Jurnal Teknologi

Full paper

Dynamic Stress and Strain of HPC Under Drop-weight Impact Loading

R. Hamid[a*], Khairol Rizal Jamalluddin[a], Abu Sufian Md Zia Hasan[a]

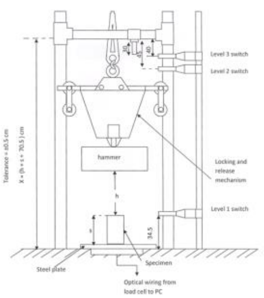
[a]*Department of Civil and Structural Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia*

*Corresponding author: roszilah@eng.ukm.my

Article history

Received :20 August 2013
Received in revised form :
25 September 2013
Accepted :15 October 2013

Graphical abstract



Abstract

Studies have been done vastly to determine the dynamic stress-strain behaviour of concrete but the results seem not to agree with each other due to difference in method. The specimen size and the loading rate effects are significant factors in determining the compressive stress-strain behaviour of concrete cylindrical specimens. This study is to provide more dynamic stress-strain data that can add to that database on high performance concrete (HPC) using drop-weight impact test. Experiments on HPC cylinders were conducted for specimens with different sizes but maintaining the length-to-diameter (L/D) ratio (slenderness) of 2, and the results show that the maximum stress occurred for specimens with smallest size and decreased as the size increased. This current test shows that the apparent dynamic stress increase more than twofold compared to its static strength for small cylinder of Ø100 mm × 200 mm at strain rate 0.20 s^{-1}. It was found that compressive stress of HPC was seen to exhibit an enormously size effect under impact loading.

Keywords: Dynamic stress and strain; drop-weight impact; specimen size; loading rate; high performance concrete

1.0 INTRODUCTION

Numerous studies have been performed to understand the effect of fracture characteristics on the material properties of concrete to evaluate the load-carrying capacity. Unfortunately, the results of experimental and theoretical investigations presented thus far on the behaviour of concrete loaded with tension, compression, shear or torsion have been inconsistent because of the large number of variables that affect the results, such as the specimen size, the geometry, the length-to-diameter ratio (L/D) which is also known as the slenderness ratio, the moisture content in the specimens, the concrete quality, the curing procedure, the age and the loading rate [1-3]. The most effective experimental method involves determining the size effect. The term size effect refers to the dependence of the concrete material strength on the specimen size.

Concrete compressive strengths are most often evaluated with tests performed on cylindrical specimens with a slenderness ratio of two. Nevertheless, when it is necessary to evaluate the in-situ concrete strength (with drilled cores), specimens with slenderness ratios lower than two are often used. Additionally, other types of specimens, such as prisms or cubes, have been adopted in many countries because of the greater amount of experimental work based on them.

Over the last 10 years, significant size effect studies on the compressive failure of concrete under static loading conditions have been performed by many researchers [4-12]. The failure stress of a series of concrete cylinder can be expressed by the following equation [12]:

$$f_{cy}(d) = \frac{0.49 f'_c}{\sqrt{1+\frac{d}{2.6}}} + 0.81 f'_c \qquad (1)$$

where f_{cy} *(d)* is the compressive strength of any arbitrary cylinder dimension and f'_c is the compressive strength (MPa) of standard cylinder and *d*(cm) is the diameter of the cylinder. These studies are based on static loading conditions, and the maximum size of the coarse aggregate is 13 mm. Even though the size of the aggregate used in this study is different than 13 mm, eq. (1) is still applicable in the study of specimen size effect.

This paper contributes in terms of size effect on the dynamic stress and strain behaviour of HPC loaded with weight drop hammer at stress rate of 0.10 to 0.20 s^{-1}. The static compressive stress and strain behaviour of the specimen is determined and the compressive strength is compared to calculated values using equation (1), and some deviations are expected due to the difference in the maximum aggregate size used (13 mm for eq. (1) and 20 mm for this study).The dynamic stress-strain results of the specimens are compared to Krauthammer *et al*., 2003 [13].

2.0 EXPERIMENTAL PROGRAM

2.1 Materials

The cement used for the HPC is ordinary Portland cement (OPC) with specific gravity 3.15 with moisture content of 0.6%. The sand and crushed granite coarse aggregate used is uniformly graded conforming to ASTMC33and ASTM C136, maximum size 4.75 mm for sand and 20 mm for granite. The specific gravity of sand and granites are 2.25 and 2.29 respectively. The moisture content of the granites is 0.7% (ASTMC127). The fineness modulus of the sand is 2.48, and moisture content (ASTM C70). The silica fume used is of Elkem Microsilica Grade 920-D type with the average particle diameter of 0.1 μm and the specific gravity is 2.20, with moisture content 1.4%. The superplasticiser used is of condensed naphthalene formaldehyde sulphate with specific gravity 1.21, 40% solid content and 0% chloride. The unit for the specific gravity of materials is in SI (kg/m^3 per 1000 kg/m^3 density of water).

The mix design is based on Sherbrook design [14]. Mixing, specimen preparation, casting, curing and static compression test are based on ASTM C143, ASTMC39, ASTMC469. Detail of the mix design is shown in Table 1.

2.2 Specimen

Table 2 shows the cylinder sizes and number of samples for static and drop-weight test. All testing ages is at 28 days.

Table 1 Detail of mix design

Components	Water/ cement ratio	Water (kg/m^3)	Cement (kg/m^3)	Silica fume (kg/m^3)	Super-plasticizer (l/m^3)	Sand (kg/m^3)	Aggregate (kg/m^3)
Quantity (per m^3)	0.25	138.11	490.95	61.67	19.00	615.67	1056.25

Table 2 Dimension of specimen

Cylinder Size (mm)	Code	No of sample for static test	No of sample for drop-weight test	Testing age (days)
Ø100 × 200	CY100	3	2	28
Ø150 × 300	CY150	3	2	28
Ø300 × 600	CY300	0	2	28

2.3 Drop-weight Impact Test

The electronic strain gauges are mounted along two opposite surface of the height of the cylinder as shown in Figure 1. For smaller samples of Ø100 mm × 200 mm (CY100), the gauges are mounted at only 2 locations along the height due to the limited space available and for samples of Ø150 mm × 300 mm (CY150), the number of gauges are 4. The locations of strain gauges and the coding of specimens are shown in Table 3. The strain gauges are connected to the dynamic data logger for the displacement measurement. The stress is measured through the load cell placed on top of a concrete base at the middle of the impact area. This is to ensure that the sample is placed right in the middle of the impact area. The load cell is connected to the personal computer by an optical wiring and a software named Dewesoft 6 is used to analyze the data. An accelerometer is connected to the dynamic data logger and the sampling rate is 100s$^{-1.}$ A 20 mm thick steel plate is located on top of the load cell at the exact predetermined location. Then, the specimen is placed at the centre of the steel plate. A weight of mass 54 kg is set to drop from a height of 3.5 m above the top of the cylindrical specimen which is placed vertically. The height of the impact can be adjusted accordingly (as shown in Figure 2):

$$x = (h + s + 70.5) \text{ cm} \quad (2)$$

where,
x is the height between the load cell plate and the adjustable shaft
h is the impact height (3.5 m)
s is the sample's height

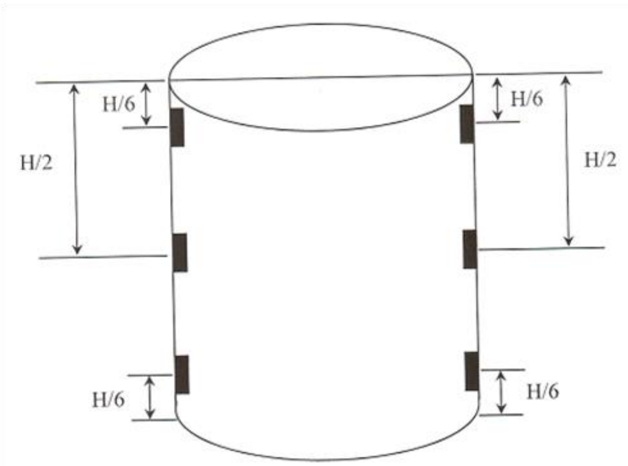


Figure 1 Schematic diagram of the mounted location of the gauges

Table 3 The locations strain gauges and the coding of specimens

Specimen	Location of strain gauge	Coding
Ø100 × 200 (Sample 1)	Middle right	CY100S11
Ø100 × 200 (Sample 1)	Middle left	CY100S12
Ø100 × 200 (Sample 2)	Middle right	CY100S21
Ø100 × 200 (Sample 2)	Middle left	CY100S22
Ø100 × 200 (Sample 3)	Middle right	CY100S31
Ø100 × 200 (Sample 3)	Middle left	CY100S32
Ø150 × 300 (Sample 1)	Upper right	CY150S11
Ø150 × 300 (Sample 1)	Upper left	CY150S12
Ø150 × 300 (Sample 1)	Lower right	CY150S13
Ø150 × 300 (Sample 1)	Lower left	CY150S14
Ø150 × 300 (Sample 2)	Upper right	CY150S21
Ø150 × 300 (Sample 2)	Upper left	CY100S22
Ø150 × 300 (Sample 2)	Lower right	CY150S23
Ø150 × 300 (Sample 2)	Lower left	CY150S24
Ø150 × 300 (Sample 3)	Upper right	CY150S31
Ø150 × 300 (Sample 3)	Upper left	CY150S32
Ø150 × 300 (Sample 3)	Lower right	CY150S33
Ø100 × 300 (Sample 3)	Lower left	CY100S34

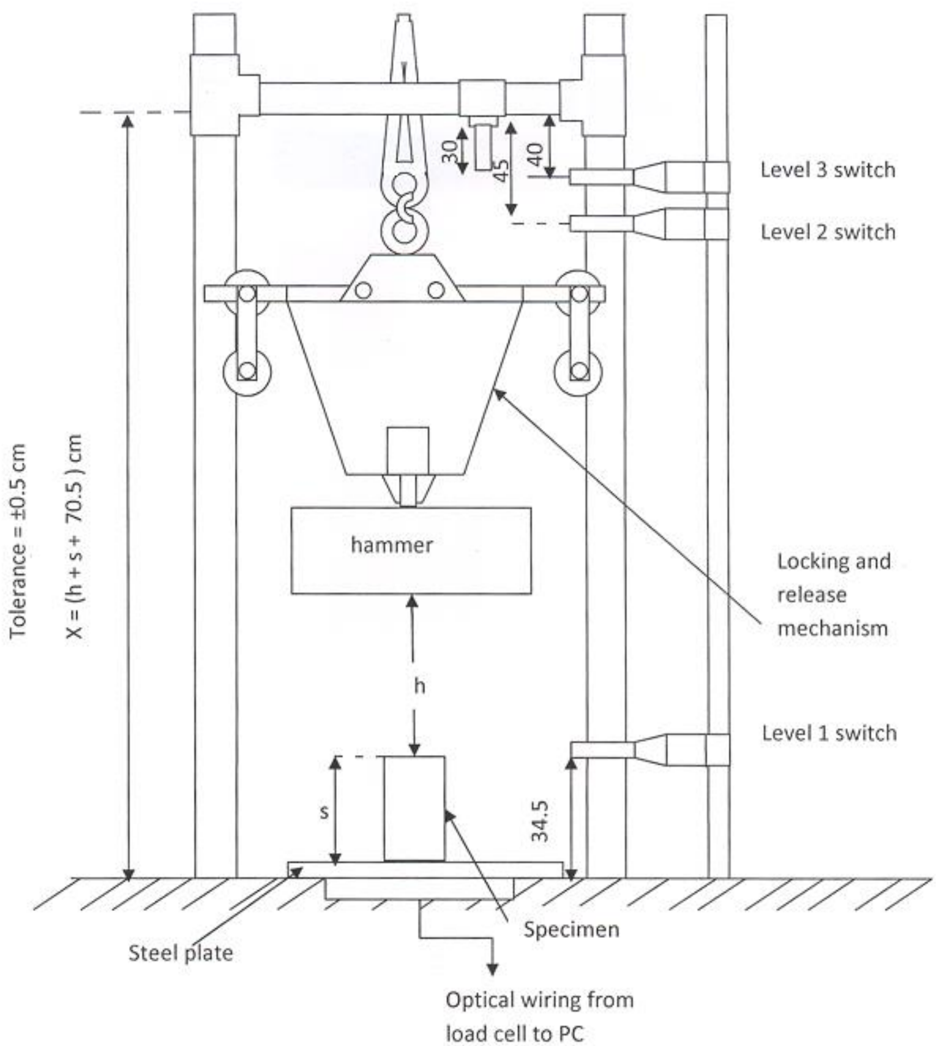


Figure 2 Schematic diagram of the Drop-weight impact equipment (all measurements are in cm)

3.0 RESULTS AND DISCUSSION

3.1 Specimen Size Effect under Static Loading

Figure 3 and 4 show the results on the stress-strain diagram of samples Ø100 mm × 200 mm (CY100) and Ø150 mm × 300 mm (CY150). Table 4 shows the maximum stress and strain for each specimen. Cylinders Ø300 mm × 600mm (CY300) are not tested for static loading due to limitation of equipment, but that particular size was successfully tested under dynamic test. However, the compressive strength of CY300 is predicted using Eq. (1). CY150 is taken as the standard cylinder strength. Table 5 shows the average maximum stress and strain of the samples. The predicted strength of CY100 is in agreement with its actual strength with a small difference; however, the predicted strength (Eq. 1) for CY150 differs from the actual test probably due to the difference in aggregate size. Smaller aggregate size had proven to lead to greater strength of concrete. Table 5 also shows that the stress increases (11.5%) with the reduction of sample size, as have been discussed earlier. The maximum static strain (ε_{smax}) recorded at maximum static stress (σ_{smax}) also decreases (3.42%) as the size increase, but the reduction is less pronounced than the reduction of stress.

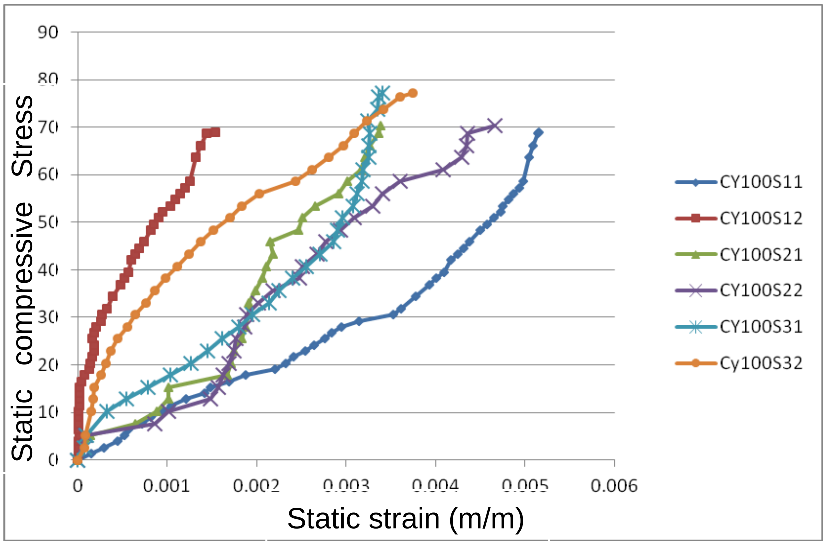


Figure 3 Static Stress-strain diagram of cylinder Ø100 mm × 200 mm

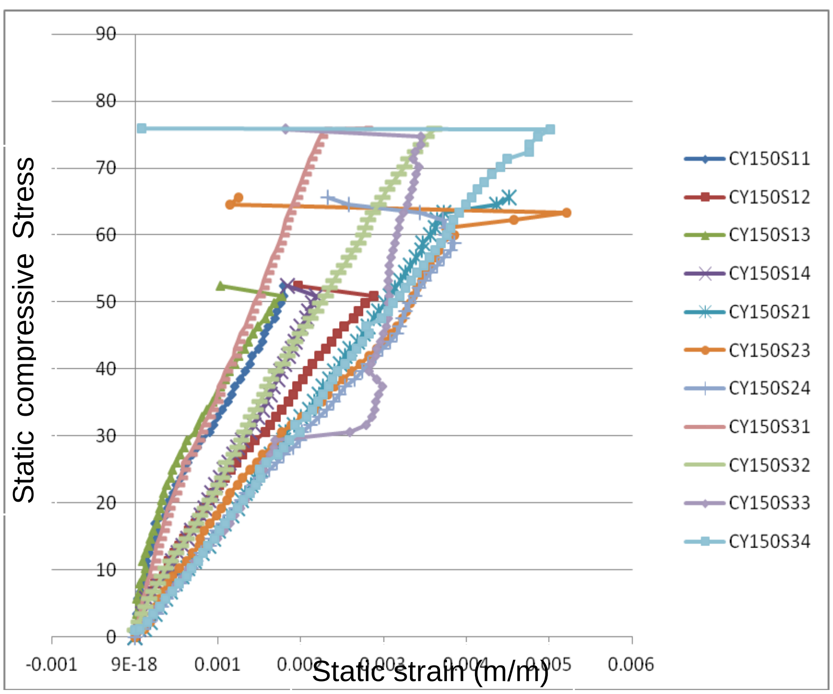


Figure 4 Static Stress-strain diagram of cylinder Ø150 mm × 300 mm

Table 4 Static stress and strain of samples of different sizes

Cylinder Size (mm)	Maximum stress, σ_{smax} (MPa)	Maximum strain, ε_{smax} ($\times10^{-3}$) (m/m)
Ø100 × 200		
S11	68.88	5.154, 1.542
S12	70.33	3.380, 4.659
S13	77.16	3.410, 3.748
Ø150 × 300		
S11	52.46	1.795, 2.886, 1.765, 2.183
S12	65.64	4.513, 5.214, 3.857, 4.126
S13	75.88	2.781, 3.610, 3.456, 5.020

Table 5 Average static maximum stress and strain of samples of different sizes

Cylinder Size (mm)	Maximum stress, $\sigma_{smax(av)}$ (MPa)	Difference (%)	Maximum strain, $\varepsilon_{smax(av)}$ ($\times10^{-3}$) (m/m)	% difference	f'_c (eq. 1) (MPa)	% difference
Ø100 × 200	72.12		3.3163		73.06	
		+ 11.5		+3.42		+3.44
Ø150 × 300	64.66		3.4338		70.63	
		NA		NA		-5.13
Ø300 × 600	NA		NA		67.01	

NA – Not available

3.2 Specimen Size Effect under Weight Drop Loading

The maximum dynamic stress, $\boldsymbol{\sigma}_{\mathbf{dmax}}$ and maximum dynamic strain, $\boldsymbol{\varepsilon}_{\mathbf{dmax}}$ are summarised in Table 6. Table 6 also shows the calculated strain rate, **έ.**

Table 6 Maximum dynamic stress and strain of cylindrical samples of different sizes

Cylinder Size (mm)	Maximum stress, σ_{max} (N/mm^2)	Time Δt (ms)	Max strain, ε_{max} ($\times10^{-3}$) (m/m)	Strain rate, έ = ε_{max}/ Δt
Ø100 × 200	152.0	11.74	2.6370	0.22
Ø150 × 300	49.5	18.55	2.4500	0.13
Ø300 × 600	14.3	4.67	1.0620	0.19

The initial potential energy of the impact,$ú_h(0)$ can be expressed as:

$$ú_h(0) = mgh \tag{3}$$

where
g = gravitational acceleration
h = impact height
In this experiment, $ú_h(0)$ is equal to 1.854 kJ, so that at impact the velocity is equal to

$$v = \sqrt{2gh} \tag{4}$$

v = 8.29 m/s where h = the drop height (3.5 m)

The present results were compared with the existing results by Krauthammer *et al*., 2003 [13] as shown in Table 7. In their experiment, the load magnitude was not the same with the current study but the strain rate is in the same category. Krauthammer *et al*., 2003 [10] in their experiment used a drop hammer of much less weight, that is only up to 29.8kN but the drop heights can be adjusted up to 28 m so that they can adjust their drop velocities by adjusting the drop height. Their tests were conducted at drop velocities of 0 m/s (static tests), 5 and 7 m/s. The specimens tested were high strength concrete (100 MPa, nominal strength) cylinders of the dimensions as shown in Table 6. The basis for choosing this experiment [13] as comparison is based on the near similarity of the drop velocities.

The strain rate used by [13] and the current study are in the range of 10^{-1} to 10^{-2} s^{-1}. The effect of strain rate to the compressive stress for both tests is at the low end of high strain rate loading and falls in the same category when calculating the amplification factor. This factor is the ratio of dynamic value of a mechanical parameter over its static value which is known as DIF. The CEB [15] formulation expresses the DIF as

$$\text{DIF} = \frac{f_d}{f_s} = \left[\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right]^{1.026\alpha} \quad \text{for } \dot{\varepsilon} \leq 30 \text{ s}^{-1} \tag{5}$$

$$\text{DIF} = \gamma_s \left[\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right]^{\frac{1}{3}} \quad \text{for } \dot{\varepsilon} > 30 \text{ s}^{-1} \tag{6}$$

where f_s and f_d are the static and dynamic compressive strength respectively, $\gamma_s = 10(6.15\alpha - 2.0)$, $\alpha = 1/(5 + 9(f_s/f_0))$, $\dot{\varepsilon}_s = 30 \times 10^{-6}$ s^{-1} and f_0 = 10 MPa. This formulation gives the DIF as a bilinear function of the strain rate in the logarithmic scale and presents a slope variation at 30 s^{-1}.

The comparative study demonstrates that a size effect existed for compressively loaded high performance concrete cylinders under both static and dynamic loads. For static loading, both researches agree on the fact that as the size of the specimen increased, the apparent stress of the concrete decreased. There is a discrepancy in data at smaller size specimen. The current study shows drastic increase when the specimen size is small, in contrast with Krauthammer *et al.*, 2003 [13]. Krauthammer *et al.*, 2003 [13] further explained that a decrease on the time required to reach σ_{max} for sizeØ75 mm × 150 mm was observed which may imply that a premature failure had taken place. Therefore, this current test revealed that the apparent stress increase more than twofold compared its static stress for smaller cylinder ofØ100 mm × 200 mm at strain rate 0.20 s^{-1}. The dynamic stress of specimens Ø150 mm × 300mm and Ø300 mm × 600 mm recorded are below the static stress.

Further comparison with Krauthammer *et al*. 2003 [13] simulation using Finite Element analysis based on Drucker-Prager model shows that the current study is in agreement with the simulation as shown in Figure 5.

Table 7 Comparison of current study with existing result

Cylindrical specimen size (mm)	Ref. [13] Simulation	Krauthammer *et al.*, 2003 Experimental [13]			Present study		
	σ_s (MPa)	$\acute{\varepsilon}$ (s^{-1})	σ_d (MPa)	f'$_c$ (MPa)	$\acute{\varepsilon}$ (s^{-1})	σ_d (MPa)	f'$_c$ (MPa)
Ø75 × 150	92.33	0.111	52.76	89.46	NA	NA	NA
		0.044	55.73				
Ø100 × 200	NA	NA	NA		0.22	152	72.1
Ø150 × 300	70.47	0.099	68.06	82.86	0.13	49.5	64.66
		0.105	109.380				
Ø300 × 600	38.85	0.046	39.29	71.10	0.19	14.3	NA
		0.066	62.50				

NA – Not available

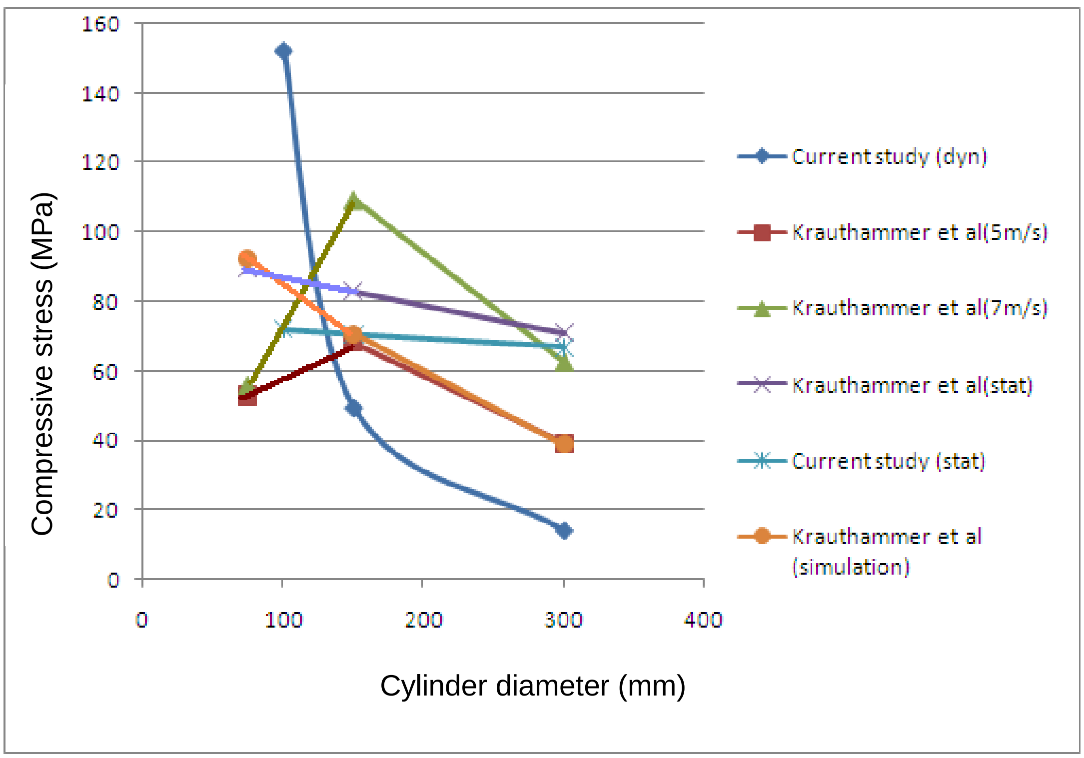


Figure 5 Comparison study on effect of specimen size

4.0 CONCLUSION

Under static load, the maximum stress increases with the reduction of sample size and the maximum strain recorded at maximum stress also decreases as the size increase, which is less pronounced than the reduction of stress. Under impact loading of strain rate between 0.10 to 0.20 s^{-1}, the apparent stress increase more than twofold compared its static stress for smaller cylinder of Ø100 mm × 200 mm and decrease below their static stress as the specimens are larger.

Acknowledgement

This work is sponsored by grant UKM-KK-02-FRGS0014-2006. We would like to thank Faculty of Mechanical Engineering, Universiti Teknologi Malaysia for allowing us to use the Weight Drop equipment.

References

[1] Bischoff, P. H, Perry, S. H. 1991. Compressive Behavior of Concrete at High Strain Rates. *J. En.g. Mech*. 24: 425–450.

[2] Cotsovos, D. M., Pavlovic, M. N. 2008. Numerical Investigation of Concrete Subjected to Compressive Impact Loading. Part 1: A Fundamental Explanation for the Apparent Strength Gain at High Loading Rates. *Computers & Structures.* 86: 145–163.

[3] Ross, C. A., Jerome, D. M., Tedesco, J. W., Hughes, M. L. 1996. Moisture and Strain Rate Effects on Concrete Strength. *ACI Materials Journal*. 93(3): 293–300.

[4] Sim, J. I., Yang, K. H., Jeon, J. K. 2013. Influence of Aggregate Size on the Compressive Size Effect According to Different Concrete Types. *Construction and Building Materials.* 44:716–725.

[5] Sim, J. I., Yang, K. H., Kim, H. Y. and Choi, B. J. 2013. Size and Shape Effects on Compressive Strength of Lightweight Concrete. *Construction and Building Materials.* 38: 854–864.

[6] del Viso, J. R., Carmona, J. R. and Ruiz, G. 2008. Shape and Size Effects on the Compressive Strength of High-strength Concrete. *Cement and Concrete Research*. 38: 386–395.

[7] Kim, J. K., Yi, S. T., Park, C. K., Eo, S. H. 1999. Size Effect on Compressive Strength of Plain and Spirally Reinforced Concrete Cylinders. ACI Structural Journal. 96(1); 88–94.

[8] Kim, J. K., Yi, S. T., Yang, E. I. 2000. Size Effect on Flexural Compressive Strength of Concrete Specimens. *ACI Struct. J*. 97(2): 291–296.

[9] Kim, J. K., Yi, S. T., Kim, J. H. J. 2001. Effect of Specimen Sizes on Flexural Compressive Strength of Concrete. *ACI Struct. J*. 98(3): 416–424.

[10] Kim, J. H., Yi, S. T., Kim, J. K. 2004. Size Effect of Concrete Members Applied with Flexural Compressive Stresses. *Int. J. Fracture.* 126(1): 79–102.

[11] Yi, S. T., Kim, J. H. J., Kim, J. K. 2002. Effect of Specimen Sizes on ACI Rectangular Stress Block for Concrete Flexural Members. *ACI Struct. J*. 99(5): 701–708.

[12] Yi, S. T., Yang, E. I. and Choi, J. C. 2006. Effect of Specimen Sizes, Specimen Shapes, and Placement Directions on Compressive Strength of Concrete. *Nuclear Engineering and Design*. 236: 115–127.

[13] Kruathammer, T., Elfahal, M. M., Lim, J., Ohno, T., Beppu, M., Markeset, G. 2003. Size Effect for High-strength Concrete Cylinders Subjected to Axial Impact. *International Journal of Impact Engineering*. 28: 1001–1016.

[14] P.-C.Aïtcin, High-Performance Concrete, Université de Sherbrooke, Québec, Canada, E & FN SPON, Routledge, London and New York, Taylor & Francis e-Library, 2004. http://www.crcnetbase.com/doi/pdfdirect/10.4324/9781420022636.fmatt.

[15] CEB. 1988. Concrete Structures Under Impact and Impulsive Loading. Bulletin No. 187, Comité Euro-International du Béton (CEB), Lausanne, Switzerland.