**Temperature related steel and synthetic fibre concrete performance.**

Alan Richardson and Rhys Ovington

Department of Mechanical and Construction Engineering, Faculty of Engineering and Environment, Northumbria University, Tyne & Wear, NE1 8ST, UK,

***Abstract***

The effect of temperature variation on concrete properties with steel and synthetic fibre additions was examined. The range of performance characteristics were determined at room temperature (20°C) and ±40°C of room temperature. Standard test methods were carried out in order to determine the flexural strength, bond strength and toughness of fibre reinforced concrete at varying temperatures. A significant increase in the performance of concrete was observed at a temperature of -20°C as well as a minor decrease in performance at temperatures of 60°C. Steel fibre concrete performed best within the parameters of this test. However synthetic fibres provided the optimal performance based on the flexural strength percentage change when compared to the control and steel fibre samples.

KEY WORDS: Steel fibres, synthetic fibres, temperature, performance.

***1.0 Introduction***

There are large fluctuations in temperature Worldwide. In Russia, Greenland and Canada, the temperature varies massively over the four seasons. It is therefore crucial to effectively predict the thermal behaviour of building materials in order to properly design structures which are capable of withstanding such extreme variations in temperature. The temperature parameters used in the research represent the effect of real world temperatures, such as those recorded in the Middle-East and Canada (DeRosa, 2012).

This research examines two fibre types, namely steel and polypropylene Type 2 macro synthetic fibres. Polypropylene has a high resistance to the flow of electrons, leading to a low rate of heat transfer within the material. At ambient to high temperatures, polypropylene is a ductile material and shows qualities of a plastic/elastic nature. At temperatures below freezing, polypropylene tends to become brittle. Hall (1981) states that the brittle nature of polypropylene is a serious disadvantage and can become problematic, especially in certain applications when mechanical performance is concerned.

The temperature parameter choice was based upon a benchmark of ambient temperature, assumed to be 20C for the UK and an even temperature differential above and below this mark to ensure the same conditions were applied to the samples, thus allowing a fair comparison to be drawn at high and low temperatures. The temperature differential was considered to be marginally above maximum expected hot and cold environment temperatures where concrete would normally be used. The upper test limit was informed by Dave and Desai (2008) who suggest a maximum temperature of 60°C for curing. These are similar temperatures found in Middle Eastern countries (Kuwait Met Office, 2017) and therefore this study is relevant to current construction practices.

Research carried out by Lau *et al* (2006) investigated the effect that elevated temperature had on steel fibre concrete. The steel fibre concrete was subject to temperatures ranging between 105°C and 1200°C. These temperatures are extreme and beyond maximum air temperature, but they do provide an understanding of the performance of steel fibre concrete under high temperatures. Lau *et al’s* (2006) research reported a decrease in elastic modulus as the temperature increased as well as a small, but not significant, reduction in strength at temperatures below 400°C. It was concluded that the use of steel fibres in concrete continues to be beneficial even at temperatures of 1200°C and that steel fibre concrete can provide a greater resistance to the effects of heating.

Mirzazadeh *et al* (2016)found that concrete beams tested at -25°C demonstrated an increase in strength and ductility of 13% and 34% respectively, compared to those tested at room temperature. This may be equally applicable to steel fibre reinforced beams? Neville (2006) suggests that, within wet specimens, the compressive strength of cooled/frozen concrete can reach values up to three times the strength at room temperature. This is believed to be due to water freezing within the pores and thus providing the increased strength.

Possibly the most beneficial effect of fibre additions in concrete is the ability to absorb energy (Velore *et al*, 1995, Richardson and Coventry 2015 and Richardson, Coventry, Lamb Mackenzie 2016). This is the main reason for the use of fibre reinforcements within floor slabs. If toughness is reduced with an increase in temperature, this could be considered a major disadvantage when designing structural elements for hot climates, such as the Middle East, where it is not unheard of for air temperatures to rise above to and beyond 40°C. This research has investigated this physical property further in order to determine whether fibre reinforced concrete should be designed with temperature induced mechanical degradation in mind. According to Bakis et al. (1998) there is a linear relationship between temperature and pull out force, tested between the values –20 ºC and 60 ºC and this research has influenced parameters of this series of tests. Temperature fluctuations between the limits of –20 and 60ºC influence nominal bond strength and this influence was not dominated by changes in elastic properties of the material properties of the fibres tested.

Despite the widespread use of fibre reinforced concrete, there is still debate within the industry as to the benefits they offer. Steel and type 2 synthetic fibres are currently used to good effect in many engineering applications however temperature changes the physical characteristics of the fibres and the composite matrix of fibres and concrete. This paper examines the relationship between fibre performance and temperature.

***2.0 Materials***

*2.1 Concrete Specification*

The concrete used for this research is specified within Eurocode 2 as strength class C28/35 at 28 days of curing. The specifications for both synthetic and steel fibres are detailed in BS EN 14889 Parts 1 and 2.

*2.2 Fibre specification*

Synthetic fibre specification is detailed in BS EN 14889-2: 2006 and the steel fibre classification is covered in BS EN14889-1.

The adopted steel fibres have a hooked end profile as shown in Figure 2, which provide additional bond strength (Richardson *et al,* 2010) and the overall fibre dimensions were 50mm x 1mm with a tensile strength of 1050 N/mm2.

[](https://www.google.co.uk/imgres?imgurl=http://www.reinforcingmesh.net/concretereinforcingproducts/images/hooked_end_reinforcing_steel_fiber_fiber_02.jpg&imgrefurl=http://www.reinforcingmesh.net/reinforcing-steel/concrete-reinforcing-steel-fibers.html&docid=fAIdg8pHsOwaKM&tbnid=kBu4FdJ8S1awJM:&vet=10ahUKEwienMi4wu_UAhWOLVAKHQ1RA_UQMwiQAShDMEM..i&w=511&h=250&bih=946&biw=1280&q=steel%20fibres%20for%20concrete&ved=0ahUKEwienMi4wu_UAhWOLVAKHQ1RA_UQMwiQAShDMEM&iact=mrc&uact=8)

Figure 1 – Steel fibre details (<http://www.reinforcingmesh.net>, accessed 04.07.2017)

Steel fibres were added to the concrete mix at 40kg/m3. Type 2 synthetic fibres, had nominal dimensions of 40 x 0.95mm and were incorporated into the mix design. Previous research shows that these fibres are generally more effective in supplying an increase in residual strength (Richardson *et al*., 2010) when compared to similar synthetic fibres used commercially. The fibre type used was a 90% polypropylene and 10% polyethylene mix with known high performance values (Richardson, 2005) and is referred within the text as simply “polypropylene”.

[](https://www.google.co.uk/url?sa=i&rct=j&q=&esrc=s&source=images&cd=&cad=rja&uact=8&ved=0ahUKEwi_3MGoxu_UAhWKh7QKHXRUCC0QjRwIBw&url=https://www.alibaba.com/product-detail/Propex-Fibermesh-Enduro-600-Concrete-Reinforcement_50010787955.html&psig=AFQjCNG3qKhkTqIOWu7E84iFk759OIFggg&ust=1499255018181749)

Figure 2 – Synthetic macro fibres ([https://www.alibaba.com/product-detail/Propex](https://www.alibaba.com/product-detail/Propex-Fibermesh-Enduro-600-Concrete-Reinforcement_50010787955.html) - accessed 04.07.2017)

Synthetic fibres were added to the concrete mix at a dosage of 4kg/m3. The relationship between the fibre dosage of 40kg/m3 for steel fibres and 4kg/m3 for synthetic fibres provides a very similar level of performance in terms of flexural strength. (Richardson A, Coventry and Landless, 2010).

***3.0 Methodology***

The test methodology was designed to determine how the mechanical properties of plain and fibre reinforced concrete vary with respect to temperature changes, at -20°C and 60°C. An environmental chamber was used to heat the specimens and a walk in freezer was used for freezing the specimens. The specimens were left in the respective heat and cold appliances for 24 hours prior to testing. To ensure the temperature change was minimised during the test, bubble wrap was used to insulate the test specimens during the test period when the specimens were removed from their storage areas. The samples as tested were surface dry at -20°C and 60°C, in addition the frozen samples were free from any surface ice.

Compressive strength was determined using BS EN 12390 - 3. (2009), and this was carried out on the plain samples only. The rationale for this decision was based upon an extensive study of the compressive strength of concrete with fibre additions and this study concluded that the addition of synthetic fibres to concrete reduced the density and compressive strength. (Richardson 2006). Steel fibres have a natural affinity with concrete due to very similar thermal coefficients, whereas synthetic fibres do not have the same qualities. It would be impossible to draw comparative conclusions using the compressive strengths of plain, synthetic and steel fibre concrete, therefore the base material for all cubes was established as a common material providing bond strength and encapsulating the fibre types.

Flexural and bond strength of concrete with the addition of steel and synthetic fibre types was established using test methods BS EN 12390-5: 2009 and BS EN 1542: 1999 for three point flexural and bond strength.

##### The energy absorption capacities of both steel and synthetic fibre reinforced was established using the area under the load deflection curve and the flexural toughness was further examined using BS EN 14651:2005+A1: 2007 at four crack mouth openings.

The flexural toughness and the total energy absorption of each beam was to be determined using the load/deflection curves which were established during the testing of flexural strength. Vellore *et al*. (1995) states that most standards are comparable and that ACI 544 uses the ratio of the load/deflection curve to determine concrete toughness, The loading configuration is shown in Figure 3.

Figure 3 – Beam loading arrangement

Load P

Cross head/tup

Fibre reinforced beam

d

CMOD

Roller Support L Roller Support

The load/deflection curve was first used to determine toughness, then in order to further evaluate the post crack toughness of the beam specimens, the test methodology specified within BS EN 14651:2005+A1: 2007 was used. This method requires the use of the load/deflection graphs which were established during the flexural strength tests. Values of flexural strength were determined using equation [1] at varies crack mouth openings. The results measured and calculated using this method are therefore more useful to designers within industry when attempting to control cracking within concrete structures (Richardson and Jackson 2011).

The points of crack mouth opening displacement (CMOD) which the flexural strength is to determined are as follows:   
CMOD1 = 0.5mm from the limit of proportionality (LOP)   
CMOD2 = 1.5mm from (LOP)   
CMOD3 = 2.5mm from (LOP)   
CMOD4 = 3.5mm from (LOP)

Equation [1] :

(BS EN 14651:2005+A1 (2007)

Where:

F = maximum load  
L = Span between the roller supports   
b = beam width  
d = beam depth

Figure 4 displays the test methodology - outlining the range of materials to be tested and the test type at different temperatures. The pull out tests were performed on plain concrete cubes with fibres embedded and the beam tests had synthetic and steel fibre doses as specified.

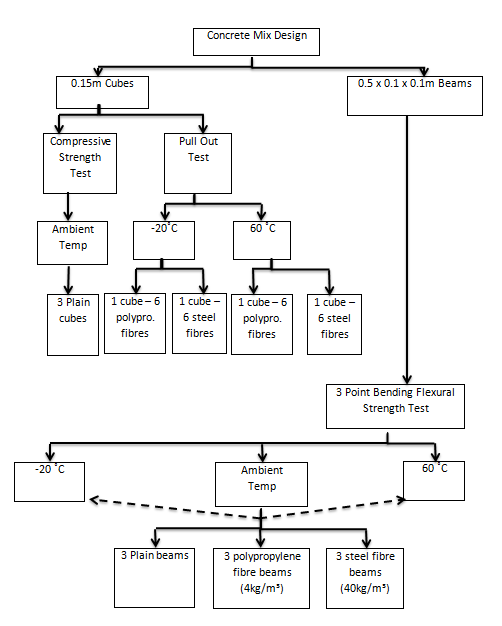


Figure 4 – Test programme

***4.0 Results***

Results were obtained for a range of tests as displayed in Figure 4 and these were flexural strength, compressive strength, pull out force and toughness.

*4.1 Compressive strength*

The average compressive strength of the concrete was 37N/mm2 and the characteristic strength using a 5% defective was 35N/mm2. The test was undertaken at ambient room temperature in accordance with BS EN 12390-3 (2009) at 28 days after batching.

*4.2 Flexural strength*

The flexural strength was determined using Equation 1 and the average values of the results are displayed in Table 1. Each beam testedwas subject to a central loading mechanism which extended at a speed of 2.2mm/min and the span between the rollers was 300mm.

Table 1 - The average flexural strength for each beam classification and temperature.

|  |  |  |  |
| --- | --- | --- | --- |
| **Concrete Type** | **Average Flexural Strength (N/mm2)** | | |
| **-20**°C | **Ambient** | **60**°C |
| Plain | 11.63 | 5.84 | 3.78 |
| Polypropylene fibre | 11.47 | 4.58 | 4.01 |
| Steel fibre | 11.74 | 6.29 | 3.85 |

The results show that Type 2 polypropylene fibres reduce the flexural strength of concrete beams at ambient temperature compared to plain concrete beams. This is a characteristic of Type 2 fibres which has been well research by Richardson *et al.* (2010).

All beams suffered from a flexural strength reduction when comparing ambient temperature to a temperature of 60°C. The plain beam showed an average 35% reduction, the polypropylene fibre beam showed an average a 12% reduction and the steel fibre beam showed an average a 49% reduction. However, at temperatures of 60°C a lesser decrease in flexural strength was observed when polypropylene fibres were used and compared to plain concrete, which could suggest that polypropylene fibre concrete can be beneficial in providing improved performance within concrete that experiences elevated temperatures. Beddar et al (2008) examined the performance of concrete curing in a hot climate

and suggested that while concrete cured at elevated temperatures develops a high early

strength, the ultimate strength may be reduced because of evaporation of the mixing water, which may adversely affect cement hydration. This strength reduction mechanism may apply to the heated samples as tested and explain the reduction in strength.

All beams tested at -20°C displayed a significant increase in flexural strength when compared to the same beam tested at ambient temperatures. The plain beam showed an average 99% increase in flexural strength, the polypropylene fibre beam showed an average a 150% increase in flexural strength and the steel fibre beam showed an average a 79% increase in flexural strength. Polypropylene fibre concrete displayed the most improved performance at higher and lower temperatures.

The beams which featured steel fibres showed improvements across the entire tested temperature range when compared to plain concrete beams. This observation was expected as steel fibres have been proven to supply increased concrete strength (Lau *et al*, 2006). The flexural strength tests also show that steel fibre concrete supplied a slightly greater strength at temperatures of 60°C when compared to plain concrete. This is backed up by Lau *et al* (2006) and, who state that steel fibre reinforced concrete continues to be beneficial to concrete after exposure to high temperatures.

The most notable trend observed from the results of the flexural strength test are that beams stored at temperatures of -20°C had the ability to withstand much larger loads before failure occurred, leading to a significant increase in flexural strength with a subsequent decrease in temperature, for all concrete types. This outcome concurs with Mirzazadeh *et al* (2016) who found an increase in strength of concrete specimens tested at -25°C. A large increase in flexural strength is believed to be due to the formation of ice within the pores of the concrete (Neville, 2006 and DeRosa, 2012).

*4.3 Pull out results*

Table 2 displays the results from the pull out tests for both polypropylene and steel fibres. The results show that as temperature decreases from 60°C to -20°C, there is a 50% increase in force required to pull out or snap the polypropylene fibres. This could be due to the fact that as concrete is cooled; it shrinks around the fibres, causing an increase in bond strength between concrete and polypropylene fibre. The synthetic fibres clearly have an improved performance at lower temperatures.

Table 2 - The average pull out force of each fibre type

|  |  |  |
| --- | --- | --- |
| **Type of Fibre** | **Average Pull Out Force (N)** | |
| **-20**°C | **60**°C |
| Polypropylene | 196.6 | 131.0 |
| Steel | 768.9 | 841.4 |

As temperature decreases, the force required to pull out the steel fibres saw a decrease by 8.6%. This value is negligible within the interpretation of these results. The reason for such a small variation in pull out force within steel fibre concrete may be due to the fact that there is a natural affinity between steel and concrete, in that their coefficient of thermal expansion is near identical (Richardson *et al*, 2010). This could be the reason that bond strength is retained as temperature changes, as both materials will deform similarly due to change in temperature. There is also a statistical degree of scatter within any results and this could be another possibility of this observation.

4.3.1 Pull out test [ambient (20ºC) and -20⁰C]

# A pull out test was carried out on a 2mm diameter polypropylene rod embedded into a concrete cube as shown in Figure 5. The test was undertaken at ambient room temperature 20ºC and at –20 ºC. When the cube was cast, grease was applied to the polypropylene rod to assist breaking the cement polypropylene bond, thus determining the effect of the temperature change only upon temperature related bond strength and this provided lower pull out values than those displayed in Table 2.

Figure 5 – Pull out – test rig



Figure 5 displays the test rig. The polypropylene rod under test was passed through a hole in the steel plate and a hanger was attached to a loop in the rod which imposed a force of 5 Newtons to the test polypropylene rod, by its self weight. A black marker pen was used to identify the join between the concrete and the rod and this was used to measure slippage (creep). At a time interval of 30 seconds, 5 Newton weights were added, until initial signs of slippage were noted on the rod at 20ºC; at 1 to 1.5 mm movement was recorded at a load of 105 N. This extension was in part due to the elastic nature of the polypropylene rod and the applied load. The polypropylene rod at -20⁰C showed no signs of slippage when subjected to a 105N load, however the rod at -20⁰C displayed a 1 to 1.5mm slippage at 125N load.The failure loads are displayed in Table 3.

Table 3 – Pull out values of polypropylene rod at different temperatures

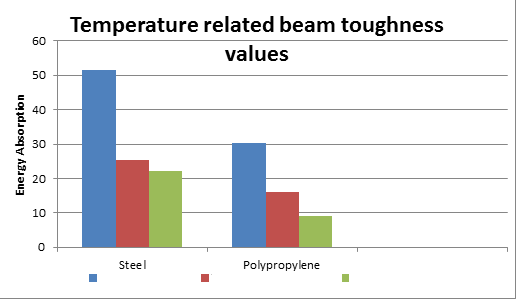
|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Length of rod embedded in mm (L) | Diameter of rod (average) mm (D) | Load to complete failure (N) | Stress (N) per mm2 (N/πDxL) |
| Cube at 20ºC | 125 | 1.9 | 126 | 0.169 |
| Cube at  -20ºC | 114 | 2.135 | 158.1 | 0.206 |

From analysis of the results, displayed in Table 3, it was clear the frozen cube achieved a much greater concrete to polypropylene rod bond, there was an 18% increase in bond when compared to the cube at 20°C. This would indicate that the bond strength was increased when the temperature is reduced, due to the fact the thermal co-efficient for polypropylene is 1.1 x 10 –4 at 20 °C and the thermal co-efficient for concrete at the same temperature is 2.2 x 10 –4 . As was seen by examining the result, the co-efficient values for concrete are much higher than polypropylene. As the temperature of the concrete was reduced towards freezing point, the concrete was more reactive than the polypropylene fibres, therefore the contraction rate of the concrete griped the polypropylene fibres tightly.

**4.4 Toughness**

The energy absorption capacities of both steel and synthetic fibre reinforced was established using the area under the load deflection curve and the results are displayed in Figure 4. The values shown are indices without any units and the calculations are based on Newtons and millimetres which provide a relative performance.

Figure 6 - The average total energy absorption of each type of beam after three point bending (the area under the load/deflection curve).



60°C

Ambient Temperature

-20°C

From examination of Figure 6 is can be taken that steel fibres outperform synthetic fibres at all temperatures. It is also apparent that a reduction in temperature equates to an improvement in performance irrespective of the fibre type. At the relative fibre dosage and fibre type, this result is predictable as the cut off point for the test is 10.5 times the initial displacement up to the point of rupture. This does not take account of the tendency for polypropylene fibre concrete to transfer loads at very high deflections.

Figures 7 and 8 display the average flexural toughness of each fibre type at each temperature tested. They show the spread of flexural strength values at each measurement of CMOD and LOP. The figures represent the ability of each beam classification to withstand load after failure and an initial crack opening has occurred.

Figure 7 – Comparison of polypropylene fibre reinforced concrete at varying temperatures, in terms of flexural strength at various CMOD

Ambient

-20°C

Figure 7 displays a clear difference between the performance of the fibres following the initial rupture of the concrete. The effect of temperature has a clear effect upon the fibre cement matrix bond. Colder fibres create a stronger bond and warmer fibres display lower bond characteristics. The results are in keeping with the earlier tests undertaken.

Figure 8 – Comparison of steel fibre reinforced concrete at varying temperatures, in terms of flexural strength at various CMOD

°C

-20°C

Figure 8 shows a significant drop in flexural strength between the LOP and a crack mouth opening of 0.5mm at -20⁰C, and this drop is a common property across all of the tested temperatures. In both steel fibre reinforced concrete and polypropylene fibre reinforced concrete, it is observed that after failure has occurred, there is a large drop in flexural strength. However, the flexural strength still remains higher at -20°C than at warmer temperatures, as the crack widens. Steel fibre concrete seems to provide greater toughness than polypropylene fibre reinforced concrete, as higher values of flexural strength are provided as the CMOD increases; this observation equals that of the total energy absorption method for determining concrete toughness. While steel fibre reinforced concrete has higher toughness values, it appears that polypropylene fibre reinforced concrete will retain a constant flexural strength from CMOD1 to CMOD4.

***5.0 Conclusion***

This research was carried out in order to determine the effects that temperature has on various types of fibre reinforced concrete. The study has illustrated that temperature does affect the properties of fibre reinforced concrete. Both steel and synthetic fibre reinforcement were tested extensively in order to draw comparisons between the various fibre reinforced concrete types as well as plain concrete. The following outcomes were established:

Regardless of the reinforcement type, concrete which is stored at -20°C for 24 hours prior to being tested has the ability to withstand a significantly higher load before failure occurs when compared to concrete at ambient temperature. This leads to a much greater flexural strength exhibited by concrete at temperatures below freezing point of water. In contrast, concrete stored for the same length of time in conditions of 60°C, can be observed to fail at lower loads and the overall flexural strength will deteriorate due to the elevated temperature, when compared to ambient temperatures.

The average force required to snap or pull out synthetic fibres increases with a decrease in temperature, possibly as a result of a stronger frictional grip generated as concrete shrinks around the fibre, as temperature is reduced. By reducing the specimen temperature, the bond strength is increased within synthetic fibre reinforced concrete at temperatures of -20°C.

Having used various methods to analyse the toughness of each concrete type, the conclusion that decreasing temperature, increases the toughness of fibre reinforced concrete has to be drawn. This outcome concurs with past research which states the reason for increase in performance of concrete at temperatures below freezing is due to the formation of ice within concrete pores, which decreases porosity and hence improves stiffness and strength.

The deterioration in mechanical properties of fibre reinforced concrete, which this research observed at temperatures of 60°C, is a potential cause for concern as world temperatures continue to rise. Recommendations for future research would be to investigate the performance of structures which feature fibre reinforced concrete elements at 60°C and beyond in order to determine whether the loss in performance may harm the fibre concrete structures within the built environment.

Both steel and Type 2 synthetic fibres are effective at providing post crack flexural toughness, and given steel fibre overall performance, compared to synthetic fibre performance at the relative dosages, it may be a consideration for use with regard to outright structural performance. However, if fibres were to be used in a hostile environment such as sea defences, then synthetic fibres would be a first choice and their performance may be less temperature dependant compared to steel fibre concrete.

**6.0 Further work**

Consideration for further structural performance testing at various depths of a concrete structure using synthetic fibres which are subject to daytime heat build up would be a useful extension of this paper.

***References***

American Society for Testing and Materials, ASTM C 1018. (1997), *Standard test method for flexural toughness and first crack strength of fibre reinforced concrete*, ASTM

Bakis C E, Uppuluri V S, Nanni A & Boothby T E, 1998, “Analysis of Bonding Mechanisms of Smooth and Lugged Fibre Reinforced Plastic Rods Embedded in Concrete*”, Composites Science and Technology*, Vol 58, Elsevier Science Ltd, GB, pp 1307 1319

Beddar M, Safer S, and Chabil H, (2008), “Performance of concrete curing in hot climate”,

Dundee Conference Proceedings, Harnessing Fibres for Concrete Construction, Ed Dhir R,

Newlands M, Mc Carthy J and Paine K, UK pp

# British Standards Institute, BS EN 12390 - 3. (2009), *Testing hardened concrete. Compressive strength of test specimens,* BSI, London

British Standards Institute, BS EN 12390-5: 2009, *Testing hardened concrete. Flexural strength of test specimens*, BSI, London

BS EN 14889 Parts 1 and 2.Fibres for concrete (2006), BSI, London

# British Standards Institute, BS EN 1542: (1999), *Products and systems for the protection and repair of concrete structures. Test methods. Measurement of bond strength by pull-off,* BSI, London

## British Standards Institute, BS EN 14651:2005+A1 (2007), *Test method for metallic fibre concrete. Measuring the flexural tensile strength (limit of proportionality (LOP), residual,* BSI, London

Dave U and Desai Y M, (2008), “Interaction between temperature and sulphate effects on polypropylene FRC”, Dundee Conference Proceedings, Harnessing Fibres for Concrete Construction, Ed Dhir R, Newlands M, Mc Carthy J and Paine K, UK pp 353 – 364

DeRosa, D. (2012). “Thermal Effects on Monitoring and Performance of Reinforced Concrete Structures”. Published MSc Thesis, Ontario, Canada.

Vellore S, Golpalaratham V.S.And Gettu R, “On The Characteristics Of Flexural Toughness In Fibre Reinforced Concrete”, Cement And Concrete Composites, Vol 17, (1995), Pp 39–254.

Hall C, (1981), *Polymer Materials*, Macmillan Press, London, pp 177 –145.

Kuwait Meteorological Department 2010, <http://www.met.gov.kw/Climate/summary.php>, accessed 05.07.2017.

Lau, A. and M. Anson. "Effect Of High Temperatures On High Performance Steel Fibre Reinforced Concrete". *Cement and Concrete Research* 36.9 (2006): 1698-1707.

Mirzazadeh, M., Noël, M. and Green, M. (2016). Effects of low temperature on the static behaviour of reinforced concrete beams with temperature differentials. *Construction and Building Materials*, 112, pp.191-201.

Neville, A.M. (2006). *Properties of concrete, 5th edition*. Pearson Education Limited, Malaysia.

pp. 53-61.

Richardson, A. (2005). Bond characteristics of structural polypropylene fibres in concrete with regard to post‐crack strength and durable design. *Structural Survey*, 23(3), pp.210-230.

Richardson A E, 2006, *Compressive Strength of Concrete with Polypropylene Fibre Additions,* Structural Survey, Vol 24, No 2, August, MCB UP Ltd, UK, pp 138 – 153.

Richardson, A., Coventry, K. and Landless, S. (2010). Synthetic and steel fibres in concrete with regard to equal toughness. *Structural Survey*, 28(5), pp.355-369.

Richardson, A. and Jackson, P. (2011). Equating steel and synthetic fibre concrete post crack performance. *INTERNATIONAL CONFERENCE ON CURRENT TRENDS IN TECHNOLOGY, ‘NUiCONE – 2011’*. Ahmedabad, India

Richardson A E, Coventry KA, (2015), “Dovetailed and hybrid synthetic fibre concrete – Impact, toughness and strength performance, *Construction and Building Materials*, January, PP 439 – 449.

Richardson A, Coventry K, Lamb T, Mackenzie D, (2016), “The addition of synthetic fibres to concrete to improve impact/ballistic toughness”, *Construction and Building Materials,* Vol 121, September, pp 612 - 621

Vellore S, Golpalaratham V.S.and Gettu R, (1995), “On the Characteristics of flexural toughness in fibre reinforced concrete”, *Cement and Concrete Composites*, Vol 17, Issue 3, pp239-254