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Temperature Related Pull-out Performance of Chemical Anchor Bolts in Fibre Concrete

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Abstract

Anchor bolts are often fixed into a concrete soffit of structures and they are used in ambient and cold store locations. The chemical anchor bolt relies purely on the tensile strength of the concrete to carry the imposed load, assuming the bond strength of the resin is greater than the tensile strength of the concrete.

The properties of concrete are changed by the addition of both steel and polypropylene fibres. This paper investigates the relative performance of each fibre type with regard to initial and final post crack failure. Anchor bolt pull-out testing was used to determine the maximum load a fixing can hold as well as the residual post crack toughness of a bolt embedded in a concrete block. The concrete used was a C40 design mix and resin anchor bolts were selected for this test for their stress-free conditions prior to loading.

The results showed that the addition of both types of fibres when used in concrete improved the maximum load and toughness of the samples, compared to plain concrete. There was not a significant difference between the results obtained for steel and polypropylene fibres. The effects of a reduction in core temperature of the samples was examined. The results show that the strength of concrete is significantly improved when tested at -20°C, compared to ambient temperature.

Key words: Resin anchor bolt, pull out, fibre concrete, temperature -20°C, toughness

1.0 Introduction

Resin fixed anchor bolts are commonly used in construction applications, including the support of building services and connecting hybrid structures. (Hariyadi, Munemoto and Sonoda, 2017) The pull out strength of anchor bolts embedded in concrete is primarily determined by both the tensile strength of the concrete embedded therein, and the strength of the bond formed between the chosen resin and surrounding concrete. (Soparat and Nanakorn, 2008).

The most common method of tensile reinforcement for concrete is the inclusion of steel rebar within the concrete structure, the design of which is covered in BS EN 1992-1-1:2004+A1:2014. However, such reinforcement is subject to minimum spacing and cover requirements outlined within section 4.4 of Eurocode 2 (Mosley *et al*, 2007). This results in areas of unreinforced plain concrete between the rebar. If an anchor bolt were to be placed in such a location, then the failure plane of the bolt would receive no rebar reinforcement and the load would be supported entirely by plain concrete (Coventry *et al*, 2011).

Anchor bolts when loaded vertically in direct tension, rely upon the tensile strength of the concrete, assuming the anchorage is sufficiently strong not to fail before the concrete reaches its ultimate tensile strength. The use of fibres change the material properties of concrete and the inclusion of steel or polypropylene type 2 fibres is examined herein to evaluate the overall anchor bolt performance at failure and post crack performance.

Sukontasukkul et al (2018) investigated the flexural performance and toughness of hybrid steel and polypropylene fibre reinforced geopolymer concrete. Their research found that both toughness and flexural strength increase with the percentage of fibres to a point of 1% volume. After this percentage volume problems with mixing can occur, which can lead to poor compaction, non-uniform fibre distribution and increase void volume. Making a direct comparison between steel and polypropylene fibres, the steel fibres have a much greater toughness. (Sukontasukkul, et al., 2018)

Mahmod et al (2018) investigated the flexural behaviour of self-compacting concrete beams strengthened with steel fibre reinforcement. Self-compacting concrete can flow underneath its own weight in its fresh state, meaning there is no need for vibration or physical compaction. Their research found that the addition of steel fibres altered the failure mechanisms of the sample from brittle to ductile failure. In addition, the fibres also prevent crack propagation in concrete. (Mahmod, et al., 2018)

Research carried out by Gencel et al (2013) investigated the mechanical properties of self-compacting concrete reinforced with polypropylene fibres. Their research showed that the properties of hardened concrete were improved, however the workability of fresh concrete was decreased significantly. Their main finding showed that polypropylene fibres enhance the strength of concrete without causing the same issues associated with steel fibres such as corrosion. (Gencel, et al., 2013)

Abdallah *et al* (2017) examined the performance of steel fibres under pull out testing at a series of elevated temperatures compared to room temperature. They discovered that the performance of the concrete-fibre bond did not vary significantly at temperatures <400°C but performance began to decrease once temperatures surpassed 400°C due to degradation in the material properties of both the concrete and fibres. Rauno *et al* (2018) corroborated these findings, also concluding that an increase in sample temperature resulted in a decrease in pull out strength for both straight and hooked-ended steel fibres. Testing was not performed at temperatures below ambient temperature thus leaving gaps in the understanding of steel fibre performance. This paper investigates this aspect of anchor bolt pull out as a paired comparison test.

2.0 Materials

2.1 Fibre types

Steel and polypropylene fibres as used were manufactured to BS EN 14889-1:2006 and BS EN 14889-2:2006 and are displayed in Figure 1.

Figure 1: Individual Steel and Polypropylene Type 2 Synthetic Fibres

The steel fibres used were 45mm in length and had a 1mm diameter with a tensile strength of 1050Mpa and incorporate hooked ends as opposed to being straight to enhance their anchorage and therefore the pull out strength provided.

The polypropylene fibres were 40mm long with a nominal 1mm diameter. The fibres themselves were crimpled along their length to promote bond formation with the surrounding concrete

For near equal strength capacity, a dosage of 40kg/m^3 of steel fibres and 6.88kg/m^3 of polypropylene fibres were used (Richardson & Jackson, 2011)

2.2 Anchor bolt specification

The anchor bolts used, were a threaded stud having a 10mm diameter and 130mm length and manufactured from class 5.8 strength steel, which is classified to BS EN ISO 898-1:2013: The specified nominal ultimate tensile strength was 500N/mm^2. A polyester resin was used as a bonding agent. Chemical anchor bolts were chosen instead of mechanical anchor bolts, as resin anchor bolts do not create shear or tensile forces within the concrete samples due to the anchorage system. This therefore allows for a stress-free condition prior to testing to ensure that more reliable results are captured.

2.3 Optimal concrete sample size

Soprat and Nanakorn (2008) recommend finite element method (FEM) as being the most effective numerical method to solve pull-out problems of anchor bolts in concrete. Further research has been undertaken by Richardson and McKenzie (2012) to determine the optimum sizing of samples to ensure cone failure as shown in Figure 3. Cone failure would be representative of the predicted failure mode, where the bond strength of the resin exceeded the tensile strength of the concrete. A sample of 150mm x 150mm x 150mm was modelled, as displayed in Figure 2. This shows that the sample was of insufficient size to achieve cone failure which is representative of an on site failure mode. The predicted failure is edge to edge. It is also worthy to note that the major stress points are shown at where the bolt would be set as opposed to the fracture plane, indicated in blue. This indicates a stronger bond when compared to the tensile strength of the concrete.

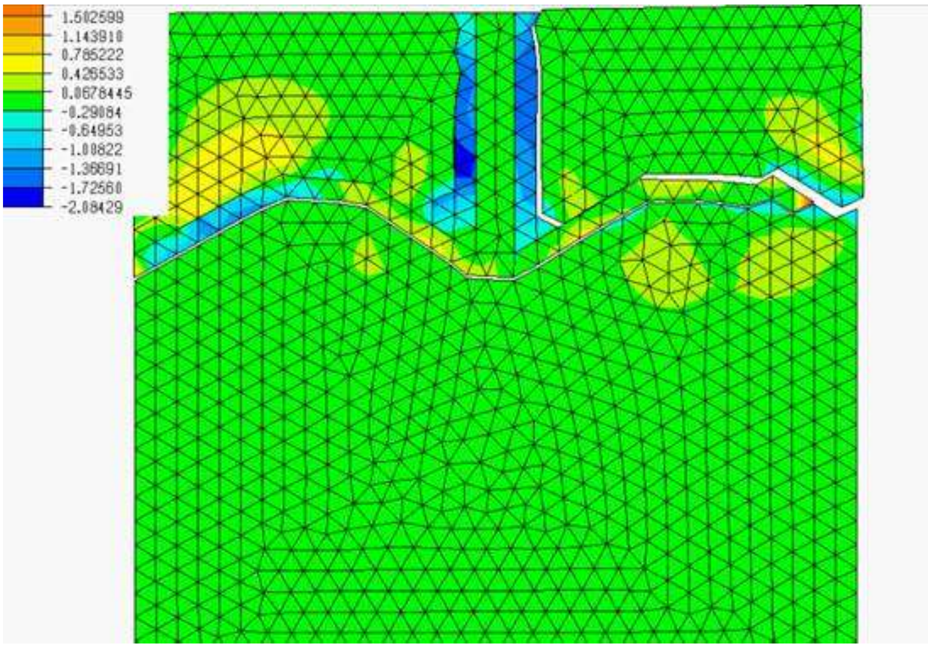

Figure 2: FEM Model for 150x150x150mm slab (Richardson & McKenzie, 2012)

Using the same FEM model, the sample size was increased to 300mm x 300mm x 150mm. The results of the modelling showed a cone failure as displayed in Figure 3. It is also worthy to note that the highest points of fracture are at the edges of the cone, as indicated in blue. This mode of fracture is significantly different to Figure 2 as much of the stress is focused to the area where the bolt is set, which could have had an impact on the results obtained. It was concluded that a 300 x 300 x 150mm C40 concrete slab is a suitable option to achieve cone failure as the rupture plane is within the proposed slab size, when the bolt is set centrally.

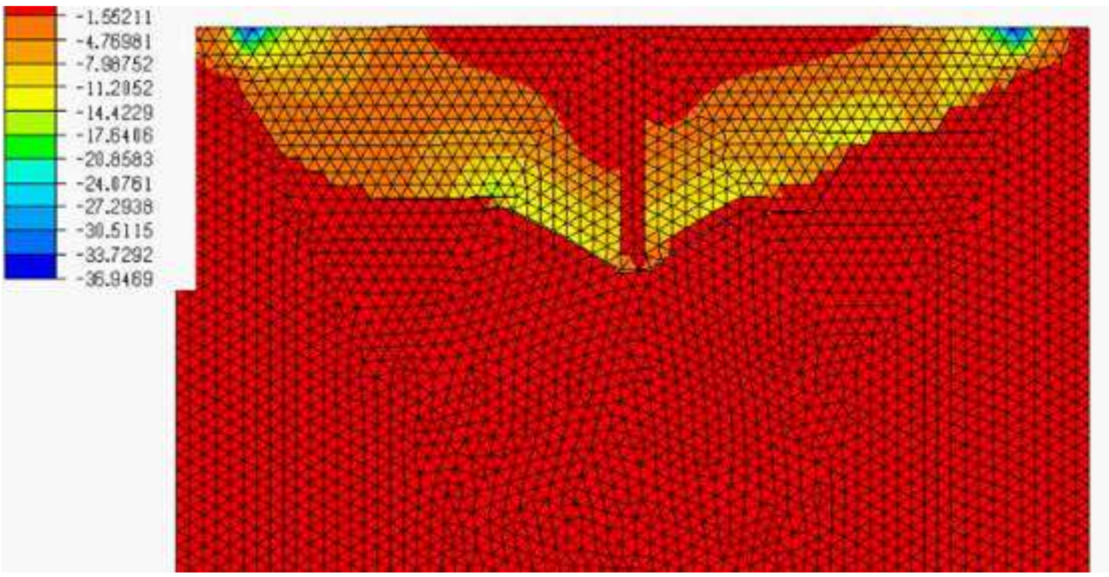

Figure 3: FEM Model for 300 x 300 x 150mm slab (Richardson & McKenzie, 2012)

3.0 Test programme and test methodology

3.1 Test Programme

The detailed test programme is shown in Figure 4. Concrete batching was carried out using a rotary drum mixer and consistency was maintained using a slump test achieving values between 30 – 60mm. The slump test was carried out in accordance to BS EN 12350-2:2009 and room temperature varied between 19 and 21° C and -20° C was achieved using a chest freezer. The frozen samples were tested immediately as they left the freezer to ensure the core temperature of the samples stayed consistent.

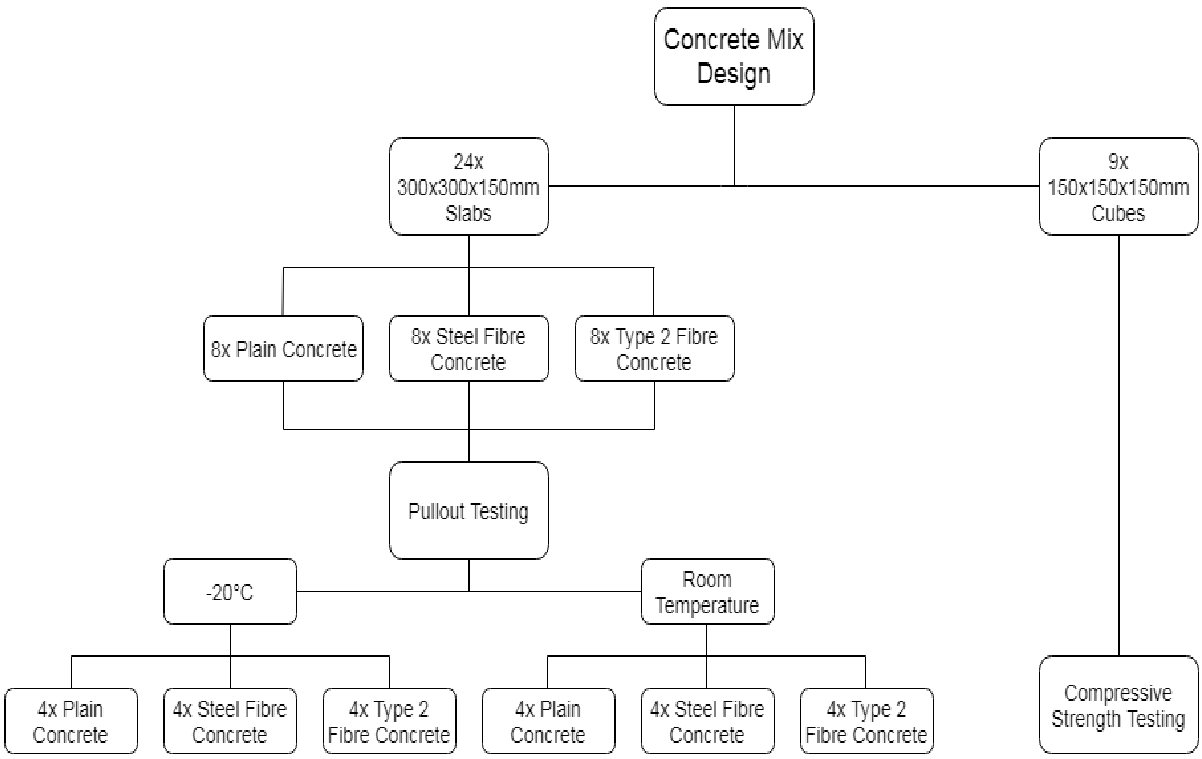

Figure 4 – Test Programme

3.2 Methodology

Compressive strength was determined using BS EN 12390-3. In total 9 cube samples were taken from the 12 concrete batches required to produce the full set of samples for this test; 3 plain, 3 steel fibre and 3 polypropylene fibre are displayed on the right hand side of Figure 4.

To set the bolts, a 12mm diameter hole was drilled to a depth of 80mm using a hammer drill and masonry drill bit. The holes were then brushed and vacuumed thoroughly to ensure any debris that may interfere with the resin bonding was cleared. The bolts were set according to the instructions provided by the resin manufacturer, each hole was filled approximately 70% with resin before the bolts were inserted with a slight twisting motion and left for 24 hours to set.

Prior to testing, the specimens selected to be tested at -20ºC were placed into a chest freezer and left for 24 hours to ensure they reached the correct core temperature.

To determine the cone pull-out failure and the toughness of each slab a three point configuration was used as shown in Figure 5.

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Figure 5 – Bolt pull out details, Lloyds LR100k apparatus

The adopted test procedure using a Lloyds LR100k apparatus used a displacement rate of 2mm/min and this was used until the maximum load was reached and the cone diameter was measured

The test apparatus recorded the load vs extension to compile graphs for each slab, thus determining the maximum load and toughness.

4.0 Results

4.1 Compressive Strength

Table 1 shows the results obtained from compressive strength testing of cube samples. All cubes tested displayed normal failure modes.

Table 1 – Cube Compressive Strength Results

Cube Reference Number		Density (kg/m³)	Compressive Strength (N/mm²)	Average (N/mm²)
Plain	1	2170.86	35.594	37.6
	2	2133.33	38.702	
	3	2142.58	38.512	
Steel	4	2224.72	38.518	37.0
	5	2154.84	36.324	
	6	2152.69	36.160	
Type 2	7	2148.81	32.232	35.5
	8	2173.76	37.435	
	9	2184.22	36.889	

The results are in keeping with earlier work by Richardson (2006) where type 2 fibre concrete displayed a lower compressive strength than plain concrete. This was in part due to a difference in bulk density of the materials; concrete has a bulk density of 2400kg/m^3 as opposed to 525kg/m^3 for the synthetic fibres resulting in a density ratio of 4.53:1. Therefore as the fibres take up a significant proportion of the cube sample, this causes a reduction in the overall bulk density which effectively leads to a reduction in compressive strength (Richardson, 2006).

4.2 Maximum load at pull out failure

Maximum load at initial failure is displayed in Table 2. Lowering the test temperature increases the performance in plain and steel fibre concrete. Type two synthetic fibre concrete shows no significant change.

Table 2: Average Maximum Load values for each category

	Testing Category	Maximum Load (N)	Standard Deviation	Percentage change compared to plain
Ambient Temperature (20°C)	Plain	16355.54	4382.9	0%
	Steel Fibres	20864.38	3804.2	27.6
	Polypropylene Fibres	27227.36	3633.3	66.5
Reduced Temperature (-20°C)	Plain	28100.91	7259.3	0%
	Steel Fibres	28682.31	4106.5	2.1
	Polypropylene Fibres	29231.38	3595.9	4.0

Lowering the temperature reduces the effect of the fibre inclusion to very small changes of little significance. The percentage increase in pull out values when comparing ambient to -20 for plain, steel fibre and polypropylene fibres is 71.8% for plain, 37% for steel fibre and 7.3%.

4.3 Toughness values

Toughness is defined as the area under the load/extension curve and values of load and displacement were recorded using a Lloyds LR100k apparatus. Samples were tested at -20°C and at ambient room temperature.

Table 3 displays average toughness values for each concrete type and percentage change in toughness values compared to plain concrete.

Table 3: Average Toughness values for each category

	Testing Category	Toughness (Nmm)	Standard Deviation	Percentage change compared to plain
Ambient Temperature (20°C)	Plain	119860.8	48728.6	0%
	Steel Fibres	298236.8	57958.1	148.8%
	Polypropylene Fibres	277570.0	102164.6	131.6%
Reduced Temperature (-20°C)	Plain	302282.0	111085.2	0%
	Steel Fibres	473388.3	167504.9	56.6%
	Polypropylene Fibres	404652.25	8293.212	33.9%

These values strongly show that the addition of fibres, whether it is steel or polypropylene, have a positive effect on the toughness performance of anchor bolts in concrete, however the greatest effect of adding fibres can be seen at ambient temperatures.

Lowering the temperature reduces the effect of the fibre inclusion. The percentage increase in toughness values when comparing ambient to -20°C for plain, steel fibre and polypropylene fibres is 152.2% for plain, 58.7% for steel fibre and 45.8% for polypropylene fibres.

Figure 6 displays the relative performance of plain, steel fibre and synthetic fibre concrete at ambient and -20°C conditions.

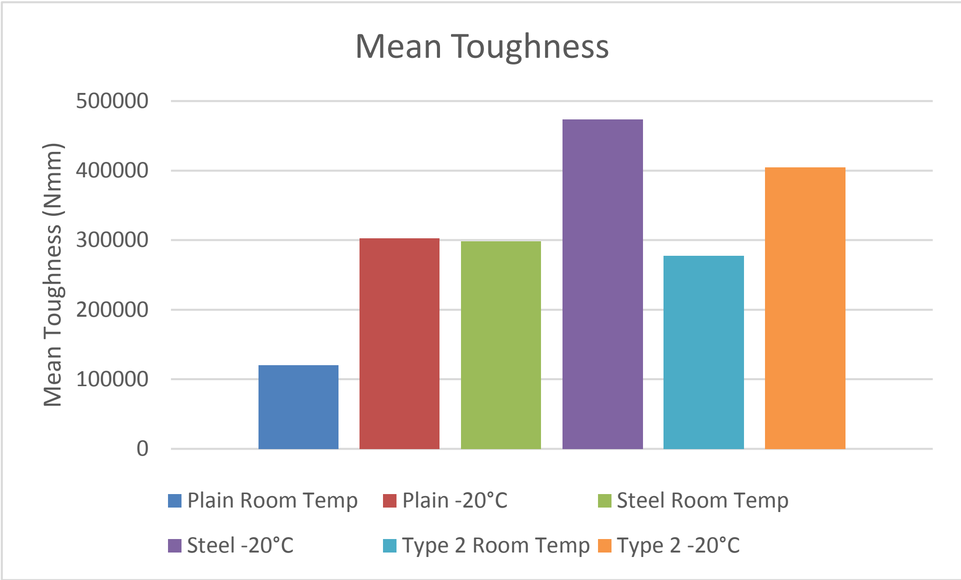

Figure 6: Mean Toughness for Each Category

The slab which reached the highest maximum load was a plain reduced temperature slab. However, this value does not correlate to the average toughness categories. This is due to the fact the concrete with the supplement of fibres have a larger area under the curve correlating to a larger toughness.

Figures 7 - 9 below show the mean load vs extension curves at room temperature and -20°C for both the plain and reinforced concrete slabs tested. The steel fibre samples display strain hardening characteristics, whereas the Type 2 synthetic fibres display strain softening. The -20°C plain sample displays strain hardening whereas the ambient room temperature samples display neither strain softening nor hardening.

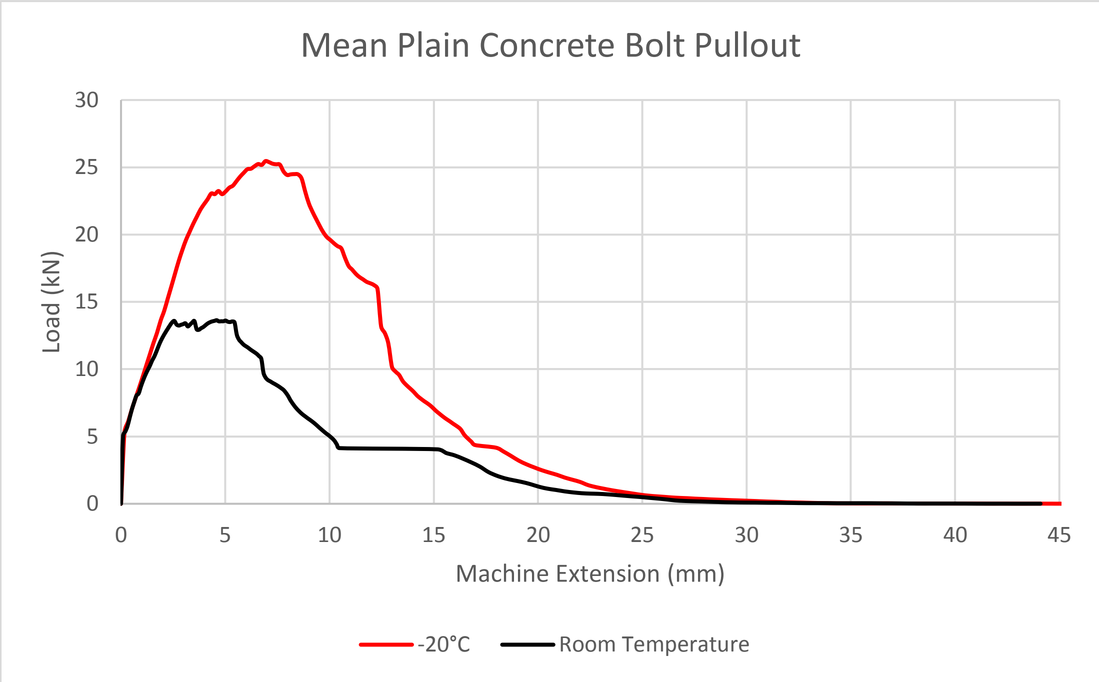

Figure 7 Plain Concrete Pull out Results

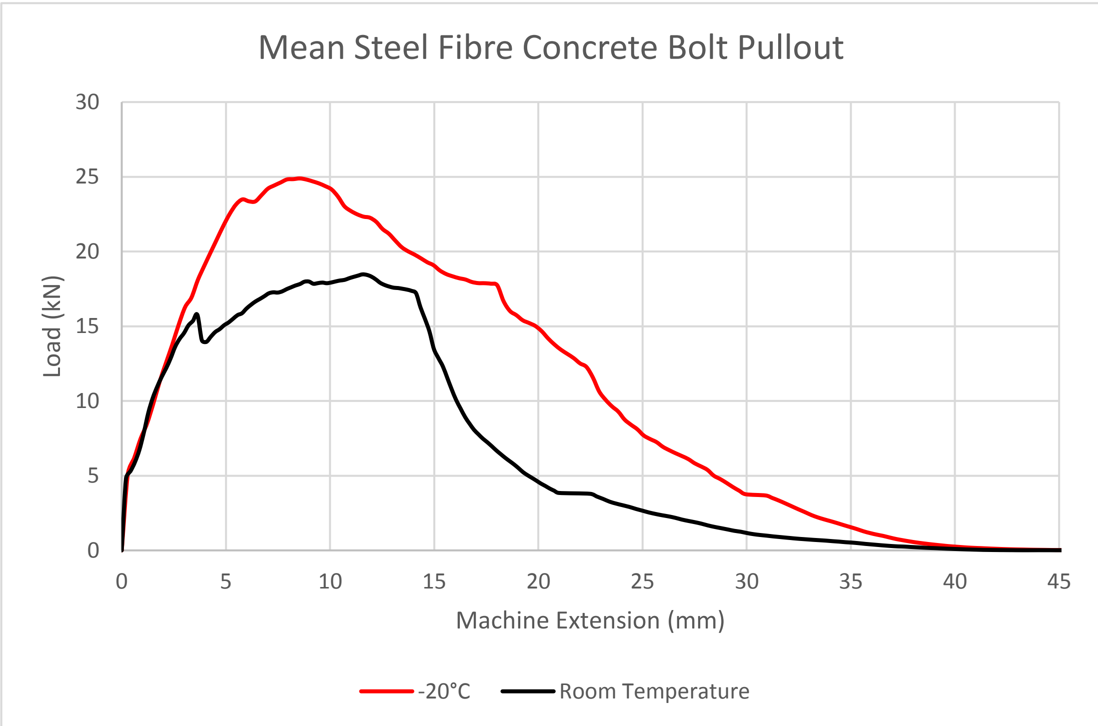

Figure 8 Steel Fibre Concrete Pull out Results

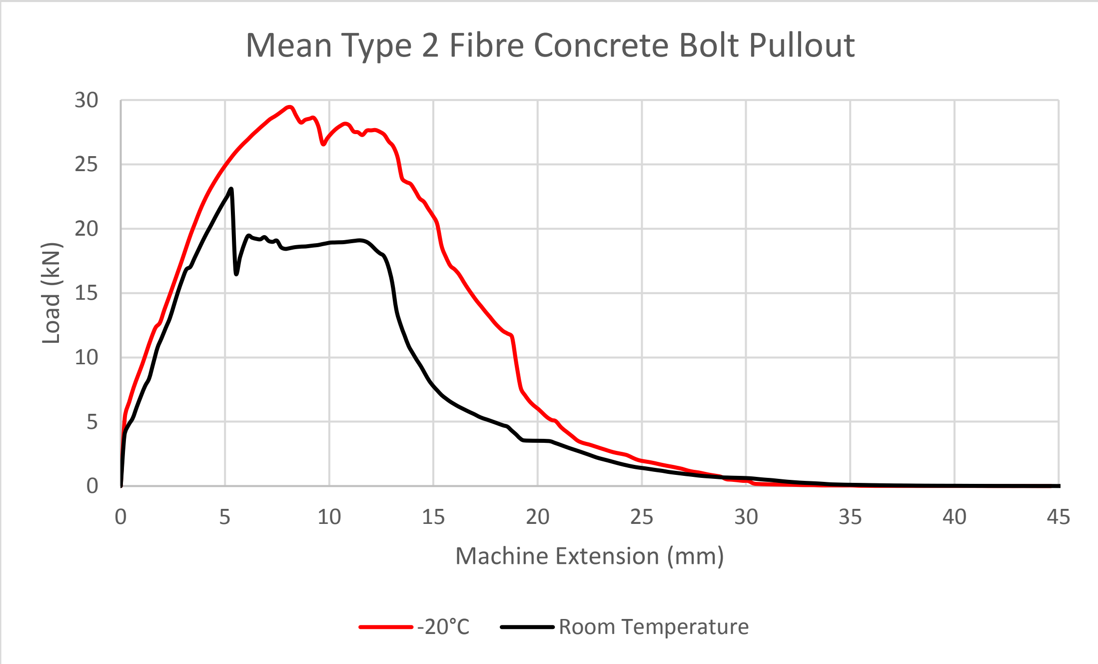

Figure 9: Polypropylene Fibre Concrete Pull out Results

Concrete has been shown to have significant performance increases when the temperature is lowered below 0°C, with regard to the compressive strength (Neville, 2012) flexural strength, and toughness of concrete (Richardson and Ovington, 2017) the increase in strength is produced through the formation of ice crystals within the voids inside the concrete matrix.

4.4 Cone pull out failure

An average cone diameter for each type of sample used is displayed in Figure 10 as a histogram. It is clear from the chart; the slabs with polypropylene fibres tested at a reduced temperature have the largest mean cone diameter, whereas the other categories are very similar to one another. It is also worthy to note that apart from the polypropylene slabs tested at -20°C, there does not seem to be a correlation between mean cone diameter and temperature.

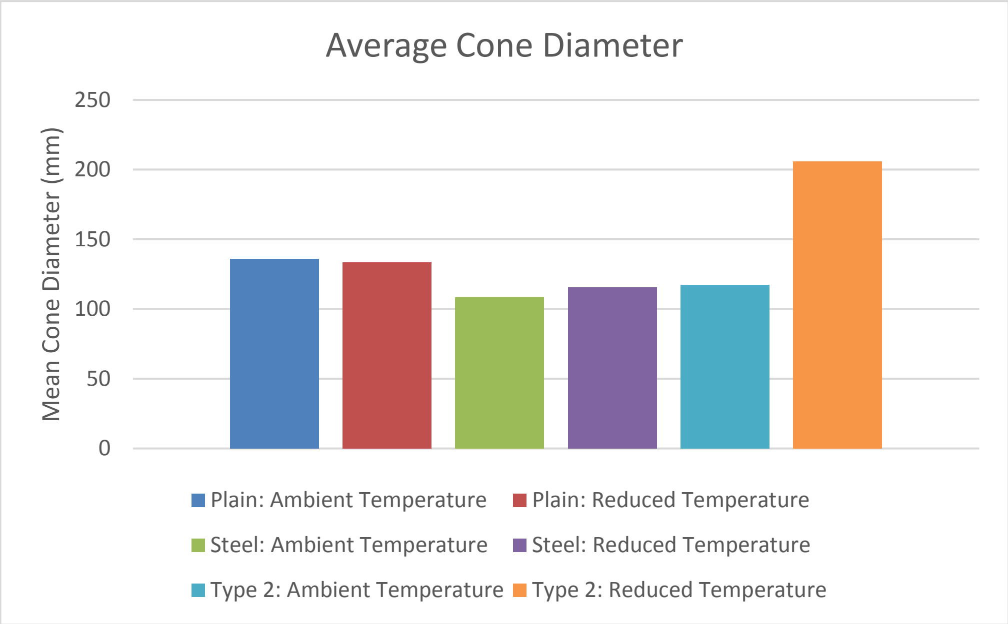

Figure 10: Average Cone Diameter

During cone failure of the polypropylene fibre reinforced slabs, it was noted that the fibres did not snap and some remained attached to the cone even after failure had occurred.

Hariyadi et al., (2017) analysed the pull out cone failure of each concrete specimen. The cone failure found during this test was of a shallower depth and smaller angle than in the design standards. As well as cone failure, bond failure was detected. To conclude their research, they stated that the values recorded for pull-out strength were low and therefore further precautions to ensure safety should be taken.

Figure 11 shows the observed cone failure angle in comparison to the theoretical fracture zone. The figure/diagram shows that the cone failure does not begin at the tip of the anchor bolt but nearer to the surface of the slab. This was due to the type of anchor bolt selected. Mechanical anchor bolts tend to push the concrete from the end of the bolt with their locking mechanism which creates a 45° angle of fracture. A potential explanation for a difference in cone failure may be due to the tensile strength at point 'A' being the same value as the pull out force. In higher strength concrete a shallower failure angle will be observed. A lower tensile strength concrete will display larger cone rupture plane angles, due to the bond from the anchor bolt and pull out force finding equilibrium. The concrete strength at point 'B' is greater than the tensile strength applied and shear failure occurs at this point, following the cone rupture occuring.

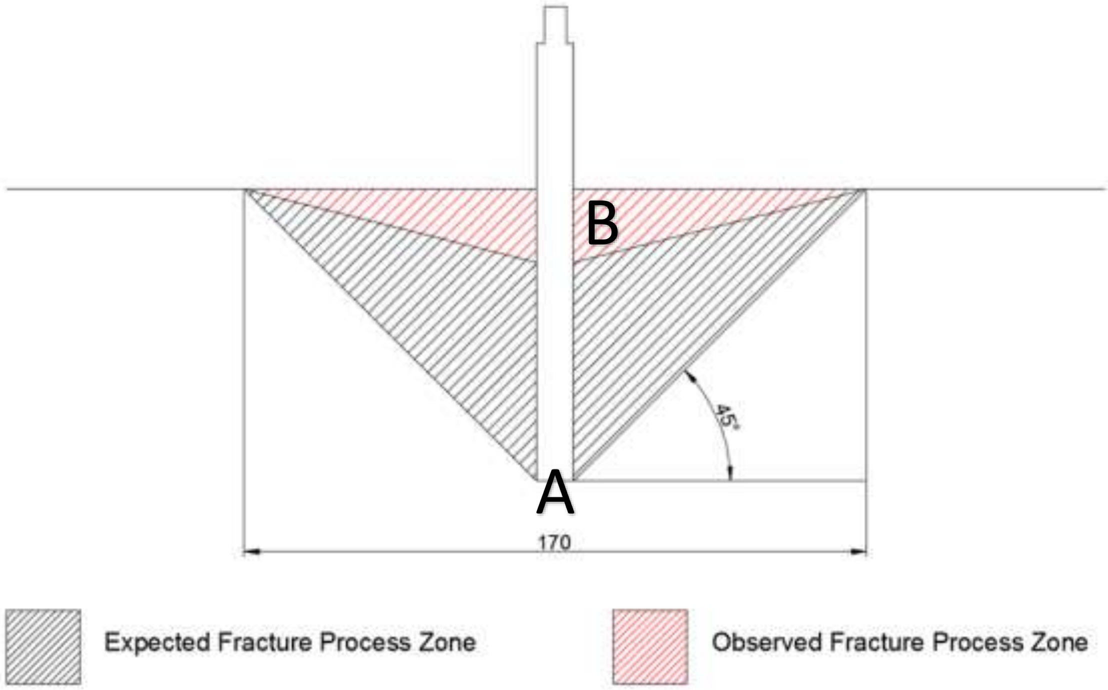

Figure 11 - Observed Fracture Zone

Figure 12 shows a typical cone failure as observed from the pull out tests. This is in keeping with results by Hariyadi et al., (2017).

Figure 12: Cone failure of Slab 7

4.5 Significance tests

Paired comparison “T-Tests” were carried out to examine toughness and maximum load. The toughness results showed that there was a significant difference at ambient and -20°C between the values for plain vs steel fibres and plain vs polypropylene fibres. This shows that the addition of fibres, both steel and polypropylene, has a positive impact on the toughness of concrete during anchor bolt pull-out testing at both ambient and -20°C. Toughness values of steel and polypropylene fibres were compared and this resulted in a null hypothesis, showing there was no significant change.

Maximum load data, as displayed in Table 2, was examined and compared for plain vs steel and plain vs type 2 at ambient temperature and this resulted in a null hypothesis, showing there was no significant change.

Examining the two batches (ambient and -20°C) the maximum load did show a significant difference at ambient temperature but not at -20°C. A further paired comparison “T-Test” was carried out to examine the maximum load results between both the steel and polypropylene fibres were compared and this resulted in a significant change with steel fibres providing the greatest values.

5.0 Conclusion

The main findings showed that in general, the addition of fibres at the prescribed doses, both steel and polypropylene, had a positive effect with regards to pull-out performance of chemical anchor bolts in concrete. After analysing the data, it was clear that steel fibres had the greatest effect with regards to the toughness of the samples, however the “T-Test” showed that the results which compared both sets of fibres were not significant.

With regards to cone failure, there was not an observed link between cone diameter and toughness. It is also worthy to note that the 25-30 degree (from near the base of the anchor bolt) expected cone failure mode as shown in Figure 3, was not observed. A possible explanation for this phenomenon was that the depth and area where the cone failure was observed had a lower tensile strength than the force exerted from the anchor bolt where the bolt was embedded. There will be a dependency of bond strength, applied force and tensile strength that will determine the depth at which the rupture plane forms.

The research showed that by reducing the temperature of concrete, there is a positive effect on the toughness of concrete. This can be seen as for all categories as tested, as there is a percentage increase for both maximum load and toughness. These results further support the research carried out be

Richardson & Ovington (2017), when it was found that a decrease in temperature leads to an improved performance of the concrete.

It is worthy to note that the addition of steel fibres had the largest effect on toughness when tested at reduced temperatures. However, in contrast to this, maximum load was reached with the addition of polypropylene fibres. Further research would need to be conducted to determine whether a larger maximum load or toughness is more favourable for the application of this research.

This discovery has the potential to benefit the application of services in cold rooms or freezers. For example, if concrete with the addition of fibres was to be implemented into abattoirs where heavy animal produce is hung from ceiling fixtures, this could make for more effective construction.

This research has the potential to benefit the construction industry by improving the toughness of concrete for building services.

6.0 Further Recommendations

To further extend this research; testing anchor bolt fibre concrete samples at higher temperatures would be recommended. This would determine whether the addition of fibres lowers the toughness of concrete at elevated temperatures as opposed to what was observed when the core temperature was reduced.

Testing concrete with a range of fibre dosage to determine the optimum dosage for pull-out performance of anchor bolts would be useful to determine whether the addition of extra fibres improves the toughness properties or not.

It would be interesting to use a different type of bolt for testing, for example a precast mechanical bolt. This type of bolt may be more successful for achieving a near 45° angle of failure as this was not consistently achieved with the chemical anchor bolts. This improvement could also make a more direct link between cone pull-out failure and maximum load/ toughness of a sample.

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