EN 206 Conformity Testing for Concrete Strength in Compression

(Date received: 20.1.16/Date accepted: 30.11.16)

[1]Daneti Saradhi Babu, [2]Li Wei and [3]Tam Chat Tim

[1]*Concrete Specialist, Alliance Concrete Singapore Pte Ltd, Singapore,* [2]*Research Associate,*
[3]*Adjunct Associate Professor, Dept. of Civil and Environmental Engineering,*
National University of Singapore, Singapore

Email: [1]*saradhibabu.daneti@allianceconcrete.com.sg*

ABSTRACT

The design of concrete structures in accordance with EN 1992-1-1 adopts the characteristic cylinder compressive strength in its equations. EN 206 provides for conformity testing for concrete strength in compression using 150mm diameter by 300mm length cylinders or 150mm cubes only. The complementary standard to EN 206 in UK, BS 8500 (SS 544 in Singapore, MS 523 in Malaysia) has added provisions (clause 12.2) for the use of 100mm cubes for conformity testing. The conformity criteria for 100mm cube specimens are to be the same as those for 150mm cubes. A series of tests based on 3 selected levels of compressive strength has been conducted to examine the relationship between these 3 types of test specimens for compressive strength of concrete. For each strength level, 100 batches of concrete were produced over a period of several months. The test results are presented with analysis based on the mean of 3 numbers for each type of test specimens prepared from the same batch at each time of preparation. The results of this study for the 3 strength levels support the relationship between standard cylinder compressive strength and standard cube compressive strength in EN 206. In addition, results also support the recommendation that standard 100mm cube compressive strength is equivalent to that of standard 150mm cube compressive strength in BS 8500. The use of the small size cubes and certification of designed concrete promote sustainability in concrete construction.

Keywords: Cube, Concrete, Conformity, Cylinder, Strength, Sustainability.

1.0 INTRODUCTION

BS EN 206 [1] adopts only 150mm diameter by 300mm length cylinders or 150mm cubes as standard specimens for determining compressive strength of concrete. Both BS EN 1992-1-1 [2] and BS EN 206 [1] provide for equivalent cube compressive strength corresponding to cylinder compressive strength. In general, up to strength class of C55/67, the ratio of 150mm cube compressive strength/150mm cylinder compressive strength is nominally 1.25 (with rounding to nearest 1 MPa). Above strength class of C55/67 up to C100/115, a constant difference of 15 MPa higher for cube compressive strength above that of cylinder compressive strength has been adopted. These relationships are examined at three strength class levels, i.e. C32/40, C50/60 and C65/80. In addition, the ratio of 100mm cube compressive strength/150mm cube compressive strength and the ratio of 100mm cube compressive strength/150mm cylinder strength at these strength levels are also determined for the same three strength class levels. The test results based on three specimens of each shape and size at the age of 28 days after standard curing are analysed to provide an assessment of their relationships. A brief summary of these results has been presented at the 40th OWICS Anniversary Conference in August 2015 by Tam *et. al*,[3]. A more in-depth analysis is reported in this paper. Although limited in scope, the analysis provides a reasonable indication of their implications in conformity assessment of the characteristic concrete compressive strength based on 100 batches of concrete for each of the three strength class levels. These were produced over a period of several months (145 to 206 days) in the same RMC plant and may be deemed to be representative of normal production in a local ready-mixed concrete (RMC) plant using constituent materials generally available in Singapore.

2.0 BACKGROUND

The topic on effect of shape and size of test specimens for determination of concrete compressive strength has been studied by various researchers as early as 1925 e.g. Gonnerman [4] Neville, [5] has reviewed research findings from extensive published literature and reported that approximately 100mm cubes to be 1.05 times of 150mm cubes and but from analysis of numerous data by Neville [6], proposed the relationship between concrete specimens of different shapes and sizes (f_c) relative to that of a 6 inch (150 mm) cube ($f_{cu,6}$) as follows:

$$f_c/f_{cu,6} = 0.56 + 0.697/(V/6hd + h/d)$$

where V = volume of specimen, (V/150hd + h/d for h and d in mm)

h = height (in inches), and

d = least lateral dimension (in inches)

Substituting dimensions of a 6 inch (150mm) cube into the above equation results in a value of 0.91 instead of the expected value of 1.0. Based on this relationship, the ratio of 4 inch (100mm) cube relative to that of a 6 inch (150mm) cube is 0.98 but adjusting with the factor of 0.91, the ratio becomes 1.08. A study by Leung and Ho (1996) [7] in Hong Kong based on data from 8 projects for grade 20 to 50 (C16/20 to C40/50), for a total of 349 batches, the mean ratio of 100mm to 150mm cubes was found to be 1.05. However, it ranges from 0.79 to 1.23 with up to 34% of individual ratios (15/44) below 1.0 in one project. For the other 7 projects the percentage of individual ratios below 1.0 varies from 4% to 22%. The mean for the total of 349 individual ratios is 17%. Similar percentage of ratios below 1.0 was also reported by Tam *et. al,* [3]. A more recent study by Wong (2103) [8] in Hong Kong compared the ratio of 150mm x 300mm cylinders to 100mm cubes and found the mean ratio is 0.78 for up to grade 80 (C65/80) and 0.80 for above grade 80 (up to 119 MPa for 100mm cubes). Taking the strength ratio of 100mm cube to 150mm cube as 1.05, the ratio for 150mm x 300mm cylinder to 150mm cubes becomes 0.82 for up to grade 80 and 0.84 for above grade 80. These findings differ slightly from values in EN 206 [1]. Even after significant number of studies there is as yet no definitive finding on the effect of specimen size for determining concrete compressive strength. Moreover, most studies are based on limited number of samples tested and generally, from a selected number of strength levels with specimens from the same sample tested at several ages. Hence, the standard deviation, arising from variability arising from constituent materials, batching and sampling on characteristic value of concrete compressive strength has not been studied. The present study aims the provided information where these factors are included in the selected strength levels.

The first objective of the current study is to compare the specified relationship between characteristic values of cylinder and cube compressive strength as given in EN 206 [1] at three strength levels. The second objective is to assess if the characteristic compressive strength at the age of 28 days of 100mm cubes to that of 150mm cubes may be deemed to be the same as stated in BS 8500-2 [9]. Both of these factors are of special interest to countries where structural design is based on cylinder compressive strength in EN 1992-1-1 [2] and conformity criteria may be based on 100mm and/or 150mm cubes.

3.0 EXPERIMENTAL DETAILS

The constituent materials for casting of all the concrete specimens are those commonly used in current production in a local RMC plant. The three concretes were produced by the same plant using Portland cement to BS EN 197-1 [10] CEM I – 42.5 R, 20mm maximum size granite and natural sand together with a superplasticiser to produce a consistence class of S4 given in BS EN 206 [1] for designed concretes, over a period of several consecutive months. Silica fume (SF) to BS EN 13263-1 [11] had been added to C65/80 concrete only. Table 1 shows the composition of the three concretes. All the specimens were cast, then demolded after 24 hours and cured at 27 ± 5 ^{o}C as recommended for Singapore laboratories under SS 544-2 [12] Annex ZZA until age of 28 days when they were tested at the saturated condition. No unexpected performance of the constituent materials was noticed during the period of this test program which used the same constituent materials for normal production of concrete in the same plant. All the three types of specimens were cast from the same batch of concrete. End preparation for all cylinder specimens was by grinding.

Table 1: Composition of concretes.

Concrete	Composition (kg/m^3)				
	Cement (SF)	Water	Fine Aggregate	Coarse Aggregate	Admixture
C32/40	395(0)	175	776	990	5.39
C50/60	530(0)	175	660	990	7.23
C65/80	550(40)	150	590	990	11.31

4.0 TEST RESULTS

The test data of the three populations of concrete are analyzed in terms of the following:

a. For each concrete, the mean and standard deviation of all the test results (average of 3 specimens).
b. For each concrete, the ratio of 150mm cube/150mm cylinder specimens ($f_{c,150cu}/f_{c,150cyl}$) for each batch of concrete.
c. For each concrete, the ratio of 100mm cube/150mm cube specimens ($f_{c,100cu}/f_{c,150cu}$) for each batch of concrete
d. For each concrete, the mean of the ratio calculated in (b) and (c) above.
e. For each concrete, the mean of the ratio of 150mm cube/150mm cylinder specimens based on their characteristic values (f_{ck}), mean (f_m) and from (a) above.
f. For each concrete, (strength class C32/40 and C50/60), distribution of the ratio of 150mm cube/150mm cylinders ($f_{c,150cu}/f_{c,150cyl}$).
g. For each batch of concrete for each concrete, distribution of the difference between 150mm cube and 150mm cylinders ($f_{c,150cu} – f_{c,150cyl}$) for strength class C65/80.
h. For each concrete; distribution of the ratio of 100mm cube/150mm cube specimens ($f_{c,100cu}/f_{c,150cu}$) for each batch of concrete.

[Note: the results of item (h) indicate that the ratios for ($f_{c,100cu}/f_{c,150cu}$) does not deviate significantly from 1.0 and hence similar analysis for the case of 100mm cubes corresponding to item (f) as item (g) is omitted for which the finding will be similar to the case of 150mm cubes in item (f)].

Annex A is a summary of the data for items (a) to (d) stated above which has been presented recently by Tam *et. al,* [3]. Annex B shows the overlapping of the distribution of compressive strength of both 100mm cubes and 150mm cubes for each of the 3 strength levels reported by Tam *et. al,* [3]. The findings are summarized as follows:

(1) The ratio of 150mm cylinders/150mm cubes for C32/40 based on characteristic strengths, ($f_{ck,150cy}/f_{ck,150cu}$) = 0.79 and based on mean strengths, ($f_{cm,150cy}/f_{cm,150cu}$) = 0.80.
(2) The ratio of 150mm cylinders/150mm cubes for C50/60 based on characteristic strengths, ($f_{ck,150cy}/f_{ck,150cu}$) = 0.82 and based on mean strengths, ($f_{cm,150cy}/f_{cm,150cu}$) = 0.83.
(3) The difference between 150mm cubes and 150mm cylinders specimens for C65/80 based on characteristic strengths, ($f_{ck,150cu} – f_{ck,150cy}$) = 12.9 MPa and based on mean strengths, ($f_{cm,150cu} – f_{cm,150cy}$) = 12.7 MPa.
(4) The ratio of 100mm cube/150mm cube for C32/40 based on characteristic strengths, ($f_{ck,100cu}/f_{ck,150cu}$) = 1.01(2) and based on mean strengths, ($f_{cm,100cu}/f_{cm,150cu}$) = 1.01(2).

Annex A

Extracted from Reference [3], Tam et al (2015)

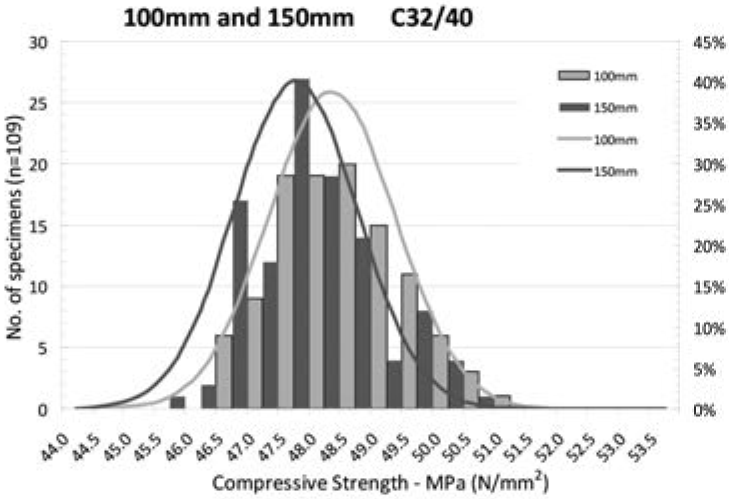
Table A.1 – Summary of test results

Strength class/property	C32/40			C50/60			C65/80		
Specimen	$f_{cu,100}$	$f_{cu,150}$	$f_{cyl,150}$	$f_{cu,100}$	$f_{cu,150}$	$f_{cyl,150}$	$f_{cu,100}$	$f_{cu,150}$	$f_{cy,150}$
Strength (3 specimens for each test)									
Mean, (f_m)	48.1	47.5	38.0	68.9	68.0	56.1	94.9	93.7	80.9
Maximum	52.5	51.3	41.6	75.4	73.9	60.6	111.1	104.3	96.3
Minimum	44.6	44.7	33.9	64.2	63.3	49.8	87.4	84.2	69.7
Range	7.9	6.6	7.7	11.2	10.6	10.8	23.4	20.1	26.6
Standard deviation (3 specimens for each test)									
Mean	0.91	0.90	0.94	1.23	1.19	1.12	1.74	1.77	1.86
Maximum	1.98	1.82	2.99	2.57	2.99	2.87	4.45	5.20	3.84
Minimum	0.17	0.16	0.21	0.13	0.21	0.21	0.29	0.29	0.54
Range	1.81	1.66	2.78	2.44	2.78	2.66	4.16	4.91	3.30
No. of data	109	109	105	109	109	109	105	105	105
Period of time (days)	151	151	145	206	206	206	155	155	155
Characteristic strength based on mean strength and mean standard deviation									
$f_{ck,cu}$	46.6	46.1		66.9	66.0		92.1	90.8	
$f_{ck,cyl}$			36.4			54.3			77.9
Ratio	Based on f_{ck}								
$(f_{ck,100cu})/(f_{ck,150cu})$	1.01 (1.012)			1.01 (1.013)			1.01 (1.014)		
$(f_{ck,150cyl})/(f_{ck,150cu})$			0.79 (0.791)			0.82 (0.822)			
$(f_{ck,150cu})-(f_{ck,150cyl})$									12.9
Ratio	Based on f_{cm}								
$(f_{cm,100cu})/(f_{cm,150cu})$	1.01 (1.012)			1.01 (1.013)			1.01 (1.013)		
$(f_{cm,150cyl})/(f_{cm,150cu})$			0.80 (0.799)			0.83 (0.825)			
$(f_{cm,150cu})-(f_{cm,150cyl})$									12.7
Ratio	Based on mean of individual ratios for each batch								
$(f_{ci,100cu})/(f_{ci,150cu})$	1.01 (1.013)			1.01 (1.014)			1.01 (1.013)		
$(f_{ci,150cyl})/(f_{ci,150cu})$			0.80 (0.800)			0.81 (0.814)			
$(f_{ci,150cu})-(f_{ci,150cyl})$									12.3

Annex B

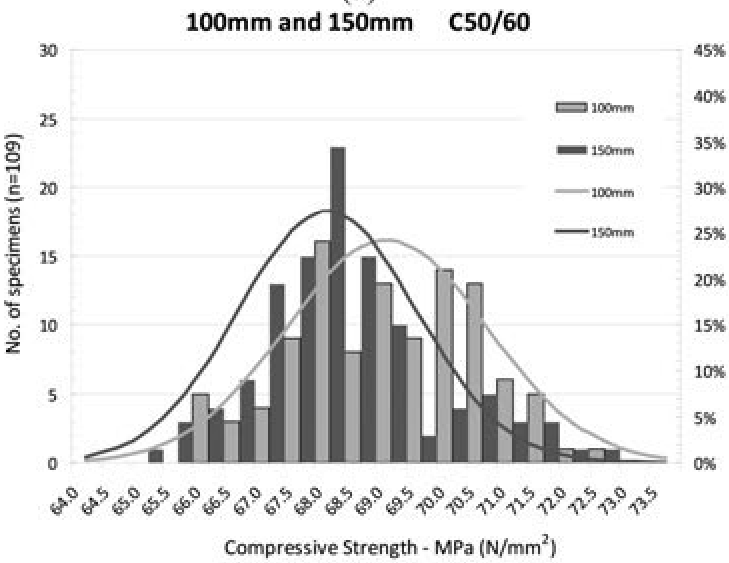
Extracted from Reference [3], Tam et al (2015)

Figure B.1 – Distribution of Cube Compressive Strength data 100 mm cubes and 150 mm cubes



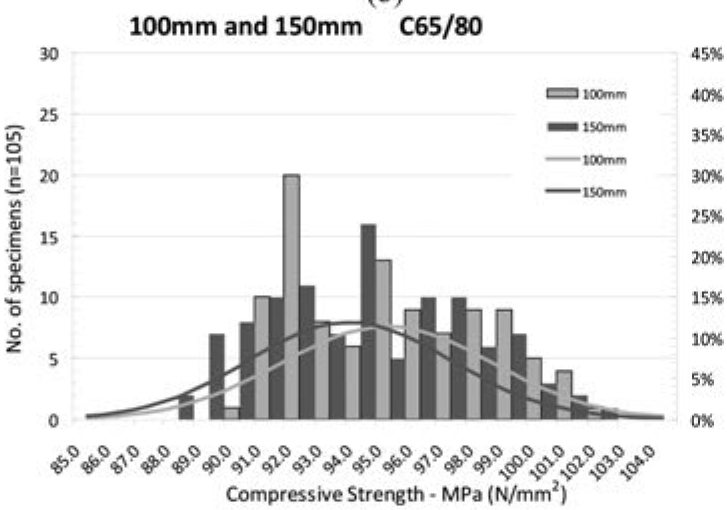
(a)

Cube	100 mm	150 mm
Mean	48.1 MPa	47.5 MPa
Std. Dev.	0.91 MPa	0.90 MPa
$f_{ck,cu}$	46.6 MPa	46.1 MPa
n	109	109



(b)

Cube	100 mm	150 mm
Mean	68.9 MPa	68.0 MPa
Std. Dev.	1.23 MPa	1.19 MPa
$f_{ck,cu}$	66.9 MPa	66.0 MPa
n	109	109



(c)

Cube	100 mm	150 mm
Mean	94.2 MPa	93.0 MPa
Std. Dev.	1.74 MPa	1.77 MPa
$f_{ck,cu}$	92.1 MPa	90.8 MPa
n	105	105

Figures B.1(a), 1(b) and 1 (c)

Table 2: Summary of Standard Deviations for Compressive Strength.

Specimen Type	Standard deviation – MPa											
	Mean			Maximum			Minimum			Range		
	$f_{cu,100}$	$f_{cu,150}$	$f_{cyl,150}$	$f_{cu,100}$	$f_{cu,150}$	$f_{cyl,150}$	$f_{cu,100}$	$f_{cu,150}$	$f_{cyl,150}$	$f_{cu,100}$	$f_{cu,150}$	$f_{cyl,150}$
C32/40	0.91	0.90	0.94	1.98	1.82	2.99	0.17	0.16	0.21	1.81	1.66	2.78
C50/60	1.23	1.19	1.12	2.57	2.99	2.87	0.13	0.21	0.21	2.44	2.78	2.66
C65/80	1.74	1.77	1.86	4.45	5.20	3.84	0.29	0.29	0.54	4.16	4.91	3.30

(5) The ratio of 100mm cube/150mm cube for C50/60 based on characteristic strengths, ($f_{ck,100cu}/f_{ck,150cu}$) = 1.01(3) and based on mean strengths ($f_{cm,100cu}/f_{cm,150cu}$) = 1.01(3).

(6) The ratio of 100mm cube/150mm cube for C65/80 based on characteristic strengths, ($f_{ck,100cu}/f_{ck,150cu}$) = 1.01(4) and based on mean strengths ($f_{cm,100cu}/f_{cm,150cu}$) = 1.01(3).

In addition, the test results in Annex A also provide the following findings:

(7) Standard deviations based on 3 specimens for each batch show generally an increasing trend with increase in compressive strength. The mean and the range of standard deviations for all the 3 types of specimens (100mm cube, 150mm cube and 150mm diameter by 300mm length cylinders) are as summarised above:

5.0 DISCUSSION

Based on the experimental test data obtained, they have indicated the following:

(1) The test results for the ratio of 150mm cylinders/150mm cubes are in agreement with those in Table 12 of BS EN 206 [1] with a nominal value of 0.80 for strength class up to C55/67. Above this strength class and up to C100/115, Table 12 of BS EN 206 [1] shows a constant difference of 15 MPa compared to 13 MPa based on test results for C65/80. Hence in designed concrete, the adoption of a difference of 15 MPa for cube compressive strength above that of cylinder compressive strength will be conservative.

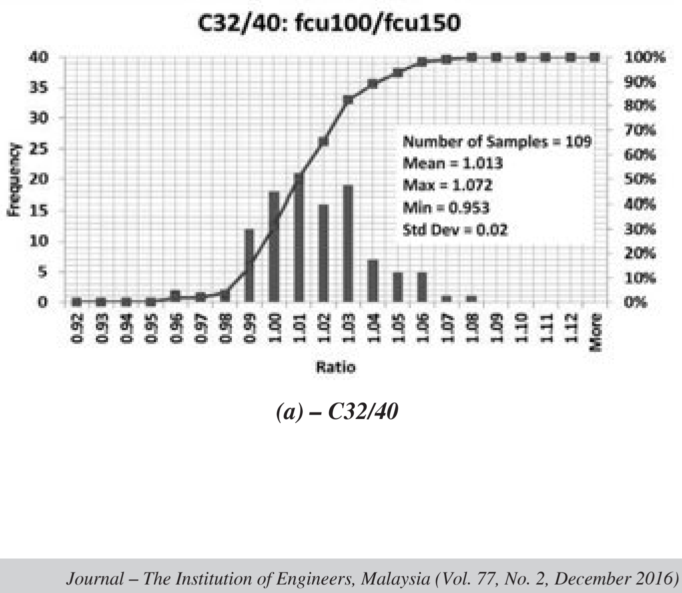
(2) The ratios of 100mm cube/150mm cube in all cases are only marginally above unity. This observation is based on 3 large populations of over 100 batches for each strength level studied. However, it may not be the case when comparison is based on small sample sizes of 2 or 3 specimens of each size generally adopted in conformity assessment. In order to illustrate the situation where the ratio may be higher or lower than unity, a more detailed analysis of the test results is presented in the following section.

(3) For each strength level, the 3 different types of test specimens show similar values of standard deviation for their mean, maximum and minimum standard deviations. However, all three values of standard deviations increase with increasing strength levels for all 3 types of specimens as well as their range of standard deviations.

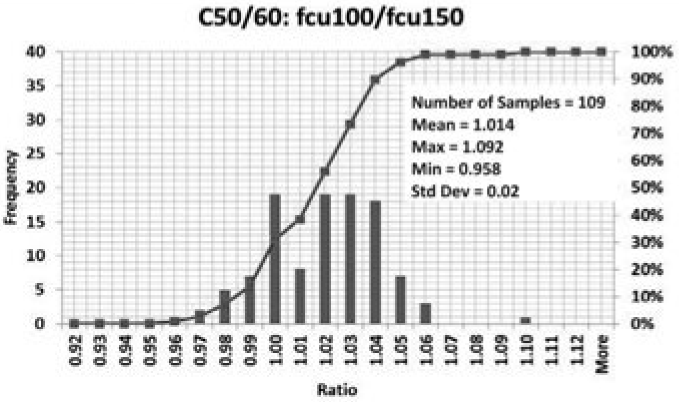
(4) For all 3 strength levels the coefficient of variation (standard deviation/mean) is approximately 2%. This is in agreement with the observation in relation to Figure 14.4 of Neville [13] that "for a constant degree of control, laboratory test data, as well as some results of actual site tests, have been shown to support the suggestion of a constant coefficient of variation for well-compacted concrete of different mix proportions with strengths higher than about 10 MPa". Although other data from construction sites, e.g. Figure 14.6 of Neville [14] show that "coefficient of variation is constant up to some limiting value of strength but, for higher strength, the standard deviation remains constant". Hence, the issue of constant standard deviation or constant coefficient of variation remains to be controversial.

5.1 Ratio of 100mm cube/150 mm cube

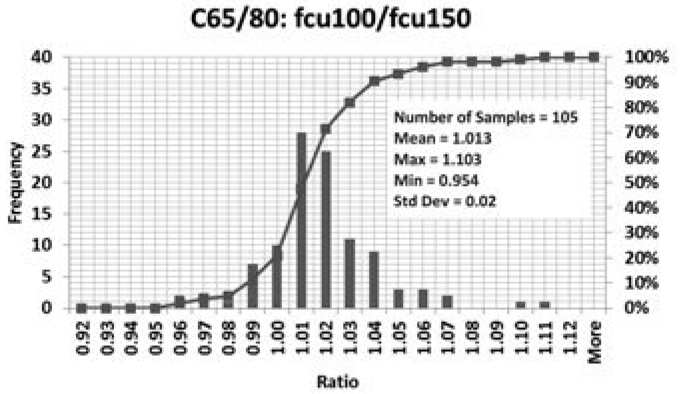
For each of the 3 strength levels, slightly over 100 batches were produced for which 3 specimens of 100mm cube and 3 specimens of 150mm cube were tested in each batch. The distribution of compressive strength at each strength level is presented in Annex B where the overlapping of the distribution of the two sizes of cubes is clearly shown in all the 3 strength levels tested. In order to provide a better understanding of the test data, the distribution of the ratio ($f_{ci,100cu}/f_{ci,150cu}$) for each batch of the slightly over 100 batches in each strength level is presented in Figure 1(a) for C32/40, Figure 1(b) for C50/60 and Figure 1(c) for C65/80.



(a) – C32/40



(b) – C50/60



(c) – C 65/80

Figure 1: Ratio of ($f_{ci,100cu}/f_{ci,150cu}$) at 3 different strength levels.

It can be seen from the Figure 1 that a wide range of the ratio is obtained for each strength level, from 0.95 to 1.07. Since around 100 batches (105 or 109) of each strength level were tested, the number of samples at a particular ratio represents approximately the percentage of test results that has been obtained. Firstly, the cumulative percentage of test results up to ratio of 1.0 in Figure 1(a) is 31%, for C32/40, in Figure 1(b) 31% for C50/60 and 21% in Figure 1(c) for C65/80. Hence, in general, 20% to 30% of cases in testing for cube compressive strength may show equal or higher strength for the 150mm cubes than corresponding 100mm cubes. This implies that test results for 1 in 5 to 1 in 6 batches, the expectation that the small size cube specimens should show a higher strength may not happen. Figure 12.17 of Neville [13], shown as Figure D.1 in Annex D, has suggested that the ratio for ($f_{ci,100cu}/f_{ci,150cu}$) is 1.04. For all the 3 strength levels, only about 10% of the ratio exceeded this ratio of 1.04. On the other hand, Figure 12.20 of Neville [13], representing data from several published studies leading to a generalized relationship between ratio of cube compressive strength of concrete specimens of a given set of dimensions, f_c, to cube compressive strength of a 6 inch (150 mm) cube, $f_{cu,6}$, as follows:

$f_c/f_{cu,6} = 0.56 + (0.697/[V/6hd + h/d)$, and for the case of 4 in. (100mm) cubes, the ratio = 0.98.

After adjusting for the case of a 6 inch (150 mm) cube giving a ratio of 0.91, the adjusted ratio = 1.07.

It can be expected that the experimental data from multiple sources for 100mm cubes may result in a range of values relative to 150mm cubes as shown in Figure 12.20 of Neville [13], but with variations in the ratio around (1.0±0.2). This may imply that the difference in measured compressive strength, if any, between 100mm and 150mm cubes is generally about 10% and of minor significance in practice. In particularly for small sample size adopted for assessment in site practice, the ratio can be either above or below unity as shown in the test data presented. The recommendation in clause 12.2 of BS 8500-2 [9] or its Singapore equivalent SS 544-2 [12], to consider the assessment of 100mm cubes with the same criteria for 150mm cubes is supported by the large populations of over 100 batches of test data for each of the 3 strength levels.

5.2 Relationship Between Cylinder and Cube Compressive Strength

The difference in measured compressive strength between 150mm diameter by 300mm length cylinder specimens and 150mm cubes is not due the difference in shape but the difference in aspect ratio (length/lateral dimension). The nominal aspect ratio (h/d) of a standard cylinder = 2, but that of a standard cube = 1. Due to this difference and hence the influence of end restraint effect on the concrete specimen has resulted in two different mode of failure. As described by Neville [13], a "complex system of stress is developed between the end surfaces of the concrete specimen and the adjacent steel platens of the testing machine". The induced bi-axial confining stress depends on the elastic properties (modulus of elasticity and Poisson's ratio) of both the steel platen and the strength level of concrete specimen and hence its modulus of elasticity. The modulus of elasticity of concrete increases with its compressive strength which results in a lower intensity of the induced bi-axial confining stress. The influence of end restraint may also extend to a shorter distance from the interface than the suggested value of $(\sqrt{3})d/2$ by Neville [13]. A constant difference of 15 MPa between cube compressive strength and cylinder compressive strength in Table 12 of BS EN 206: [1] for strength class of C60/75 and above leading to the ratio of ($f_{ck,150cu}/f_{ck,150cyl}$) decreasing from nominally 1.25 for strength class up to C55/67 to 1.15 for C100/115. From the experimental data, for C32/40, the mean ratio = 0.80 (51% of results), for C50/60, mean ratio = 0.83 (0.82 at 39%, 0.83 at 64%) and for C65/80, the mean ratio = 0.86 (50 at 0.85). There is a tendency for the ratio to increase with strength levels. In addition, both the minimum value and the maximum ratio also increased with strength level, 0.78 to 0.84 for C32/40, 0.79 to 0.87 for C50/60 and 0.81 to 0.95 for C65/80. For C65/80, the nominal difference of 15 MPa between 150mm cubes and 150mm diameter by 300mm length cylinders is indicated in Table 12 of BS EN 206 [1]. The range of this difference obtained ranges from 5 MPa to 19 MPa, mean = 13 MPa (47%) and 64% of results up to 15 MPa. However, unlike experience with strength classes up to C55/67, there is much less published data on the relationship between cube compressive strength and cylinder compressive strength for C60/75 and above. It is prudent to test of both types of specimens during the stage of initial tests in the development of high strength concrete to gain more data on this relationship, particularly with locally available materials for concrete production.

The study by Wong (2013) [8] in Hong Kong recommended a constant factor of 0.80 for cube strength of 80 MPa and above. Hence for cube strengths of 80, 90 and 100 MPa, the corresponding cylinder strengths are 64, 72 and 80 MPa showing a difference of 16, 18 and 20 MPa respectively. These differences are higher than the nominal value of 15 MPa in EN 206 and may require design target strength based on cubes to be more conservative and hence higher economic impact in production.

6.0 SUSTAINABILITY IN CONCRETE STRENGTH ASSESSMENT

Significant volume of concrete is used in the assessment of compressive strength of concrete for initial/trial mix testing, production conformity during production as well as samples taken on site at the time of delivery for conformity assessment in relation to the project specification. After testing the specimens have to be disposed as waste, at best sent to aggregate recycling plants. Hence, a reduction in the volume of concrete involved in such testing is a step forward towards a more sustainable concrete industry.

6.1 Specimen size

The adoption of the smaller size cube specimens has significant effect on the sustainable use of concrete, as the volume of each 150mm cube is more than sufficient to make 3 numbers of 100mm cubes. This smaller volume of concrete needed for routine testing in conformity assessment conserves materials resources for concrete and reduces the volume of waste for storage and later disposal after testing. In addition, curing capacity of existing facilities is able to cater for 3 times more test samples and time for testing and energy for loading are also reduced to achieve the same failure stress, besides easier handling of test specimens leading to better productivity and/or resource savings in the test laboratory. This green practice has been successfully implemented by Singapore's Housing & Development Board (HDB) since 2007 and provides strong evidence for the local concrete industry to adopt this practice, a forward step towards a more sustainable concrete industry. It may be of interest to note that in the first edition of Properties of Concrete, Neville [14], on the section of "specimen size and aggregate size" the issue of recommended value for the ratio of the minimum dimension of the test specimen to the maximum aggregate size was stated as follows: "BS 1881: 1952 prescribes a test cube not smaller than 4 in. when ¾ in. aggregate is used, i.e. a ratio of 5-1/3, but 6 in. cubes may be used with 1½ in. aggregate. A.S.T.M. Standard C192-57 limits the ratio of the diameter of the cylinder to the maximum aggregate size to 3, and the U.S. Bureau of Reclamation to 4. A value of between 3 and 4 is generally accepted as satisfactory". Hence, it is convenient in practice for one size of cubes to cater for both 20mm and 40mm maximum aggregate size rather than due to technical requirement that 150mm cubes are commonly specified in evaluation of compressive strength.

6.2 Concrete Specification

Currently, it is a common practice to specify for 3 rounds of successful initial/trail mix testing of a given concrete strength for assessment before concrete is accepted for delivery to a project. This is routinely conducted for commonly specified concrete to strength classes of C25/30 to C40/50 at slump range of 75mm to 150mm even the RMC plant has been producing these strength classes on a regular basis for several years. This practice is still continued although in Singapore all structural grade concretes are now produced under certification (certificate of conformity) by accredited RMC certification bodies (CB's) of Singapore Accreditation Council (SAC), since 1 October 2010 mandated by BCA [15]. This move is in support of the new approach to replace the practice of initial/trail mix testing with "certified concretes" each with their performance guaranteed by the RMC producer for which the particular concretes are under regular production conformity evaluation within the plant and the data for which are subject to verification by a CB under the SAC's Certification Scheme for RMC. An example of an RMC production control data for C32/40 over a period of 12 consecutive calendar months is present by Tam, *et. al,* [3] and reproduced in Annex C, Figure C.1. In addition, trial mixes that were conducted for projects for this same concrete for which their data are also plotted for the dates in which production control date were also available. It can be noted that the initial/trail mix test results are always higher than the mean strength of the production control data.

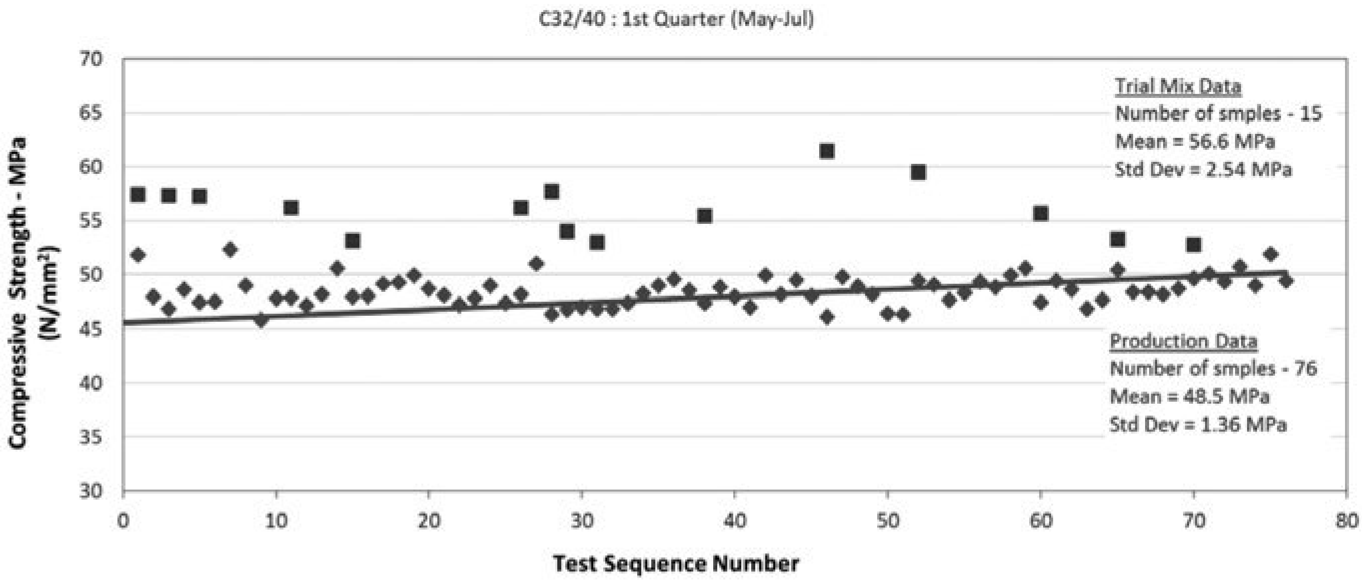


Figure 2: (a) Production control data - 1st Quarter.

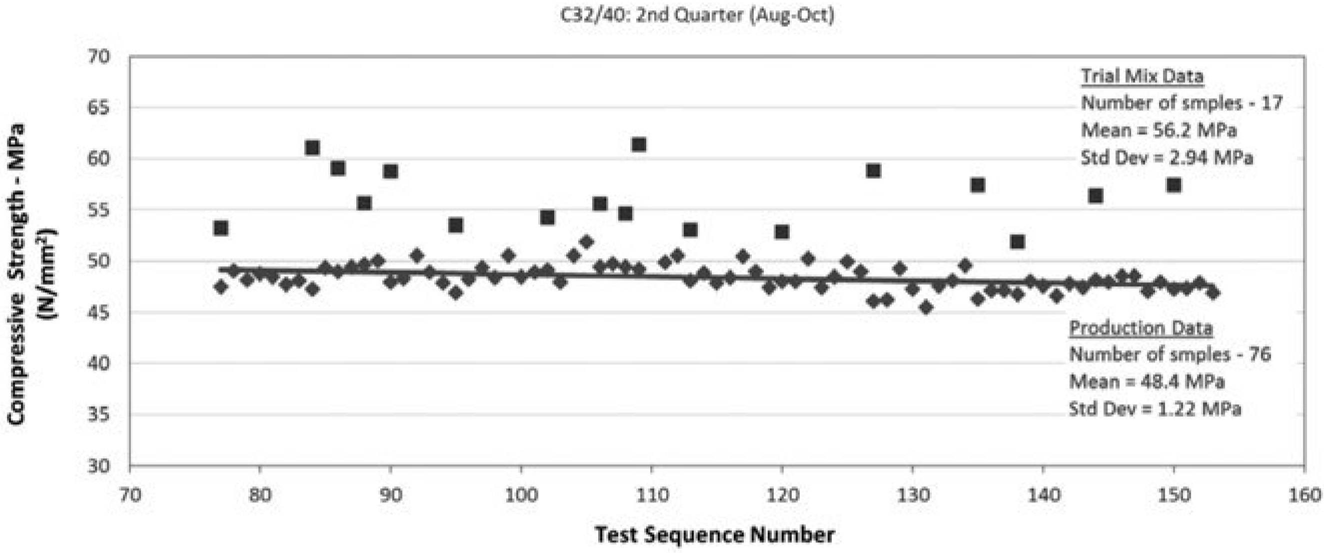


Figure 2: (b) Production control data - 2nd Quarter.

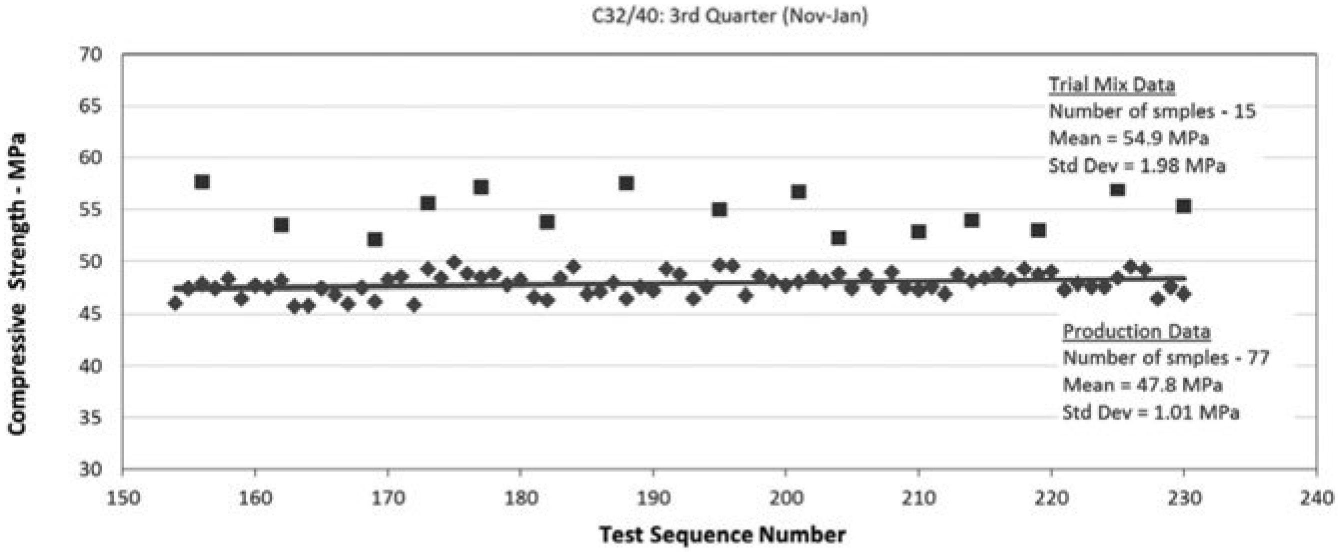


Figure 2: (c) Production control data - 3rd Quarter.

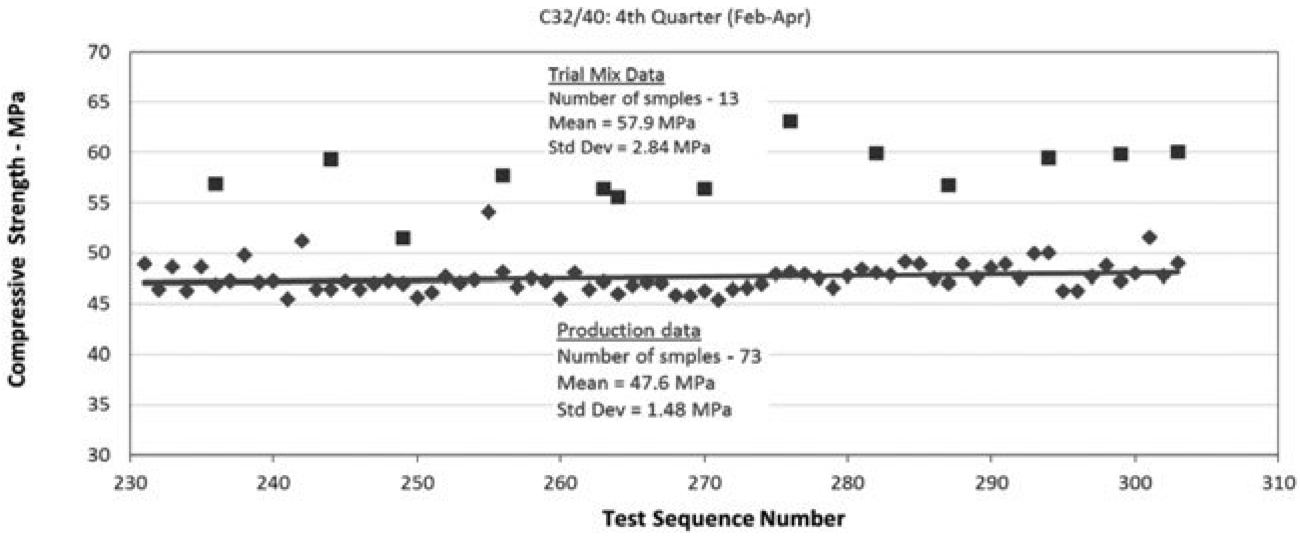


Figure 2: (d) Production control data - 4th Quarter.

Annex C
Extracted from Reference [3], Tam et. al, (2015).

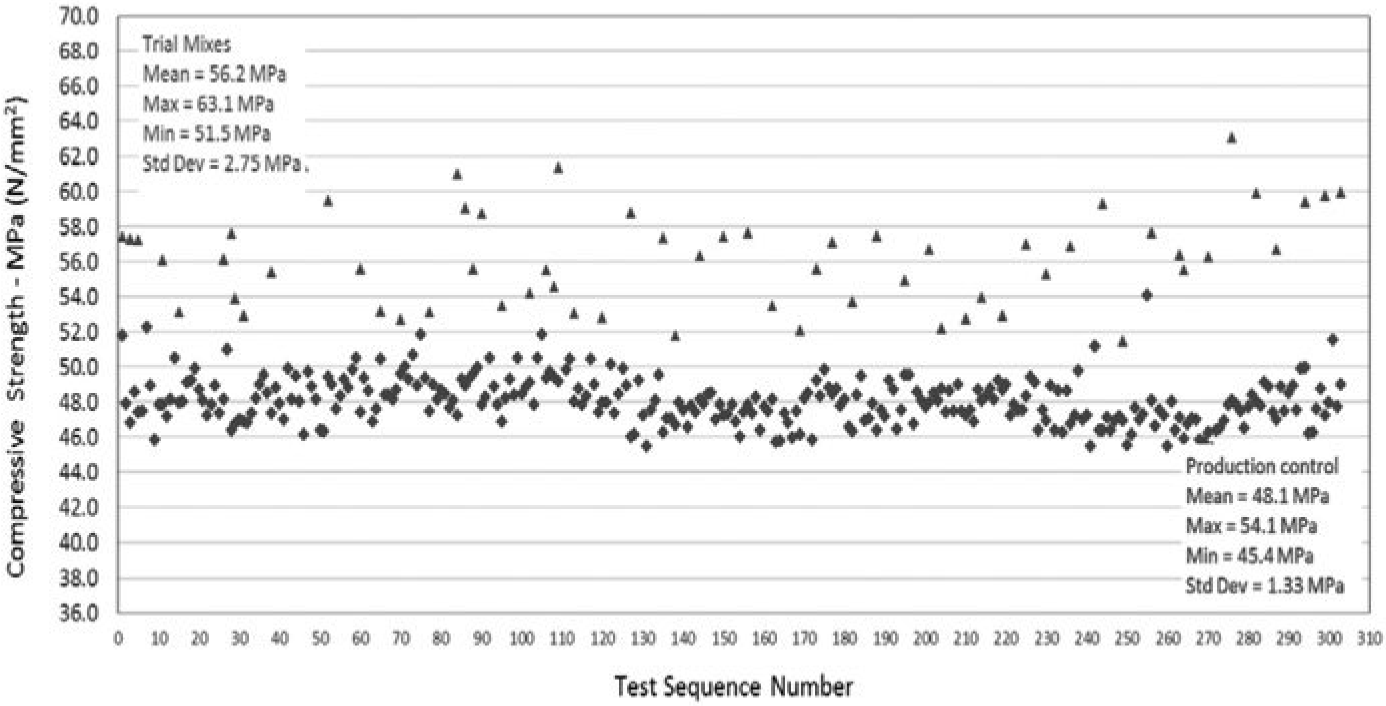


Figure C.1: RMC production control data for C32/40 over a period of 12 consecutive calendar months.

The Figures 2 (a) to 2 (d) suggest that a more reliable approach is to consider the recent production performance, e.g. latest 3 months production with at least 30 data sets, than conducting traditional trial mixes testing for potential future production quality. In order to illustrate this concept, the production control data shown in Figure C.1 (Annex C), is divided into each of the 4 consecutive calendar months as shown in Figure 2 (a), (b), (c) and (d) below. Although the design margin for C32/40 is 8 MPa, the production data is within the range of (40±4) MPa due to low variability of production (standard deviation < 2 MPa) in each.

The summary of number of samples, mean and standard deviations for each quarter is given in Table 3.

The Table 3 performance results indicate that the mean and standard deviation over a quarter of a year with at least 70 testing results can serve as a reliable basis for expecting acceptable characteristic strength for delivery of concrete in the following months. This is demonstrated by the performance in the succeeding quarters of production. The adoption of this alternate approach to conducting trial mixes of a certified concrete in production over several months enables a project to accept delivery of the selected concrete without delay time taken for confirmation by trial mixes. In addition, this leads to better productivity and/or savings in both manpower and materials resources at the initial stage of a project in concrete construction. Such situation is practiced in a precast concrete plant based on continuing production performance of a concrete without the need for any occasional trial mixes to verify the same concrete for continuing production.

6.3 Impact on sustainability

Based on the above findings, it can be seen that firstly the volume of test specimens needed for conformity testing can be reduced by 2/3 when 100mm cubes are adopted in place of 150mm cubes. The volume of test specimens to be disposed after testing is also reduced by this factor. Existing curing capacity is effectively increase by a factor of 3. The time required for loading of test specimens is also reduced besides ease of handling resulting in higher productivity in the testing laboratory.

By adopting certification of designed concrete, the practice of requiring satisfactory trial mixes to be conducted before concrete can be delivered to each project site for the same designed concrete produced by the same RMC plant can be limited only to new designed concrete for which initial tests

Table 3: Summary of analysis for 4 consecutive calendar months.

Duration	Number of samples	Mean (MPa)	Maximum (MPa)	Minimum (MPa)	Range (MPa)	Standard deviation (MPa)
1st Quarter (May-Jul)	76	48.5	52.3	45.9	6.4	1.36
2nd Quarter (Aug-Oct)	76	48.4	51.9	45.5	6.4	1.22
3rd Quarter (Nov-Jan)	77	47.8	49.9	45.8	4.1	1.01
4th Quarter (Feb-Apr)	73	47.6	54.1	45.4	8.7	1.48

are performed for conformity of specified requirements before production. Significant savings in cost in staff time and resources are achieved besides increasing productivity on site.

7.0 CONCLUDING REMARKS

Only 3 strength levels up to C65/80 have been tested and until data from more concretes above C60/75 are available, the findings lead to the following observations:

a. 100mm cubes provide similar measured compressive strength as 150mm with only a very small difference which is of little practical significance in conformity assessment, particularly when small sample size of two or three specimens taken on site at delivery.
b. Strength ratio in compression between 150mm cubes and 150mm diameter by 300mm length cylinders tends to decrease with increasing compressive strength levels supporting the commonly accepted value of 1.25 up to C50/60 to 1.15 at C100/115 based on a constant difference of 15 MPa as provided in BS EN 206 [1].
c. Difference in compressive strength between 150mm cubes and 150mm diameter by 300mm length cylinders for C65/80 is about the same as the nominal value of 15 MPa in BS EN 206 [1] for strength classes of C60/75 and above.
d. The use of 100mm cubes for production conformity testing instead of current practice of specifying only 150mm cubes as well as for identity testing of site samples is a significant reduction in concrete volume for preparing test samples as well as the amount of waste disposal of tested specimens to promote sustainable concrete construction.
e. The replacement of current practice of trial mixes for each new project with certification of RMC production reduces both time and resources before the start of delivery and hence overall productivity on construction sites.

The production performance data over a calendar year for C32/40 together with the occasional trial mixes carried out over the same period for various projects illustrate its reliability to provide the alternate approach to the need for trial mixes when a certified concrete is in good conformity control over a continuous period of months with at least 70 test results.

The adoption of 100mm cubes for conformity evaluation of compressive strength and the alternate approach of production performance data in place of trial mixes is recommended as a step towards promoting a more sustainable concrete construction. ■

REFERENCES

[1] BS EN 206 (2013), “Concrete – Specification, performance, production and conformity”, *British Standards Institution*, London, 2013.

[2] BS EN 1992-1-1 (2004), “Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings”, *British Standards Institution*, London, 2004.

[3] C.T. Tam, S.B. Daneti and W. Li, “EN 206 Strength conformity for sustainable concrete construction”, *40th Conference on Our World In Concrete & Structures*, 27-28 August, 2015, Singapore, CI-Premier, Singapore, 2015, pp 459-465.

[4] H.F. Gonnerman, “Effect of size and shape of test specimen on compressive strength of concrete”, *Proc. ASTM*, 25, Part II, pp. 237-50, 1925.

[5] A. M. Neville, “Some aspects of the strength of concrete”, *Civil Engineering (London)*, 54, Part 1, pp 1153-5 (Oct. 1959); Part 2, pp1308-11 (Nov. 1959); Part 3, pp 1435-9 (Dec. 1959).

[6] A.M. Neville, “A general relation for strengths of concrete specimens of different shapes and sizes”, *J. Amer. Concr. Inst*., 63, pp 1095-109, October, 1966.

[7] W.C. Leung and K.S, “Ho, Special Project Report, SPR3/96, Report on strength comparison f 100 mm and 150 mm cubes”, *Material Division, Public Works Central Laboratory*, Hong Kong, June 1996.

[8] H.D. Wong, “Cylinder strength versus cube strength”, *Annual Concrete Seminar 2013*, Standing Committee on Concrete Technology, 18 April, 2013, E/PWCL Standard & Testing Division, Geotechnical Engineering Office, Civil Engineering and Development Department, Hong Kong, 2013.

[9] BS 8500-2 (2014), “Concrete – Complimentary British standard to BS EN 206 – Part 2: Specification for constituent materials and concrete”, *British Standards Institution*, London, 2014.

[10] BS EN 197-1 (2011), “Cement – Part 1: Composition, specifications and conformity criteria for common cements”, *British Standards Institution*, London, 2011.

[11] BS EN 13263-1 (2009), “Silica fume for concrete – Part 1: Definition, requirements and conformity criteria”, *British Standards Institution*, London, 2009.

[12] SS 544-2 (2014), “Concrete – Complimentary Singapore standard to SS EN 206 – Part 2: Specification for constituent materials and concrete”, SPRING, Singapore, 2014.

[13] A.M. Neville, “Properties of Concrete”, *5th Edition, Prentice Hall*, United Kingdom, 2011.

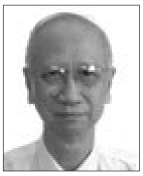
[14] A.M. Neville, “Properties of Concrete”, *1st Edition*, Pitman, United Kingdom, 1963.

[15] BCA (2010), “Requirements for ready-mixed concrete (RMC) certification for structural works”, (*BCA BC 15.0.3*, 4 January, 2010).

PROFILES

DR DANETI SARADHI BABU is currently a Concrete Specialist in the Alliance Concrete Singapore Pte Ltd, Singapore. He received his PhD degree and MS (by research) degree from National University Singapore, Singapore and Indian Institute of Technology Madras, India, respectively. He has over 15 years of industrial consultancy, R&D, teaching and training experience in the area of Concrete Technology and published several papers in international journals and conferences. His research interests include new product development, lightweight concretes, self compacting concrete, use of fibers and recycled materials in concrete and durability. Email: saradhibabu.daneti@allianceconcrete.com.sg.

LI WEI is currently a Research Associate in the National University of Singapore, Civil & Environmental department for more than 7 years. Li Wei has co-authored a number of journal and conference papers. Her main role in the research projects focuses on the materials experimental design, setup and analysis. Email: liwei@nus.edu.sg.



TAM CHAT TIM is currently an Adjunct Associate Professor in the Department of Civil & Environmental Engineering of National University of Singapore. Since retiring in 1996, he has continued in his research and providing technical advice to the concrete industry and served on technical committees of SPRING Singapore in the development of standards relating to concrete and its constituent materials. He is a Fellow of the Institution of Engineers, Malaysia, Institution of Engineers, Singapore, Institution of Structural Engineers, UK, American Concrete Institute and Concrete Society, UK. Email: tamct@nus.edu.sg.