Table 2. Comparison of splitting tensile strength formulas

Compressive Strength		ACI 318-99		CEB-FIB Code	
Mpa	Psi	Mpa	Psi	Mpa	Psi
34.5	5000	3.29	476.8	3.18	460.8
41.4	6000	3.60	522.3	3.59	520.4
48.3	7000	3.89	564.2	3.98	576.7
55.2	8000	4.16	603.1	4.35	630.4
62.1	9000	4.41	639.7	4.70	681.9
69.0	10000	4.65	674.3	5.05	731.5
75.9	11000	4.88	707.2	5.38	779.5
82.8	12000	5.09	738.7	5.70	826.1

fibre reinforced segments can provide similar bursting load capacities as the conventional reinforced segments.

Since the concrete used to manufacture segments is usually high strength, the designer may question whether the formulas contained in the structural concrete codes in Europe and U.S. are appropriate for high strength concrete. A recent paper evaluated the splitting tensile strength formulas for a number of sources for application with concrete's up to 120 Mpa (17,400 psi) (5). The results of their integral absolute error analysis showed that the CEB-FIB code formula gives a good correlation to observed data. In contrast, the formula in ACI-318-99 did not have a very good correlation, particularly at higher compressive strengths where there is a significant divergence between the two methods. Table 2 tabulates splitting tensile strength values calculated using the two methods.

The CEB-FIB formula for splitting tensile strength is:

$$f_{tsp} = 0.3 f_c^{2/3} \quad \text{(metric units)}$$

$$f_{tsp} = 1.57 f_c^{2/3} \quad \text{(imperial units)}$$

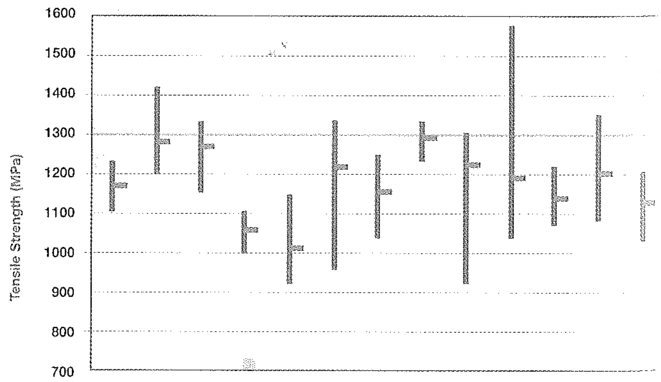
Experience on past projects has shown that when the steel fibre contents are determined for the flexural resistance requirements then the splitting tensile resistance requirements are usually met. Design engineers should specify the required value for splitting tensile needed to carry the applied loads.

Test methods used to determine splitting tensile strength include ASTM C496, BS 1881 – Part 117 for cast cylinders or the "Brazilian Method" for cores obtained from finished segments. Since there is no standardized test method for preparing cylinders for splitting tensile tests it may be prudent to place in the specification some language to indicate that cylinders for splitting tensile strength should be consolidated using external vibration not by rodding the sample. Rodding will disturb the random orientation of the steel fibres which may affect the test results.

4.0 ALL FIBRES ARE NOT EQUAL

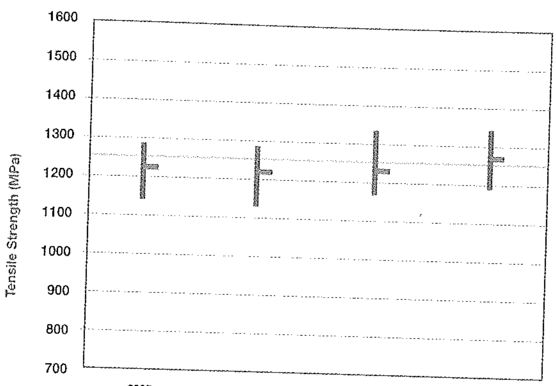
Steel fibres have been used successfully for over 20 years to reinforce concrete segments. However, contractors should be wary of selecting a supplier based simply on price, as there are many low-quality look-a-likes currently on the market. Many suppliers do not manufacture their own fibres. Distributors purchase from manufacture and place their label on the bag. Often these distributors change suppliers and don't inform their customers.

As an example of quality issues that have been identified for steel fibre suppliers, examine the data in Figures 8 and 9. Figure 8 shows the results of tensile tests conducted on 10 individual fibres from 10 different suppliers taken over a 7 year span. Most were sampled once but one was sampled 4 times in 1 year. The published tensile specification was the same for all of the suppliers; an average of 1300 Mpa ±100. The results are startling. Only 1 test was within the published specification, 11 tests had minimum values significantly outside of the specification, and only 3 tests were close to the published average value. Contrast the data in Figure 9, which was



	A 2000	B 2002	C 2003	D 2003	E 2003	F 2003	F 2003	F 2003	F 2003	G 2004	H 2005	I 2005	J 2007
HIGH	1236	1425	1337	1116	1153	1340	1252	1338	1305	1580	1226	1355	1207
AVERAGE	1175.1	1280.4	1270.5	1064.1	1016.9	1222.9	1156.6	1293.8	1214.1	1192.1	1140.8	1205.7	1133
LOW	1105	1204	1157	1008	927	958	1044	1233	918	1038	1073	1085	1034

Figure 8. Tensile strengths of various suppliers (specification is 1300 Mpa+100)



	2005 Jan – Mar	2005 Jan – Jun	2005 Jul – Sep	2005 Oct – Dec
HIGH	1277	1277	1326	1335
AVERAGE	1222	1216	1227	1263
LOW	1145	1127	1168	1191

Figure 9. Tensile strengths of one supplier (specification is 1260 Mpa +100)

collected over a 1 year time span for a single supplier. The results show a consistent pattern of tensile strengths within the published specification.

Fibre quality can be determined by the consistency of not only length and diameter but tensile strength and hook formation. In order to ensure that a project is supplied with consistent quality steel fibres it is recommended that the following specification language be placed in the contract documents:

Test steel fibre in accordance with ASTM A820 or EN-14489-1. Test 10 fibres per lot with the lot size to be proposed by the precast segment manufacturer.

- *Determine steel fibre length, diameter and aspect ratio. Individual samples shall be ±10% of specified values and the average of 10 samples shall not deviate more than ±5% of the specified values.*

- *Determine tensile strength of steel fibre. No more than 10% of the individual samples shall be below the specified values.*

- *Determine compliance with bending requirement.*

In reference to manufacturer or supplier experience, the following language is also recommended:

The steel fibre supplier shall have a minimum 5 years experience and provide a list of job histories that demonstrates their product has been used successfully in a minimum of five projects of similar type, size and complexity.

If the supplier of the steel fibres is not the manufacturer, the distributor shall document that they have a minimum 5 years experience in distributing steel fibers from the same source.

If steel fibres are supplied from different manufacturing facilities the supplier shall provide documentation that material being produced meets the same quality at all locations.

5.0 CONCLUSIONS

The use of steel fibre concrete in tunnel segments in the right geologic conditions offers many technical and commercial advantages over rebar reinforcement cages. However, it is imperative that the design engineers specify acceptance criterion that align with the assumptions made in design. Otherwise, the delivered segment performance may not meet their expectations.

The recommendations offered herein aim to provide clear and concise guidance for the preparation of project specifications. When implemented steel fibres will be supplied from a consistent quality manufacturer and provide the flexural resistance and bursting strength needed to match the design.

6.0 REFERENCES

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2. EN 14489-1, Fibres for concrete – Part 1 Steel Fibres – Definitions, Specifications and Conformity.

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4. JCI, Method of Test for Flexural Strength and Flexural Toughness for Fibre Reinforced Concrete, JSCE SF-4 Japan Concrete Institute 1984 (Also published by Japan Society of Civil Engineers 1985).

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6. N. Anoglu, Z. C. Girgin and E. Anoglu, Evaluation of Ratio Between Splitting Tensile Strength and Compressive Strength for Concretes up to 120 Mpa and its Application in Strength Criterion, ACI Materials Journal, 103-M03, 2006.