



CHARACTERISATION OF NATURAL FIBRES FOR ENHANCEMENT OF CONCRETE PROPERTIES

A. C. Da Costa Santos¹, P. Archbold¹

¹ Faculty of Engineering & Informatics, Athlone Institute of Technology, Dublin Road, Athlone, Co. Westmeath, N37 HD68, IE

*Corresponding author; e-mail: a.cdcosta@research.ait.ie

Abstract

The use of fibres as reinforcement of composites is widely applicable for mechanical, materials and construction sectors. For instance, most of those fibres are not produced from renewable sources or by ecological procedures and researchers have been trying to develop smart solutions to replace them efficiently keeping a competitive price.

Natural fibres are commonly considered as an ecologic alternative. They can be extracted from abundant vegetable, mineral or animal sources and if submitted to adequate treatment, they are able of providing important materials for the industry. Despite the aim of this paper is focused on concrete, results obtained experimentally for this study are still applicable for other purposes of application.

Considering natural fibres as light and low-cost materials, when added to a composite mixture, they can become a sustainable alternative for other fibres to produce materials with better thermo-acoustic properties and reducing weight and density of the final composite.

One of the current issues related to natural fibres is that while the currently used fibres are produced under controlled methodology and their properties can be easily characterized, natural fibres are still no standardized and even under the same process of extraction, singular fibres, when compared among themselves can present distinct characteristics. This study examines results obtained for mechanical properties of flax, jute, hemp and basalt fibres found experimentally, compares and analyses the compression strength of concrete with the addition of hemp, basalt, steel and polymer fibres into concrete mixture designed under the same parameters. As result for singular fibres, flax and basalt presented the highest tensile strength and Young's modulus when compared to jute and hemp. On the other hand, when added to concrete, hemp fibres in a proportion of 0.5% achieved results comparable with the mixtures containing polypropylene in 1.0% and Steel in 0.15%.

Keywords:

Natural Fibres, cementitious bio-composites, reinforced concrete.

1 INTRODUCTION

About 40% of the total amount of CO₂ emissions are attributed to the construction industry, of which 15% are represented by the production of materials. Even though the percentage is relatively low if compared to the active influence of buildings, it is expected the use and development of more sustainable materials for the future constructions [Fan 2017].

The need for materials presenting numerous properties to achieve technical requirements for the industry is every day increasing [Lopes-Alba 2018], the author discusses the topic applied to the automotive industry. However, it is equally important to the construction sector as it is one of the largest consumers of composite materials in the world [Fan 2017].

Concrete is a cementitious composite that offers great performance in terms of compression and durability. On the other hand, when it is submitted to tensile stress the behaviour of the concrete cannot be considered

significant and for this reason, additional reinforcement is required if any tensile strength is expected from the concrete structure [Nguyen 2017].

The most common reinforcement used is with steel bars, nevertheless, depending on the purpose of the mixture, fibres are added composing the Fibres Reinforced Concrete (FRC) [Grzymiski 2019]. A large number of fibres can be added to matrixes to improve their properties, to develop their performance and to reduce their costs. When fibres extracted from natural sources are added to the concrete the mixture it is denominated as Natural Fibres Reinforced Concrete (NFRC).

Natural fibres are classified according to the sources they are extracted from and are divided into animal, mineral and vegetable fibres. While the animal-based fibres comprise specific proteins as wool, silk and hair fibres, the mineral fibres can be produced from asbestos, wollastonite, basalt, palygorskite, etc. And, the plant-based fibres can be extracted from seeds,

bastes, leaves, stalks, canes, grasses or reeds. It includes numerous vegetable sources as bamboo, sisal, flax, pineapple, jute, banana, hemp, ramie, coir, etc. [Onuaguluchi 2016] [Sanjay 2018]. Properties such as density, diameter, tensile strength, Young's modulus and elongation at break found in the literature for a selection of relevant natural fibres for this study are summarized in Tab. 1.

[Lau 2018] affirms that the absence of a precise manufacturing process to produce the fibres is the main reason for the large difference of results obtained by different authors.

The target of the work described in this paper was to independently characterise some of the mechanical, physical and chemical properties of basalt, jute, flax as potential reinforcement fibres. The work here is aimed particularly at fibre reinforced concrete, but the properties identified will be useful in assessing the suitability of these fibres in polymer reinforcement also.

2 METHODOLOGY

This study was divided in two stages: firstly, a range of both organic and inorganic fibres have been tested to the aim of characterizing their chemical, physical and mechanical properties.

The second part was focused on comparing the effects of the addition of two natural fibres into concrete, basalt and hemp. As benchmarks for the other materials, FRC mixtures containing conventional fibres such as steel and polypropylene were also tested under the same parameters.

2.1 Materials

All the procedures here described were executed using fibres acquired from different providers. Basalt and jute fibres were purchased from Irish suppliers while flax and hemp from the UK. Flax was extracted from the straw, basalt was prepared from continuous fibres. Their length to be used in concrete was 24mm. Hemp and jute were prepared from ropes and manually separated and cut according to the desired length.

A standard concrete mixture was designed for slump 10-30mm, C30 at 7 days with 5% of defectives and standard deviation equals to 8 (target mean strength as 43.12N/mm²). Cement type II used, 42 MPa at 28 days, grading of fine aggregate 52%, uncrushed, relative density of coarse aggregate 2.6g/cm³, crushed.

2.2 Chemical Properties of Natural Fibres

According to [Jones 2017], X-Ray diffraction spectroscopy is a common method for chemical composition analysis by measuring the chemical bonds and functional groups of the natural fibres. This experiment was carried out by an external laboratory and the results are presented in 3 RESULTS AND DISCUSSION.

2.3 Mechanical Properties of Fibres

For analysis of the mechanical properties of fibres, were measured the maximum force (F_{max}), force at break (F_{break}), elongation at maximum force (dL at F_{max}) and elongation at break (dL at break) following the procedures presented by the Standard Test Method for Tensile Strength and Young's Modulus of Fibre [ASTM C1557 2014]. The method provided by this standard is applicable for singular fibres and can be applied for fibres with diameters greater than 250x10⁻⁶ m.

For each type of fibre were built one sample composed of 40 specimens with fibres of 45mm length (L). The tabs designed for the test were as showed in Fig. 1, printed in sulphite paper and singular fibres were fixed using superglue to leave the exact length required between the two fixed points. The circle centred was manually cut and each specimen was labelled with its respective number and type of fibre.

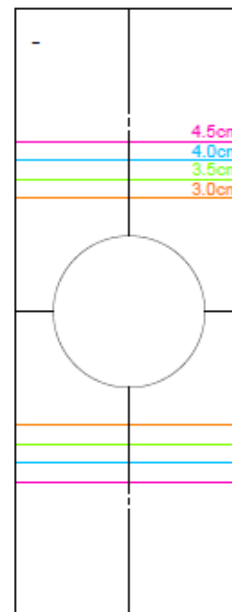


Fig. 19: Specimen tab model.

The test was led using the tensile strength equipment Zwick/Roell Z1010 with grips as exhibited in Fig. 2. The software was set for cross-section shape of the specimen as yarn, pre-load of 0.1N, speed of pre-load 50mm/min, and the test speed with position controlled 0.6mm/min. The force shutdown threshold of 80% of the F_{max}. Each specimen of basalt, hemp, flax and jute fibres was positioned, and the paper was cut in the horizontal centre line of the tab remaining only the singular fibre in between the grips ready to be tested, as recommended by the followed standard. The specimens that presented any damage at this stage were not considered for the study.

Tab. 1: Mechanical properties of singular natural fibres. Adapted from [Sanjay 2018], [Lau 2018], [Zheng 2019], [Bevitori 2010] [Grubeša 2018], [Goudenhoof 2019] and [Khan 2018].

Type of fibre	Density g/cm ³	Diameter (µm)	Tensile Strength (N/mm ²)	Young's Modulus (GPa)	Elongation at Break %
Basalt	2.6	7-15	4150-4840	>40	3.2
Flax	1.5	18-28	345-1500	27.6-80	1.2-4.0
Hemp	1.48	500	550-900	30-70	1.5-4.0
Jute	1.46	40-180	200-800	20-55	1.5-3.0

After rupture, the diameter (d) of each fibre was measured as specified in 2.4.



Fig. 20: Tensile Strength equipment.

All the specimens were tested and the results read were used to calculate the Tensile Strength (1), the Young's Modulus (2) and the %Elongation at break (3) using the equations ahead and the final results are presented in Tab. 2.

$$\text{Tensile Strength} = (F_{max}) \div (A) \quad (1)$$

$$\text{Young's Modulus} = (L \times F_{break}) \div (A \times dL \text{ at break}) \quad (2)$$

$$\% \text{Elongation at break} = (dL \text{ at break}) \div L \quad (3)$$

2.4 Physical Properties of Fibres

Diameter

Using a digital microscope Nikon ShuttlePix P-MFSC (Fig.3) the diameter of each fibre tested was measured. The readings were made in at least two different points of each side of the broken fibres as closest as possible to the failure area. The values were recorded and the diameters, on average, used to calculate the circular cross-section (A) of each specimen.



Fig. 21: Digital microscope used

Density

Before proceeding with the density test, a sample of the fibres as shown in Fig. 4 was left in the oven at 105°C for 24 hours to dry any surface moisture content. The density of each fibre was measured using the digital density balance rolbach model RBDT-01 showed in Fig. 5. Readings were repeated 5 times for each type of fibre studied and their mean was recorded. The results gotten are indicated in 3.3.



Fig. 22: Samples of natural fibres.



Fig. 23: Digital density balance.

2.5 Mechanical Properties of Fibre Reinforced Concrete (FRC)

Sample preparation

Ten concrete mixtures were made and for each one, slump test was done and 3 beams (15x15x55cm) and 3 cubes (15x15x15) were moulded. All the beams were vibrated using an electric concrete vibrator.

The mixtures were prepared to contain natural and not natural fibres in different percentages per volume as listed below. The hemp fibres, purchased in ropes, were manually separated and cut with a length of 40mm each as exhibited in Fig. 6. The amount of fibres to be added is listed below and were calculated based on the % volume and the density of each type of fibre.

- Control mixture: 0% of fibres
- Basalt fibre: 0.5% and 1.0% of the volume
- Hemp fibre: 0.5% and 1.0% of the volume
- Polypropylene fibre: 0.5% and 1.0% of the volume
- Steel fibre: 0.05%, 0.1%, 0.15% of the volume

The percentages of steel adopted were decided to be smaller than the others due to its high density, to make its results comparable with the other fibres the % by volume was reduced.

An electric concrete mixer was used for the mixes and tests were conducted with them in fresh and hardened states.



Fig. 24: Hemp fibres cut with a length of 40mm.

Workability and consistency of fresh concrete

At fresh state, the workability of the mixtures was measured through the consistency test, conducted according to the standard BS EN 12350-2: 2009. The test procedure has the aim of measuring the differences in the workability between the control mixture and the addition of natural and non-natural fibres.

The slump test was led by filling the cone in three layers of equal depth and each layer was rodded 25 times with the rod penetrating only the layer below. The final level was fixed by rolling the rod on the top of the cone. The sides of the cone were cleaned, and the cone was straighten lifted during 5 to 10 seconds.

The distance between the rod on the upturned cone and the top of the mix was recorded as the value of slump.

The results are presented in 3.4 Mechanical Properties of Fibre Reinforced Concrete (FRC).

Compressive Strength

Each cube was tested for compressive and flexural tensile strength at 7 or 8 days following the parameters given by the British Standard EN 12390-3:2009 and the European Standard EN 14651: 2005. Before each test, the dimensions of the cubes were measured using an electronic Vanier calliper and the density of the cubes was measured using a digital density balance, similar to the one showed in Fig. 5, but with bigger capacity. The compressive strength test was run for each cube using the equipment ELE International ADR 2000kN BS/EN Compression machine (Fig. 7).



Fig. 25: Compression machine.

After the concrete failure, broken parts of the cube were manually removed, and an analysis of the post-cracking

behaviour was done. The shape of the post-cracked cubes indicates if occurred a satisfactory failure or not. It is known that ideal ruptures should indicate that the centre of the cube was holding the strength and that there was a good adhesion in between the cement paste and aggregates. Results and pictures are provided in 3.4 Mechanical Properties of Fibre Reinforced Concrete (FRC).

3 RESULTS AND DISCUSSION

3.1 Chemical Properties of Natural Fibres

Oposing to the expected, the X-Ray diffraction was not conclusive for chemical characterization of the fibres.

The quantity of crystalline components presents into the organic fibres tested was not enough for a successful chemical estimation, nevertheless, basalt, an inorganic fibre, also did not present sufficient crystallinity. The mainly uniform spectroscopy represents a material with amorphous composition. The spectroscopies obtained are presented below in Fig. 8. The position and size of each peak of the graphs could not be used to classify any chemical property and, therefore, X-Ray diffraction was not an adequate experiment for this purpose.

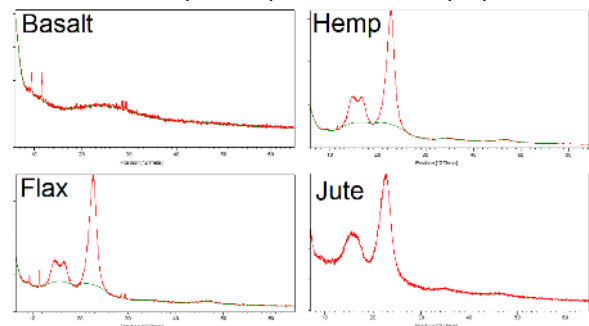


Fig. 26: Spectroscopies of Natural Fibres.

3.2 Mechanical Properties of Fibres

From the experiment conducted using the tensile strength equipment was possible to measure the parameters required to calculate the relevant properties by using the equations described in 2.3 au-dessus, the results obtained after the break and the reading of the diameters of all the specimens containing singular fibres, in average, are presented in Tab. 2.

A statistical analysis of the data calculated in each sample was performed to examine the confidence interval of the distribution. The histogram of each sample is exposed in Fig. 9.

The confidence interval of the samples was 69% for basalt, 67% for flax, 64% for hemp and 70% for jute what configures the data in a real-valued normal distribution.

Tab. 2: Mechanical properties of singular natural fibres.

Material	Tensile Strength (N/mm ²)	Young's Modulus (GPa)	Elongation at Break (%)
Basalt	1519.15	136.18	1.67%
Flax	865.96	40.78	2.09%
Hemp	262.68	22.44	1.47%
Jute	362.96	21.61	1.63%

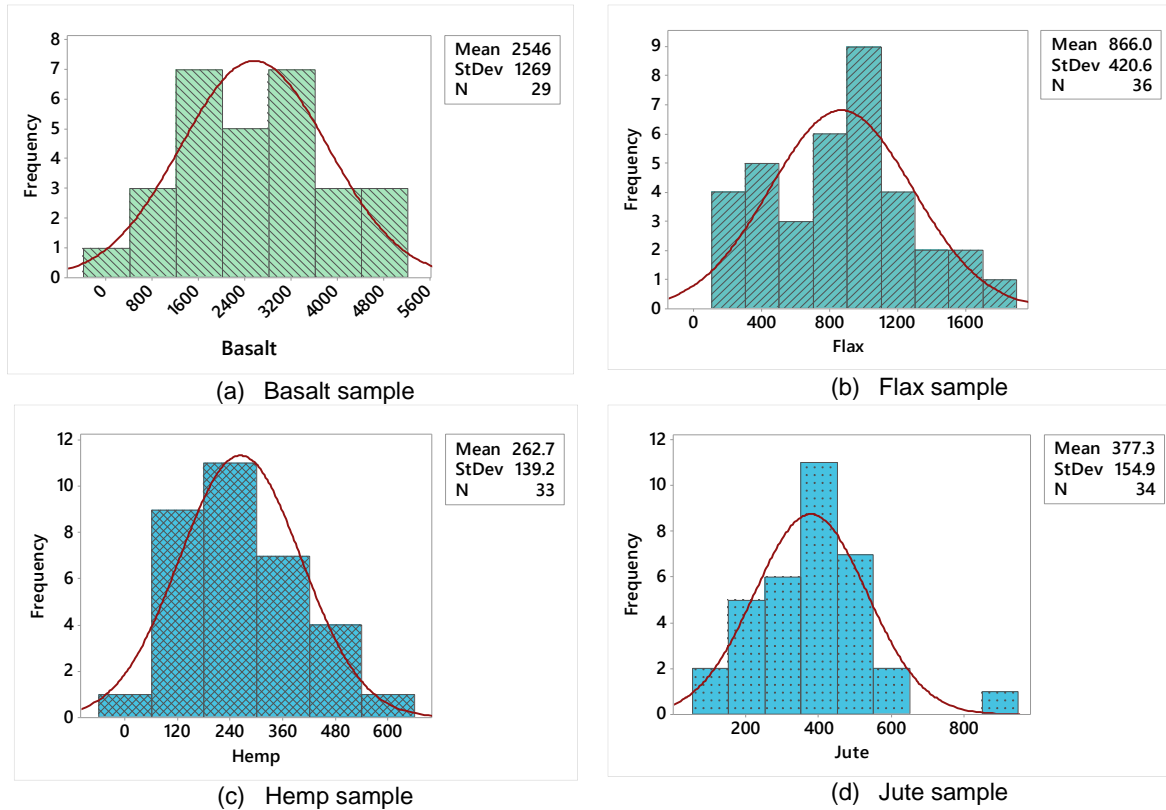


Fig. 27: Histogram and normal distribution of samples tested.

Comparing the results from Tab. 1 with those obtained experimentally, the tensile strength of basalt and % elongation at break fibres were about 20% and 50% of the value measured by other authors respectively. Its Young's Modulus was greater than 40GPa, so it was coherent to the expected.

The marks achieved by flax and jute fibres were all well comparable with previously published work, while hemp fibres, similarly to the basalt, presented in this study all the parameters smaller than those found in the literature.

3.3 Physical Properties of Fibres

The average of diameters and densities measured is presented bellow in Tab. 3.

Tab. 3: Physical properties of fibres.

Material	Diameter (µm)	Density (g/cm ³)
Basalt	14.0	2.2
Flax	82.4	1.1
Hemp	73.0	1.1
Jute	60.2	1.1

Comparing Tab. 3 to Tab. 1, the diameters and density measured for basalt and jute fibres can be considered statistically equal to those obtained by other authors, whereas the diameter of flax was almost 3 times bigger and for hemp 7 times smaller than those previously measured.

Densities measured in this study were 20-25% smaller than the values present in the literature.

3.4 Mechanical Properties of Fibre Reinforced Concrete (FRC)

Workability and consistency of fresh concrete

At fresh state, the slump of each mixture was measured, and they are plotted in Tab. 4.

Comparing the control slump with the others, the addition of all types of natural fibres presented smaller values, what represents a reduction in the workability of the mixtures. Polypropylene also increased the consistency of concrete. The drop of this property was possibly caused by the rise of friction between the components of the mixture and reduction of the free water content as the fibres tend to absorb it [Archbold 2016], what explains the increase of slump proportionally to the addition of steel fibres, as their surface does not present significant porosity and they do not absorb water.

Tab. 4: Slump of fresh concrete mixtures.

Mixture	Slump (mm)
Control	30
Basalt 0.5%	8
Basalt 1.0%	2
Hemp 0.5%	0
Hemp 1.0%	0
Polypropylene 0.5%	12
Polypropylene 1.0%	10
Steel 0.05%	25
Steel 0.1%	29
Steel 0.15%	51

Compressive Strength

At the hardened state, the cubes tested at 7 or 8 days and the values for compressive strength are presented in Tab.5.

The C30 control mixture was designed to achieve the strength at 7 days of 43.12N/mm². The control mix presented, on average, reached 95% of the target compressive strength.

Tab. 5: Compressive Strength (N/mm²) of concrete at 7(*) and 8(**) days.

Mixture	1	2	3	Average
Control*	40.4	40.4	42.7	41.2
Basalt 0.5%*	34.3	36.6	34.9	35.3
Basalt 1.0%*	40.2	41.3	-	40.8
Hemp 0.5%*	38.2	38.4	38.8	38.5
Hemp 1.0%*	29.4	31.7	24.2	28.5
Polypropylene 0.5%*	35.2	33.9	35.0	34.7
Polypropylene 1.0%*	39.3	39.5	38.6	39.2
Steel 0.05%**	42.4	39.1	40.1	40.5
Steel 0.1%**	44.5	43.4	45.9	44.6
Steel 0.15%*	41.3	41.4	40.9	41.2

The addition of steel fibres in 0.1% and 0.15% did not interfere negatively in this property. Diversely, the addition of all the other fibres reduced at some level the compressive strength achieved by the control mixture.

Fig. 10 contains a bar graph of the average results for a better visual analysis. Generally, the addition of natural

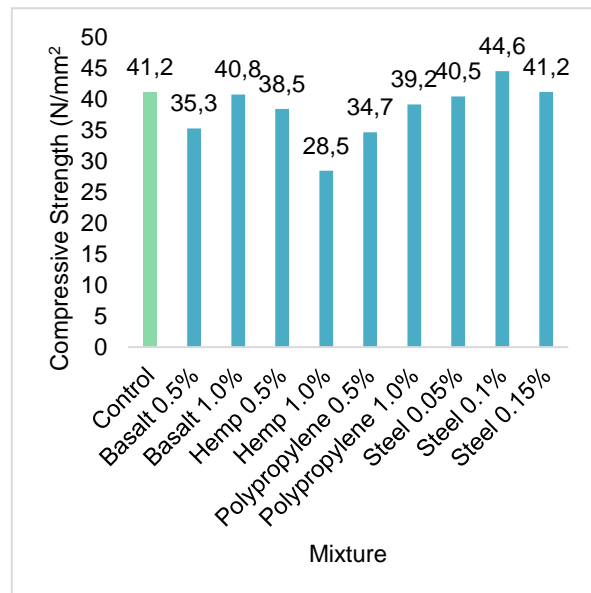


Fig. 10: Graph of the average compressive strength or not fibres reduced the compressive strength in less than 10% but the samples tested containing 0.5% of basalt and polypropylene and 1.0% of hemp fibres, presented a reduction up to 30% when compared to the control mix.

This reduction is possibly caused by the hard adhesion between the fibres and the concrete and as it happens regardless the type of fibre, researchers are commonly trying to develop composites able to increase the bond between fibres and matrix.

Post-cracking analysis

The shape of the remaining part of the cubes after failures are shown in Fig. 11.



(a) Control mixture.



(b) 0.5% of basalt.



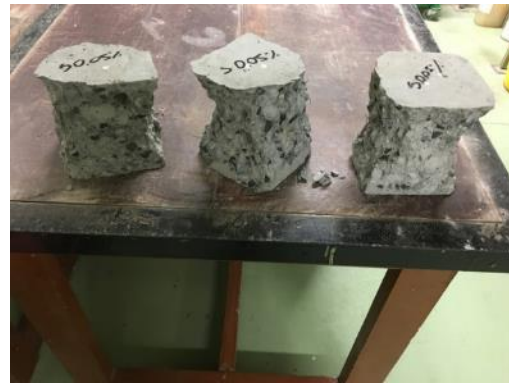
(c) 1.0% of basalt.



(d) 0.5% of hemp.



(e) 1.0% of hemp.



(f) 0.05% of steel.



(g) 0.1% of steel.



(h) 0.15% of steel.



(i) 0.5% of polypropylene.



(j) 1.0% of polypropylene.

Fig. 11 Post-cracking shapes

The results got for mixtures containing 1.0% of basalt, 0.5% of hemp and polypropylene, 0.05, 0.1 and 0.15% of steel indicated a satisfactory failure

Their apple or pyramid-shape confirms that the strength of the cubes was well centred. In all the specimens was noticed both aggregate and mortar failure, what represents a good adhesion of the mixtures.

The cubes containing 1.0% of hemp and polypropylene post-cracking behaviour could not be analysed. Was not possible to separate the cracked parts from the rest due to the strong bond between fibres and concrete.

4 CONCLUSIONS

From this preliminary study about mechanical properties of natural fibres, among the sources studied, was possible to conclude that X-Ray diffraction was not an adequate method for measurement of chemical composition of the fibres studied.

In terms of mechanical properties, the results obtained were mainly related to the content present in literature,

but for this study, basalt, a mineral fibre, presented higher tensile strength and Young's Modulus than the organic fibres.

Among the vegetable fibres, flax represented the strongest material in terms of tensile strength. Furthermore, the elongation at break of all the fibres was numerically the same for all the vegetable fibres and greater for basalt.

When comparing and analysing the effects of the addition of natural and non-natural fibres into concrete, in this work, hemp and basalt fibres, in controlled proportions, can be successfully compared to polypropylene and even steel, in a smaller percentage.

It is important to mention that the difference in the results obtained by the mixtures tested with 7 and 8 days was not representative, therefore the authors did not submit them to any mathematic treatment to the end of estimating their values at the same age. Moreover, the length of the fibres added was not subject to analysis and it could be a topic to be considered in future studies.

5 ACKNOWLEDGEMENTS

This research was funded by the Government of Ireland Scholarship.

6 REFERENCES

- [Archbold 2016] Archbold, P.; Da Costa Santos, A. C.; Loonam, A. The Influence of Basalt Fibres on the Mechanical Properties of Concrete, *Civil Engineering Research in Ireland* (2016), 1-5.
- [ASTM C1557 2014] Active Standard ASTM International. C1557. 2014.
- [Bevitori 2010] Bevitori, A.B.; Da Silva, I.L.A.; Lopes, F.P.D.; Monteiro, S.N.; Diameter dependence of tensile strength by Weibull analysis: Part II jute fiber. *Revista Materia*, 2010, v. 15, 117-123, ISSN 1517-7076.
- [BS EN 12350-2: 2009] British Standards Institution. Testing fresh concrete. Slump-test. EN 12350-2. 2009.
- [BS EN 12390-3:2009] British Standards Institution. Testing hardened concrete. Compressive strength of test specimens. 2009.
- [BS EN 14651: 2005] British Standards Institution. Test method for metallic fibre concrete. Measuring the flexural tensile strength (limit of proportionality (LOP), residual). 2005.
- [Fan 2017] Fan, M.; Fu, F.; 1 - Introduction: A perspective – natural fibre composites in construction. *Advanced High Strength Natural Fibre Composites in Construction*, 2017, 1-20.
- [Goudenhoof 2019] Goudenhoof, C.; Bourmaud, A.; Baley, C.; Study of plant gravitropic response: Exploring the influence of lodging and recovery on the mechanical performances of flax fibers, *Industrial Crops & Products*, 2019, 128, 235–238.
- [Grubeša 2018] Grubeša, I.N. et al.; Effect of hemp fibers on fire resistance of concrete. *Construction and Building Materials*, 2018, 184, 473-484.
- [Grzymiski, 2019] Grzymiski, F.; Musial, M.; Trapko, T.; Mechanical properties of fibre reinforced concrete with recycled fibres. *Construction and Building Materials*, 2019, 198, 323-331.
- [Jones 2017] Jones, D. et al.; Chemical compositions of natural fibres. *Advanced High Strength Natural Fibre Composites in Construction*, cap. 2, 23 – 58.
- [Khan 2018] Khan, M.; Cao, M.; Ali, M.; Effect of basalt fibers on mechanical properties of calcium carbonate whisker-steel fiber reinforced concrete, *Construction and Building Materials*, 2018, 192, 742–753.
- [Lau 2018] Lau, K. et al.; Properties of natural fibre composites for structural engineering applications. *Composites Part B*, 2018, 136, 222-233.
- [López-Alba 2018] López-Alba, E.; Schmeer, S.; Díaz, F.; Energy Absorption Capacity in Natural Fiber Reinforcement Composites Structures. *Materials*, Mar 2018, 11, 418, 1-18.
- [Nguyen 2017] Nguyen, D. H.; Dao V. T. N.; Lura P.; Tensile properties of concrete at very early ages. *Construction and Building Materials*, 2017, 134, 563-573.
- [Onuaguluchi 2016] Onuaguluchi, O.; Banthia, N.; Plant-based natural fibre reinforced cement composites: A review, *Cement and Concrete Composites* 68 (2016), 96-108.
- [Sanjay 2018] Sanjay, M. R. et al, Characterization and properties of natural fiber polymer composites: A comprehensive review, *Journal of Cleaner Production* 172 (2018), 566-581.
- [Zheng 2019] Zheng, Y.; Zhang, P.; Cai, Y.; Jin, Z., Moshtagh, E.; Cracking resistance and mechanical properties of basalt fibers reinforced cement-stabilized macadam. *Composites Part B*, 2019, 165, 312-334.