4 Strain(ε_m) at maximum compressive stress of plain concrete versus section diameter of specimen (cylinder)

of hardened concrete according to the specimen size.

(2) Strain at maximum compressive stress

Figures 3 and 4 show the effect of specimen size on the strain(ε_m) at maximum compressive stress of prisms and cylinders, respectively. Following statements can be drawn from the figures.

i) The size effects on the strain at maximum compressive stress observed for prisms and cylinders are very similar. As shown in Fig.3, the value of ε_m of concrete increases with increasing size of specimen for b=4.5∿9.7cm, while it is almost constant for b=9.7∿15.0cm. Quite similar tendency is observed in Fig.4.

ii) The value of ε_m of concrete decreases with increasing value of ϕa for the same size of specimen.

iii) The value of ε_m of mortar decreases with increasing size of specimen.

Morita et al.[10] reported that any significant effect of the specimen size (d=1.25∿15cm) on the value of ε_m was not observed for the concrete of same mixture (ϕa=2.5, 5 or 10mm). Also, it was reported that in the microconcrete (d/ϕa=5, d=1.25∿15cm), the value of ε_m became smaller with increasing size of specimen. In the result of the present experiment, any significant size effect on the value of ε_m was not observed for the microconcrete (see Fig.7(a) to 7(c)).

(3) Stress-strain curve

Figure 5 shows the effect of specimen size on the stress(σ)-strain(ε) curve (hereinafter, $\sigma-\varepsilon$ curve) of the prisms for ϕa=25mm. It is shown that the compressive strength and initial modulus of elasticity become larger, and the slope of stress descending portion becomes steeper with increasing size of specimen. The $\sigma-\varepsilon$ curves converge at $\varepsilon=(3\sim4)\times10^{-3}$, which is similar tendency observed between the curves of concretes of different W/C or compressive strength.

Figure 6 shows the effect of the value of ϕa on $\sigma-\varepsilon$ curve of the prisms of b=7.3cm. The compressive strength and the strain at maximum compressive stress become smaller, and the slope of stress descending portion becomes less steep to a small extent with increasing value of ϕa.

Figures 7(a) to 7(c) show comparisons of the $\sigma-\varepsilon$ curves of concretes having almost same b/ϕa ratio. The compressive strengths decrease and the descending portions of $\sigma-\varepsilon$ curve show more ductile behavior for the smaller value of b or ϕa. Hence, it can be concluded that the microconcrete provides more ductile behavior than the concrete in actual structural members.

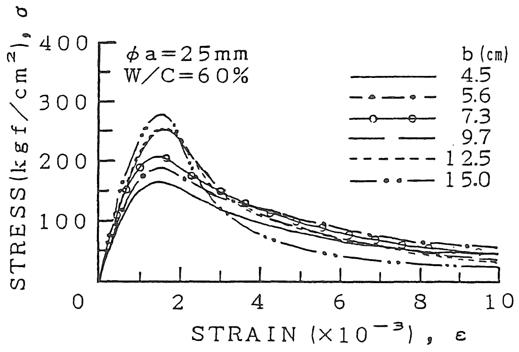


Fig.5 Stress-strain curve of prism of ϕa=25mm

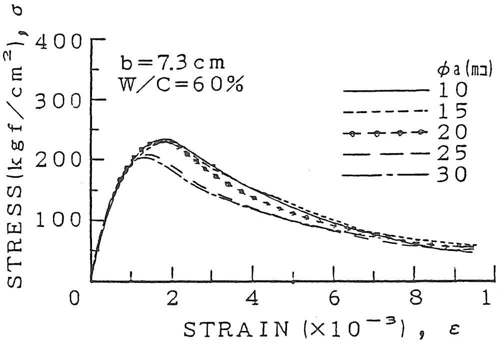
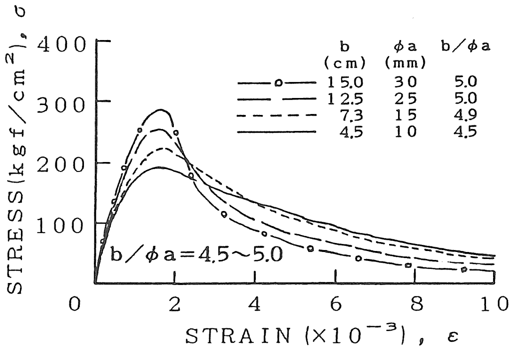


Fig.6 Stress-strain curve of prism of b=7.3cm

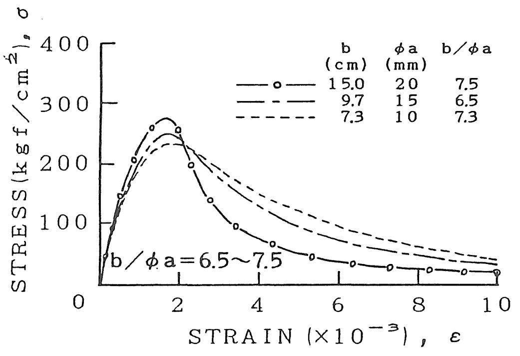
3. SIZE EFFECT OF CONFINED CONCRETE

3.1 Outline of experiment

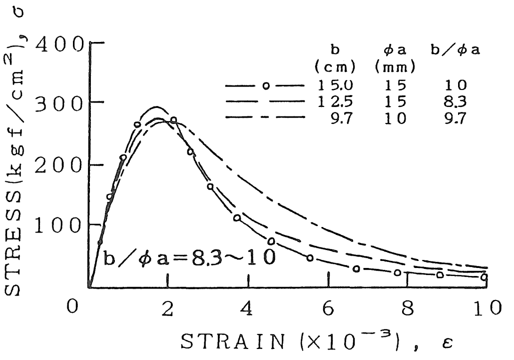
The details of confined concrete are shown in Table 2. The test variables include the size of a specimen (bxbx3b, b=7.3, 9.7, 12.5, 15.0, 20.0cm) and the spacing of hoops (S=b/4, b/2, b, ∞).



(a) b/φa=4.5∿5.0



(b) b/φa=6.5∿7.5



(c) b/φa=8.3∿10

Fig.7 Comparison of stress-strain curve of concrete of almost same b/φa ratio

The size of specimens and the arrangement of hoops are schematically shown in Figs.8 and 9, respectively. Diameters of hoops were selected for the lateral reinforcement ratio (A_h/A_c, where, A_h: cross-sectional area of hoops, A_c: vertical cross-sectional area of specimen) to be approximately 0.3% in the case of the specimen with hoops of S=b. The number of specimens prepared for each combination of variables was 12, and the total number was 240. Water-cement ratio was set to 55%. The yield strengths of hoops used are shown in Table 3. Methods of fabrication, curing of specimen, and measurement of strain were the same as those of plain concrete

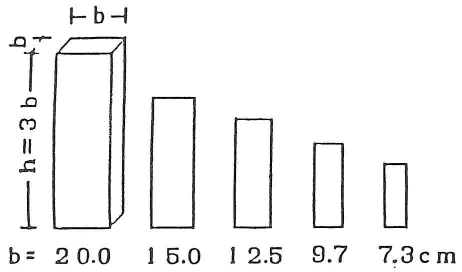


Fig.8 Size of confined concrete specimen

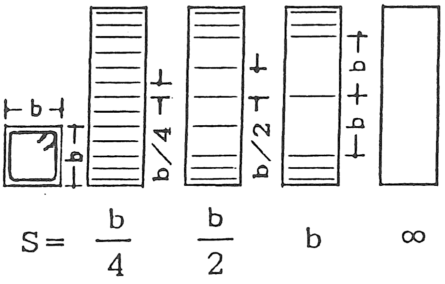


Fig.9 Arrangement of hoop

Table 2 Detailes of confined concrete specimens

Size of prism		Hoop	
Section b×b (cm)	Height h=3b (cm)	Diameter φ (mm)	Spacing S
7.3× 7.3	21.9	3.2	b/4 b/2 b ∞
9.7× 9.7	29.1	3.9	
12.5×12.5	37.5	4.9	
15.0×15.0	45.0	5.7	
20.0×20.0	60.0	8.0	

mentioned in Section 2.1. These specimens were loaded under the constant strain rate of about 2x10^{-3}/min. up to the specified strain (ε=15x10^{-3}) in general.

3.2 Test results and discussion

(1) Compressive strength

Figure 10 shows the effect of specimen size on the compressive strength of confined concrete for various spacing of hoops. It is shown that, for plain concrete (S=∞) and confined concrete with large spacing (S=b) of hoops, the compressive strength increases with increasing size of specimen, which is similar tendency observed for the plain concrete in Chap. 2. Such size effect, however, is not recognized for the confined concrete with small spacing (S=b/4, b/2) of hoops.

(2) Strain at maximum compressive stress

Figure 11 shows the effect of specimen size on the strain (ε_m) at maximum compressive stress of the confined concrete for various spacing of hoops. It is shown that, for plain concrete (S=∞) and confined concrete with large spacing (S=b) of hoops, the value of ε_m is hardly affected by the specimen size for b>9.7cm. For confined concrete with small spacing (S=b/4, b/2) of hoops, however, the value of ε_m decreases almost constantly with increasing size of specimen.

(3) Stress-strain curve

Figures 12(a) to 12(d) show the effect of specimen size on the σ-ε curve of confined concrete for various spacings of hoops. Here, damage of concrete

Table 3 Yield strength of hoop

Diameter of hoop (mm)	Yield strength (kgf/cm^2)
3.2	2415
3.9	2280
4.9	1937
5.7	2983
8.0	2654

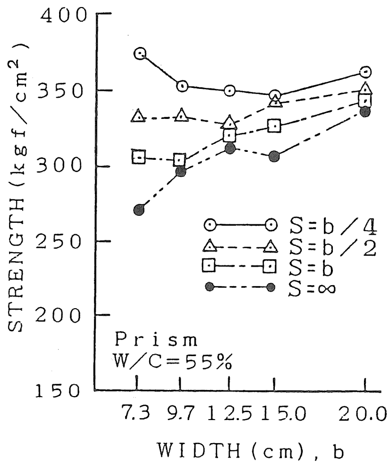


Fig.10 Compressive strength of confined concrete (prism)

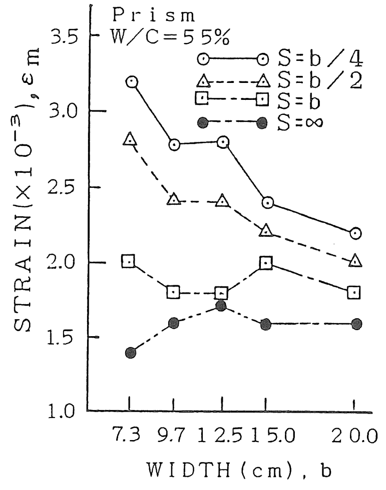
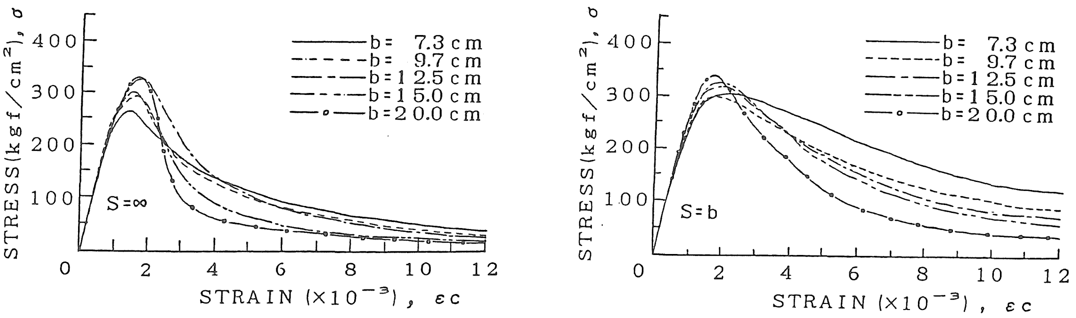
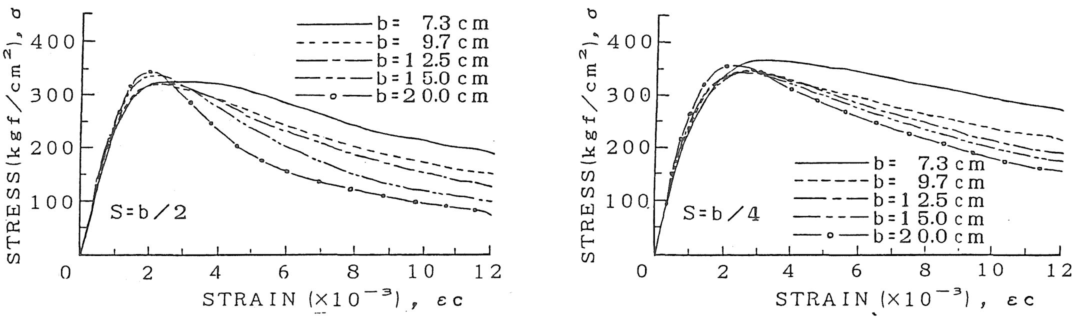


Fig.11 Strain(ε_m) at maximum compressive stress of confined concrete (prism)

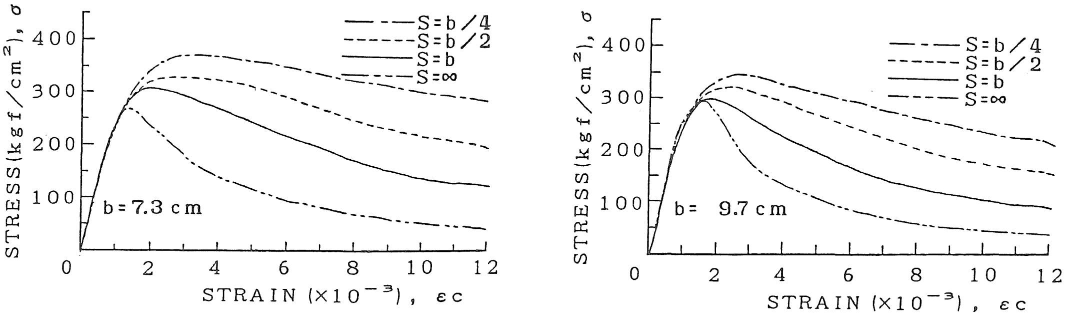


(a) S= ∞ (b) S=b

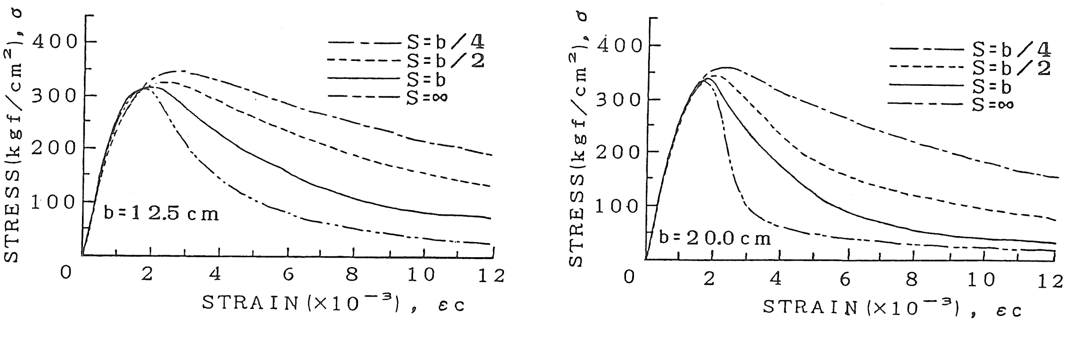


(c) S=b/2 (d) S=b/4

Fig.12 Effect of specimen size of stress-strain curve of confined concrete



(a) b=7.3cm (b) b=9.7cm



(c) b=12.5cm (d) b=20.0cm

Fig.13 Effect of spacing of hoop on stress-strain curve of confined concrete concentrated around the mid-hight of specimens, so that all the damage concentrated zones were within the strain measurement region of specimens. The figures show that the descending portions of σ - ε curves become steeper with increasing size of specimen regardless of the spacing of hoops.

Figures 13(a) to 13(d) show the effect of spacing of hoops on the σ - ε curve of confined concrete for various sizes of specimen. Familiar tendency is observed that the compressive strength is higher and the descending portion of σ - ε curve is less steep for the smaller spacing of hoops. Note that this tendency is more remarkable for the smaller specimens.

4. CONCLUSION

The effect of the size of specimens and aggregates on the deformation behavior of plain and confined concretes was discussed. The following statements can be drawn from the study.

1) For plain concrete, stress(σ)-strain(ε) curves are quite different between microconcretes in which the maximum size of coarse aggregate is reduced in proportion to the size of specimen. Namely, the compressive strength decreases and the descending portion of σ - ε curve shows more ductile behavior with decreasing size of specimen or aggregate (Fig.7(a) to 7(c)). Hence, it can be concluded that the behavior of the microconcrete may be more ductile than the concrete in actual structural members.

2) The compressive strength of confined concrete increases with increasing size of specimen for large spacing of hoops. Such size effect, however, is not recognized for small spacing of hoops (Fig.10).

3) The behavior of confined concrete becomes more brittle with increasing size of specimen regardless of the spacing of hoops (Fig.12(a) to 12(d)).

REFERENCES

1) ACI Publication SP-24, Models for Concrete Structures, 1970.

2) Alami,Z.Y., and Ferguson,P.M., "Accuracy of Models Used in Research on Reinforced Concrete", Journal of ACI, Proeedings Vol.60, No.11, Nov. 1963, pp.1643-1664.

3) Sanga,C.M. and R.K.Dhir, "Strength and Complete Stress-Strain Relationships for Concrete Tested in Uniaxial Compression under Different Test Conditions", Materiaux et Constructions, Vol.5, No.30, 1972, pp.361-370.

4) Koike,S., Okufuji,K. and Kobayashi,N., "Size Effect on Inelastic Deformation Behavior and Expression for Stress-Strain Curves of Concrete", Cement Association of Japan, Review of the 41st General Meeting / Technical Session, 1987, pp.244-247.

5) Hughes,B.P. and G.P.Chapman, "The Deformation of Concrete and Microconcrete in Compression and Tension with Particular Reference to Aggregate Size", Magazine of Concrete Research, Vol.18, No.54, March 1966, pp.19-24.

6) Pons,G., Ramoda,S.A. and Maso,J.C., "Influence of the Loading History on Fracture Mechanics Parameters of Microconcrete: Effects of Low-Frequency Cyclic Loading", ACI Material Journal, No.85-M37, Sept.-Oct. 1988, pp.341-346.

7) Gonnerman,H.F., "Effect of Size and Shape of Test Specimen on Compressive Strength of Concrete", Proceedings of ASTM, Vol.25, Part II, 1925, pp.237-250.

8) Neville,A.M., "The Effect of Slope and Size of Concrete Test Cubes on Mean Strength and Standard Deviation", Magazine of Concrete Research, Vol.8, No.23, Aug. 1956, pp.101-110.

9) Tanigawa,Y. and Yamada,K., "Size Effect in Compressive Strength of Concrete", Cement and Concrete Research, Vol.8, 1978, pp.181-190.

10) Morita,S., Fujii,S. Ishizuka,H. and Nakanishi,H., "Size Effect in Model Test of Reinforced Concrete (Part 1. Size Effect in Model Concrete", Proceedings of the Annual Meeting of AIJ, 1985, pp.477-478 (in Japanese).

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