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Strength and Deformability of Waste Tyre Rubber-Filled Reinforced Concrete Columns

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ABSTRACT

This study aims to investigate the efficiency of waste tyre rubber-filled concrete to improve the deformability and energy absorption capacity of RC columns by considering different concrete compressive strength, size of waste tyre rubber particles and rubber content. Twelve column specimens were tested using concrete of compressive strength 24 and 28 MPa mixed with 0.6 and 1 mm tyre rubber particles. For each concrete batch, 27 control specimens were prepared to examine the concrete properties. Using waste tyre rubber-filled concrete leads to a slightly lower compressive strength and modulus of elasticity, but the curvature ductility can increase up to 90%. It is concluded that this type of concrete can offer good energy dissipation capacity and ductility, which makes it suitable for seismic applications.

Key words: Rubber-filled concrete, Buckling, Waste tyre, Curvature ductility, Energy absorption

1- INTRODUCTION

Rubber waste is a highly durable material and it is highly resistant to most natural environments. As a result, disposal of used tyres is a major concern as inappropriate disposal can lead to significant environmental and aesthetic problems. This is especially true in developing countries, where environmental legislation is usually the only driving force behind the prudent management of used tyres. Following the implementation of various EU directives [1, 2], reuse and material recovery are considered as the most environmentally viable ways for managing waste materials.

Using recycled tyre rubber in cement concrete can provide an efficient way of utilizing rubber. In addition to environmental benefits, the use of tyre rubber particles could provide a new type of concrete with unique mechanical and fracture characteristics. Although recycled tyre rubber has been widely used in highway asphalt [3], there are limited studies on its application in cement concrete [4]. Eldin and Senouci [5, 6] conducted some experimental work to examine the strength and toughness properties of rubberized Portland cement concrete. While concrete containing rubber did not exhibit brittle failure under compression or split tension, their results indicate that there was always a reduction in the compressive strength when aggregates were replaced by rubber. Khatib and Bayomy [7] showed that by replacing a portion of aggregates with fine crumb rubber and tyre chips, the compressive strength of the concrete was decreased, while its toughness and ability to absorb fracture energy was significantly enhanced. Based on the results of their study, they proposed an equation to estimate the compressive strength of rubber-filled concrete.

Mechanical properties of concrete containing tyre-rubber particles have been investigated in many studies [8-14]. Although the strength of rubber-filled concrete was reduced, all of these studies showed that adding waste tyre rubber to traditional concrete could result in an increase in the deformability and ductility of rubberized concrete members. Therefore, due to the higher toughness, the waste tyre rubber-filled concrete is expected to have higher fracture and cracking resistance.

Concrete strength is greatly influenced by the properties of its constituents and the mixture design parameters [8]. Therefore, an appropriate mix design is required to optimize the tyre content in the concrete mix. The effects of particle size and content of tyre rubbers on the mechanical properties of concrete have been investigated by Son [15] and Choi et al. [16]. To find the most appropriate mixing design, different amounts of rubber-tyre particles with sizes varying from 0.4 to 10 mm were used in these studies. The results indicated that increasing the weight fraction of waste tyre rubber particles generally leads to a reduction in the compressive strength of waste tyre rubber-filled concrete. Therefore, to control the compressive strength of rubber-filled concrete, there should be a limit for the maximum amount of waste tyre rubber particles. They showed that this maximum limit is a function of the waste rubber particle size and the nominal compressive strength of the concrete. Hernandez-Olivares et al. [17] have reported that, in general, addition of crumb tyre rubber with volume fractions up to 5% does not yield a significant variation in concrete mechanical properties.

Despite several studies on the mechanical properties of rubberized concrete, studies on the structural behaviour of RC members built with this type of concrete are very limited. This paper aims to examine the deformability and energy absorption capacity of RC columns with waste tyre rubber-filled concrete. The effects of concrete compressive strength, size of waste tyre rubber particles and waste tyre mix proportion are studied.

2- EXPERIMENTAL PROGRAMME

2.1 Materials

To investigate the effect of concrete compressive strength on the buckling behaviour of waste tyre rubber-filled RC columns, two types of normal weight concrete with target 28-day strength of 24 and 28 MPa were used. These are the most commercially used concrete strengths in the construction of 15 to 20 storey apartment buildings in Korea. For each concrete batch, the compressive strength of concrete was monitored by 27 control cylinders, 200 mm in height and 100 mm in diameter. The maximum aggregate size was 25 mm and the water cement ratio was 0.54 and 0.5 for 24 and 28 MPa concrete mixes, respectively. The cement used was Ordinary Portland Cement with pulverised fly ash. The mix design proportions are shown in Table 1. These control mix designs were used as the basis for preparation of different rubberized concrete mixes in this study.

Two different sizes of crumb rubber particles (0.6 and 1 mm) were used as shown in Figure 1. These waste tyre particles were produced in Seoul and are commercially available in Korea.

Pyrolysis-chemical tests results (composition ratio) of the utilized waste tyre particles are shown in Table 2. Previous investigations [15, 16] showed that utilizing 0.6 and 1 mm particles with the weight fraction of rubber 0.5 to 1% (volume fraction of 2.7 to 5.4%) leads to better mechanical properties for 24 and 28 MPa concrete. Based on these results, a total of six different batches of concrete were prepared by using 1 and 0.6 mm rubber particles for 28 and 24 MPa concrete, respectively. The different rubberized concrete mixes were designated by using three numbers representing diameter of waste tyre particles, compressive strength of control concrete and waste tyre weight proportion. For instance, 06-24-05 represents a 24 MPa concrete batch that is mixed with 0.6 mm waste tyre rubber particles while the weight fraction of rubber is equal to 0.5% (0.5% of total aggregate weight).

All column and cylinder specimens were cast from the same batch and cured under similar conditions. Specimens were demoulded 24 hours after casting and were then water cured in a construction site (in Seoul, Korea) until the time of testing. The average-day curing temperature ranged from 21 to 26 degrees Celsius, while the air-moisture content ranged from 57 to 92%. All column and cylinder specimens were cast in plastic moulds and were compacted with electrical vibrators. The characteristic value of yield stress of both longitudinal and transverse reinforcement used in column specimens was 400 MPa (grade 60 steel).

2.2 Specimens

Four types of waste tyre rubber-filled concrete columns were prepared using different rubberized concrete mixes to evaluate the effect of mix design proportion on the buckling behaviour of specimens. Two types of normal concrete columns were also cast for comparison purposes. To ensure repeatability, two identical samples were cast for each type of column (12 column specimens in total). The parameters examined experimentally were the concrete compressive strength, size of waste tyre rubber particles and waste tyre mix proportion. All columns were (half scale) 160 cm long, 30 cm deep and 20 cm wide and contained both longitudinal and transverse reinforcement. The longitudinal reinforcement comprised six, 13 mm in diameter, rebars and the transverse reinforcement consisted of shear links, 10 mm in diameter. The spacing of the shear links was 156 mm along the length of the columns. A clear concrete cover of 30 mm was provided in all column specimens. Geometric and reinforcement details of the tested columns are shown in Figure 2. A strengthening jacket (shown in Figure 3) was provided at both ends of each column in order to minimize the effect of end buckling of the longitudinal reinforcement. In practice, the column reinforcement will be continuous into the next storey and, hence, these local end problems are avoided [18]. Using jacket strengthening did not completely eliminate all the issues at the interface between the concrete and compressive rebars; however, failure owing to buckling of the reinforcement was avoided.

2.3 Experimental setup

The column specimens were tested under pure axial load by using a standard compressive loading procedure. Structural tests were performed using a 10,000 kN compression testing machine at the test centre of Hanyang University in Korea. Figure 4 shows the experimental set-up for the column specimens. The applied load was manually controlled and was increased at 20 kN increments. Hinge support along the x-axes was provided at both ends of the columns as shown in Figures 4 and 5. A steel plate (200x300x20mm) was placed on top and bottom of each specimen in order to distribute the axial load. The actuator itself was hinged in the y-direction, at the point of reaction with the frame. For all of the tested columns, the front side corresponded to the bottom of the specimens as cast.

Two linear variable displacement transducers (LVDT) were fixed at the mid-height of the columns to measure lateral deflections as shown in Figure 4. For each column specimen, eight concrete strain gauges and three steel strain gauges (shown in Figure 4) were used to measure axial strains at ¼, ½ and ¾ column height. All data (load, strains and deflections) were collected by a data acquisition system, and downloaded to a PC each second.

3- EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Concrete properties

Based on the experimental tests on the 27 cylindrical specimens, the mechanical properties of normal and waste tyre concretes were evaluated at different ages of curing. Compressive strength tests were carried out according to KS F 2405 [19]. Figure 6 compares the compressive strength and the elastic modulus of concrete mixtures as a function of rubber content. Concrete properties shown in Figure 6 are calculated based on the average of three specimens tested 28 days after casting (Table 3). It is shown that compressive strength of concrete decreases with an increase in the rubber content. The results indicate that, on average, compressive strength of 24 MPa concrete with 0.5 and 1% rubber content is almost 13 and 22% less than similar concrete mix without waste tyre particles, respectively. Similar results were obtained for 28 MPa concrete where using 0.5 and 1% rubber contents resulted in a 12 and 19% decrease in the compressive strength of concrete. Based on the results, to control the compressive strength of the concrete (i.e. limit its reduction to 20%), the weight fractions of rubber particles should be limited to 0.5 and 1% for 24 and 28 MPa concrete mixtures, respectively. This is in agreement with the results of previous studies [15, 16]. It should be mentioned that workability and durability could be other factors affecting the application of rubber-filled concrete. However, a previous study [4] shows that using up to 2.5% rubber weight fraction (15% rubber volume fraction) does not affect the workability of rubber-filled concrete. Trials by the authors with 100% replacement of aggregates with rubber chips show that workability issues can be resolved by appropriate mix design.

Figure 6-b shows that the modulus of elasticity of waste tyre concrete was lower compared to normal concrete and it decreases with an increase in the rubber content. The results indicate that, on average, adding 0.5 to 1% waste-rubber particles to the 24 MPa and 28 MPa concrete mixtures resulted in a 10 to 15% decrease in the elastic modulus of concrete.

3.2 Failure modes in columns

The ratio of unsupported length to least dimension of the cross section for the tested columns is equal to 8 (see Figure 4). Therefore, the column specimens are relatively slender. As mentioned before, local rebar buckling failure was also prevented by using steel jackets at both ends of column specimens. As a result, the global buckling of the column was always the dominant failure mode (see Figure 7) since failure always occurred prior to concrete compressive crushing. As expected, in all columns, bending occurred towards the front, since the back-side of the column had marginally weaker concrete and, hence, went into compression. This could also be encouraged by shrinkage strains, which are expected to be higher in the back side of the column that was more exposed to the environment during curing. The shrinkage strains can lead to a small bowing of the column and provide the initial imperfection necessary to force buckling to occur always in the same direction. Though in practice, columns are cast vertically and, hence, there is no difference in the concrete quality between the front and back of the column, material and geometric imperfections always exists. Thus, the results can be considered to be relevant to practical applications as well.

3.3 Strains in concrete and reinforcement

Typical load-strain curves for column specimens with 24 and 28 MPa target concrete strength are shown in Figure 8 and 9, respectively. The locations of the concrete strain gauges are shown in Figure 4. Comparison between the compressive strain in the back side and the tensile strain in the front side of the specimens shows that the tested columns were overall buckled in the z-y plane (out of plane). However, in some of the specimens (e.g. 10-28-10 shown in Figure 9-c), there is indication of some bending in the z-x plane. This eccentric buckling could be due to local segregation of waste tyre particles leading to local imperfections. The strain profiles show that, despite the P-δ effects, the columns remain in compression, at least in the middle section. In general, the results from two identical samples for each type of column had good consistency. Therefore, it can be confirmed that the materials used, the production of the specimens and the test procedure were all well controlled.

The results shown in Figure 8 and 9 indicate that, for the same axial load, the area under the load-strain curves is relatively higher for waste tyre rubber-filled concrete columns compared to the normal concrete specimens. This implies that rubber-mixed concrete columns are capable of absorbing higher amount of energy before failure due to excessive axial loads.

3.4 Compressive load-carrying capacity

The results indicate that the compressive load-carrying capacity of column specimens decreases with an increase in the rubber content. Figure 10 compares the compressive load-carrying capacity of the tested columns as a function of rubber content. It is shown that the compressive capacity of RC columns with 24 MPa concrete decreased 8 and 32% by adding 0.5 and 1% rubber particles to the concrete mixture, respectively. Similarly, using 0.5 and 1% rubber particles in the 28 MPa concrete mixture resulted in a 14 and 18% reduction in the compressive capacity of the column specimens, respectively. The results indicate that, to limit the reduction of axial load-carrying capacity of columns to 20%, the waste tyre proportion should be limited to 0.5 and 1% for 24 and 28 MPa concrete mixtures, respectively. This is in agreement with the results obtained from the compressive strength of tests as discussed in section 3.1.

3.5 Load deformation response

Figure 11 shows typical load versus mid-span lateral deflection curves for different types of tested columns. The presented lateral deflection is the average of the deflections measured at the front and back of each column. The results indicate that waste tyre rubber-filled concrete columns were capable of undergoing much higher lateral deformation before buckling failure compared to similar normal concrete columns. This implies that using tyre-particles in concrete leads to concrete failures with larger deformations, and therefore, higher fracture energy dissipation.

Lateral deflections for the column specimens are compared in Figure 12. As buckling was the dominant failure mode of the tested columns, lateral mid-span deflection corresponding to the compressive load-capacity of columns was considered as buckling deflection. It is shown that the mid-span buckling deflection of RC columns with 24 MPa concrete increased from 6 to 7.5 and 12 mm by adding 0.5 and 1% rubber particles to the concrete mix, respectively. Similar results were obtained for RC columns with 28 MPa concrete, where adding 0.5 and 1% rubber particles to the concrete mix resulted in enhancement of mid-span lateral deflection capacity from 4 to 9 and 6.5 mm, respectively. It should be mentioned that the results of 10-28-10 column contradicts the general trend in lateral deformation. This is mainly due to the fact that this specific column experienced some bending in the y axes as indicated by the Left and Right strain-gauges in Figure 9 c.

To visualise qualitatively the energy absorption/dissipation capacity of the tested columns, the area under load-lateral deformation curves for different concrete mix designs are compared in Figure 13. The results indicate that waste tyre rubber-filled concrete provides better energy dissipation capacity as the lateral deformation capacity of a rubber-filled RC column could be more than 2 times higher compared to a similar conventional RC column. This is especially important for seismic design applications where structures should be capable of sustaining large deformations without collapse.

3.6 Curvature ductility

Using the experimental concrete strain (ε_c), the rebar strain (ε_s), and the effective reinforcement depth (*d*), the curvature (ϕ) at every load level was evaluated from the test results according to the general approach of CEB [20], as follows:

$$\varphi = \frac{1}{r} = \frac{\varepsilon_c - \varepsilon_s}{d} \tag{1}$$

To calculate the experimental curvature, it is assumed that plane section remains plane after deformation. The experimentally derived load-curvature relationships, in general, compare well to those derived by cracked-section analysis. Using Equation 2, the experimentally derived moment-curvature relationships were used to calculate the mid-span lateral deflections ,δ, for tested columns.

$$\delta = \int_0^{\frac{L}{2}} s(\frac{1}{r})ds \tag{2}$$

where s is distance to the hinge support. To calculate lateral mid-span deflection, it is assumed that curvature along the height of the column is uniformly distributed.

Calculated lateral mid-span deflections for the 24-normal and 06-24-05 column specimens are compared with the measured LVDT deflections in Figure 14. It is shown that the calculated lateral mid-span deflections agree well with the measured deflections over the entire loading range. This emphasizes the reliability of the recorded strains.

Curvature ductility, μ_k, is an appropriate performance criterion for the seismic assessment of structural elements [21], and can be calculated by:

$$\mu_k = \phi_u / \phi_y \tag{3}$$

where, ϕ_u and ϕ_y are ultimate curvature and yield curvature, respectively.

To investigate the effects of rubber content on the curvature ductility of RC columns, ϕ_u was calculated for the column specimens by using concrete and steel strains at the mid-span corresponding to the ultimate axial load state. The yield curvatures of the columns were computed using conventional section analysis including the effect of axial loads. Computed curvatures are used since the experimental strain measurements from the tests are not considered to be accurate enough to measure representative average strains. Figure 15 compares the curvature ductility of tested columns using 24 and 28 MPa concrete mix with different waste tyre-rubber content. The results indicate that tyre-rubber concrete specimens can develop considerably higher curvature ductility compared to similar conventional concrete columns. It is shown that curvature ductility of RC columns with 24 MPa concrete can increase 45 and 90% by adding 0.5 and 1% rubber particles to the concrete mix, respectively. Similarly, using 0.5 and 1% rubber particles in the 28 MPa concrete mix can result in a 78 and 67% enhancement in the curvature ductility of the column specimens, respectively. Having higher curvature ductility is usually accompanied by better seismic performance and less structural damage during strong earthquakes. Therefore, waste rubber-filled concrete is shown to be a potentially suitable material for seismic applications. However, further research is required to investigate the performance of rubber-filled RC elements subjected to lateral cyclic loading and dynamic loads.

4- CONCLUSIONS

This study investigated the effect of using waste tyre rubber-filled concrete on the compressive strength and deformability of reinforced concrete columns. Based on the results, the following conclusions can be drawn:

- Using waste tyre rubber in concrete can lead to a lower concrete compressive strength and modulus of elasticity. It is shown that utilizing 0.6 and 1mm waste tyre particles with the weight fraction of rubber 0.5 to 1%, on average, resulted in a 12 to 20% reduction in the compressive strength, and 10 to 15% reduction in the elastic modulus of concrete, respectively.

- Compressive load-carrying capacity of column specimens decreased with an increase in the rubber content. It is shown that utilizing 1% rubber content could lead up to 32 and 18% reduction in the compressive load-carrying capacity of columns with 24 and 28 MPa concrete.
- Waste tyre rubber-filled concrete columns are capable of undergoing up to twice the lateral deformations before buckling failure compared to similar normal concrete columns. The results indicate that utilizing 0.5 to 1 % waste tyre particles in the concrete mixtures can result in 45 to 90% improvement in the curvature ductility of column specimens.
- Waste tyre rubber-filled concrete provides better energy dissipation capacity and ductility than normal concrete and could find use in seismic applications.

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List of Figure Captions

Table 1. Concrete mix design proportions

	24MPa Concrete	28MPa Concrete
Material	Weight (kg/m^3)	Weight (kg/m^3)
Cement	299	329
Water	144	149
Coarse Aggregate	936	936
Fine Aggregate	921	884
Additives*	1.6	1.8
Total	2302	2300

*AE water reducing agent

Table 2. Pyrolysis-chemical composition % ratio of waste tyre particles

Ignition loss	0.8
Organics	9.7
Polymer	53.7
Carbon Black	30.4
Ash	5.4

Table 3. Compressive strength and modulus of elasticity for different concrete mix

Concrete Mix	Test No.	Compressive Strength (MPa)		Elastic Modulus (kN/mm^2)	
24-Normal	1	25.1	Ave. 24.3 Var. 0.6	22.2	Ave. 21.5 Var. 0.4
	2	23.6		21.0	
	3	24.2		21.3	
06-24-05	1	20.9	Ave. 21.2 Var. 0.8	19.5	Ave. 19.3 Var. 0.5
	2	20.5		18.5	
	3	22.2		19.9	
06-24-10	1	18.6	Ave. 19.0 Var. 0.3	17.5	Ave. 18.0 Var. 0.2
	2	19.6		18.4	
	3	18.8		18.2	
28-Normal	1	28.1	Ave. 27.9 Var. 0.8	24.2	Ave. 24.0 Var. 0.6
	2	28.7		24.6	
	3	26.9		23.1	
10-28-05	1	24.4	Ave. 24.5 Var. 0.4	21.6	Ave. 21.7 Var. 0.3
	2	25.2		22.3	
	3	23.9		21.3	
10-28-10	1	23.3	Ave. 22.6 Var. 0.5	20.0	Ave. 19.9 Var. 0.4
	2	21.9		19.2	
	3	22.6		20.5	

Fig. 1. Crumb rubber particles (1 mm)

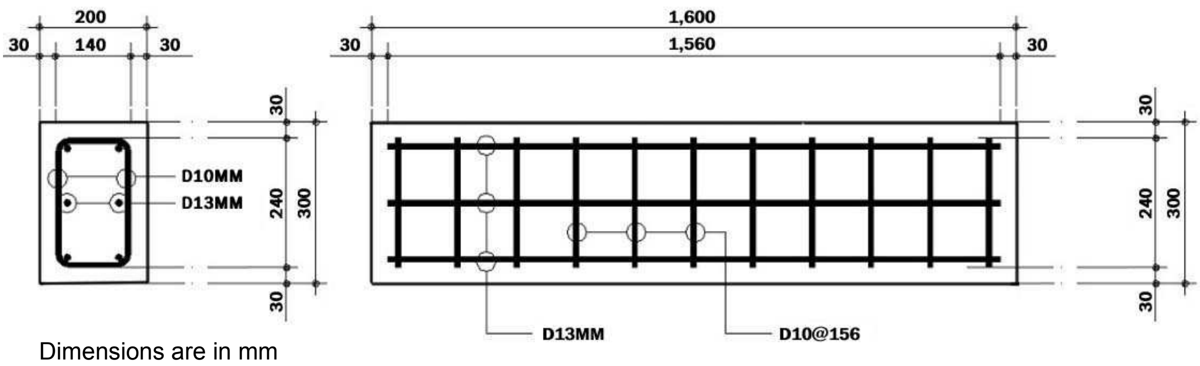

Fig. 2. (a) Geometric and reinforcement details of the test columns

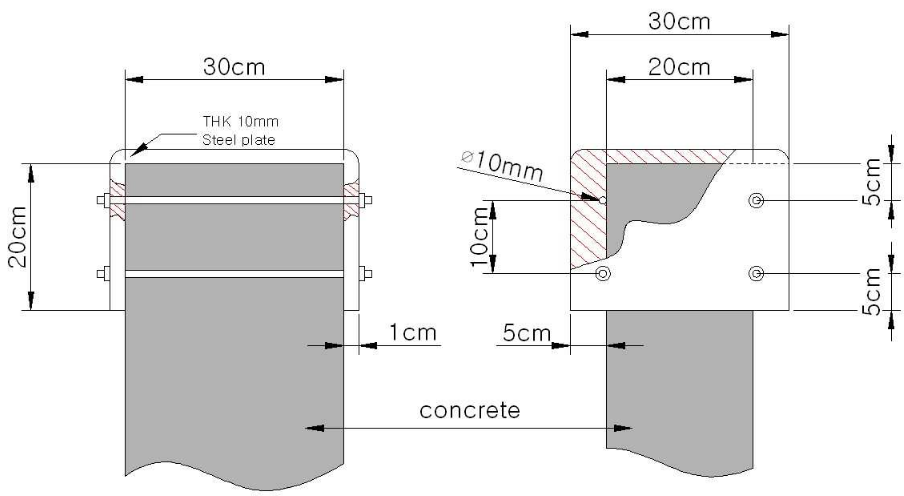

Fig. 3. Steel jacket to prevent local buckling of longitudinal reinforcement at column ends (side view)

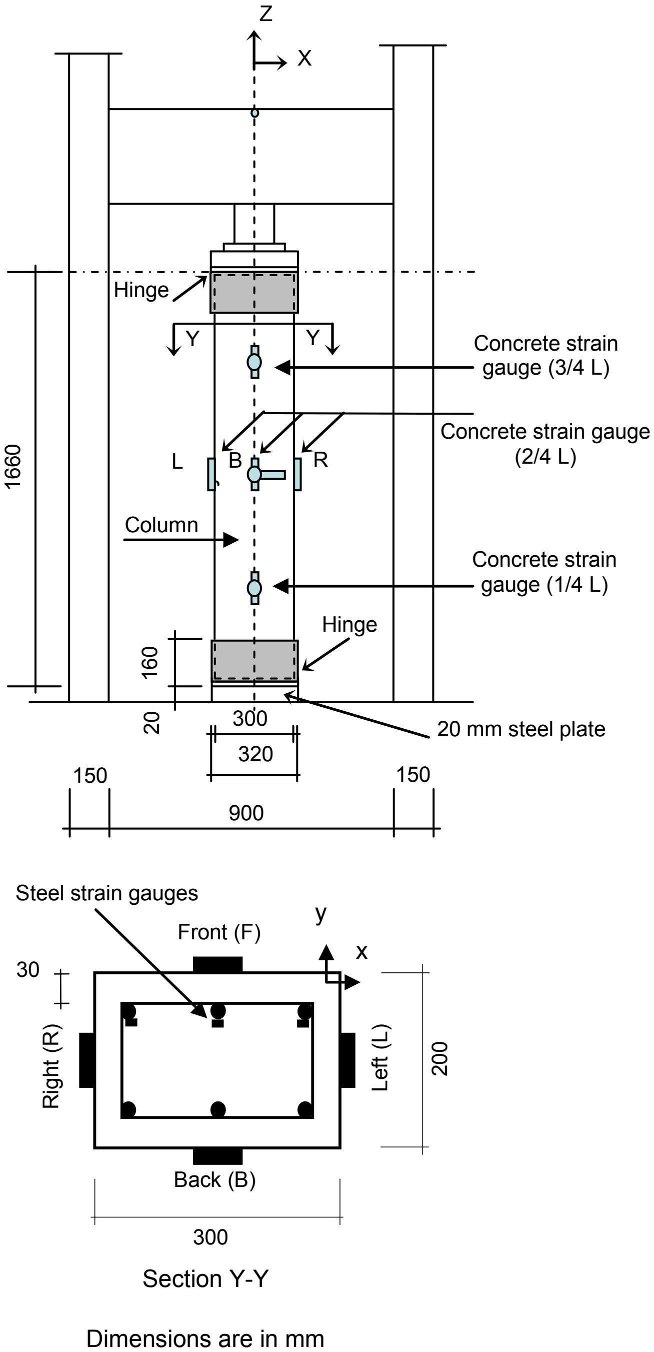

Fig. 4. Experimental set-up for column specimens

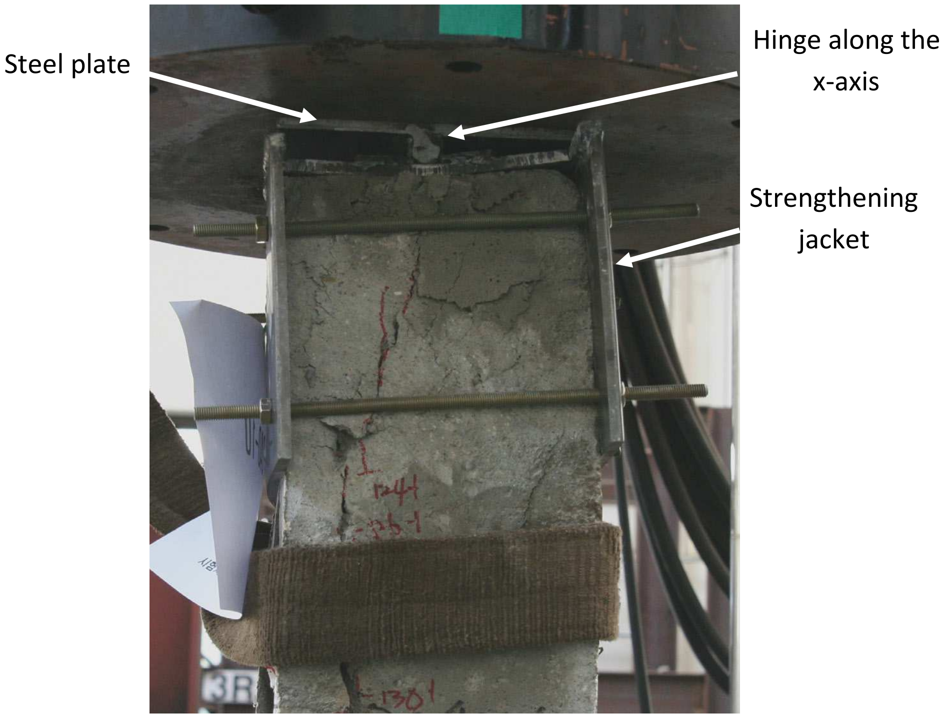

Fig. 5. Hinge above top surface of column

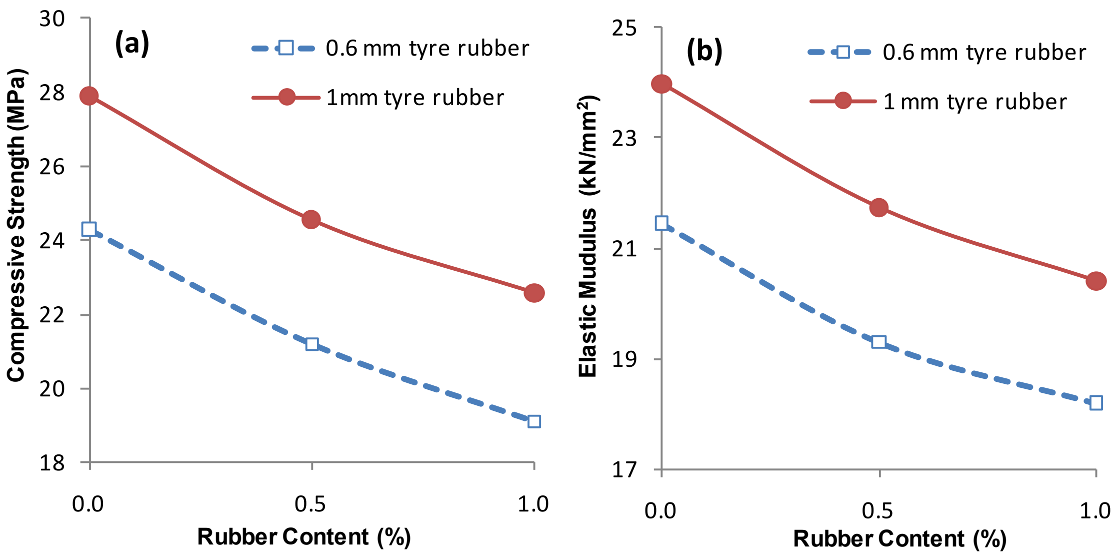

Fig. 6. (a) Compressive strength and (b) Elastic modulus of concrete mixtures

Fig. 7. Failure mode of column specimens

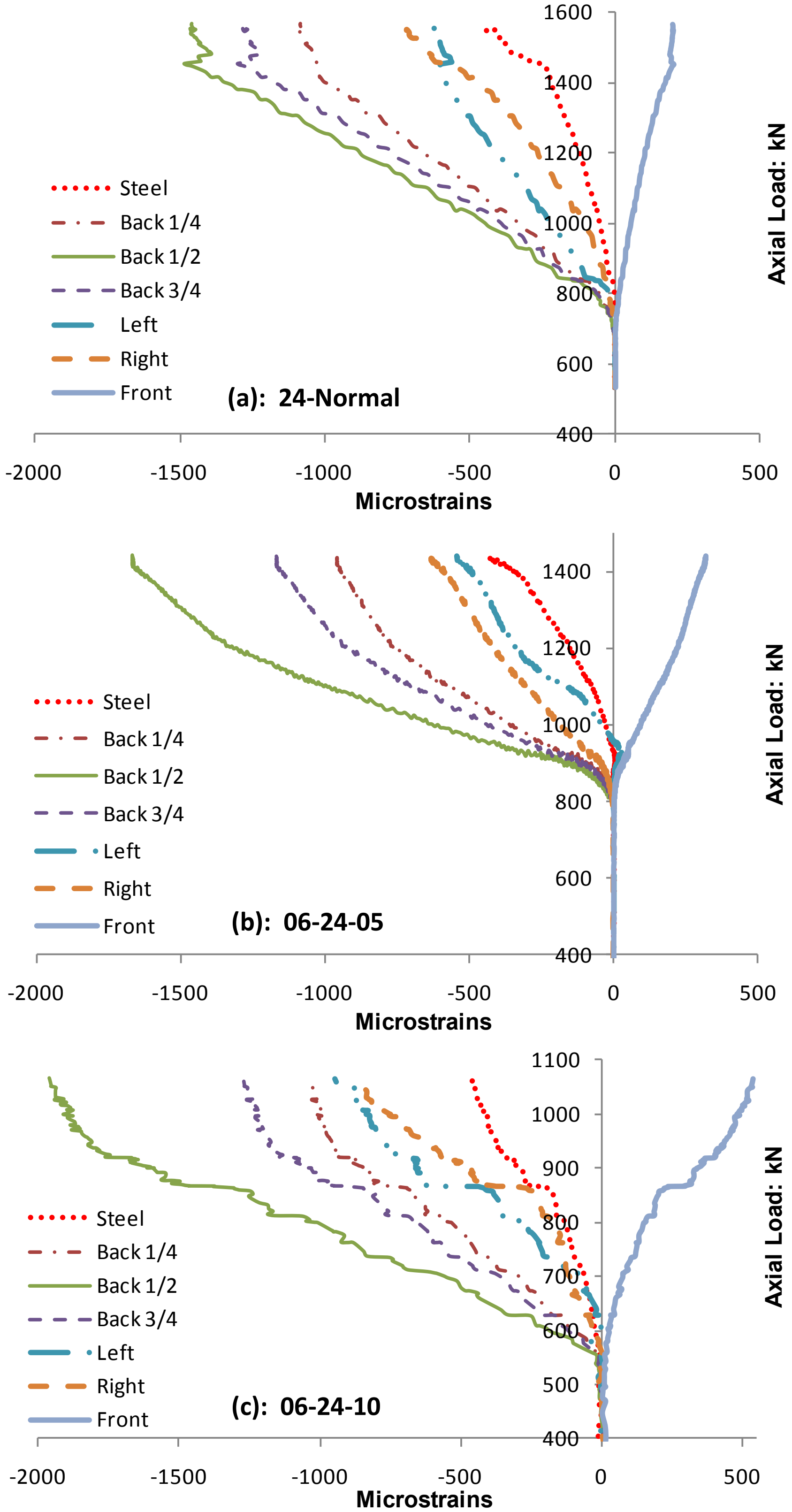

Fig. 8. Typical Load versus strain curves for columns with 24MPa concrete; (a): Normal concrete; (b): 0.5% rubber content; (c): 1% rubber content

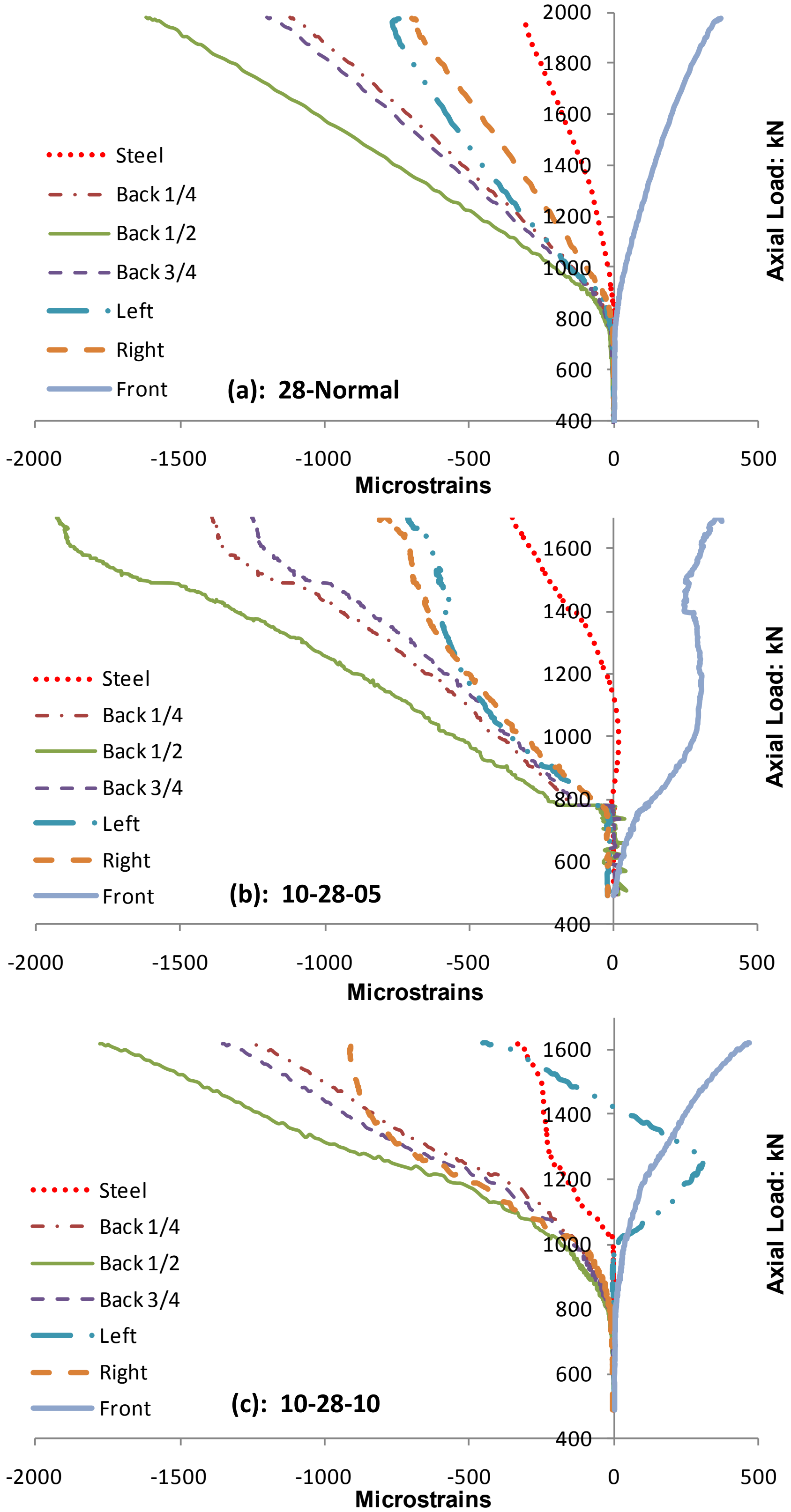

Fig. 9. Typical Load versus strain curves for columns with 28MPa concrete; (a): Normal concrete; (b): 0.5% rubber content; (c): 1% rubber content

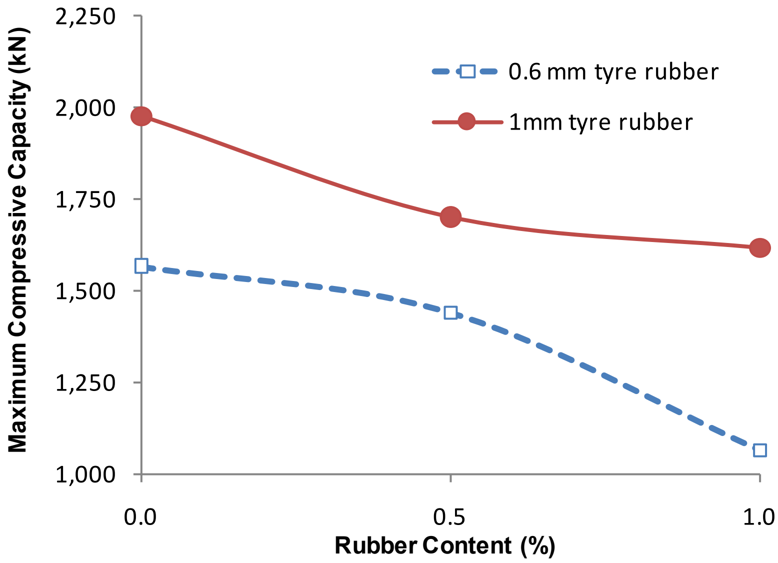

Fig. 10. Compressive load-carrying capacity of column specimens

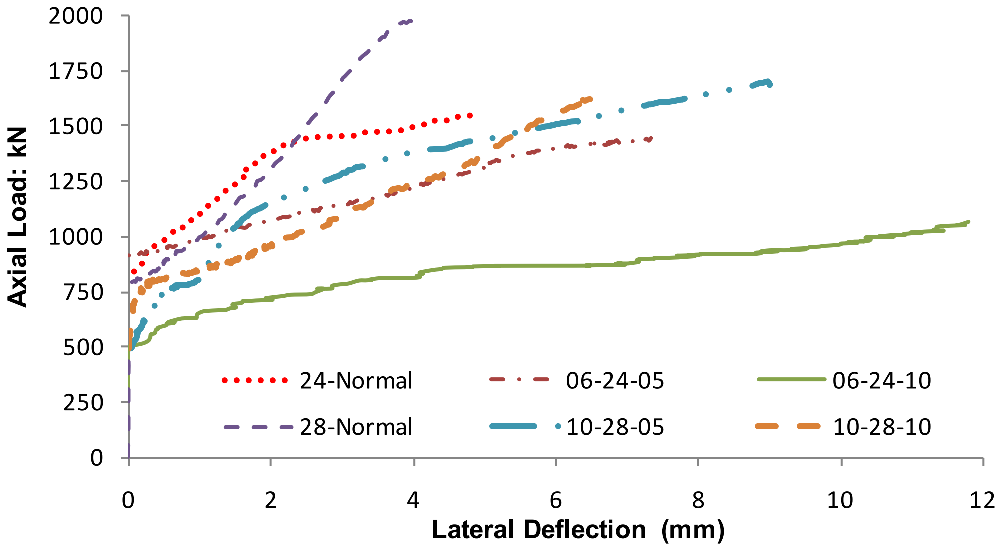

Fig. 11 Typical axial load versus mid-span lateral deflection curves

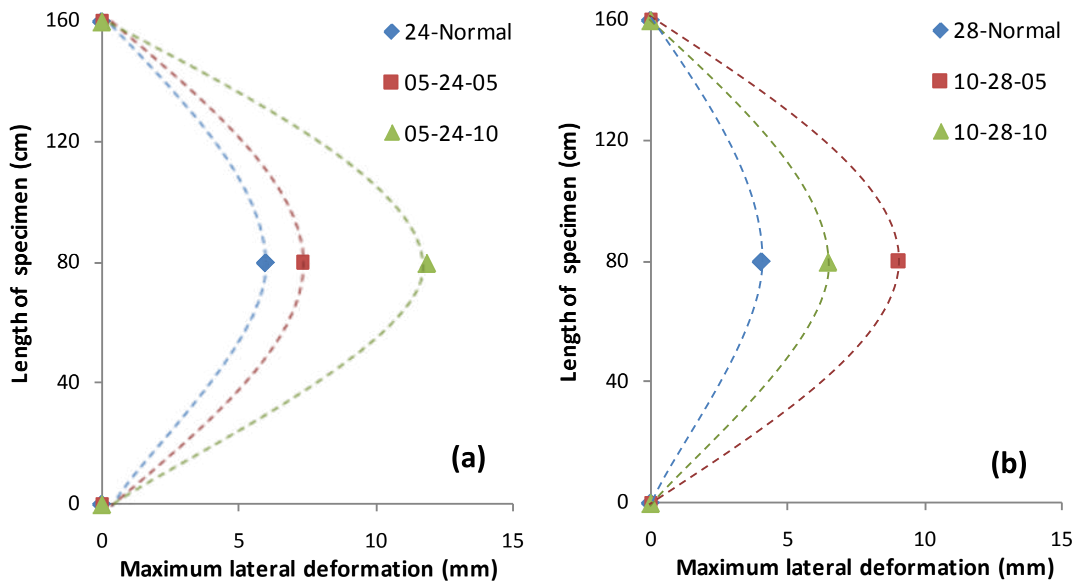

Fig. 12. Average lateral buckling deflection; (a): 24 MPa concrete; (b): 28 MPa concrete

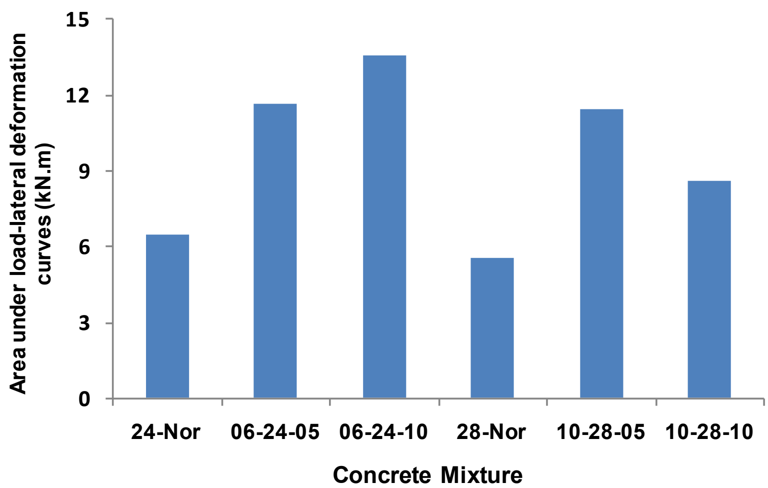

Fig. 13. The area under load-lateral deflection curves for different columns

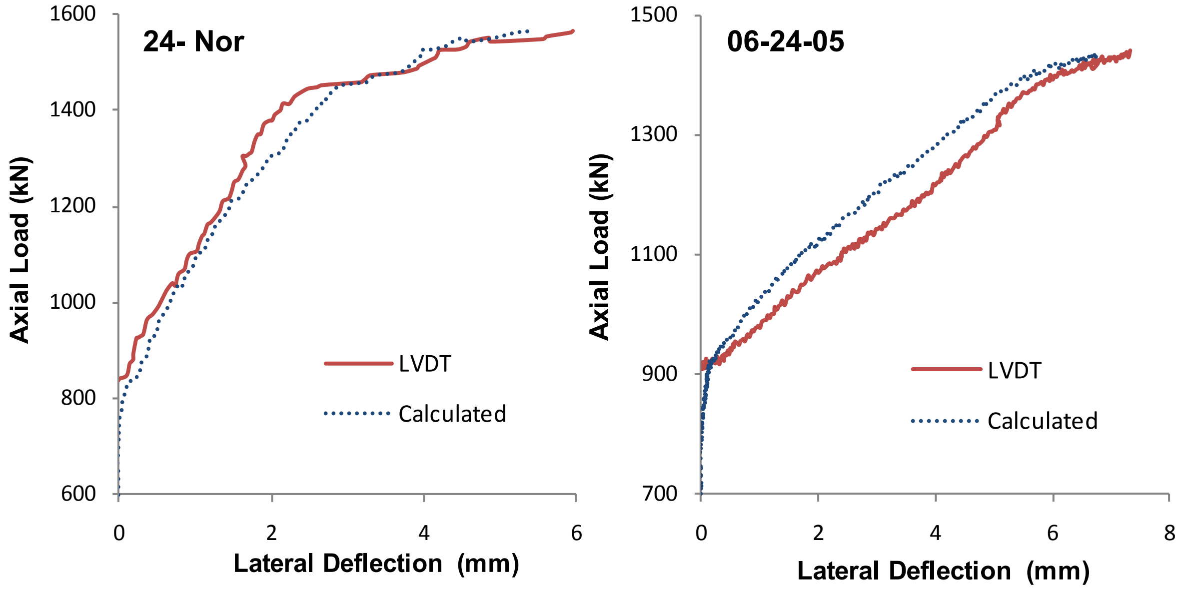

Fig. 14. Comparison between measured lateral mid-span deflections and calculated deflection using experimentally derived moment-curvatures

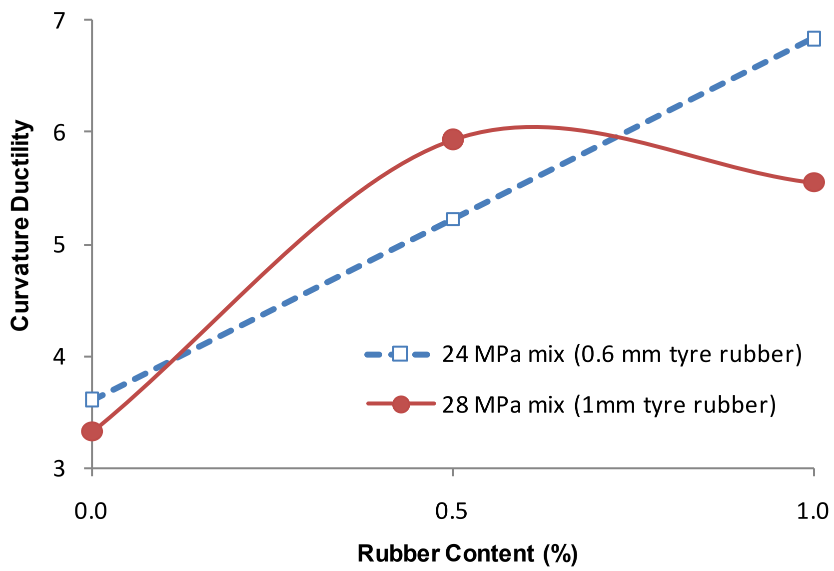

Fig. 15. Curvature ductility as a function of rubber content (%)