Design and elastic behaviour influence of recycled RC buildings subjected to earthquakes.

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SUMMARY:
Experimental testing has been used, in different researches, to define reduction factors of physical and mechanical properties in recycled concrete, depending on the quantity of recycled material used to produce new concrete. These reduction factors were applied to design different five-storey buildings having recycled aggregates percentages in the RC of 0%, 15%, 30%, 60% and 100%. These structures, subjected to seismic load from an accelerogram database, were analysed elastically and designed according to the Mexico City Seismic Code. Models with different amount of recycled aggregates were compared with models with conventional concrete to evaluate the dimensional variation of columns and girders, the required longitudinal reinforcing steel, the maximum displacements and the moments and shear forces in elements. Results show that using recycled aggregates in percentages from 15% to 100%, produces increases, compared with conventional concrete buildings, in the structural elements dimensions (in percentages from 5% to 45%), reinforcing steel (20% to 60%), and the general response of the structure, in percentages of up to 14%.

Keywords: Recycled concrete, seismic behaviour, buildings elastic response

1. ANTECEDENTS

After the Second World War, the first uses of recovered materials, product of demolitions, were accomplished. It was due to the accumulation of these materials, debris of bombing and the lack of natural aggregates. In 1946, it was determined that recycled aggregates have a minor specific weight and less strength. Also, it was demonstrated that tensile strength of concrete with recycled aggregates was greater than natural concretes. In 1977, some researches proved that recycled concrete has minor adherence and greater cement content, than traditional concrete (Gómez, 2002, Lovato, 2012, López, 2008 and Maier and Durham, 2012).

1.1. Mechanical properties of recycled concrete

The conventional aggregates have a density between 24525 to 26487 N/m^3, while these values for recycled concrete are between 20601 to 23544 kg/m^3. This is due to the fact that reprocessed materials have more mortar with lesser density. Because of this cause, also the texture of recycled aggregates is more porous than natural materials The volumetric weight depends on the replacement percentage of the natural aggregate by recycled one, see table 1.1 (Gómez, 2002a and 2002b).

When the compressive strength test is accomplished, the failure of recycled-aggregate concrete is similar to conventional-aggregate concretes, although the ultimate load is 40% to 60% lesser in the concrete. The final strength is function of the concrete original quality, the water/cement ratio, the crushing process and the percentage of substitution. Hendriks and Henrichsen (Gómez, 2002) propose equation 1.1 to estimate the simple compression resistance in recycled concretes, for a water/cement relation less than 0.8.

$$f'_{cm} = (f'_{cm}GR^{n}) * (f'_{cm}M^{(1-n)}) \qquad (1.1)$$

where f'_{cm} is the compressive strength of recycled concrete, $f'_{cm}GR^{n}$ is the compressive strength of coarse aggregates generate by concrete, $f'_{cm}M$ is the compressive strength of mortar and n is the volume percentage of the recycled aggregate.

Flexural strength of both, conventional and recycled concretes, is minor. Ikeda, Tamame and Sakamto (Gómez, 2002) relate compressive and flexural strength by equation 1.2.

$$f_t = f'_{cm}/7 \qquad (1.2)$$

where f_t is the flexural strength of recycled concrete and f'_{cm} is the compressive strength of the same material.

The elastic modulus depends on some factors, such as: form and size of aggregates, characteristic surfaces and the age of concrete. The recycled aggregates have an elastic modulus lesser than natural materials, then the recycled concrete have a lesser elastic modulus than conventional one. Between some proposed expressions, López (2008) evaluated the elastic modulus of recycled concretes using equation 1.3

$$E = 2.1x10^{5} \ (\rho/2.3)^{1.5} * \sqrt{f'_{cm}}/200 \qquad (1.3)$$

where ρ is the concrete density

Table 1.1. Recycled concrete volumetric weight

Aggregate substitution (%)	Volumetric weight (N/m^3)
0 (conventional)	23544.0
15	25250.9
30	25074.4
60	24897.8
100	24652.5

Shear strength of recycled concretes can be 40% lesser than in conventional concretes, in function of the aggregates replacement percentage. Ikeda, Yamame and Sakamto (Gómez, 2002) defined shear strength of these materials using equation 1.4.

$$\text{Shear strength} = f'cm/7 \qquad (1.4)$$

The strain of recycled concretes is between 15% and 30% minor than the strain in conventional concretes, depending on the percentage of recycled aggregates used. Some values for strain of these materials at 28-day age, and for a variety of percentages of replacement are shown in table 1.2.

Table 1.2. Strains of recycled concrete at 28-day age (Gómez, 2002)

Factor	Basic ε_c (mm/m)	Total ε_c (mm/m)	Dry ε_c (mm/m)
r = 1.00	0.0010	0.2411	0.2401
r = 0.60	-0.0283	0.2231	0.2514
r = 0.30	-0.0017	0.2307	0.2324
r = 0.15	-0.0120	0.2367	0.2487
r = 0.00	-0.0190	0.2060	0.2250
Conventional	-0.0170	0.0771	0.0941

In conventional concretes the Poisson coefficient changes between 0.11 and 0.21. In recycled concretes experimental tests were used to define the values of this parameter. Some values of the

Poisson coefficient for different percentages of aggregate replacement are shown in table 1.3.

Table 1.3. Maximum, minimum and mean values of Poisson coefficient for recycled concretes (Gómez, 2002)

Value	Age (days)	Percentage of recycled aggregate (%)				
		0	15	30	60	100
Máx.	7	0.33	0.28	0.26	0.42	0.29
Mín.		0.14	0.16	0.12	0.10	0.07
Mean		0.22	0.22	0.19	0.17	0.16
Máx.	28	0.24	0.37	0.21	0.32	0.51
Mín.		0.12	0.09	0.00	0.09	0.07
Mean		0.19	0.19	0.13	0.16	0.16
Máx.	90	0.21	0.25	0.23	0.22	0.21
Mín.		0.05	0.06	0.05	0.00	0.04
Mean		0.16	0.16	0.15	0.13	0.14

2. DESIGN OF STRUCTURES USING RECYCLED CONCRETE

To define the influence of the recycled concrete use, three types of buildings were studied, considering the mechanical properties defined by experimental researches. The structures, analyzed with conventional and recycled concrete, were designed considering vertical and seismic loads. The elastic responses of buildings with the same configuration were compared.

2.1. Conventional concrete buildings

Different 5-story buildings, with 3.3 m of height per story and span lengths of 5 m, but different geometries in plant, were studied. The structures have square (same longitude in both sides), rectangular and L form plants. The two first structures are classified as regular by the local code; the third presents only one out of eleven irregular conditions considered by local code; so a factor of 0.9 is used to modify the design spectrum. The elastic models of the selected structures are shown in figure 1, where elevation and plant dimensions are shown.

The structural elements were designed in accordance with the local code (RCDF 2004), taking into account a system with a moderate ductility and a seismic coefficient of 0.16, locating the buildings in the rigid soil zone of the Mexico City. The seismic load was assumed considering the 30% combination rule, as the local code suggest.

The fundamental periods were 1.01 s, 0.87 s and 0.95 s for the square, rectangular and L buildings, respectively. The spectral ordinates for seismic loads were defined with these periods. The elastic spectrum was defined as the local code indicates for the zone where structures were located. For the design, the same-dimension column was considered each two stories and two types of girders, external and central, were assumed. As much as possible, the same dimensions were used for all buildings, only reinforcing steel was changed. For buildings with conventional concrete, the elements dimensions are shown in table 2.1, while the reinforcing steel used is presented in table 2.2.

2.2. Recycled concrete buildings

The structures of figure 1 were also designed considering they are composed of recycled concrete, with different percentages of replacement of natural aggregates by recycled material. The percentages of replacement were 15%, 30%, 60% and 100%. For these percentages, the used modification factors of the mechanical properties, obtained by diverse experimental test, are described in table 2.3 (Gómez, 2002). The volumetric weight and the Poisson modulus are shown in tables 1.1 and 1.3.

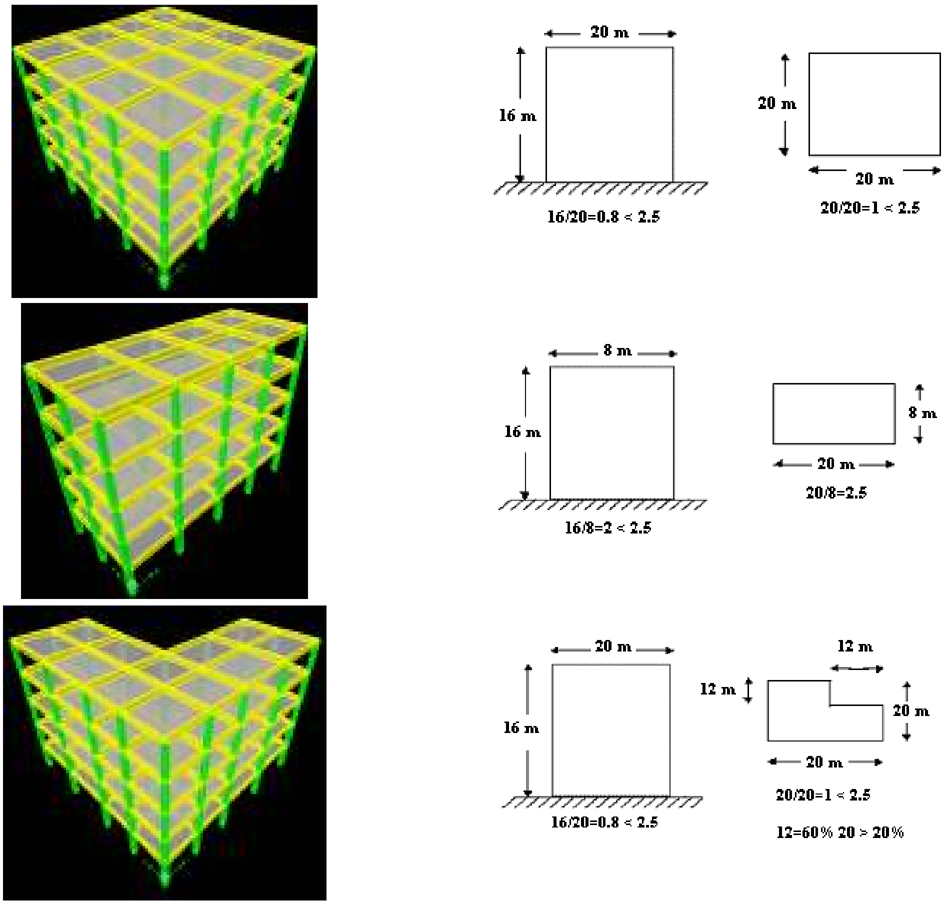

Figure 1. Elastic models and general dimensions of the structures

Table 2.1. Dimensions of girders and columns of conventional concrete buildings

Beams			Columns	
Level	b (cm)	d (cm)	Level	Side (cm)
N1, N2 external	25	45	PB, N1	50
N1, N2 central	30	50	N2, N3	40
N3, N4 external	30	50	N4	35
N3, N4 central	30	55	-	-
N5 external	25	45	-	-
N5 central	25	45		

Table 2.2. Reinforcing steel for the conventional concrete buildings

Beams	Steel (cm^2), Square		Steel (cm^2), Rectangular		Steel (cm^2), L	
	Tension	Compression	Tension	Compression	Tension	Compression
N1, N2 e	4#9	4#8	3#8	2#9	3#9	3#8
N1, N2 c	4#9	3#9	3#9	3#8	4#8	3#8
N3, N4 e	3#9	3#8	3#8	2#9	3#8	3#8
N3, N4 c	3#9	2#9	3#8	2#9	3#9	3#7
N5 e	2#7	2#6	2#6	2#6	2#7	2#7
N5 c	4#9	4#8	2#7	2#7	3#7	3#6
Columns						
PB	12#9		12#8		12#8	
N1	8#9		8#8		12#7	
N2	12#8		8#7		8#9	
N3	8#8		8#7		8#8	
N4	4#9		4#8		8#8	

Table 2.3. Modification factors of mechanical properties of recycled concrete

% replacement	f´c	Shear strength	Flexural strength	Tension strength	Elastic module	Maximum strains (mm/m)
0	1	1	1	1	1	0.003
15	0.9891	0.9505	0.990	0.9758	0.9616	0.0022
30	0.9551	0.9011	0.980	0.9619	0.9357	0.0021
60	0.9149	0.8025	0.966	0.9273	0.8826	0.0022
100	0.9001	0.6700	0.948	0.9165	0.8578	0.0024

The four elastic models of each structure described in figure 1 were defined using the values of table 2.3. These 12 buildings were designed employing the local seismic code (RCDF 2004), with the same considerations. Elements dimensions for different replacement percentages of recycled material are shown in table 2.4. The proposed reinforcing steel for these models are presented in tables 2.5 to 2.7, for square, rectangular and L systems.

Table 2.4. Beam and columns dimensions for recycled concrete buildings

Element	% replacement of recycled concrete								
	Level	15		30		60		100	
		b (cm)	d (cm)	b (cm)	d (cm)	b (cm)	d (cm)	b (cm)	d (cm)
Beams	N1,N2 e	30	60	30	60	30	60	35	60
	N1,N2 c	30	60	30	60	35	60	40	65
	N3,N4 e	25	50	25	50	25	50	25	55
	N3,N4 c	30	55	30	55	35	60	35	60
	N5 e	25	50	25	50	25	50	25	50
	N5 c	30	50	30	50	30	50	35	55
Columns		Side (cm)		Side (cm)		Side (cm)		Side (cm)	
	PB, N1	60		60		60		65	
	N2 N3	55		55		60		60	
	N4	50		50		55		55	

Table 2.5. Reinforcing steel for recycled-concrete square buildings

	% of replacement							
Beams	15%		30%		60%		100%	
	T	C	T	C	T	C	T	C
N1,N2 e	6#9	4#9	6#9	4#9	7#9	5#9	7#9	6#9
N1, N2 c	7#9	5#9	7#9	5#9	7#9	5#9	8#9	7#9
N3,N4 e	6#9	4#8	6#9	4#8	7#9	5#8	7#9	6#8
N3,N4 c	5#9	4#9	7#9	5#9	7#9	5#9	7#9	6#9
N5 e	5#9	4#8	5#9	4#8	6#9	4#8	6#9	4#8
N5 c	5#9	4#9	6#9	5#9	7#9	5#9	7#9	5#9
Columns								
PB	8#11		9#11		10#11		10#11	
N1	8#11		9#11		10#11		10#11	
N2	11#9		11#9		12#9		12#9	
N3	9#9		9#9		9#9		9#9	
N4	8#9		8#9		9#9		9#9	

For square buildings, the percentages of variation, between conventional and recycled systems, of tension and compression reinforcing steel for girders and steel for columns are shown in figures 2 to 4, respectively. As it is observed in these figures, the trends of the percentages of variation are not regulars, for girders are more irregular than for columns. These variations for rectangular and L systems are presented in figures 5 to 7 and 8 to 10, respectively.

Table 2.6. Reinforcing steel for the recycled-concrete rectangular building

	% of replacement							
Beams	15%		30%		60%		100%	
	T	C	T	C	T	C	T	C
N1,N2 e	6#9	4#8	6#9	4#8	6#9	4#8	7#9	5#8
N1, N2 c	7#9	5#9	7#9	5#9	7#9	5#9	8#9	6#9
N3,N4 e	6#9	3#8	6#9	4#8	6#9	4#8	7#9	5#8
N3,N4 c	6#9	4#9	6#9	5#9	6#9	5#9	7#9	5#9
N5 e	4#9	4#8	4#9	4#8	4#9	4#8	5#9	4#8
N5 c	5#9	4#9	5#9	4#9	5#9	4#9	6#9	5#9
Columns								
PB	10#9		10#9		11#9		12#9	
N1	10#9		10#9		11#9		12#9	
N2	9#9		9#9		10#9		10#9	
N3	8#9		9#9		9#9		9#9	
N4	6#9		6#9		7#9		7#9	

Table 2.7. Reinforcing steel for the recycled-concrete L buildings

	% of replacement							
Beams	15%		30%		60%		100%	
	T	C	T	C	T	C	T	C
N1,N2 e	5#9	4#8	5#9	4#8	5#9	4#8	6#9	5#8
N1, N2 c	7#9	5#9	7#9	5#9	8#9	8#9	9#9	6#9
N3,N4 e	4#9	3#8	4#9	3#8	5#9	4#8	7#9	5#8
N3,N4 c	5#9	4#9	6#9	4#9	7#9	5#9	8#9	5#9
N5 e	3#9	3#8	3#9	3#8	4#9	3#8	5#9	4#8
N5 c	4#9	3#9	4#9	3#9	5#9	4#9	6#9	5#9
Columns								
PB	9#9		9#9		10#9		10#9	
N1	8#9		8#9		9#9		9#9	
N2	8#9		8#9		7#9		9#9	
N3	7#9		7#9		7#9		8#9	
N4	6#9		6#9		6#9		7#9	

From the obtained results, it is possible to conclude that the replacement of conventional concrete for different percentages of recycled aggregate, increments the dimensions in 5% to 45% for girders and in 5% and 25% for columns. The increment of reinforcing steel in recycled systems is in 20% to 60% in girders and in 20% to 45% for columns, As it can be observed in figures 2 to 10, the trend curves of the variation of longitudinal steel in columns is asymptotic for cases where the replacement percentages is greater than 50%. In girders, there is more variance in the tendency curves for the compression reinforcing steel, than for the tension reinforcing steel. Results are similar for the three buildings types, although the variation tendency curves are not equals.

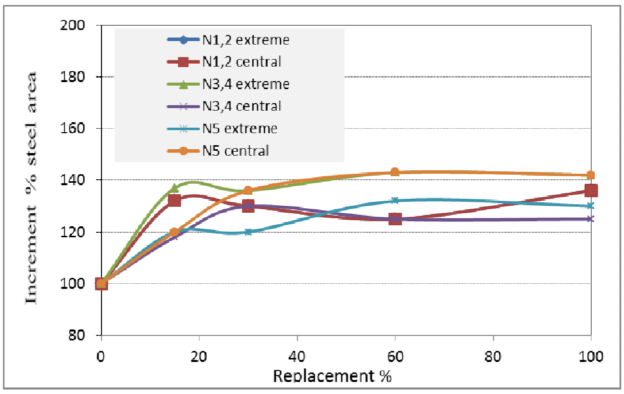

Figure 2. Trend lines of variation percentages for tension steel, for girders. Square building

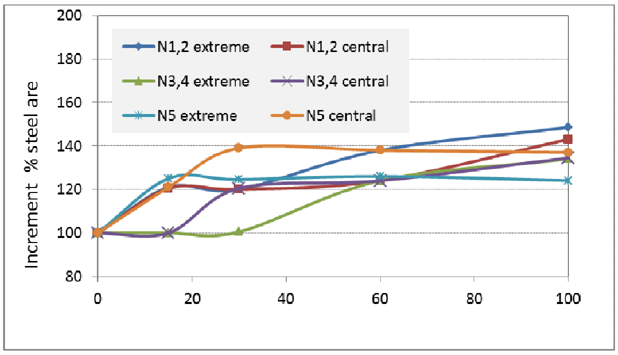

Figure 3. Trend lines of variation percentages in compression steel of girders. Square building

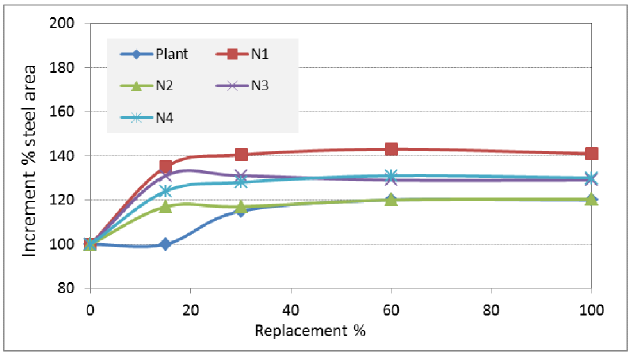

Figure 4. Trend lines of variation percentages in longitudinal steel of columns. Square building

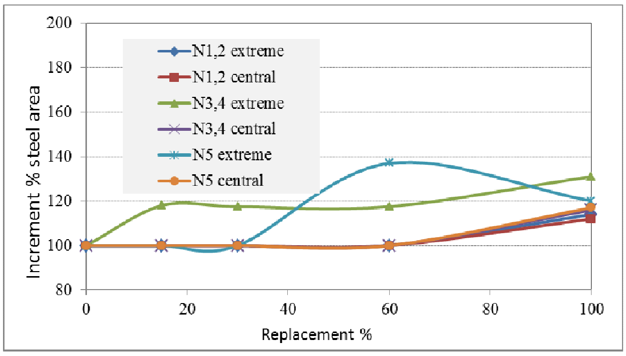

Figure 5. Trend lines of variation percentages in tension steel of girders. Rectangular building

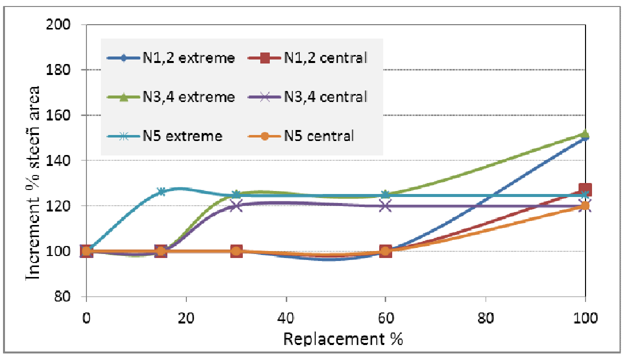

Figure 6. Trend lines of variation percentages in compression steel of girders. Rectangular building

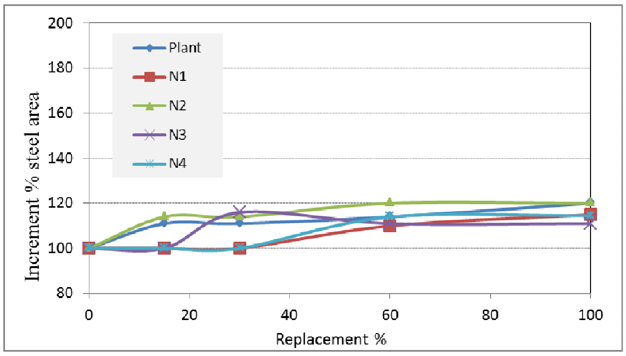

Figure 7. Trend lines of variation percentages in longitudinal steel of columns. Rectangular building

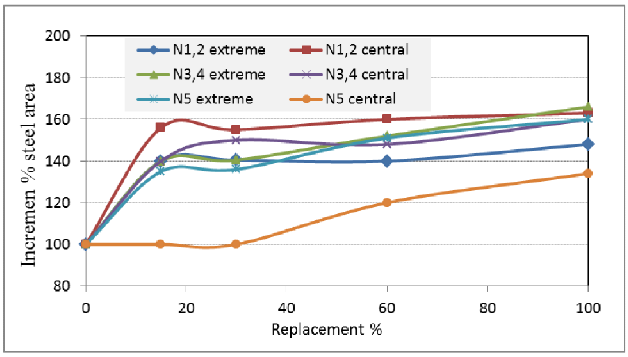

Figure 8. Trend lines of variation percentages in tension steel of girders. L building

3. ELASTIC ANALYSES

In addition to evaluate the influence of recycled concrete in the design of structures, it is important to know if this produces an adequate seismic-resistant behaviour. To do that, structures with conventional and recycled concrete were subjected to a small number of accelerograms registered at the zone where structures are located. Starting from elastic analyses, maximum flexion moments were compared for buildings with the same configuration and different materials. So, five records, between 1985 and 1999 were selected from the Mexican Database of Strong Earthquakes (MDSE, 20000). The principal characteristics of the selected records are presented in table 3.1.

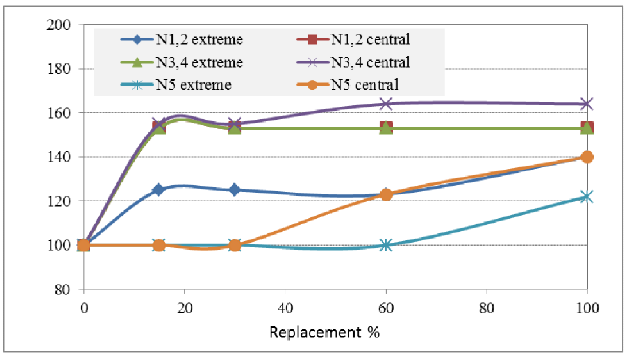

Figure 9. Trend lines of variation percentages in compression steel of girders. L building

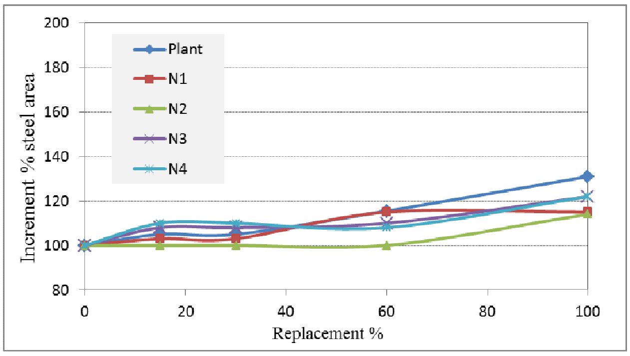

Figure 10. Trend lines of variation percentages in longitudinal steel of columns. L building

3.1. Maximum moments

The models of buildings were analysed using the acelerograms of table 3.1. The mean value moments for columns and girders are shown in tables 3.2 and 3.3, respectively. These tables shown than for the square building columns, the maximum absolute moments change 6.3% to 11% when recycled concrete is used with different percentages of replacement of aggregates. Similar values were obtained for other configuration of buildings. Then, practically, there are not remarkable difference in utilise 15% or 30% of replacement of recycled aggregates.

For girders, the maximum absolute moments in square buildings with recycled concrete have a difference of 9l.8%, 10.9%, 12.52% and 14.65% with respect to conventional concrete building. Similar values were defined for structures with rectangular and L plants. It is possible to say that the replacement until 100% of aggregates only generates a maximum change of 14% in moments of the structure.

Table 3.1. Characteristics of earthquake records used in elastic analysis

Station name	Date	Magnitude	Duration (s)	PGA 1 (cm/s^2)	PGA 2 (cm/s^2)
Apatlaco	14/09/95	7.2	185.02	51.7	23.6
Central de Abastos	19/09/85	8.1	143.19	91.1	91.1
SCT-B1	19/09/85	8.1	183.51	94.1	162
UAM-Xochimilco	30/09/99	7.5	229.19	57.3	33.1
Tlahuac	25/04/89	6.9	115.20	53.9	72.1

Table 3.2. Mean values of absolute flexion moments in columns

Replacement percentage					
x-Moment (ton-m)					
	0	15	30	60	100
Square	95.49	101.27	101.47	103.79	105.75
Rectangular	86.1	91.55	91.55	96.82	95.60
L	85	90.38	90.38	92.63	94.38
y-Moment (ton-m)					
Square	175.09	185.92	186.1	190.55	194.16
Rectangular	113.24	120.40	120.40	123.39	125.73
L	105.65	112.33	112.33	115.13	117.30

Table 3.3. Means of absolute flexion moments for beams

Replacement percentage					
	0	15	30	60	100
Square	127.41	139.89	141.32	143.36	146.12
Rectangular	108.82	119.48	120.70	122.44	104.84
L	137.77	151.26	152.80	155.01	157.95

4. FINAL COMMENTARIES

A comparative analysis of the design and elastic behaviour or buildings with conventional and recycled concrete is presented in this work. Three five-storey buildings configurations were studied, with square, rectangular and L plants. Mechanical properties were modified in buildings with recycled concrete, with replacement percentages of 15%, 30%, 60% and 100% of the coarse aggregate, based on experimental test available in literature. All buildings were designed based on the local code and were subjected to a small number of earthquakes, representative from the structures location. Dimensions, utilization of reinforcing steel and maximum moments in elements of buildings with the same configuration and different material were compared.

From the design results of the buildings, it is observed that the substitution of natural aggregates by percentages of recycled ones increment the concrete elements dimensions from 5% to 45% in girders and from 5% to 25% in columns. In addition more longitudinal steel is required, from 20% to 60%, in girders, and from 20% and 45% in columns; depending on the replacement percentages. Results are comparable for the three buildings configurations, since the trend lines are dissimilar. There is more variation for the required tension steel in girders, than the utilization of compression steel. In columns, the variation is minor and the trend lines are asymptotic when more than 60% of the natural aggregate is substitute by recycled material.

Elastic analysis show that the replacement of natural aggregates by 15%, 30%, 60% and 100% of recycled aggregates, produces increments of 6.3%, 6.3%, 8.9% and 11% in mean values of maximum absolute moments in columns. These variation percentages for girders were 9.8%, 10.9%, 12.52% and 14.65%. Results are similar for all buildings configurations, so it could be say that the plant geometry of the buildings does not have influence.

More studies are necessary to understand the influence of recycled material in buildings subjected to earthquakes. It is necessary to evaluate irregular structures and used more earthquakes to consider diverse characteristics. Also, it is important to evaluate costs, including the ones generated by the recycled material production. The availability of natural aggregates and the ambient impact should be considered.

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