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Effect of aggregate on the performance of confined concrete

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Abstract

This paper presents an experimental investigation for the mechanical behavior of confined concrete specimens made with different types of coarse aggregates and subjected to concentric loads. The response of the specimens varies with the variation in the properties of the aggregates. The effect of different levels of transverse reinforcement ratio on the behavior of the studied types of concrete is investigated and the results are analyzed and presented in the study. The study included forty-eight cylindrical specimens of 100 mm diameter and 650 mm height. The results of the study show considerable effect for the type of the used aggregate on the mechanical behavior of the specimens. The effect of changing the spacing of the stirrups and the configuration of the stirrup closure are also investigated and analyzed in the paper.

Keywords: Aggregate; Compressive strength; Concrete; Confinement

1. Introduction

Confinement of concrete elements using transverse reinforcement has been of great interest for the researchers over the past century. In 1928, Richart [1] started investigating the mechanical behavior of concrete specimens confined by hydraulic pressure. Many researchers investigated the confinement of concrete elements [2–6]. The previous studies investigated many parameters that extended to include the strength of concrete, yield strength of the confining reinforcement, volumetric ratio of the confining reinforcement to the concrete core, spacing of the confining reinforcement, diameter of transverse reinforcement, dimensions of the column, and configuration of the lateral confining reinforcement. However, the parameters mentioned above are not sufficient to determine the mechanical behavior of confined concrete elements as stated by Van Mier [7] and Shah and Ahmad [8].

Concretes with the same mechanical properties and under the same configurations may perform differently because of material properties. Concrete constituents such as cement type, coarse and fine aggregates, water–cement ratio, additives, admixtures, temperature, mixing procedure, and mix proportions have a considerable contribution on the strength and strain experienced by the confined element. However, the effect of these parameters on the behavior of confined concrete elements has not been investigated thoroughly. It is intended in this study to investigate the effect of using different types of coarse aggregate on the behavior of confined concrete columns.

2. Confined concrete under concentric load

Concrete subjected to concentric loading exhibits lateral expansion due to Poisson's effect. In the early stage of loading the lateral expansion is small, resulting in little or no confining stress from the lateral reinforcement and having an insignificant effect on the confined concrete stress–strain relationship. As the material approaches its compressive strength, its lateral dilation increases resulting in larger transverse strain and consequently attracts larger confining stress [9]. On further loading, the axial stress increases, the concrete begins to fail, and lateral expansion increases

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rapidly. At this stage, the confining stress becomes very large, and the concrete begins to benefit greatly due to the confinement. When the confining steel reaches yield strength, the magnitude of the confining stress essentially remains constant. Well beyond the maximum resistance stage, the lateral expansion can eventually become so large that the confining steel may fracture, resulting in a complete failure [10–13].

The bond between the paste and aggregate tends to set an upper limit on the strength of concrete. Bond is influenced by the surface texture, particle size and shape, and cleanliness of the aggregate. Cement paste normally bonds better to a rough-textured surface than to a smooth surface. Angular particles and those having rough, vesicular surfaces have a higher water requirement than rounded material. Nevertheless, crushed and natural coarse aggregates generally give substantially the same compressive strengths for a given cement factor. The angularity of aggregates may cause stress concentrations that affect the performance of concrete. Moreover, the strength of aggregate and its porosity affect the mechanical behavior of concrete from both strength and ductility points of view. These effects contribute to the failure pattern of concrete and consequently its behavior under lateral pressure [14,15].

Previous investigations have shown that confinement by suitable arrangement of transverse reinforcement results in a significant increase in both the strength and ductility of compressed concrete. These previous researches were directed to investigate the effect of lateral confinement on strength and strain enhancements and the changes in the slope of the descending branch of the concrete stress–strain curve of reinforced concrete columns. For lightly confined columns, the lateral reinforcement may not reach the yield strength but the contribution of the lateral reinforcement may be considerable if the strain is close to yield strain. It was shown that increasing of the volumetric ratio of lateral reinforcement to concrete core more than 1% increased the strength and ductility considerably [2,3,5,6,13,16–18].

In this paper, only the parameters that differentiate among different types of aggregates are considered. Other features, that may affect the behavior of the same type of aggregate, need to be studied later.

3. Experimental program

The principal target of the experimental program was to determine the contribution of the aggregate type to the improvement of the mechanical behavior of the confined concrete columns subject to concentric loading.

3.1. Methodology

Forty-eight concrete cylindrical specimens of 100 mm diameter and 650 mm height were tested under concentric loading to examine the contribution of aggregate type to the improvement of mechanical behavior of confined columns. The height of the specimen was chosen as the maximum height could be used with the testing machine to minimize the effect of the friction at the end of the specimens on the failure mode. The load capacity of the used testing machine was 1200 kN which controlled the choice of the cross sectional area of the specimens. Three types of aggregates were utilized in the study. The confinement level was intended to be controlled by the spacing of the stirrups that generate the lateral pressure. The spacing between stirrups was varied between 20 and 80 mm. It was considered in the program to study the effect of the stirrup closure on the lateral confinement and the consequent behavior of concrete elements. Two types of stirrup closure were utilized; welded stirrups and closed hoops (overlapped) stirrups. Two replicates for each configuration were tested to minimize the bias expected in concreting processes.

3.2. Procedure

3.2.1. Materials

In order to investigate the responsibility of the type of aggregate in the uncertainty in the behavior of confined concrete columns; three types of aggregates were utilized in the study. The first was siliceous river gravel with specific gravity of 2.55 and absorption ratio of 2.05%. The Gravel was rounded natural aggregate with smooth surface. The second was Dolomite with specific gravity of 2.65 and absorption ration of 1.34%. The third type of aggregate was Basalt with specific gravity of 2.60 and absorption ration of 1.53%. The maximum grain size of the aggregate was 20 mm for all types. Dolomite and Basalt were crushed stones. Hence, the used aggregates from the late types were angular with rough surfaces. All aggregates are obtained from the East Desert, Egypt. Self-compacting admixture that is complying with ASTM C-494 was used. The utilized cement in the study was Ordinary Portland Cement.

3.2.2. Mix proportions

Numerous trial batches were made. Standard specimens of 150 mm-cubes were cast and tested to determine the targeted strength of 37 MPa. The required strength was assigned based on mean compressive strength that is corresponding to characteristic strength of 25 MPa. The constituents were used in different fractions to determine mixture proportions that would yield the targeted compressive strength at a test age of 28 days. The optimum mix proportions included 800 kg of coarse aggregate, 800 kg of sand, 450 kg of cement, and 170 l of water to yield a cubic meter of concrete. 1.5% of cement weight of self-compacting concrete admixture was used to facilitate the placement of concrete in molds. The real strength of control cubes, as an average of sets of three cubes each, came up to 40 MPa

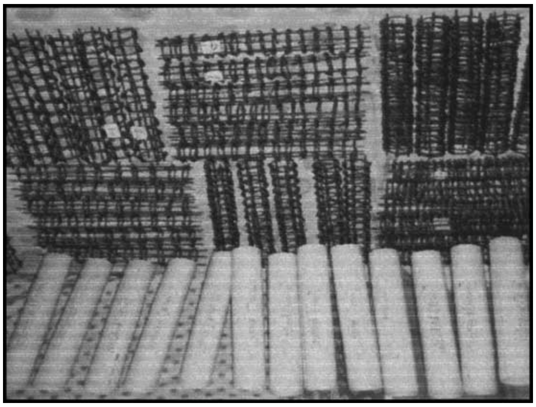

Fig. 1. Arrangement of molds and reinforcement cages.

for Gravel-concrete, 44 MPa for Dolomite-concrete, and 43 MPa for Basalt-concrete.

3.2.3. Reinforcing steel

Plain reinforcing steel of 370 MPa yield strength was utilized for both longitudinal reinforcement and transverse reinforcement. Each specimen was provided by six bars of 6-mm diameter as longitudinal reinforcement distributed uniformly on the perimeter of the specimen. The total reinforcement area was 170 mm^2 with reinforcement ratio of 2.1%. The transverse reinforcement was arranged in spacings of 20, 40, 60, and 80 mm to examine the effect of variation of lateral confining pressure for each type of concrete. These spacings yield volumetric reinforcement ration of 0.0283, 0.0141, 0.0071, and 0.0035; respectively. Figs. 1 and 2 present the preparation for the tests and the details of the reinforcement cages.

In order to avoid the disturbance near the machine platens during loading stages, steel rings of 6 mm thickness and 120 mm height were placed at the ends of the specimen to enhance the resistance of the concrete columns at these zones. The rings were screw-tightened to the specimens to ensure full contact with concrete to produce the required improvement in the concrete behavior at these regions.

4. Experimental results

The tested specimens experienced similar failure modes. All failure took place at the middle third of the specimen's height. Initially, cracks developed between the aggregates and paste. As the load increased the cracks propagate up to failure. Minor fractures were noticed in the aggregates after failure. The stirrups experienced noticeable displacement before crushing. The welded stirrups were slightly distorted in the cases of 80, 60, and 40 mm spacings. Welded stirrups with spacing of 20 mm experienced partial necking which means that the yield strength was reached.

The recorded results of the experimental program show a noticeable variation in the response of the confined concrete specimens with respect to the main variables considered in the study; aggregate type. It can be observed from the results given in Table 1 that changing the type of coarse aggregate leads to variability in the response of the confined concrete columns to lateral confinement. Also, the style of used stirrups; welded or hooked, affects the mechanical behavior of confined concrete. Finally, the spacing of utilized stirrups and the consequent confinement pressure at high loads contributes to the improvement in the concrete strength and strain.

4.1. Effect of type of aggregate

The behavior of confined concrete is affected by the type of used coarse aggregate as noticed from the results of the experiments illustrated in Table 1. The strength of Gravel-concrete confined by welded stirrups spaced at 20 mm apart recorded 97% enhancement. A

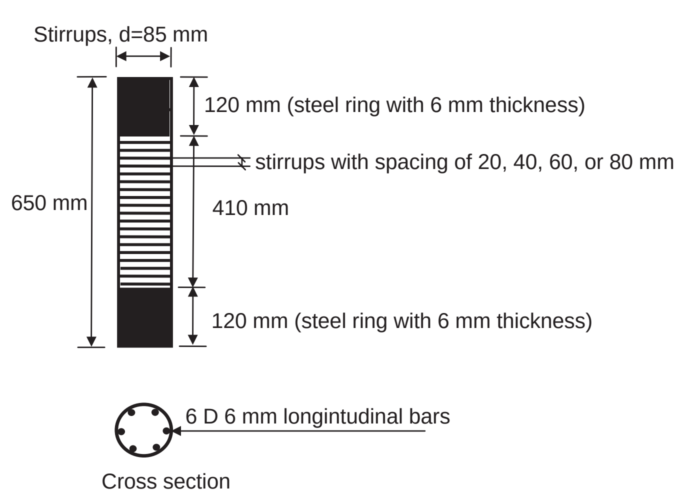

Fig. 2. Arrangement of reinforcement.

Table 1
Experimental program and results

#	Title	Aggregate type	Hoop closure	Stirrup spacing (mm)	Peak deformation (mm)	Peak strain	Peak load (kN)	Strength (MPa)
1	GW-2-1	Gravel	Welded	20.0	1.86	0.0093	640.10	81.5
2	GW-2-2	Gravel	Welded	20.0	2.50	0.0125	541.14	68.9
3	GH-2-1	Gravel	Overlapped	20.0	0.93	0.0047	399.77	50.9
4	GH-2-2	Gravel	Overlapped	20.0	1.38	0.0069	450.03	57.3
5	GW-4-1	Gravel	Welded	40.0	0.90	0.0045	380.13	48.4
6	GW-4-2	Gravel	Welded	40.0	0.84	0.0042	322.01	41.0
7	GH-4-1	Gravel	Overlapped	40.0	0.70	0.0035	349.50	44.5
8	GH-4-2	Gravel	Overlapped	40.0	0.85	0.0043	300.02	38.2
9	GW-6-1	Gravel	Welded	60.0	0.56	0.0028	276.46	35.2
10	GW-6-2	Gravel	Welded	60.0	0.52	0.0026	273.32	34.8
11	GH-6-1	Gravel	Overlapped	60.0	0.53	0.0027	253.68	32.3
12	GH-6-2	Gravel	Overlapped	60.0	0.48	0.0024	248.97	31.7
13	GW-8-1	Gravel	Welded	80.0	0.42	0.0021	251.33	32.0
14	GW-8-2	Gravel	Welded	80.0	0.40	0.0020	250.93	31.9
15	GH-8-1	Gravel	Overlapped	80.0	0.43	0.0022	250.54	31.9
16	GH-8-2	Gravel	Overlapped	80.0	0.42	0.0021	248.19	31.6
17	DW-2-1	Dolomite	Welded	20.0	2.22	0.0111	549.78	70.0
18	DW-2-2	Dolomite	Welded	20.0	1.70	0.0085	600.04	76.4
19	DH-2-1	Dolomite	Overlapped	20.0	1.22	0.0061	500.30	63.7
20	DH-2-2	Dolomite	Overlapped	20.0	0.73	0.0037	498.73	63.5
21	DW-4-1	Dolomite	Welded	40.0	0.86	0.0043	424.12	54.0
22	DW-4-2	Dolomite	Welded	40.0	0.84	0.0042	472.81	60.2
23	DH-4-1	Dolomite	Overlapped	40.0	0.90	0.0045	398.98	50.8
24	DH-4-2	Dolomite	Overlapped	40.0	0.72	0.0036	450.03	57.3
25	DW-6-1	Dolomite	Welded	60.0	0.74	0.0037	349.50	44.5
26	DW-6-2	Dolomite	Welded	60.0	0.50	0.0025	387.20	49.3
27	DH-6-1	Dolomite	Overlapped	60.0	0.50	0.0025	349.50	44.5
28	DH-6-2	Dolomite	Overlapped	60.0	0.51	0.0026	418.62	53.3
29	DW-8-1	Dolomite	Welded	80.0	0.46	0.0023	321.23	40.9
30	DW-8-2	Dolomite	Welded	80.0	0.50	0.0025	289.03	36.8
31	DH-8-1	Dolomite	Overlapped	80.0	0.42	0.0021	300.02	38.2
32	DH-8-2	Dolomite	Overlapped	80.0	0.46	0.0023	349.50	44.5
33	BW-2-1	Basalt	Welded	20.0	1.33	0.0067	450.03	57.3
34	BW-2-2	Basalt	Welded	20.0	0.94	0.0047	399.21	50.8
35	BH-2-1	Basalt	Overlapped	20.0	0.76	0.0038	398.58	50.7
36	BH-2-2	Basalt	Overlapped	20.0	1.01	0.0051	401.34	51.1
37	BW-4-1	Basalt	Welded	40.0	0.70	0.0035	390.34	49.7
38	BW-4-2	Basalt	Welded	40.0	0.56	0.0028	349.50	44.5
39	BH-4-1	Basalt	Overlapped	40.0	0.53	0.0027	403.69	51.4
40	BH-4-2	Basalt	Overlapped	40.0	0.60	0.0030	351.86	44.8
41	BW-6-1	Basalt	Welded	60.0	0.60	0.0030	302.38	38.5
42	BW-6-2	Basalt	Welded	60.0	0.60	0.0030	299.24	38.1
43	BH-6-1	Basalt	Overlapped	60.0	0.58	0.0029	350.13	44.6
44	BH-6-2	Basalt	Overlapped	60.0	0.48	0.0024	322.01	41.0
45	BW-8-1	Basalt	Welded	80.0	0.60	0.0030	285.10	36.3
46	BW-8-2	Basalt	Welded	80.0	0.50	0.0025	282.74	36.0
47	BH-8-1	Basalt	Overlapped	80.0	0.42	0.0021	300.10	38.2
48	BH-8-2	Basalt	Overlapped	80.0	0.48	0.0024	255.25	32.5

strain of 0.0109 at the maximum stress was recorded for the same specimens, on the average. The Dolomite-concrete with the same stirrup configuration recorded strength enhancement of 74% and strain of 0.0098 at the peak point. On the other hand, the Basalt-concrete specimens recorded strength enhancement of 32% and peak strain of 0.0057.

The roundness of the siliceous gravel helped to preserve uniform lateral pressure through the concrete element. This uniformity allowed the concrete to benefit from the lateral pressure to experience higher strength and ductility. On the other hand, angular aggregates led to stress concentration around the grains that helped to form cracks in the paste and to propagate these cracks as the load increased.

4.2. Effect of stirrup closure

When the stirrups used are changed to closed hooks instead of welded stirrups the enhancement in performance is reduced noticeably. The Gravel-concrete specimens with hooked stirrups spaced at 20 mm recorded strength enhancement of 42% corresponding to 97% enhancement for welded stirrups with the same diameter and spacing of stirrups. The corresponding strain for hooked stirrups is 0.0058 versus 0.0109 for welded stirrups. When Dolomite-concrete was utilized with the same configuration of stirrups, the recorded strength enhancement is 51% versus 74% for welded stirrups and the recorded strain is 0.0049 versus 0.0098 for welded stirrups. For Basalt-concrete, the recorded strength enhancement is 24% versus 32% for welded stirrups and the corresponding strain is 0.0045 versus 0.0057 for welded stirrups.

It was noticed that the welded stirrups reached the yield strength when the spacing of stirrups was 20 mm while hooked stirrups did not reach yield strength. The welded stirrups ensured the lateral pressure all around the specimen until the stress passed the yield strength. Meanwhile, hooked stirrups experienced some deformation at the hook before failure. This deformation led to the loss of lateral confinement.

4.3. Effect of stirrup spacing

The results reported in this study show that volumetric ratio of transverse reinforcement at 0.7% makes the concrete gains little enhancement in strength and ductility of concrete columns for all types of aggregate. When volumetric ratio of 1.4% of transverse reinforcement is used the enhancements become more effective. The enhancement in strength and ductility for specimens with welded stirrups is impressive when the transverse reinforcement volumetric ratio reaches 2.8% as shown in Table 1. Valuable enhancements in strength and ductility are obtained for specimens with hooked stirrups but not as high as for specimens with welded stirrups. The enhancement of confined concrete elements with the increase in the volumetric ratio of the transverse reinforcement to the concrete core is well-established in previous reports [13,16–18].

5. Sensitivity analysis

In order to examine the solidity of the outcomes of the study, a sensitivity analysis was performed to test the variability of the strength and the corresponding strain with respect to each type of the coarse aggregates used in the investigation as well as the type of stirrup closure. The results of the sensitivity analysis are presented hereafter.

5.1. Strength of confined concrete

The following relationships show the relative sensitivity of the concrete confined strength, f_{cc}, with respect to the spacing between the welded stirrups, s;

$$f_{cc} = 485(s)^{-0.63} \quad (1)$$

for Gravel-concrete,

$$f_{cc} = 286(s)^{-0.45} \quad (2)$$

for Dolomite-concrete, and

$$f_{cc} = 137(s)^{-0.30} \quad (3)$$

for Basalt-concrete.

Fig. 3 shows the outputs of the experiments as the concrete confined strength of the specimens versus the spacing of the welded stirrups. The presented results are for the averages of each two replicates of the specimens. The figure illustrates the sensitivity of the different types of concretes used in the investigation with respect to the strength enhancements. Dolomite-concrete recorded the highest strengths for all levels of confinement. On the other hand, Gravel-concrete recorded the highest sensitivity and enhancement in the strength with the variation of the lateral confinement. Basalt-concrete recorded the least response to the increase in lateral confinement. It can be noticed that Dolomite-concrete has higher strength than Gravel-concrete at low levels of confinement but when transverse reinforcement is intensified, Gravel-concrete improvement supersedes that of the Dolomite-concrete. The powers in Eqs. (1)–(3) with the values of 0.63, 0.45, and 0.30 reflect the sensitivity of the used types of Gravel, Dolomite, and Basalt when utilized as coarse aggregates in concrete columns.

For concrete specimens with hooked stirrups, the following relationships were obtained;

$$f_{cc} = 59 - 0.38(s) \quad (4)$$

for Gravel-concrete,

$$f_{cc} = 70 - 0.36(s) \quad (5)$$

for Dolomite-concrete, and

$$f_{cc} = 57 - 0.26(s) \quad (6)$$

for Basalt-concrete.

Fig. 4 shows the results of the experimental investigation for the strengths of the specimens when confined by hooked

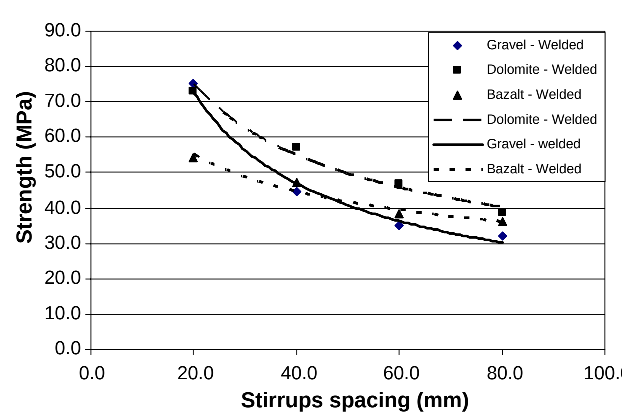

Fig. 3. Effect of spacing of welded stirrups on strength.

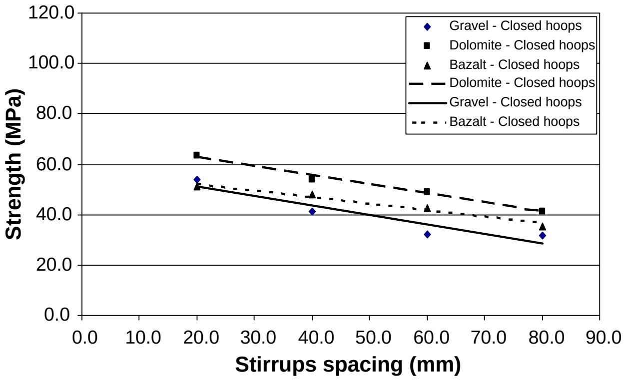

Fig. 4. Effect of spacing of closed hoops on strength.

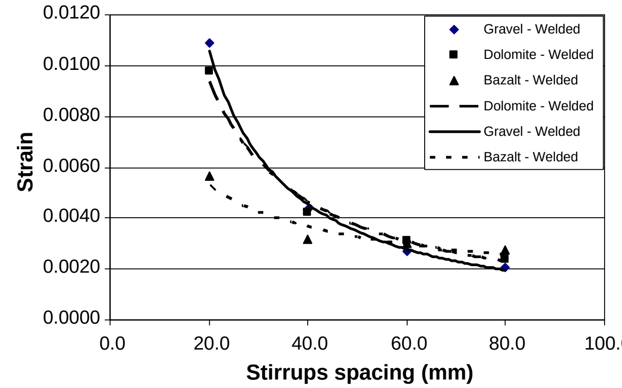

Fig. 5. Effect of spacing of welded stirrups on peak strain.

stirrups. The improvement in the mechanical behavior in the different types of concrete is similar to the improvement reported for the concrete strength for specimens confined by welded stirrups in their relationship to each other. However, the enhancement in the values of the strength when the stirrups are hooked is almost linear for all of the three types while it is non-linear in the case of welded stirrups. Dolomite-concrete has the highest strength with distinguished difference than that for Gravel-concrete and Basalt-concrete. While, Dolomite-concrete recorded less improvement in strength with respect to Gravel-concrete as lateral confinement is intensified. The coefficients of the spacing, s, in Eqs. (4)–(6); 0.38, 0.36, and 0.26; represent the sensitivity of Gravel-, Dolomite-, and Basalt-concretes to the change of stirrup spacing; respectively.

5.2. Strain at maximum stress

The following relationships show the relative sensitivity of the strain at maximum stress, ε_{cc}, with respect to the spacing between the welded stirrups;

$$\varepsilon_{cc} = 0.406(s)^{-1.22} \qquad (7)$$

for Gravel-concrete,

$$\varepsilon_{cc} = 0.195(s)^{-1.01} \qquad (8)$$

for Dolomite-concrete, and

$$\varepsilon_{cc} = 0.025(s)^{-0.52} \qquad (9)$$

for Basalt-concrete.

Fig. 5 shows the strain of the tested specimens against the spacing of the welded confining stirrups. The strains gained by Gravel- and Dolomite-concretes have very close values with slight favor for the Gravel-concrete at higher levels of confinement. While the values reported for Basalt-concrete are close to the other types when the confinement is low and get much lower as the lateral confinement increases. The powers in Eqs. (7)–(9) with the values of 1.22, 1.01, and 0.52 reflect the sensitivity of the used types of Gravel, Dolomite, and Basalt with respect to the strain at maximum stress against stirrup spacing.

For concrete specimens with hooked stirrups, the following relationships were obtained;

$$\varepsilon_{cc} = 0.00665 - 0.000062(s) \qquad (10)$$

for Gravel-concrete,

$$\varepsilon_{cc} = 0.00580 - 0.000048(s) \qquad (11)$$

for Dolomite-concrete, and

$$\varepsilon_{cc} = 0.00471 - 0.000034(s) \qquad (12)$$

for Basalt-concrete.

Fig. 6 shows the results of the experimental investigation for the strains of the specimens when confined by hooked stirrups. The improvement in the ductility in the different types of concretes is similar to the improvement reported for the ductility for specimens confined by welded stirrups in their relationship to each other. However, the enhancement in the values of the strains when the stirrups are hooked is almost linear for all of the three types while it is non-linear in the case of welded stirrups. Dolomite-concrete has the highest strength with distinguished difference than that for Gravel-concrete and Basalt-concrete. While, Dolomite-concrete recorded less improvement in strength with respect to Gravel-concrete as lateral confinement is intensified. The coefficients of the spacing, s, in Eqs. (10)–(12); 0.000062, 0.000048, and 0.000034; represent the sensitivity of Gravel-, Dolomite-, and Basalt-concretes; respectively.

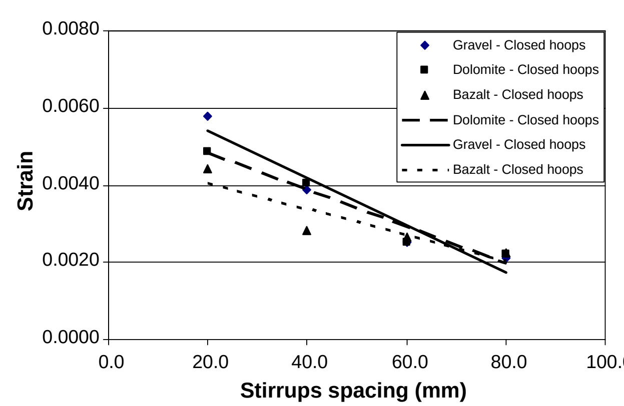

Fig. 6. Effect of spacing of closed hoops on peak strain.

6. Conclusions

Based on the conducted experimental program and the analysis, the following conclusions can be extracted:

– The traditional parameters such as strength of concrete, yield strength of the confining reinforcement, volumetric ratio of the confining reinforcement to the concrete core, spacing of the confining reinforcement, diameter of transverse reinforcement, dimensions of the column, and configuration of the lateral confining reinforcement are not sufficient to predict the mechanical and behavior of the confined concrete element. The parameters controlling the matrix, aggregates, and their bond need to be investigated deeply to determine their contribution to the behavior of confined concrete strength and ductility.
– The three types of coarse aggregates used in the study show that there is a wide range for the expected behavior of laterally confined concrete columns based on the used type of aggregate.
– The siliceous Gravel-concrete experiences large enhancement in both strength and ductility when the transverse reinforcement is higher than 1.4% in volumetric ratio. The strength enhancement reaches 97% when the volumetric ratio was 2.8% and the stirrups are welded. The corresponding strain is 0.0109.
– Dolomite-concrete experiences slightly less enhancements in strength and strain with respect to those experienced by Gravel-concrete. The strength enhancement is 74% and the corresponding strain is 0.0098 for the same previous specimen.
– Basalt-concrete experiences noticeably lower enhancements in the strength and strains with respect to the other two types utilized in the study. The strength enhancement is 32% and the corresponding strain is 0.0057 for the same specimen.
– The roundness of aggregate assists to distribute the lateral confinement and helps the concrete element to experience higher stress. On the other hand, angular grains lead to stress concentration that lowers the ability of the element to experience the same high stress.
– Welding the used stirrups proofs the uniformity of lateral pressure all around the concrete specimen. This uniformity magnifies the effect of lateral confinement on the behavior of concrete columns compared to the effect of hooked stirrups.
– Reducing the pacing between transverse reinforcement and, hence, increasing the volumetric ratio of the transverse reinforcement to the concrete core enhances the behavior of the confined concrete element, especially if this ratio is 1.4% or higher as shown in the current experimental program.

References

[1] R.E. Richart, A Study of the Failure of Concrete Under Combined Compressive Stresses, Engineering Experiment Station, University of Illinois, Urbana, Bulletin 185, 1928.
[2] S.H. Ahmad, S.P. Shah, Complete triaxial stress–strain curves for concrete, Journal of Structural Engineering, vol. 108 (4), ASCE, 1982, pp. 728–742.
[3] S. Martinez, A.H. Nilson, F.O. Slate, Spirally reinforced high-strength concrete columns, ACI Journal, Proceedings, 1984 (September–October), pp. 431–442.
[4] D. Cusson, P. Paultre, Stress–strain model for confined high-strength concrete, Journal of Structural Engineering, vol. 121 (3), ASCE, 1995, pp. 468–477.
[5] S. Pessiki, A. Pieroni, Axial load behavior of large-scale spirally-reinforced high-strength concrete columns, ACI Structural Journal 94 (3) (1997) 304–314.
[6] J. Liu, S.J. Foster, M.M. Attard, Strength of tied high-strength concrete columns loaded in concentric compression, ACI Structural Journal 97 (1) (2000) 149–156.
[7] J.G.M. VanMier, Fracture of Concrete under Complex Stress, HERON, Delft University of Technology, Netherlands, 1986.
[8] S.P. Shah, S.H. Ahmad, High Performance Concrete: Properties and Applications, McGraw-Hill, Inc., 1994.
[9] M. Sargin, S.K. Ghosh, V.K. Handa, Effects of lateral reinforcement upon the strength and deformation properties of concrete, Magazine of Concrete Research 23 (75–76) (1971) 99–110.
[10] O. Bayrak, S.A. Sheikh, Confinement reinforcement design considerations for Ductile HSC columns, Journal of Structural Engineering, vol. 124 (9), ASCE, 1998, pp. 999–1010.
[11] S.T. Mau, A.E. Elwi, S.Z. Zhou, Analytical study of spacing of lateral steel and column confinement, Journal of Structural Engineering, vol. 124 (3), ASCE, 1998, pp. 262–269.
[12] M. Samaan, A. Miramiran, M. Shahawy, Model of concrete confined by fiber composites, Journal of Structural Engineering, vol. 124 (9), ASCE, 1998, pp. 1025–1031.
[13] S.R. Razvi, M. Saatcioglu, Circular high-strength concrete columns under concentric compression, ACI Structural Journal 96 (5) (1999) 817–825.
[14] A.M. Neville, Properties of Concrete, Longman, ELBS Fourth Edition, Malaysia, 1997.
[15] ACI 221R, Guide for Use of Normal Weight and Heavyweight Aggregate in Concrete, American Concrete Institute, Michigan, USA, 1996.
[16] A.I. Karabinis, P.D. Kiousis, Effects of confinement on concrete columns: plasticity approach, Journal of Structural Engineering, vol. 120 (9), ASCE, 1994, pp. 2747–2767.
[17] M. Saatcioglu, S.R. Razvi, Strength and ductility of confined concrete, Journal of Structural Engineering, vol. 124 (12), ASCE, 1992, pp. 1438–1447.
[18] S.J. Foster, J. Liu, S.A. Sheikh, Cover spalling in HSC columns loaded in concentric compression, Journal of Structural Engineering, vol. 124 (12), ASCE, 1998, pp. 1431–1437.