The Compressive and Split Tensile Strength of Nylon Cable Tie Fibre-Reinforced Concrete

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Abstract. This study was done to investigate the compressive and split tensile strength of nylon cable tie-fibre reinforced concrete. The strength of nylon cable tie fibre-reinforced concrete was then compared to that of conventional concrete. The optimum fibre content which produces the highest compressive and split tensile strength was also obtained. Nylon cable tie is used as fibres because it is a processed nylon which is able to withstand a certain amount of stress before it breaks. Standard concrete cylinder of Grade 30 was casted as trial samples to test the mix designed using Concrete Mix Design Handbook from Faculty of Civil Engineering, Universiti Teknologi Malaysia (UTM), which refers to DOE design method published by British Research Establishment (BRE), 1997. Nylon cable ties were cut to length of 50 mm. The concentration of nylon cable tie content is varied in percentages of 0%, 1%, 3% and 5% of weight of cement used. Cylinder concrete mould of 100 mm diameter x 200 mm height was used for all samples. Concrete samples were tested after being cured for 28 days in water. Compression test and split tensile test was done on concrete cylinders according to ASTM C39 and ASTM C496 respectively. The optimum nylon cable tie content for both compressive and split tensile strength was obtained, which is at 1% fibre content. Nylon cable tie fibre-reinforced concrete with 3% fibre content shows a lower compressive strength, but a higher tensile strength compared to the controlled sample, while concrete with 5% nylon cable tie fibre content produces a lower compressive and split tensile strength than that of controlled sample.

Introduction

Fibre reinforced concrete (FRC) is a concrete that is made up of typical concrete materials of cement, water, fine and coarse aggregate, but are added with discontinuous fibres in the mixture. The nature of concrete is it has a high compressive strength, but has a low tensile strength, estimated at only 10% of its compressive strength. Even before any load is being applied to concrete, micro cracks have already developed internally due to shrinkage during drying. These cracks will continue to develop when the concrete experiences compressive or tensile stresses, until the concrete ultimately fractures and fail. By adding fibres into a conventional concrete mix, the fibres will slow down the failure of concrete. This happens because when concrete starts to crack due to excessive loading, the fibres will be activated, developing a post tensile stress capacity which will continue to hold the concrete together. This allows fibre-reinforced concrete being able to withstand more compressive and tensile stress before it fails. Fibre reinforced concrete provides a more economical alternative to conventional reinforced concrete as fibres, if added in optimum dosages, can sufficiently improve the compressive and tensile strength of concrete. This eliminates the need for steel reinforcements at structures that does not experience high compressive and tensile stress. In some cases, fibre reinforced concrete also enables a thinner design to be used; further reducing the cost of construction materials.

The objective of this study is to determine the compressive and split tensile strength of nylon cable tie fibre-reinforced concrete. Also, this study compares the compressive and split tensile strength of nylon cable tie fibre-reinforced concrete with that of conventional concrete. After the comparison is made, the optimum percentage of nylon cable tie to be added into concrete will be determined. Nylon cable ties are added into concrete in relative to the weight of cement used in concrete. Grade 30 concrete (C30/C7) was designed and used in this study for all concrete specimens. Ordinary Portland Cement (OPC) was used, and no mineral or chemical admixtures apart from nylon cable ties were added into the concrete mix. The compressive and split tensile strength of nylon cable tie fibre-reinforced concrete is tested on controlled samples and samples with nylon cable tie content of 1%, 3% and 5% only.

Previous Studies

Fibres are added and are randomly distributed in the concrete with the main purpose of increasing the concrete toughness, the concrete energy absorption capacity, as well as improving the tensile, compressive and flexural strength of concrete. FRCs have an improved post-cracking behaviour as compared to conventional concrete. Also, even though the ultimate tensile strength of FRCs does not improve significantly as compared to conventional concrete, the tensile strains at rupture do increase appreciably. FRCs are also found to be much tougher and can resist more impact. The optimum percentage of fibres to be added in concrete ranges from 0.5% to 5%; depending on the type of fibres used [1]. Apart from fibre content, the aspect ratio of fibres used also plays a part in producing a high quality FRC. The ratio of W.l/d < 600 gives the best result in increment of strength, where W is the percentage of weight of fibres in concrete, and l/d being the aspect ratio of length divided by diameter. [2].

A cable tie is a type of fastener that ties several things together. A typical cable tie consists of a strip of jagged edges on one side of the strip and smooth surface on the other, and a head that has a locking mechanism. Cable ties can be made up of several materials; with the most common materials being used are nylon and stainless steel. Nylon cable ties have a high strength. They also have a high level of toughness and can sustain repeated impact without breaking [3]. Nylon cable ties exhibit nylon properties when added as fibres in concrete. Nylon is a hydrophilic fibre. They hold natural moisture of about 4.5% and are also found to have a higher aspect ratio as compared to other synthetic fibres. This means that the reinforcing effects caused by other synthetic fibres can be replicated by nylon fibres with smaller amount being added to concrete [1,4].

Many studies were made to investigate the behaviour of fibre reinforced concrete. One of the studies on fibre reinforced concrete was made in India in 2011. The research was done to investigate the strength of reinforced concrete added with polythene waste plastics. An addition of 0.5% of polythene plastics increases the compressive strength of concrete grade M20 by 5.12% at a concrete age of 28 days, while an increase of 3.84% was seen in split tensile strength at the same concrete age [5]. In 2004, a research was made to study the strength properties of nylon fibre reinforced concrete. From the research, when 1% of nylon fibre was added into concrete, it is found that a higher compressive strength was produced, which is at 12% higher than conventional concrete. The split tensile strength of nylon FRC samples are also found to be higher than that of normal concrete, with an increase of 17.1%. Nylon FRCs also have a higher impact resistance in terms of its failure strengths, with an increase of 30.5% compared to normal concrete. From their research, nylon FRCs have outperformed conventional concrete in terms of compressive strength, split tensile strength, and impact resistance [6]. However, this study uses raw nylon fibres, which are different from nylon cable ties. Nylon cable ties are processed nylon which can sustain a higher stress before breaking [3]. Since fibres in concrete contribute in resisting the development of cracks, nylon cable ties are expected to increase the compressive and split tensile strength of concrete compared to raw nylon.

Laboratory Works

In order to ensure the smoothness of this study, several steps were taken and designed specifically. Background information was first obtained and understood from previous researches to produce fibre-reinforced concrete. After sufficient background information was gathered and analysed, the type of laboratory tests to be used in this study were determined. Also, the material preparation, especially the fibres, was done carefully. After laboratory tests were carried out on conventional concrete and nylon cable tie FRCs, the results were analysed and conclusions were made.

Concrete Mix Design

Prior to the casting of nylon cable tie FRCs and normal concrete, a concrete mix design was carried out to calculate the materials needed to produce a concrete of Grade 30 (C30/37). The method of design was referred from the Concrete Mix Design Experiment Handbook from the Faculty of Civil Engineering, Universiti Teknologi Malaysia (UTM). The handbook refers to the DOE design method as specified by 'Design of Normal Mixes', which was published by the British Research Establishment (BRE) in 1997.

Concrete Volume Calculation

For this research, the volume of concrete needed was calculated as shown in Table 1. A total of 30 concrete cylinders were casted for this research, where 12 concrete cylinders were tested for split tensile strength, while another 12 concrete cylinders were tested for compressive strength. 6 samples of concrete were casted for a pilot test of concrete mix to check whether the concrete mix designed achieved the desired Grade 30 concrete.

Table 1: Concrete volume calculation

Sample	Diameter (mm)	Height (mm)	No. of Sample	Volume (m^3)
Cylinder	100	200	30	0.047
			+ 30% Wastage	0.014
			Total	0.061

Materials Preparation

Nylon Cable Tie Preparation. Nylon cable ties with tensile strength of 225 N are used in this study. The nylon cable ties were prepared by cutting them into lengths of 50 mm each. Since the minimum length of cable ties that exist on the market is 100 mm, the cutting of cable ties into 50 mm each was necessary in order for the nylon cable ties to have an optimum *l/d* fibre ratio. An optimum *l/d* ratio is important to ensure that the nylon cable-ties efficiently act as fibres in the concrete. No alteration was done to the cable ties because the cable ties already have a jagged surface, which is vital to ensure a good bond formed between fibres and cement.

Material Preparation. The materials needed for concrete mixing were precisely weighed and prepared in advance. Nylon cable ties are added as a percentage of cement used. Thus, the mass of nylon cable ties will differ for each batch, with one batch have no fibres added (0%), one batch with 1% of fibres added in terms of cement used, one batch with 3% and one batch with 5%. Each batch consists of 6 samples. The materials composition for each batch was shown in Table 2.

Table 2: Material Composition for Different Fibre Percentages

Fibre Percentage (%)	:	1	3	5
Cement (kg)	4.66	4.66	4.66	4.66
Fine Aggregate (kg)	8.64	8.64	8.64	8.64
Coarse Aggregate (kg)	12.38	12.38	12.38	12.38
Water (kg)	2.51	2.51	2.51	2.51
Nylon Cable Ties Fibres (g)	0.00	46.56	139.67	232.79

Concrete Mixing

The concrete was divided into four batches, varying in fibre content percentages. Water was first added into the mixing drum to wet the inside surface of the mixer, and excess water was removed. Coarse aggregates, fine aggregates and cement was loaded into the mixing drum and was dry-mixed for 1 minute. Water was then added gradually to allow a thoroughly mixed concrete and to ensure the desired concrete consistency is achieved. After the concrete was done mixing, nylon cable tie fibres were added bit by bit to prevent clumping of fibres in the mixing drum. This also allows the fibres to be spread evenly in the concrete. Once the mixing of concrete is completed, the mixed concrete was poured into 6 cylinder moulds of size 100 mm x 200 mm in 3 layers. Each layer was compacted 35 times using a steel rod to ensure an evenly compacted concrete and to prevent porosity in the concrete. The procedure was repeated four times for four different fibre content percentages. Controlled specimen was mixed as mentioned above, but with no fibres added into the concrete.

Curing Process

Curing of concrete will enhance strength and reduces permeability and crack developments. Concrete that was poured into the moulds are being left to dry for 24 hours in room temperature. Then, the hardened concrete cylinders were removed from their moulds and are then being cured by submerging them in a tank filled with water for 28 days. The concrete samples were then tested on the 28th day.

Laboratory Tests

Laboratory tests were done on fresh and hardened FRC to obtain the properties of the concrete designed. Slump test was carried out to determine the workability of fresh FRC. After the concrete is hardened and cured for 28 days, compression and splitting tensile tests were done to determine the compressive and split tensile strength of FRCs and of conventional concrete.

Slump Test. Slump tests were carried out to determine the workability of fresh concrete. The slump of each batch of concrete was measured to determine whether the workability of fresh concrete decreases with percentage of fibre added or remains the same. Slump test was done in accordance with ASTM C143.

Split Tensile Test. This test was done to harden FRC in order to determine the split tensile strength of the sample. It is a test that is widely used in the concrete industry because it is simple to be carried out and gives a uniform result. The test was carried out on a cylindrical FRC sample after it has been cured for 28 days in a curing tank. Split tensile test procedure is according to ASTM C496.

Compression Test. Compression test were carried out on cylinders of FRC and conventional concrete to determine the compressive strength of the samples. This test was also being carried out after the nylon cable tie FRC and controlled specimen was cured for 28 days. The compressive strength obtained from this test is also known as f_{ck} value, which is an important value used in the design of concrete structures. The procedure for this compression test was done according to ASTM C39.

Results and Discussions

The results obtained from the laboratory tests done on conventional concrete and nylon cable tie fibre-reinforced concrete were analysed to fulfil the objectives of this study. The slump of each concrete batch was measured to determine the workability of concrete when added with nylon cable tie. The compressive and split tensile strength of all batches of nylon cable tie fibre-reinforced concrete was calculated based on the results obtained from respective tests. The results are then compared to that of conventional concrete. After comparisons of strength were carried out, the optimum nylon cable tie content was determined.

Slump Test

The designed slump for all concrete batches was set to be in the range of 10 mm to 30 mm in accordance with the UTM Concrete Mix Design Handbook. This is to allow a decent workability of concrete during the casting of samples. True slump was obtained for all batches. However, it was seen that as the amount of nylon cable tie added to the mix increases, the slump for the concrete batch decreases. This means that the concrete workability decreases as the fibre content increases. Table 3 shows the slump values obtained for concrete batches with different nylon cable tie content.

Table 3: Slump values for controlled sample and nylon cable tie fibre reinforced concrete

Sample	**Type of Slump**	**Slump (mm)**
Controlled (0%)	True Slump	25
Concrete with 1% Nylon Cable Tie	True Slump	23
Concrete with 3% Nylon Cable Tie	True Slump	16
Concrete with 5% Nylon Cable Tie	True Slump	15

Compressive Strength

Compressive test was carried out on the controlled sample and the nylon cable tie fibre-reinforced with 1%, 3% and 5% fibre content. The test was carried out after all samples were cured for 28 days in a curing tank with water temperature of 22 ± 2 ˚C. The results obtained are as shown in Table 4.

Table 4: Compression test results on cylinder samples at age of 28 days

Fibre Content	Sample	Compressive Strength (MPa)	Mean Strength (MPa)	Standard Deviation
0%	Comp. 0A	28.69	30.40	1.99
	Comp. 0B	29.92		
	Comp. 0C	32.58		
1%	Comp. 1A	28.83	32.10	4.75
	Comp. 1B	29.92		
	Comp. 1C	37.54		
3%	Comp. 3A	25.91	26.39	4.63
	Comp. 3B	22.02		
	Comp. 3C	31.24		
5%	Comp. 5A	21.71	23.61	1.86
	Comp. 5B	25.42		
	Comp. 5C	23.70		

From the results shown in Table 4, it was seen that the optimum nylon cable tie content added into concrete is 1%, which produced the highest mean compressive strength of 32.10 MPa. Compared to the controlled sample, the strength of concrete added with 1% fibre increased by 5.59%. For concrete with fibre content of 3%, the mean compressive strength is lower than that of controlled sample. The recorded strength is 26.39 MPa, a decrease of 13.19% as compared to controlled sample. For concrete with added nylon cable tie of 5%, the strength further decreased with a recorded strength of 23.61 MPa, 22.34% lower than that of controlled sample. The summary of compressive strength of normal concrete and nylon cable tie fibre reinforced concrete for fibre percentages of 1%, 3% and 5% are as shown in Figure 1.

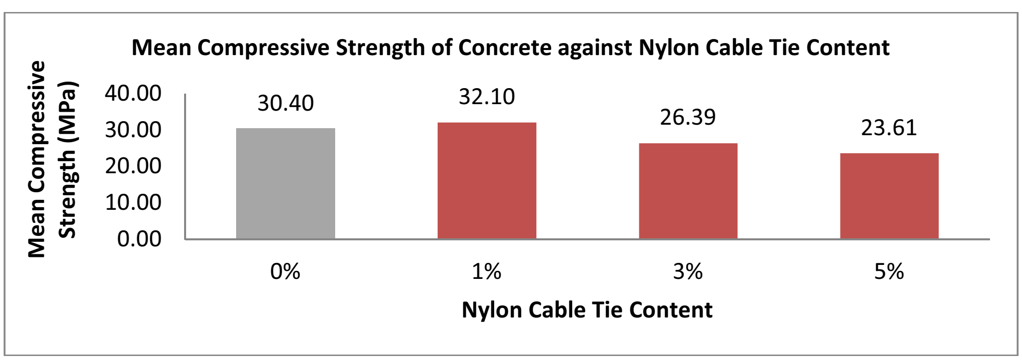

Figure 1: Bar chart of mean compressive strength for different nylon cable tie content

Split Tensile Strength

Split tensile test was carried out on controlled and nylon cable tie fibre reinforced concrete samples with fibre content of 1%, 3% and 5%. The test was done at a concrete age of 28 days for all samples. The tensile strength of concrete was calculated from the split tensile test by using the formula.

$$Split\ Tensile\ Strength = \frac{2P}{\pi DL} \quad (1)$$

Where, P = maximum load applied (kN)
D = diameter of specimen (m)
L = length of specimen (m)

After the results of split tensile test were obtained, the values for the split tensile strength and the determination of mean split tensile strength for a total of 3 samples were calculated and was tabled in Table 5.

Table 5: Split tensile test results on cylinder samples at age of 28 days

Fibre Content	Sample	Maximum Compression Load Applied (kN)	Split Tensile Strength (MPa)	Mean Split Tensile Strength (MPa)	Standard Deviation
0%	ST 0A	84.75	2.07	2.89	0.17
	ST 0B	95.21	3.03		
	ST 0C	92.04	2.93		
1%	ST 1A	104.43	3.32	3.11	0.19
	ST 1B	96.02	3.06		
	ST 1C	93.11	2.96		
3%	ST 3A	99.82	3.18	3.02	0.31
	ST 3B	83.68	2.66		
	ST 3C	100.93	3.21		
5%	ST 5A	77.15	2.46	2.84	0.55
	ST 5B	109.00	3.47		
	ST 5C	81.93	2.61		

From Table 5, the optimum nylon cable tie content to be added in concrete is 1%. It resulted in a split tensile strength of 3.11 MPa. The split tensile strength increased by 7.07% as compared to that of controlled sample. For concrete with 3% added fibres, the split tensile strength obtained is 3.02 MPa, 4.30% higher than that of controlled sample, but is lower than concrete with 1% fibre content. For concrete with 5% added fibres, the split tensile strength recorded is lower than the strength of controlled sample, which is at 2.84 MPa, a percentage decrease of 1.73% as compared to the split tensile strength of controlled sample. The summary for the split tensile strength for controlled sample and samples with 1%, 3% and 5% nylon cable tie content are as shown in Figure 2.

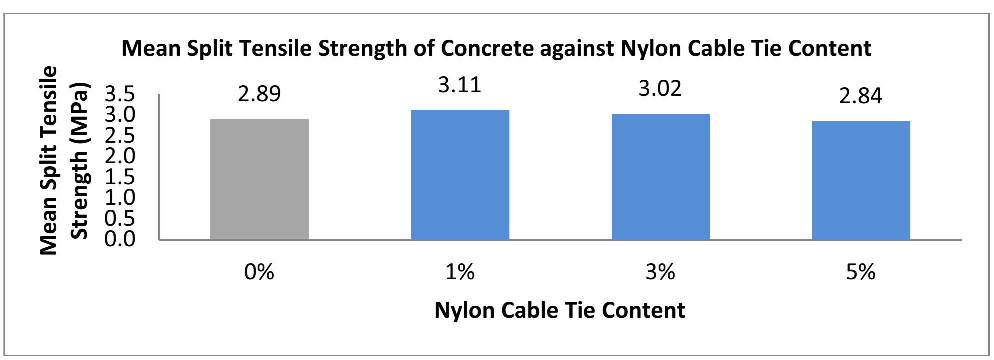

Figure 2: Bar chart of mean split tensile strength for different nylon cable tie content

Relationship between Nylon Cable Tie Content and the Compression and Split Tensile Strength of Concrete

The existence of fibres in concrete develop a post tensile stress capacity which can hold the concrete together when excessive loading is applied to it before the concrete ultimately fails [1]. The nylon cable tie in this research acts as fibres in concrete and the effect it brought to the compression and split tensile strength of concrete was analysed.

The concrete with 1% added fibre has higher mean compression and split tensile strength than that of the controlled sample and other percentage of added fibre because when fibre reinforced concrete cracks due to load being applied to it; the fibres were activated, arresting the formation of further cracks. The development of cracks will be slowed down by the fibre, until the fibre fails [6]. The low dosage of fibre added also causes the water-cement ratio to be slightly lower than controlled sample, resulting in a higher strength concrete.

However, the inversely proportional relationship between the amount of fibres added into concrete and the water content in concrete causes detrimental effects on concrete with nylon cable tie content of 3% and 5%. As the amount of nylon cable tie increases in concrete, it absorbs more water from the concrete mix, resulting in a lower water-cement ratio. When the water-cement ratio is too low, it produces a less workable concrete. Concrete that has low workability will trap more air than highly workable concrete, creating larger voids and honeycombed surface [1]. The existence of large air voids reduces the strength of concrete due to less friction and poor interlocking between aggregates. This is why concrete samples with nylon cable tie content of 3% and 5% show a decreasing trend in terms of the compression and split tensile strength as the fibre content increases. When nylon cable tie is added into concrete with a dosage of more than 5%, it is expected that the compression and split tensile strength will continue to decrease.

Failure Mode of Nylon Cable Tie Fibre-Reinforced Concrete

The failure mode of nylon cable tie fibre reinforced concrete were observed after compressive and split tensile test were carried out to the concrete specimens.

For nylon cable tie FRCs samples tested with compressive test, it was seen that the concrete specimens crushes parallel to the direction of the loading during failure. The crushing of concrete reduces as the nylon cable tie content in concrete increases. It was also observed that at locations where fibres are present, the crushing of concrete was not as bad as locations where fibres are absent, as seen in Figure 3. For nylon cable tie FRCs samples tested with split tensile test, a crack was developed parallel to the direction of loading upon failure for all specimens. However, the crack that was developed is clearly visible in concrete with nylon cable tie content of 1%, but is less visible in concrete with fibre content of 3% and 5%. The mode of failures for concrete specimens can be seen from Figure 4 to Figure 6.

The failure modes obtained from this study show similarities with the failure modes obtained by a study made in 2015. In that study, it was found that concrete prisms with added fibres developed a small crack at the midspan of a prism upon failure, but does not break the prism into two. The fibres that are added in concrete holds the concrete together, creating a concrete that does not break abruptly upon failure [7].

Figure 3: Failure Mode due to Compression.

Figure 4: Failure mode for concrete with 1% fibre content due to split tensile

Figure 5: Failure mode for concrete with 3% fibre content due to split tensile

Figure 6: failure mode for concrete with 5% fibre content due to split tensile

Conclusion

Four batches of concrete were used to produce nylon cable tie fibre reinforced concrete with varying fibre content. Analyses were done on the results obtained. This research fulfilled all of its objectives. A few conclusions were deduced from this study, which are as follows:

1. In slump test, the value of slump produced decreases as the nylon cable tie content increases. A slump of 15 mm was obtained when 5% of nylon cable tie were added into concrete. This shows that as the nylon cable tie content increases, the workability of concrete decreases.
2. The optimum nylon cable tie content which produces the highest compressive strength was obtained. At 1% of nylon cable tie content, the mean compressive strength recorded was 32.10 MPa, the highest strength recorded compared to other batches. The compressive strength showed an increase of 5.59% compared to that of controlled sample. The compressive strength of concrete decreases as the nylon cable tie content increases beyond 1%.

3. The optimum nylon cable tie content which produces maximum split tensile strength was obtained. By adding 1% of nylon cable tie into concrete, the highest split tensile strength was recorded which is at 3.11 MPa. An increase of 7.07% split tensile strength was obtained as compared to that of controlled sample. The split tensile strength of concrete continues to decrease as the nylon cable tie increases beyond 1%.
4. Nylon cable tie, when added as fibres, can improve the compressive and split tensile strength of concrete. At optimum fibre content, the nylon cable tie fibre reinforced concrete performs better than conventional concrete in terms of compressive and split tensile strength.

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