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Confinement State of Reinforced Concrete Columns Made with Recycled Aggregates

Bashar Alomari, Rabab Allouzi*, Amer Alkloub

Department of Civil Engineering, The University of Jordan, Amman, Jordan

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Abstract Recycled aggregates are one of the options that can be used to form the concrete because they can be considered as environmental-friendly. Using of high replacement ratio of recycled aggregates decreases the compressive strength of the concrete and weakens the rest mechanical properties. This study intended to investigate the effect of the confinement on Reinforced concrete (RC) columns that are made with recycled aggregates since it raises the compressive strength of concrete and improves the behavior of RC columns. This study is analytical and conducted based on the available data in literature of 34 columns that were tested experimentally under axial load only by other researchers, containing various ratios of recycled aggregates. The collected data of axial load capacity are compared with ACI318-19 provisions. It can be used to estimate axial load capacity. Confinement factors are calculated and compared with Mander's formula. It is concluded that Mander's equation can be used after being multiplied by the modification factors derived in this study to better reflect the confinement state. Also, a new formula is derived to estimate the unconfined compressive strength of the concrete based on the used replacement ratio of recycled aggregates.

Keywords Recycled Aggregates, Confinement, Columns, Axial Performance

1. Introduction

This study intended to investigate the effect of the confinement on RC columns that are made with recycled aggregates. This study is analytical and conducted based on the available data in literature of 34 columns that were tested experimentally under axial load only by other researchers, containing various ratios of recycled aggregates. Table 1 shows the details of those columns. Also, a new formula is derived to estimate the unconfined compressive strength of the concrete based on the used replacement ratio of recycled aggregates.

Ozbakkaloglu et al. [8] investigated the effect of recycled aggregates on the properties of the concrete using 14 experimental specimens. Their study concluded that the increasing ratio of recycled aggregates decreases the compressive strength and weaken other mechanical properties like modulus of elasticity, modulus of rupture, etc. In addition to the reduction in the density and the increase in the porosity (more permeable).

Pareek et al. [9] recommended reducing the damages of using recycled aggregates by using additives such as micro silica, fly ash or other materials because they fill the pores in concrete thus increasing its strength and improving the rest of the mechanical properties.

Gholampour et al. [7] obtained new equations for mechanical properties of recycled aggregates concrete to understand and estimate the mechanical properties of concrete theoretically and can be used for material definition in numerical models that are Finite Element Method (FEM) oriented such as Abaqus, Ansys, etc. From this study, it was found that the water-cement (w/c) ratio can improve the mixture of concrete if decreased so the decreasing of the w/c ratio is also one of the solutions to compensate for the damage caused by using recycled aggregates.

Jin-Jun Xu et al. [10] carried out FEM analysis using Seismo-struct software to simulate columns under axial loads and they used the formulas that were obtained from Gholampour et al. [7], then compared the numerical results with experimental results. Their results were matching very well, and this study concludes that using recycled aggregates reduces axial load capacity.

Wang et al. [11] carried out also FEM analysis using Seismo-struct software to simulate columns under lateral cyclic loads and they used the formulas that were obtained from Gholampour et al. [7], then compared the numerical results with experimental results. Their results were matching very well, and this study concludes that using recycled aggregates reduces lateral capacity.

Also, there are many kinds of research-tested experimentally RC columns made with various ratios of recycled aggregates, the data collected to analyze them in this study include most of them. The database includes 34 specimens of RC columns that were tested under axial loads only.

Nomenclature

A_g	Cross sectional area of column	P_n	Axial load capacity
A_{core}	Cross sectional area of concrete core	r	Replacement ratio of recycled aggregates
A_s	Cross sectional area of longitudinal reinforcement	S	Spacing between ties
b_c	Length or width of column core	w	Spacing between vertical bars
d_s	Diameter of ties	w/c	Water-Cement ratio
d_c	Diameter of circular column core	¥	Modification factor
h and b	Width and length of column	ρ_{cc}	Ratio of longitudinal reinforcement area to area of column core
f'_c	Unconfined compressive strength of concrete	α	Confinement factor
$f'_{c\,(r=0)}$	Unconfined compressive strength of concrete that doesn't contain recycled aggregates		
f'_{cc}	Confined compressive strength of concrete		
f_{yb}	Yield strength of longitudinal reinforcement		
f_{ys}	Yield strength of transverse reinforcement		

Table 1. Details of the specimens

Reference	Specimen ID	r(%)	w/c (%)	f'_c(MPa)	$b=h$ (mm)	A_s (mm2)	f_{yb}(Mpa)	d_s(mm)	S (mm)	f_{ys}(Mpa)	P_n (kN)
Choi and Yun [1]	CRC0	0	43.6	37.05	400	2267	405.6	10	200	402	6136
	CRC30	30	43.6	33.81	400	2267	405.6	10	200	402	6253
	CRC60	60	43.6	32.35	400	2267	405.6	10	200	402	5814
	CRC100	100	43.6	29.17	400	2267	405.6	10	200	402	5579
	HCRC0	0	33	36.78	400	2267	427.8	10	200	483.2	6845
	HCRC30	30	33	34.86	400	2267	427.8	10	200	483.2	6607
	HCRC60	60	33	37.69	400	2267	427.8	10	200	483.2	6886
	CRC0F0	0	41.4	27.18	400	2267	451	10	200	556	5849
	CRC15F60	15	41.4	31.95	400	2267	451	10	200	556	6510
	CRC30F45	30	40.7	31.28	400	2267	451	10	200	556	6657
	CRC60F15	60	40.7	31.61	400	2267	451	10	200	556	6472
Ajdukiexicz and Kliszczewicz [2]	ONNm-c	0	49.3	50.9	150	452	410	4.5	100	210	1300
	ORNm-c	70	60.3	51.5	150	452	410	4.5	100	210	1506
	GNNm-c	0	36	60.2	150	452	410	4.5	100	210	1445
	GRRm-c	100	41.4	59.2	150	452	410	4.5	100	210	1459
	BNNm-c	0	23.7	55.7	150	452	410	4.5	100	210	1297
	BRNm-c	70	23.7	61.1	150	452	410	4.5	100	210	1252
	BRRm-c	100	26.6	55.5	150	452	410	4.5	100	210	1203
	BRRm-c	100	26.6	55.5	150	452	410	4.5	100	210	1203
Shtaratetal.[3]	NA	0	57	37.6	170	314	397	10	150	397	1132.39
	RCA20	20	57	37.6	170	314	397	10	150	397	1198.91
	RCA40	40	57	31.2	170	314	397	10	150	397	895.44
	RCA60	60	57	32	170	314	397	10	150	397	893.11
	RCA80	80	57	29.6	170	314	397	10	150	397	822.01
	RCA100	100	57	24	170	314	397	10	150	397	812.01
Wang et al.[4]	rrac-30-0-1	0	45	36.24	150	678	380	8	50	315	997
	rrac-30-0-2	0	45	36.24	150	678	381	8	50	315	1021
	rrac-30-0-3	0	45	36.24	150	678	382	8	50	315	1037
	rrac-30-0.5-1	50	45	37.36	150	678	383	8	50	315	1011
	rrac-30-1-1	100	45	34.48	150	678	386	8	50	315	946
	rrac-30-1-2	100	45	34.48	150	678	387	8	50	315	959
	rrac-30-1-3	100	45	34.48	150	678	388	8	50	315	984
	rrac-50-1-1	100	31	57.6	150	678	389	8	50	315	1383
	rrac-50-1-2	100	31	57.6	150	678	390	8	50	315	1357
	rrac-50-1-3	100	31	57.6	150	678	391	8	50	315	1296

2. Analytical Procedure

The axial load capacity of the specimens is compared with ACI318-19 provisions, ACI318-19 provisions presents equation 1 to estimate the nominal axial load capacity of RC columns. According to this equation, the confinement from ties is not considered although the confinement has a clear effect on axial behavior, so this equation needs to consider confined compressive strength of concrete core instead of the unconfined values based on equation (2)

$$P_n = 0.85f'_c(A_g - A_s) + f_{yb}A_s \quad (1)$$

$$P_n = 0.85f'_c(A_g - A_{core}) + 0.85f'_{cc}(A_{core} - A_s) + +f_{yb}A_s \quad (2)$$

Table 2 and Figure 1 show a comparison between calculated axial load capacity using the ACI formula without consideration of confinement and experimental values. In this paper, unconfined compressive strength of concrete is multiplied by confinement factor $(\alpha)$to obtain theconfined compressive strength of concrete. After arranging equation 1 and equation 2, the formula that can be used to estimate the experimental confinement factor is presented in equation 4. Calculated confinement factors are presented in Table 2.

$$f'_{cc} = \alpha f'_{c} \quad (3)$$

$$\alpha = \frac{P_n - 0.85f'_c(A_g - A_{core}) - f_{yb}A_s}{0.85f'_c(A_{core} - A_s)} \quad (4)$$

Calculated experimental confinement factors are compared with Mander's formula [6] as shown in Figure 2. Mander's formula is found to need modification to be used for columns that are made with recycled aggregates because most of the results that obtained by Mander's formula are found conservative.

Symbol (¥) is used as a modification factor to be multiplied with Mander's factor. It's found that ¥ shall be related to $\frac{f'_1}{f'_c}$because this ratio covers all perimeters that affect the confinement state of the columns like unconfined compressive strength of concrete, longitudinal reinforcement details, and transverse reinforcement details. Since Mander's calculations of circular columns are considered minimal for circular tied columns, the formula of modification factor is derived only for rectangular tied columns.

Also, a new formula is derived to estimate the unconfined compressive strength of the concrete based on the replacement ratio of recycled aggregates and water-cement ratio based on the data that is used in this study.

3. Results

Modification factor of Mander's confinement factor (¥)is derived based on the regression analysis as shown in Figure 3 for the rectangular tied columns and Figure 4 for circular tied columns. The suggested modification factor (¥), shown in Figure 3 for rectangular tied columns, is suggested as presented in equation 5. Table 4 and Figure 4 show the comparison between modified and unmodified factors and the experimental factors.

$$¥ = 1660\left(\frac{f'_1}{f'_c}\right)^2 - 45.3\left(\frac{f'_1}{f'_c}\right) + 1.41 \quad (5)$$

where

$$f'_1 = k_e \rho f_{ys} \quad (6)$$

$$\rho = \frac{A_s}{S\, b_c} \quad (7)$$

$$k_e = \frac{\left(1-\frac{s}{2b_c}\right)\left(1-\frac{s}{2d_c}\right)\left(1-\sum_{i=1}^{n}\left(\frac{w_i^2}{6\, b_c d_c}\right)\right)}{1-\rho_{cc}} \quad (8)$$

A new equation to estimate the unconfined compressive strength of recycled concrete based on the replacement ratio is presented in equation 9 and Figure 5. However, Ghalampour et al. [7] obtained a relationship between the unconfined compressive strength of concrete and the replacement ratio of recycled aggregates considering w/c ratio as presented in equation 10. The differences between experimental and calculated values of unconfined compressive strength of concrete are presented in Figure 6 and Table 5.

$$\frac{f'_c}{f'_{c(r=0)}} = 1 - 10^{-5} r \left(\frac{w}{c}\right) \quad (9)$$

$$f'_c = \frac{23.5 * 0.998^r * ((w/c)+0.09)}{(w/c)^{1.7}} \quad (10)$$

From the comparison shown in Figure 6, the derived formula (equation 9) is found more accurate and more representative than Ghalampour's formula (equation 10), so it's used in the derivation of the modification factor.

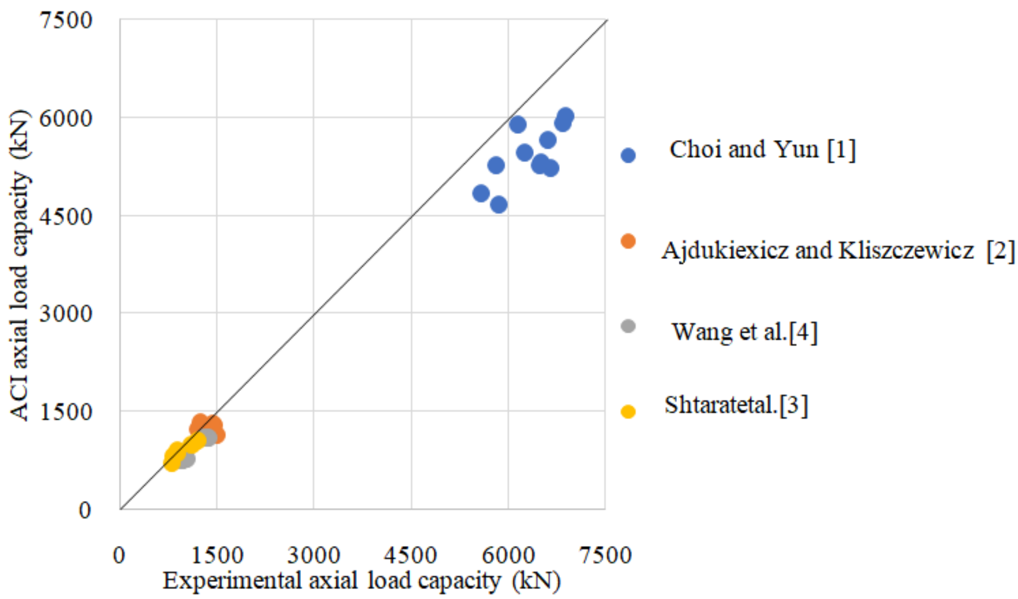

Figure 1. Comparison of experimental axial load capacity with calculated based on ACI318-19 provisions of columns that is made with recycled aggregates

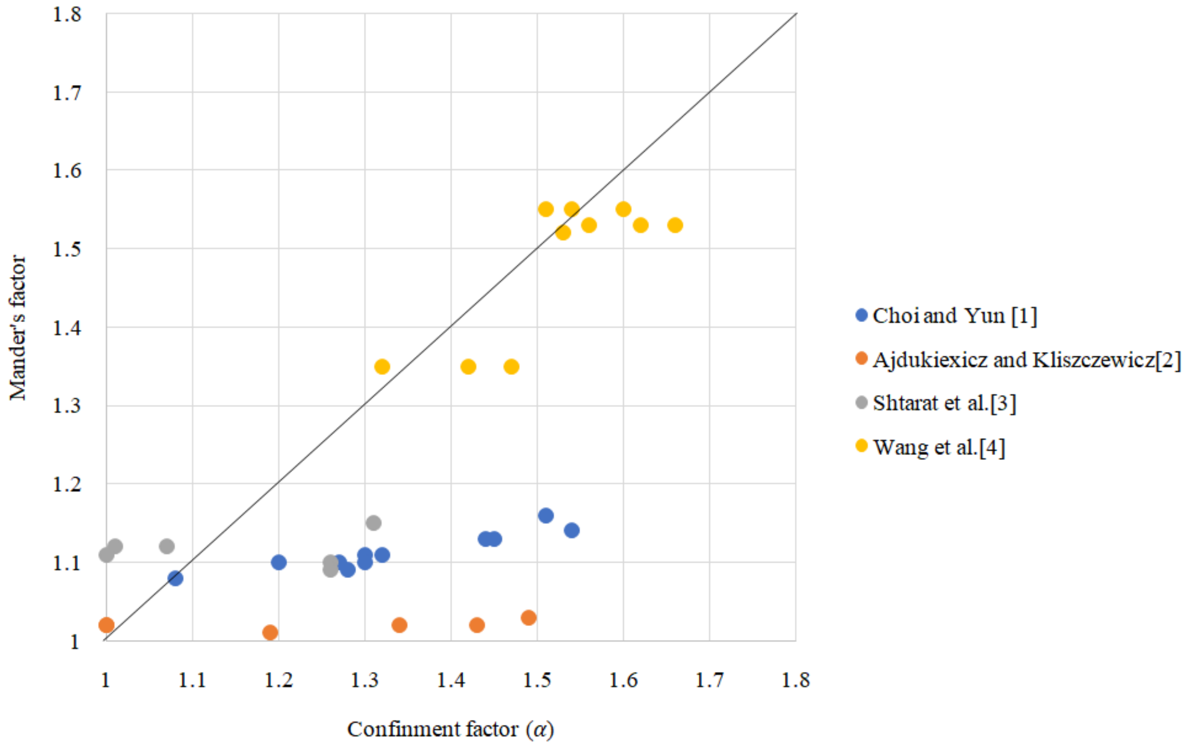

Figure 2. Comparison of calculated confinement factor with Mander's factor for columns that is made with recycled aggregates

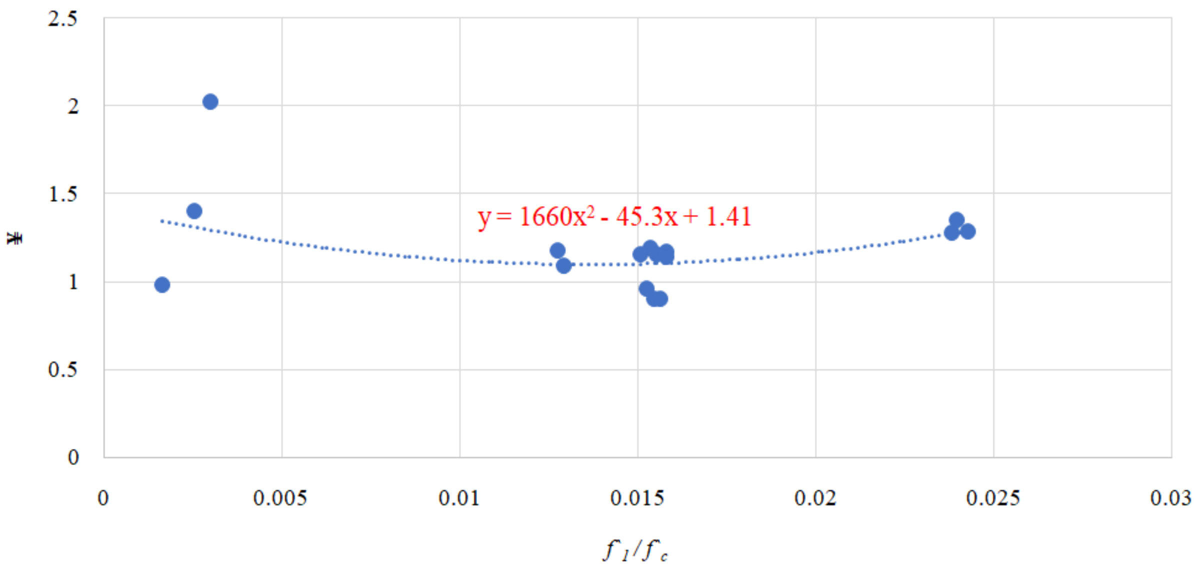

Figure 3. Derivation of modification factor ¥

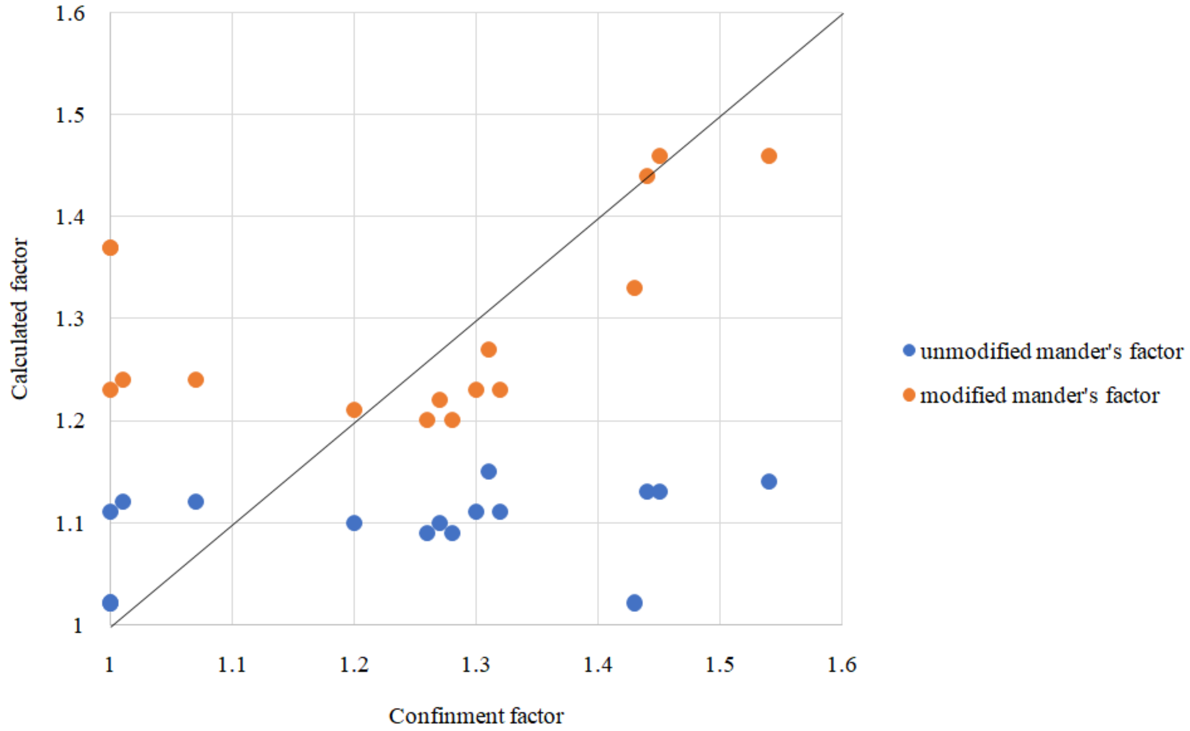

Figure 4. Comparison between Mander's modified and unmodified factors with estimated factors of rectangular tied columns

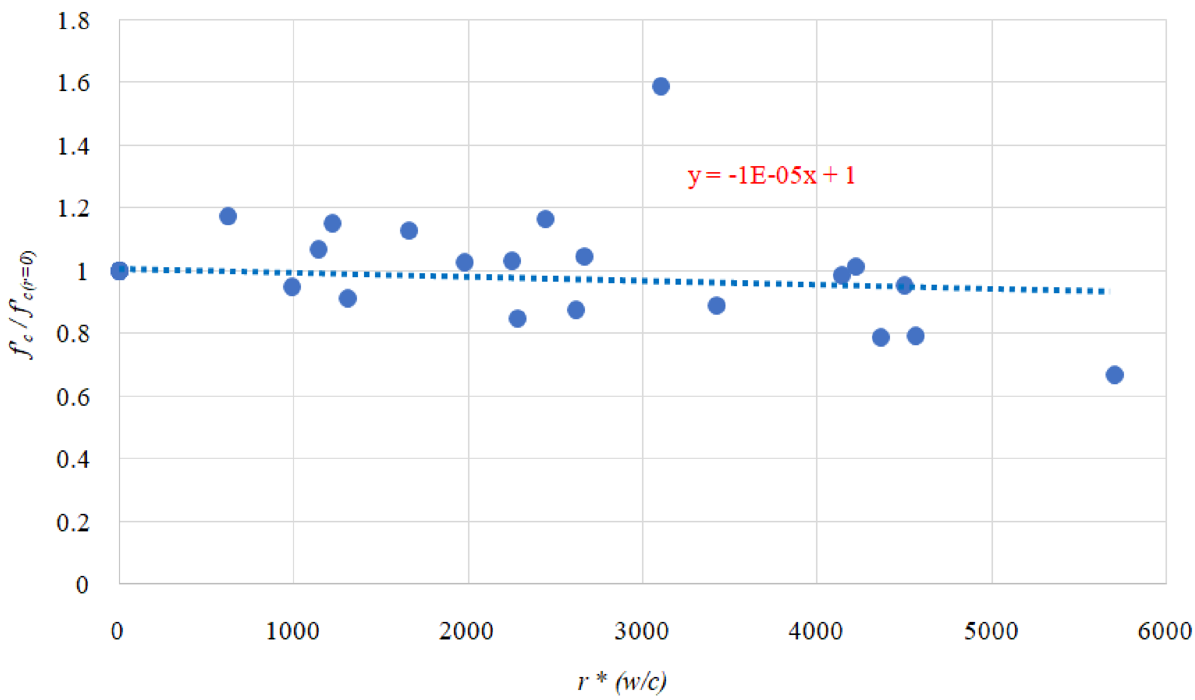

Figure 5. Derivation of new formula of unconfined compressive strength of concrete that containing recycled aggregates

Table 2. Comparison of experimental axial load capacity with calculated based on ACI318-19 provisions of columns that are made with recycled aggregates

Specimen ID	Experimental P_n (kN)	ACI P_n (kN)	Difference in P_n (%)	Confinement factor
CRC0	6136	5886.9	-4.06	1.08
CRC30	6253	5452.51	-12.8	1.28
CRC60	5814	5256.76	-9.58	1.2
CRC100	5579	4830.41	-13.42	1.3
HCRC0	6845	5901.03	-13.79	1.3
HCRC30	6607	5643.61	-14.58	1.32
HCRC60	6886	6023.04	-12.53	1.27
CRC0F0	5849	4666.52	-20.22	1.51
CRC15F60	6510	5306.05	-18.49	1.44
CRC30F45	6657	5216.22	-21.64	1.54
CRC60F15	6472	5260.47	-18.72	1.45
ONNm-c	1300	1139.23	-12.37	1.08
ORNm-c	1506	1150.47	-23.61	1.28
GNNm-c	1445	1313.52	-9.1	1.2
GRRm-c	1459	1294.78	-11.26	1.3
BNNm-c	1297	1229.18	-5.23	1.3
BRNm-c	1252	1330.38	6.26	1.32
BRRm-c	1203	1225.43	1.86	1.27
NA	1132.39	999.39	-11.75	1.51
RCA20	1198.91	1060.13	-11.58	1.44
RCA40	895.44	865.75	-3.32	1.54
RCA60	893.11	902.2	1.02	1.45
RCA80	822.01	817.15	-0.59	1.08
RCA100	812.01	707.81	-12.83	1.28
rrac-30-0-1	997	780.83	-21.68	1.2
rrac-30-0-2	1021	781.51	-23.46	1.3
rrac-30-0-3	1037	782.19	-24.57	1.3
rrac-30-0.5-1	1011	799.03	-20.97	1.32
rrac-30-1-1	946	759.49	-19.72	1.27
rrac-30-1-2	959	760.17	-20.73	1.51
rrac-30-1-3	984	760.85	-22.68	1.44
rrac-50-1-1	1383	1095.3	-20.8	1.54
rrac-50-1-2	1357	1095.98	-19.24	1.45
rrac-50-1-3	1296	1096.66	-15.38	1.08

Table 3. Comparison of calculated confinement factor with Mander's factor for columns that is made with recycled aggregates

Specimen ID	Confinement factor	Mander's factor	Difference (%)
CRC0	1.08	1.08	0
CRC30	1.28	1.09	-14.84
CRC60	1.2	1.1	-8.33
CRC100	1.3	1.11	-14.62
HCRC0	1.3	1.1	-15.38
HCRC30	1.32	1.11	-15.91
HCRC60	1.27	1.1	-13.39
CRC0F0	1.51	1.16	-23.18
CRC15F60	1.44	1.13	-21.53
CRC30F45	1.54	1.14	-25.97
CRC60F15	1.45	1.13	-22.07
ONNm-c	1.49	1.03	-30.87
ORNm-c	2.06	1.02	-50.49
GNNm-c	1.34	1.02	-23.88
GRRm-c	1.43	1.02	-28.67
BNNm-c	1.19	1.01	-15.13
BRNm-c	1	1.02	2
BRRm-c	1	1.02	2
NA	1.26	1.1	-12.7
RCA20	1.26	1.09	-13.49
RCA40	1.07	1.12	4.67
RCA60	1	1.11	11
RCA80	1.01	1.12	10.89
RCA100	1.31	1.15	-12.21
rrac-30-0-1	1.56	1.53	-1.92
rrac-30-0-2	1.62	1.53	-5.56
rrac-30-0-3	1.66	1.53	-7.83
rrac-30-0.5-1	1.53	1.52	-0.65
rrac-30-1-1	1.51	1.55	2.65
rrac-30-1-2	1.54	1.55	0.65
rrac-30-1-3	1.6	1.55	-3.13
rrac-50-1-1	1.47	1.35	-8.16
rrac-50-1-2	1.42	1.35	-4.93
rrac-50-1-3	1.32	1.35	2.27

Table 4. Comparison between Mander's unmodified and modified factors with experimental factors of rectangular tied columns

Specimen ID	Experimental Confinement factor	Mander's unmodified formula	Difference with Unmodified (%)	Mander's modified formula	Difference with Modified (%)
CRC30	1.28	1.09	-14.84	1.2	-6.25
CRC60	1.2	1.1	-8.33	1.21	0.83
CRC100	1.3	1.11	-14.62	1.23	-5.38
HCRC30	1.32	1.11	-15.91	1.23	-6.82
HCRC60	1.27	1.1	-13.39	1.22	-3.94
CRC15F60	1.44	1.13	-21.53	1.44	0
CRC30F45	1.54	1.14	-25.97	1.46	-5.19
CRC60F15	1.45	1.13	-22.07	1.46	0.69
ORNm-c	2.06	1.02	-50.49	1.32	-35.92
GRRm-c	1.43	1.02	-28.67	1.33	-6.99
BRNm-c	1	1.02	2	1.37	37
BRRm-c	1	1.02	2	1.37	37
RCA20	1.26	1.09	-13.49	1.2	-4.76
RCA40	1.07	1.12	4.67	1.24	15.89
RCA60	1	1.11	11	1.23	23
RCA80	1.01	1.12	10.89	1.24	22.77
RCA100	1.31	1.15	-12.21	1.27	-3.05

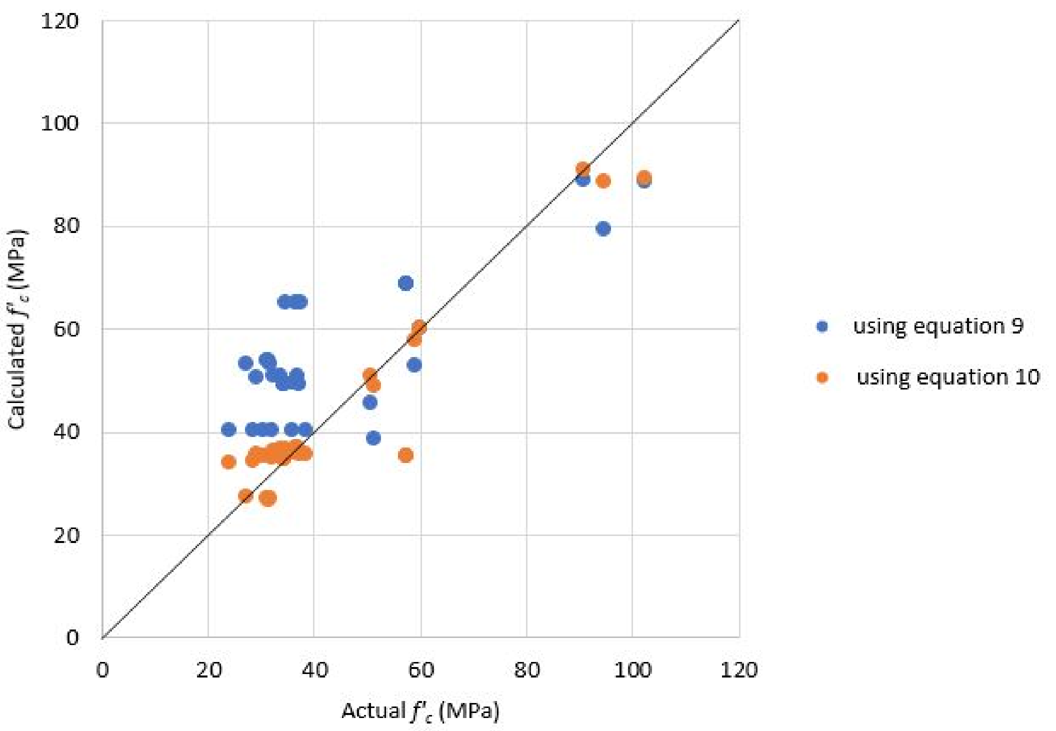

Figure 6. The difference in experimental and calculated unconfined compressive strength of concrete

Table 5. The difference in experimental and calculated unconfined compressive strength of concrete

Specimen ID	Experimental f'_c(Mpa)	Ghalampour'sf'_c (MPa)	Difference in f'_c (%)	Calculated f'_c (MPa)	Difference in f'_c (%)
CRC0	37.05	50.69	36.82	37.05	0
CRC30	33.81	50.66	49.84	36.57	8.16
CRC60	32.35	50.63	56.51	36.08	11.53
CRC100	29.17	50.59	73.43	35.43	21.46
HCRC0	36.78	64.99	76.7	36.78	0
HCRC30	34.86	64.95	86.32	36.42	4.48
HCRC60	37.69	64.91	72.22	36.05	-4.35
CRC0F0	27.18	53.04	95.14	27.18	0
CRC15F60	31.95	53.02	65.95	27.01	-15.46
CRC30F45	31.28	53.81	72.03	26.85	-14.16
CRC60F15	31.61	53.78	70.14	26.52	-16.1
ONNm-c	50.9	45.59	-10.43	50.9	0
ORNm-c	51.5	38.43	-25.38	48.75	-5.34
GNNm-c	60.2	60.06	-0.23	60.2	0
GRRm-c	59.2	52.93	-10.59	57.71	-2.52
BNNm-c	90.8	88.83	-2.17	90.8	0
BRNm-c	102.5	88.7	-13.46	89.29	-12.89
BRRm-c	94.7	79.31	-16.25	88.38	-6.67
NA	36	40.33	12.03	36	0
RCA20	38.5	40.31	4.7	35.59	-7.56
RCA40	30.5	40.3	32.13	35.18	15.34
RCA60	32	40.28	25.88	34.77	8.66
RCA80	28.5	40.27	41.3	34.36	20.56
RCA100	24	40.25	67.71	33.95	41.46
rrac-30-0-1	36.24	49.32	36.09	36.24	0
rrac-30-0-2	36.24	49.32	36.09	36.24	0
rrac-30-0-3	36.24	49.32	36.09	36.24	0
rrac-30-0.5-1	37.36	49.27	31.88	35.42	-5.19
rrac-30-1-1	34.48	49.22	42.75	34.61	0.38
rrac-30-1-2	34.48	49.22	42.75	34.61	0.38
rrac-30-1-3	34.48	49.22	42.75	34.61	0.38
rrac-50-1-1	57.6	68.7	19.27	35.12	-39.03
rrac-50-1-2	57.6	68.7	19.27	35.12	-39.03
rrac-50-1-3	57.6	68.7	19.27	35.12	-39.03

4. Conclusions

This study uses the data that are collected from literature which includes 34 specimens of RC columns containing various ratios of recycled aggregates that were tested experimentally under axial loads only. The following conclusions are made:

a Axial load capacities are compared with ACI318-19 provisions. The values of axial load capacity calculated using these provisions are close to experimental values or less, so these provisions can be used.

b Confinement factors are calculated and compared also with Mander's formula. There are differences between them especially for rectangular tied columns, so modification factor is derived and can be used to better reflect the confinement effect in the design.

c Gholampour's formula which is used to estimate the unconfined compressive strength of concrete can be used but the suggested derived formula in this study is better because it is closer to experimental values.

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