USE OF 1200 MM DIAMETER ROUND PANELS FOR QUALITY CONTROL TESTING OF SFRC USED IN PRE-CAST TUNNEL LINING SEGMENTS

[1]WOLFGANG MERRETZ, [2]JULIAN BORGERT, [3]GODFREY SMITH, [4]STEFAN BERNARD

[1] Director Engineering, Structural Concrete Industries (Aust) Pty Ltd
[2] Director of Operations, Structural Concrete Industries (Aust) Pty Ltd
[3] Managing Director, Structural Concrete Industries (Aust) Pty Ltd
[4] Head of Research, Engineered Material Solutions Pty Ltd

Abstract- An earlier paper [1] examined the variability of test results obtained for beam tests performed on steel-fibre reinforced concrete used in the manufacture of precast segmental tunnel lining units as part of a commercial supply contract. It confirmed the existence of a commercially unacceptably high coefficient of variation (COV) in the order of 28% for results obtained by the ASTM C1609/C1609M beam test method [2]. This paper continues the investigation of high variability of test results for SFRC beams tested to ASTM C1609/C1609M method and presents an arguably superior alternative test for determining residual flexural strength using 1200mm diameter panels that provides substantially reduced variability. A robust analysis of the results obtained from numerous tests on sets of panels and beams has demonstrated a correlation between the two test methods within a 2.5% error margin. This margin can be considered negligible as well as conservative. It can therefore be accepted that a design residual strength at 3mm determined using ASTM C1609/C1609M beams is equivalent to an identical design residual strength at 10 mm determined using the 1200mm diameter panels tested in a manner similar to ASTM C1550. Based on this correlation, the equivalent minimum characteristic residual strength obtained using the panel tests has been determined and this equivalent minimum characteristic value can be satisfactorily used for acceptance criteria during production quality control testing.

Keywords- Testing, panel, correlation, residual flexural strength, steel fibre reinforced concrete, variability.

I. BACKGROUND

A critical aspect of the design of tunnel lining segments relies upon the concrete lining being able to achieve a high and consistent flexural resistance after cracking of the concrete has occurred. This property has traditionally been determined and verified in Australia using the ASTM C-1609/C1609M beam test for quality control in manufacture. Previous experience with ASTM C-1609/C1609M for testing of SFRC shows poor test repeatability [1] and a very large specified margin between target and design performance. The value of Coefficient of Variation (COV), defined as the standard deviation divided by the mean expressed as a percentage, is known to exceed 28 percent. With a COV of this magnitude, it is clear that the ASTM C-1609/C1609M beam test is unsuitable for quality control purposes and should, therefore, not be specified. Over recent years Structural Concrete Industries (SCI) has sought a better method of assessing performance and, through research conducted with Bernard, has proposed the use of a 1200 mm large round panel. Bernard has been using 1200 mm diameter round panels for several years as a research tool, mainly applied to FRC slabs. Testing of panel specimens made in the laboratory has shown a very low level of within-batch COV suggesting that this type of specimen could be used for quality control (QC) in construction. The present investigation has extended previous work on panel performance evaluation [3] by developing an expression for residual strength at any level of deflection.

II. CONCRETE TRIAL MIX PROGRAM

As part of a trial mix development program a major consideration was the conceptual, logistical and operational parameters that would permit 150 x 150 mm beam and 1200 mm diameter panel test specimens to be made concurrently in sufficient quantities to allow statistically valid and meaningful analysis to be conducted. Substantial specimen quantities were necessary to derive correlation and flexural resistance equivalence so as to be able to use the results of panel tests in lieu of beam tests for residual flexural strength for QC in the manufacture of tunnel segments. The composition of the trial mixes for a recent tunneling project in Australia is shown in Table 1. These consisted of 10 trials using steel fibre Type A with fibre dose rates of 35, 45, 55 and 65 kg/m^3 and 12 trials using steel fibre Type B with dose rates of 30, 40, 50 and 60 kg/m^3. Table 2 shows typical flexural strength results for minimum and maximum fibre contents for fibre Types A and B.

Table 1. Steel fibre content used in trial mix (pre-production) program for correlation

Steel Fibre Type A		Steel Fibre Type B	
Dose Rate (kg/m^3)	Trial Mix Number	Dose Rate (kg/m^3)	Trial Mix Number
35	1, 5	30	9, 13, 21
45	2, 6	40	10, 14, 22
55	3, 7, 17, 18	50	11, 15, 19, 20
65	4, 8	60	12, 16

In total 22 x 9 = 198 beams and 22 x 6 = 132 panels were prepared and tested. The sample sizes consisting of 9 beams and 6 panels per trial were chosen to optimize the analysis using the statistical Student's-t distribution for small sample sizes. All trials were prepared from the same base concrete proportions in 2.2 m^3 batches per sample mixed in a high efficiency transit agitator truck.

2.1 Probability distribution of data from ASTM C1609 beams

The normal distribution is generally regarded as the most appropriate probability function to represent the distribution of flexural strength data from SFRC. Results from previous studies [4] have shown that the mean values of flexural strength have no significant dependency on the number of samples. The COV, however, depends on the number of samples and is generally under-estimated when small numbers of specimens are tested. In order to estimate the characteristic 95th percentile value of residual strength at 3 mm central deflection from the pre-production test data, normal distribution equations were applied to the trial mix test beams to verify the performance of the sample SFRC mixes using appropriate corrections to estimate the variability of the population. Within-batch COV's in the order of 28% have been determined from earlier research [1].

2.2 Probability distribution of data from 1200 mm round panels

Previous studies by Bernard et al [4] have determined that the mean estimate of flexural strength data from a sample of specimens (denoted $\overline{x}$, or average) does not depend on the number of test results. It has, however, been shown that within-batch variability is more dependent on the sample size, a phenomenon that is primarily related to the inclusion of a square root function within the expression for standard deviation. The calculated COV is smaller for a small number of specimens (n<10) than for a large population. The true COV is always larger than estimates obtained using small numbers of specimens. The implication is that using a COV obtained for a relatively small number of tests for a particular concrete mix could significantly underestimate the true variability of the data. To address this problem, a minimum sample size of 6 panels and 9 beams per trial mix was established for the pre-production test program. For this test program it was also proposed to apply a COV correction factor as presented by Bernard et al [4] to calculate the COV of a population of panels based on the variation determined for a small sample COV as shown in Table 3. The correction equation is:

For: $$\frac{COV}{COV_{\inf}} = \frac{n-1.02}{n-0.24} \quad \text{Eqn - (1)}$$

and thus: $COV_{infinity} = 1.1566 \times COV_{n=6}$ or $1.0977 \times COV_{n=9}$ Eqn – (2)

The mean within-batch COV for pre-production panel tests was found to be 10.08% for sets of six samples and 11.66% when adjusted for a large number of samples in accordance with Eqn (1). Similarly, the same concrete trials yielded values for beams of 20.31% for the sets of nine samples and 22.30% when adjusted for a large number of samples in accordance with Eqn (1).

Table 2. Flexural strength results for Trial mixes 1, 8, 9 and 16 (representing the minimum and maximum dosages of fibre used in all the trials)

Trial Number	Trial 1		Trial 8		Trial 9		Trial 16	
	Result	Average	Result	Average	Result	Average	Result	Average
Fibre Type	Type A		Type A		Type B		Type B	
Nominal Fibre Dose (kg/m3)	35		65		30		60	
Results of Flexural Strength Tests								
ASTM C1609 Beam Test Flexural Strength at First Crack f_b (MOR)	5.89	6.05	6.49	6.47	6.38	6.05	5.44	5.96
	6.25		6.79		6.02		6.23	
	6.01		6.13		5.74		6.21	
	5.47	5.91	6.20	6.05	5.80	5.52	6.01	6.02
	6.12		5.99		5.68		6.15	
	6.15		5.95		5.08		5.91	
	6.34	6.26	6.10	6.10	5.50	5.48	6.33	6.24
	6.40		6.10		5.94		6.00	
	6.05		6.10		4.99		6.38	
ASTM C1609 Beam Test Residual Flexural Strength at 3mm Deflection f^D_{150}	2.46	2.82	3.64	3.94	2.50	2.38	6.05	4.54
	2.80		5.16		2.56		3.80	
	3.21		3.03		2.08		3.76	
	2.48	3.37	3.56	4.01	3.50	2.80	4.70	4.49
	4.14		4.63		3.45		3.76	
	3.50		3.83		1.45		5.02	
	2.55	2.30	3.45	3.93	3.77	3.29	4.33	4.02
	2.03		3.67		3.64		2.85	
	2.33		4.67		2.46		4.88	
1200 Diameter Round Determinate Panel Test ASTM 1550 Flexual Strength at Cracking (Mpa)	5.94	5.57	6.24	5.88	5.81	5.66	4.95	5.51
	6.08		5.87		5.92		5.82	
	5.26		5.99		5.52		5.48	
	5.68		5.73		5.20		5.73	
	5.38		5.95		5.86		5.31	
	5.07		5.49		5.64		5.80	
1200 Diameter Round Determinate Panel Test ASTM 1550 Residual Flexural Strength at δ=10mm	3.08	3.14	4.12	3.92	3.79	3.78	3.86	4.10
	3.35		3.78		3.85		4.26	
	2.53		4.02		4.05		4.21	
	3.43		3.79		3.81		4.41	
	3.53		3.79		4.04		3.45	
	2.92		4.05		3.14		4.44	
Statistical Analysis of Results Beams								

Beams							
Flex MOR Average	6.09		6.07		5.50		6.13	
Flex MOR SD	0.33		0.09		0.39		0.19	
Flex MOR COV	5.44%		1.48%		7.06%		3.12%	
Flex 3mm Average	2.83		3.96		2.82		4.35	
Flex 3mm SD	0.67		0.70		0.80		0.93	
Flex 3mm COV	23.47%		17.59%		28.44%		21.49%	
Panels								
RDP MOR Average	5.57		5.88		5.66		5.51	
RDP MOR SD	0.40		0.25		0.27		0.34	
RDP MOR COV	7.14%		4.31%		4.77%		6.17%	
RDP 10mm Average	3.14		3.92		3.78		4.10	
RDP 10mm SD	0.37		0.15		0.34		0.38	
RDP 10mm COV	11.88%		3.92%		8.87%		9.30%	
MOR = Modulus of Rupture SD = Standard Deviation COV = Coefficient of Variation								

III. THE 1200 MM DIAMETER PANEL TEST METHOD

ASTM C1550 round panels [5] have become an essential tool for the assessment of post-crack performance in Fibre Reinforced Shotcrete (FRS) within the underground construction and mining industries. These specimens exhibit a lower within-batch COV in performance than any other test method for FRC, due mainly to the large crack length experienced during testing. However, the ASTM C1550 round panel is only 75 mm thick and is therefore considered too thin to be applicable for Quality Control testing of FRC used in thick elements. The reason for this is that the flexural performance of FRC depends on the thickness of the member subjected to bending. This is because fibres embedded within concrete are of a finite length and post-crack pull-out resistance generally falls as crack width increases. The maximum crack width experienced in a thin member is smaller than the maximum crack width experienced within a thick member subjected to the same degree of curvature. It is therefore important to assess post-crack performance in specimens with a thickness comparable to the thickness of the intended FRC application. The 1200 mm round panel test is an adaptation of ASTM C1550 but involves a specimen measuring 1200 mm in diameter and 150 mm thick. The thickness of the presently used large round panels was chosen to match the thickness of beams tested using ASTM C1609/C1609M, which is a simply-supported beam test commonly used for the assessment of post-crack flexural performance of FRC. The beam test method expresses flexural performance in terms of a Modulus of Rupture at first peak in the load-deflection curve, plus energy absorption and residual strength at L/600 and L/150 central deflection (where L is the span of the beam, 450 mm for a 150×150 mm beam cross-section). Many designers of tunnel segments have preferred to use the residual strength at L/150 (3.0 mm central deflection) as the main design parameter, and in most pre-cast tunnel segment designs this parameter has tended to govern mix design proportions and fibre content. In order to use the 1200 mm large round panel as an alternative performance assessment tool, it has therefore been necessary to develop a correlation in performance between residual strength at 3.0 mm in the ASTM C1609/C1609M beam test and the residual strength at an equivalent deflection in the 1200 mm diameter, 150 mm thick round panel adjusted by thickness correction functions.

Table 3. Coefficients of Variation (%) from pre-production trials for small sample numbers of beams and panels based on a small sample number standard deviation.

Trial Mix Number	Beam 3mm COV	1200 mm panel 10mm COV	Trial Mix Number	Beam 3mm COV	1200 mm panel 10mm COV
1	23.47	11.88	12	22.78	11.46
2	12.02	8.65	13	14.02	13.28
3	16.64	7.73	14	16.29	12.21
4	13.52	13.89	15	13.82	4.30
5	26.98	14.88	16	21.49	9.30
6	25.96	15.79	17	28.22	9.24
7	12.80	13.25	18	20.48	8.26
8	17.59	3.92	19	22.27	5.30
9	28.44	8.87	20	10.67	6.75
10	20.95	11.60	21	33.47	13.49
11	25.38	4.88	22	19.80	12.79
			Average COV	**20.31**	**10.08**

The 1200 mm diameter large round panels were tested in a manner similar to conventional ASTM C1550 round panels. The specimen is supported on three pivoted supports and subjected to a central point load as shown in Figure 1. The load is advanced progressively and a load-deflection curve is recorded indicating the resistance of the panel as a function of central deflection. Bernard [3] demonstrated that 10 mm central deflection in the 1200 mm diameter round panel results in an average maximum crack width that is equivalent to the 4.0 mm maximum crack width experienced by an ASTM C1609/C1609M beam at 3.0 mm central deflection. Post-crack performance in the form of a residual flexural strength was therefore assessed at 10 mm central deflection in the 1200 mm diameter round panels.

3.1 Panel thickness correction functions

Thickness correction functions were developed for the panels [3] to correct the results for residual load (P). The expression for residual load took the form:

$P = P'(t_0 / t)^{\alpha} . (d_0 / d)$in which $\alpha = 2.0 – (\delta – \eta) / \xi$

where P is the corrected residual load resistance, P' is the measured residual load resistance at a central deflection of δ, t is the measured thickness of the panel, t_0 is the standard thickness of 150 mm, d is the measured diameter of the panel, d_0 is the standard diameter of 1200 mm, and η and ξ remain to be determined. The most suitable correction function for residual load resistance was identified by a process in which successive values of η were chosen after which the magnitude of ξ was varied until the value corresponding to the smallest sum of residuals squared was identified and taken to represent the optimum. This was repeated until the optimum values were identified. These corrections for load resistance have been applied in the testing laboratory and are independent of the structural design process for designers. Users of test results can therefore be confident that variability in thickness of test panels is taken account of in the determination of load resistance.

3.2 The 1200 mm round panel test panel

The residual strength of a simply supported beam is determined using a plastic model of moment distribution throughout the span of the beam combined with an elastic distribution of strain through the cross-section. A similar method of analysis was used to determine a plastic distribution of moment throughout the plane of the panel while an elastic distribution of strain was taken to prevail throughout the thickness. This permitted comparable estimates of residual strength to be calculated in both the ASTM C1609/C1609M beams and 1200 mm diameter panels. Bernard [6] and Tran et al [7] have shown that yield-line methods of analysis produce a very accurate estimate of the point load resistance of an ASTM C1550-like panel compared to the flexural capacity of the concrete both at first crack and in the post-crack range. Using data previously generated and a series of tests on beams and panels produced using numerous batches of FRC, an analysis was undertaken to confirm that the residual strengths determined through calculation for the ASTM C1609/C1609M beams and 1200 mm diameter panels did, in fact, correlate.

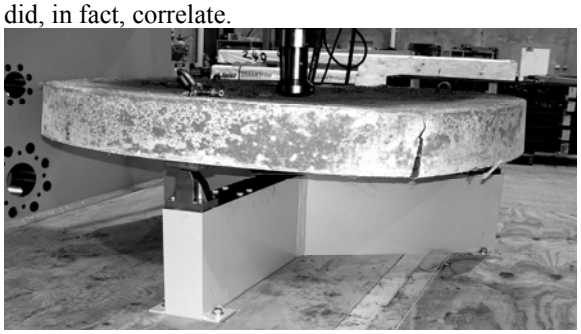


Figure 1. 1200 mm round panel being tested

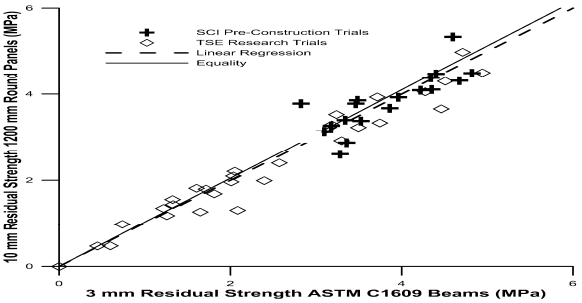


Figure 2. Beam/ Panel Correlation

A correlation in performance between ASTM C1609/C1609M beams assessed at 3.0 mm and 1200 mm diameter large round panels assessed at 10 mm central deflection has previously been published by Bernard [3] for a series of mix designs including both steel and macro-synthetic FRC. However, those trials were primarily intended to develop factors for the correlation of energy absorption and residual strength for non-standard thickness. They also did not include high strength FRC mixes incorporating 30-60 kg of steel fibres. The present process of test method validation therefore included an assessment of a possible correlation in performance between the two test methods using the mix designs under consideration for tunnel segment production. This study also provided data that would improve the confidence that tunnel designers can have in the QC results produced. Several other investigations were conducted concurrently at the TSE laboratory in which sets of 1200 mm diameter large round panels were cast concurrently with ASTM C1609/C1609M beams used in other investigations. These trials yielded a series of additional correlation points that assisted in strengthening the correlation and provided the designers confidence that this correlation was valid for a wide range of FRC mix designs, including both steel and macro-synthetic FRC mixes. The result is the correlation shown in Figure 2. A regression analysis of the data (with weighting for the number of specimens in each set) revealed that residual strength of FRC mixes assessed at 10 mm central deflection using 1200 mm large round panels is equal to 97.5% of the residual strength obtained for nominally identical FRC assessed at 3 mm in ASTM C1609/C1609M beams. The correlation is close to equality and slightly conservative. It is therefore acceptable to base the structural design of FRC tunnel segments on the post-crack residual flexural performance of 1200 mm diameter large round panels in the place of residual strength estimates obtained using ASTM C1609/C1609M beams. To date, approximately 1500 large round panels and 3000 ASTM C1609/C1609M beams produced in over 50 mix trials have been used to develop the correlation shown in Figure 2. The large number of specimens and wide range of fibre types, dosages and concrete mix designs used improves the confidence designers can have in the universal applicability of the (close to) 1:1 correlation herein demonstrated.

The primary reason why 1200 mm diameter round panels were examined as a possible replacement for ASTM C1609/C1609M beams (or any of the other beam tests) is the promise of reduced variability in test results. The within-batch COV was therefore carefully monitored for every set of specimens produced in the pre-production trials as well as in the concurrent investigations undertaken at TSE prior to commencement of production of tunnel segments. The results are listed in Table 4, and once adjusted for the number of samples in each trial, the population COV (estimated for a large number of samples, n) was 11.66%. This result contrasts markedly with the population COV for residual strength at 3.0 mm obtained from the ASTM C1609/C1609M beams tested in parallel with the 1200 mm diameter round panels (21.8%) and estimates of population COV (24.5%) obtained in previous large-scale investigations involving over 1300 ASTM C1609/C1609M beams [8]. These trials therefore demonstrated that the within-batch COV in residual strength at 10 mm central deflection obtained with 1200 mm round panels in a full scale production environment was approximately equal to half the within-batch COV obtained using beam tests.

Table 4. Within-batch COV for ASTM C1609/C1609M SFRC beams, and 1200 mm diameter round panels obtained in various investigations (all results adjusted for large sample size n)

Investigation	COV for ASTM C1609 Beams	COV for 1200 mm diameter Panels
Pre-production Trials	22.3	11.7
Production QC	-----	13.1
Bernard [3]	21.7	13.3
TSE Research projects	24.8	11.0

An obvious question arises concerning these results: why are the residual strengths generated using the large round panel so much more repeatable than the residual strengths generated using the beams? It is believed that the primary reason lies with the much greater crack area subjected to deformation and the larger number of fibres present across the cracks. The post-crack flexural performance of FRC is very sensitive to the number and location of fibres at the crack face. As the number of fibres increases the aggregated flexural performance is less sensitive to the number and location of individual fibres and thus variability in performance falls. Large test specimens therefore produce more consistent results than small specimens. The significant improvement in repeatability seen in the residual strength estimates obtained using the 1200 mm round panel test compared to the ASTM C1609/C1609M beam test makes it possible to apply conventional statistical techniques and analyses of data to calculate margins between minimum design requirements and target performance for FRC in the same way as is done for most other structural engineering materials. This avoids the need for specification of dubious empirical design expressions and statistical inventions to compensate for the inadequacy of beam test data.

IV. PRODUCTION QUALITY CONTROL TESTING OF SFRC

Production quality control testing for flexural resistance during segment manufacture is being performed at a contractual rate of two (2) panels per week of segment production. In an effort to maximize understanding of actual panel performance for the current project, four (4) panels have been manufactured from the same batch of concrete once per week. The concrete is deemed acceptable when the characteristic flexural strength calculated based on a 95% confidence meets the requirements for residual strength at 3.0 mm specified for the beams. This has now been expressed as residual strength at 10 mm in the 1200 mm round panels.

The characteristic flexural strength (f'_b) at 95% confidence interval is:

$f'_b = \overline{x} - 1.645 \cdot s$ where $s = COV_m \cdot \overline{x}$ and COV_m = 11.66%, being the corrected (for large n) average value for the pre-production trials.

The initial calculation of f'_b for the trial mix data used COV_m = 11.66%. As further weekly results were obtained, they were added to the trial mix residual flexural strength data to form a population. Each time weekly production data was added to the population, the population mean and the calculated characteristic value, f'b, was re-calculated.

The 1200 mm diameter panels were constructed in accordance with the SCI NATA accredited procedure for construction of 1200 mm diameter round panels. This procedure utilises twin steel moulds fixed to rigid vibrating tables such that the panels produced measure 1200mm diameter +/- 2mm and 150mm thick +/- 2mm. The SFRC is placed into the moulds and then compacted in a manner similar to that used in manufacture of the tunnel segments.

4.1 Residual flexural strength results for panel production testing

Determination of flexural strength for production mixes 1 and 2 are performed weekly under contract quality control testing procedures and results to date are shown in Figure 3. As the manufacture of segments progresses for this project, more test data will be added to the pool. It can be reported however that, at this early stage, the test method is providing

remarkably good repeatability. After nine (9) weeks of production the COV_m for all results to date (i.e. production and trial results combined) is 12.08%.

4.2 Workplace Health and Safety issues relating to the mass of super-sized RDPs

Unlike the production of ASTM C1609/C1609M flexural toughness beams, which involves extensive and arduous manual handling, there are no manual handling issues with the manufacture of 1200 mm diameter round panels. This is because the panels are mechanically handled throughout the process of production, curing, transport, and testing. The concrete is discharged directly into the test specimen mould via the concrete truck delivery chute with compaction being achieved through the use of the test mould's integral vibration system. The test panels are transferred to a wet curing facility via forklift with the lifting equipment attached to cast-in lifting devices. The same system is used to load the test panels onto the delivery vehicle for transport to the test laboratory where they are mechanically loaded into the test machine. Accordingly, all manual handling risks are eliminated through the use of standard industry load handling methods.

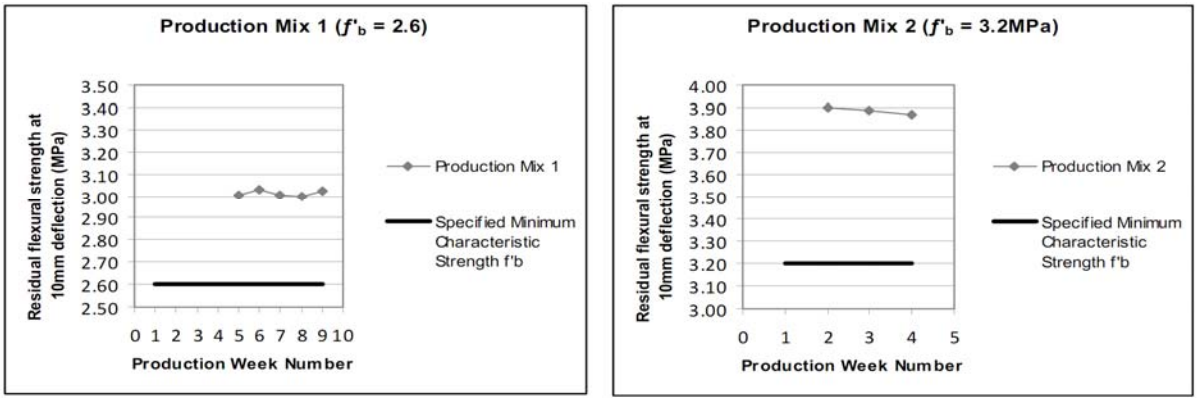


Figure 3. Residual flexural strength results from 1200 mm diameter panels for production mixes determined at 10 mm central deflection

CONCLUSIONS

Variability in QC post-crack performance tests of FRC using beams has, in the past, been excessive and this large variability has caused designers to ignore legitimate statistical concepts that are applied to all other engineering materials used in structural design. The current research together with data generated by Bernard has shown emphatically that the problem of high variability lies with the beam test method, not the material itself, and that large panels offer levels of test repeatability that are comparable to variability evident in other engineering material test methods.

The new 1200 mm diameter panel test offers designers a much more reliable design tool than beams. As well, it offers SFRC user contractors and constructors a reliable test method that will lead to a greatly reduced possibility of segment rejection as well as smaller required margins between minimum design requirements and target performance in production. This will substantially improve the economics of and reduce the risks associated with segment manufacture using SFRC. It will also help to maintain the economic advantage of SFRC over conventionally reinforced concrete as specified segment performance requirements increase over time.

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