CEMENTITIOUS MATERIAL WITH BIO-BASED RECYCLED AGRICULTURAL WASTE

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AbstractFibre reinforced concrete (FRC) is a significant achievement of modern construction. Fibres increase the ductile capacity of concrete by enabling it to undergo large deformation before failure. The tensile strength of concrete is increased whereas it would otherwise only be strong in compression. Although FRC has several advantages, the use of steel fibres means it only provides a little contribution towards sustainability; therefore a shift towards new and innovative building materials is an urgent necessity. Most manmade fibres such as steel, synthetic or polymer are industrially manufactured and widely used. Such fibres are non-degradable, non-renewable and expensive. In this research, natural and innovative biodegradable fibres, their preparation and properties and interaction with concrete have been highlighted. Agricultural fibres viz. rice and wheat straw have been used. Rice and wheat are a staple food all over the world. After harvesting the commercial crop there remains huge quantities of straw produced. This straw has generally been seen as a waste product and disposed of since it has a very few economic benefits. One of the major problems of today is the disposal of straw by open air burning and its impact on air pollution has been well documented. Thus the wastage of straw could be minimised if a viable use for it can be found in the construction industry. Being a relatively new material, in this research, the chemical and physical properties of agricultural fibres have been studied. The influence of the addition of fibres in both fresh and hardened concrete has also been investigated. The findings present an interesting insight into agricultural fibres. Due to its easy availability and low-cost, straw has the potential to be a promising bio-based construction material.

Keywords:
Agricultural waste, cementitious material, fibre reinforced concrete, mechanical properties, straw

1 INTRODUCTION

In tropical and sub-tropical climates, rice is one of the primary crops. Mediterranean climates are also favourable for some varieties of rice. Wheat is produced mainly in temperate and Mediterranean climates. Depending on location, temperature and availability of water, combined harvesting is also common in most of the agricultural regions. The agricultural waste of rice and wheat production, mainly straw, can be mixed with concrete as fibre reinforcement. The durability and strength properties of resulting hardened concrete is the main focus of this paper. A fibre percentage by volume of 0.5% of the concrete is used to prepare rice and wheat straw fibre reinforced concrete and physical test results of the FRC are analysed.

Wherever there is sufficient water supply in tropical climates, more than one crop of rice can be grown per year. This also indicates straw is generated more than once a year. South and East Asia: China, India, Pakistan, Indonesia, Bangladesh, and Vietnam are the largest producers of rice globally. Wheat is produced in huge amounts in Southern Asia, Eastern Europe, Northern America and Eastern and Central Asia. And European countries are important contributors of wheat in comparison to rice [Bakker 2010].

Rice grain or often referred to as paddy rice or rough rice is a staple food for humans, while the remaining straw is used for animal feed and other applications. More than two-thirds of the wheat produced is consumed by humans, generally in the form of flour to produce bread. About 17% of the global production is used for animal feed, although this varies from country to country (in Europe and North America, more wheat is used for feed) [Bakker 2010].Globally, approximately 740 million tonnes of rice paddy and a similar amount of wheat is produced each year [FAOSTAT 2014]. The year on year production of both the crops from 2004 to 2014 is shown in Figure 1. It is estimated that about 20% of the final yield product is husk, giving an annual total production of 300 million tonnes. For every 1000kilograms of paddy milled, about 220 kilograms (22%) of husk is produced [Kumar 2012].

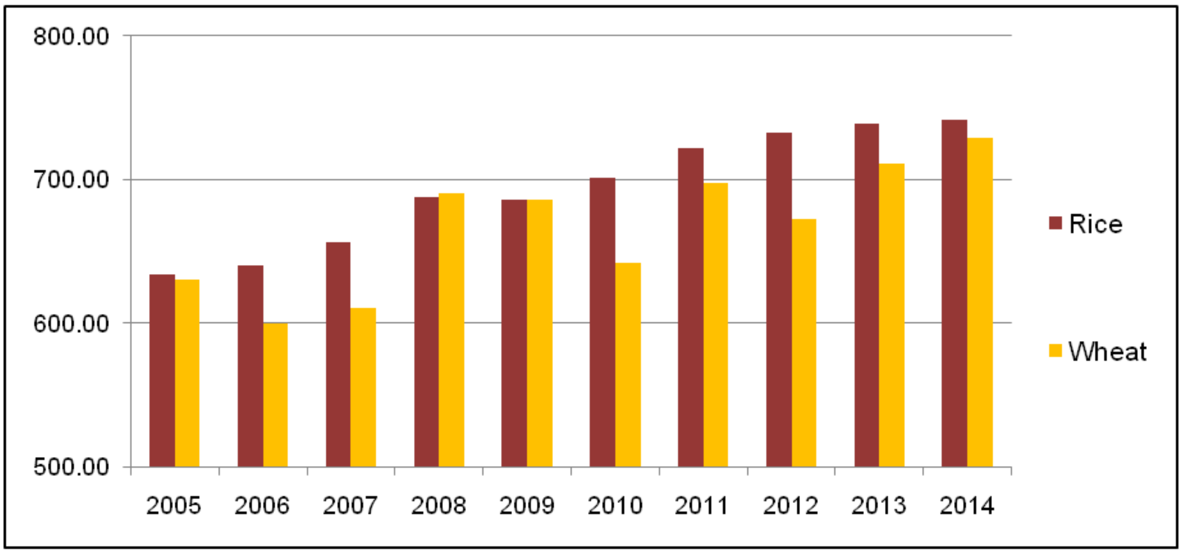

Fig. 82 Rice and wheat production globally from 2004 to 2014 (in million tonnes) [FAOSTAT 2014]

Farmers across the globe use several methods to dispose of or use straw after harvesting. Most common are either the straw is removed from the field, burned in situ, piled or spread in the field, incorporated into the soil, or used as mulch i.e. it can be ploughed into the field or left as a layer that covers the top soil. Figure 2 shows a wheat straw field which is a common sight in most of the world. The most common method of straw disposal is by burning in the field for fast disposal purposes, a process which is referred to as open field burning. One of the main motivations of this hazardous practice is the short turnover time between the rice harvests. The rice that is harvested at the end of the rainy season is removed as early as possible in the autumn so that other crops can be established. Higher temperatures and longer days in the early autumn are beneficial for the following crop season, as a result rice straw is cleared or burned as an easy and cheap way of clearing the field. A number of studies indicate that open field burning produces several harmful pollutants. The depletion of energy resources and increasing awareness of global environmental problems provides the motivation for new, green and sustainable materials. The use of such green materials provides alternative ways of solving the problems associated with agricultural residues.

Fibre reinforced concrete is one of the most innovative ideas in the modern construction industry. Mixing of fibres either steel or synthetic to increase the strength and ductility of concrete has long been studied and published. Its industrial applications have now widely been accepted and applied in the construction industry. However, the uses of FRCs are cost effective, efficient and serve the design purpose, innovation and sustainability aspect of such concrete have not been explored. There has, however, been minimal research on the use of green fibres such as fibres extracted from trees, plants and other fruits but not in an application based approach. Common natural fibres are coconut fibres, bamboo, coir and jute fibres.

Fibres are of high tensile strength that supplements the compressive strength of plain concrete. Several previous research studies of natural fibre reveal theinteresting behaviour of such fibres and their intrinsic properties. The tensile performance of natural fibres compares favourably with synthetic ones but one of the disadvantages of using natural fibres is that they have highly variable properties which could lead to unpredictable concrete properties. [Torgal 2011] showed that natural fibres have a high tensile strength, as much as 500 MPa for Sisal and Bamboo fibres also they have a low modulus of elasticity as low as 2 GPa for wheat straw. [Zhang 2012] investigated climatic and cultivation conditions on three continents. Rice husks and straws obtained from three countries (Egypt, Cuba and China) were evaluated in this study. The bulk density values of rice straws were lower than those of rice husks. The results obtained from this study showed significant differences in the physical properties like moisture content, particle size distribution, bulk density and porosity.

Apart from physical properties, several researchers have published their studies on chemical properties of agricultural fibres. [Hou 2015] studied chemical composition to understand the compositional changes of biomass during the separation process, the contents of cellulose, hemicellulose, lignin, starch and ash of rice husk were determined. [Ramaswamy 1983] conducted one of the prominent researches very early in 1983. Short discrete vegetable fibres namely jute, coir and bamboo were examined for their suitability for incorporation in cement concrete. The engineering properties such as compressive strength, splitting tensile strength, modulus of rupture and impact toughness of the fibre concretes were also investigated. The results of the various experiments presented in the paper showed that vegetable fibres such as jute, coir and bamboo can be used with advantage in concrete in a manner similar to other fibres.

Fig. 83: Wheat straw field

Few researches conducted with natural FRC indicate that these fibres are comparable with the properties of the steel or synthetic fibres. [Yalley 2009] experimented and published their study on the use of coconut fibres as an enhancement of concrete. In this study, a total of 60 specimens of basic concrete mixes were selected. They were divided into four mixes in accordance with the percentage weight fraction of fibres. Three cubes and three cylinders from each mix were tested for compression and splitting tensile strength at 28 days after casting. The compressive strength was within the range of 20-40 MPa and the splitting tensile strength of the coconut fibre was within the range of 2.5-3.5 MPa for the samples with fibre contents 0.25, 0.5 and 0.75%.

Our approach in this paper is focused on widely available straw fibres to develop bio-based cementitious material that could guide the concrete industry towards reusability, sustainability and efficiency. This research focuses on the use of rice and wheat straw fibres, its properties, mix with concrete and critical analysis of test results and its comparison with plain concrete, steel fibres and polypropylene fibres. Steel and polypropylene fibre reinforced concrete are widely used in construction and are both man-made and unsustainable. This paper will hopefully open a new dimension in agricultural straw FRC and its application in construction.

2 MATERIALS

A concrete mix was prepared using Portland Pozzolona cement. The mix design of the concrete was based on the characteristic strength of 37 MPa for cubes which is equivalent to 30 MPa for cylinders. The aspect ratio of all steel fibre types offered by main producers are from 20.4 to 152 [Pajak 2013]. After fixing a length of 45 mm and a width of 1 mm, the aspect ratio was calculated and fixed around 95 for consistency.The surface area ofthe fibres plays an important role, an aspect ratio of 95 was chosen to develop proper bond with the matrix and bridging action of fibres to be efficient. Concrete with fibre volume fraction of 0.5% are prepared. The physical and chemical properties of fibres are the most critical and are thoroughly understood and analysed. Since the strength and durability of the ultimate matrix is purely dependent on the properties of fibres, it was carefully studied.

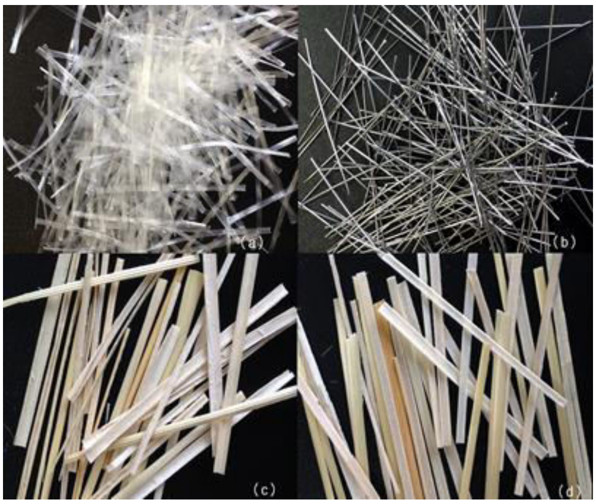

Fig. 84: (a) Polypropylene (b) Steel (c) Rice straw and (d) Wheat straw fibres

2.1 Rice and wheat straw fibres

Rice and wheat fibres are procured from the local agricultural production. Both crops being widely grown across all geographies, the straw is easily available and cheap. The fibres are cut into small lengths and further trimmed manually to match the dimensions and aspect ratio of 95. However for industrial application, manual trimming of fibres is difficult and hence automated cutting machines are to be developed that can produce desired fibre size with no manual effort. The fibres are stored in a dry place throughout the duration of preparation to avoid moisture attack. The fibres used in the research are shown in Figures 3 (a), (b), (c) and (d) as synthetic polypropylene fibres, steel fibres, agricultural rice straw and wheat straw fibres.

2.2 Physical and chemical properties

Several experiments are performed to understand the properties of natural fibres. Due to lack of literature in this, it was of prime importance to understand these properties before finalising the concrete mix.

The tensile strength of straw was determined using a grip mechanism as shown in Figure 4.The specimen was tightly fixed into the grips and a tension force was applied. The maximum tensile strength of rice straw fibre is reached at 77 N for a displacement of 0.016 mm. The tensile stress is 246 MPa and modulus of elasticity is 15.38 GPa. When compared to the tensile strength of Sisal fibres of 347-378 MPa, rice straw fibre has a good tensile capacity. Various studies show that natural fibres such as coconut fibres have a tensile strength as low as 95-118 MPa and 250-350 MPa forJute straw [Nepal 2015].

The densityof fibres is essential in understanding the property of straw and also to determine the quantity in mix design of concrete. The densities of fibres were determined by using a density analyser and was found to be 1.1 and 0.6 gm/cm^3 for rice and wheat straw.

Fig. 85: Tensile strength test of rice straw fibre

For the water absorption capacity of fibres, samples were oven dried for 24 hrs at 60o C and then submerged in water. The duration of submergence varied from 1, 2, 5, 10, 30 and 60 min and 24 hrs. The fibres were then brought to a saturated condition. The weight of the fibres in the dry condition was compared to that of the saturated condition and the water absorption capacity was determined. The results are shown in Figure 5.

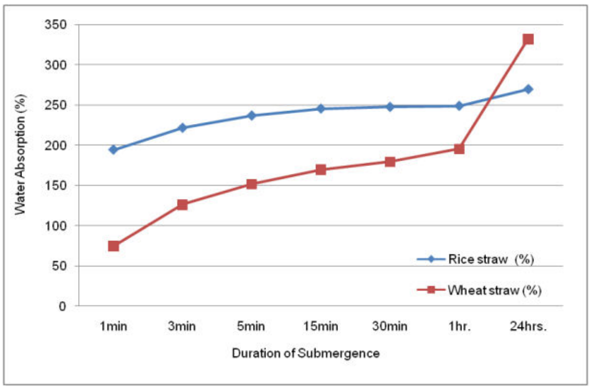

Fig. 86: Water absorption capacity of rice and wheat straw (%)

Rice straw absorbed more water initially. However, the 24 hour result indicates that the wheat has slower water absorption at initial conditions but the capacity significantly increases after 24 hours compared to rice. A Scanning Electron Microscopy (SEM) was used for the detailed study of both the fibres. The Hitachi Tabletop Microscope TM 3000, one of the most powerful microscopes available, was used. Figure 6 shows the images from the SEM of rice and wheat straw. Images 6 (a) and (d) are the cross section of the fibres. Image (b) and (e) are of the inside surface and (c) and (f) are of the outside surface of rice and wheat straw, respectively. These figures show a complex structure with a very similar texture. The cross section images of fibres with a magnification of 100 times shows different layers of vascular bundles. A number of holes can be seen in the region.The outermost surface of the rice straw is corrugated, whereas that of wheat is smoother. The inner section of the rice straw is filled with more voids compared to wheat straws which also are verified from the results of the water absorption test that rice absorbs more water than wheat straws. The inside and outer surfaces of both types of straws also offer an insight into its surface. The inside surface of rice straw is more uniform compared to that of wheat straw which is very rough. The outer surface of both rice and wheat straw are smooth surfaces with less porosity and uneven surfaces.

The fibres were analysed for its chemical composition. The analysis was carried using a Fibretech TM 2010 and was performed in the FOSS laboratory. Figures 7 (a) and (b) show the Fibretech instrument used for the analysis. Figures 7 (c) and (d) shows the fibres used in the analysis kept in the centrifuge

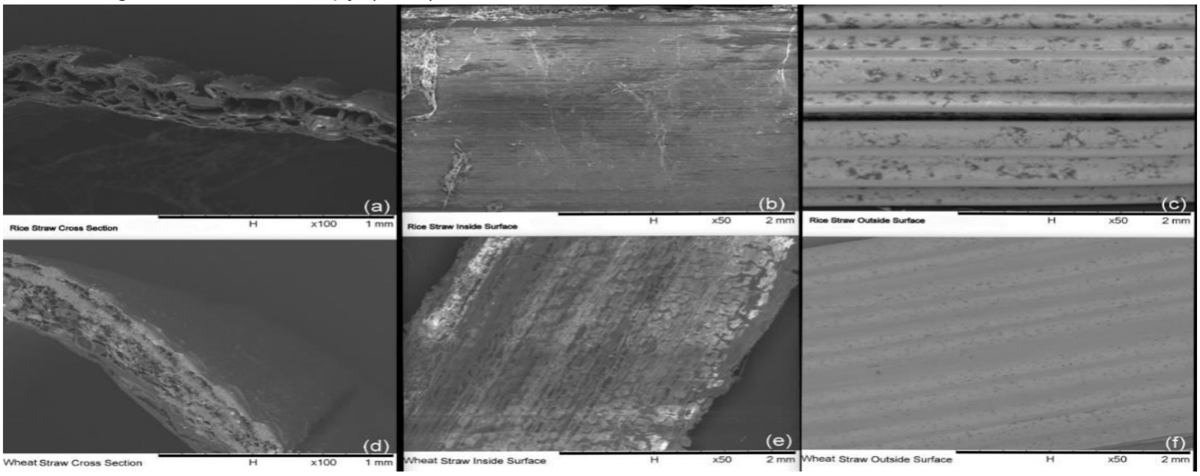

Fig. 87: SEM images of rice and wheat straw

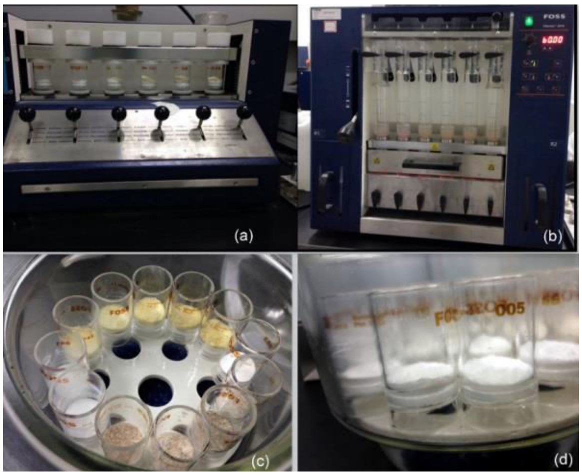

Fig. 88: Fibertech test

3 EXPERIMENTAL INVESTIGATION OF CONCRETE

The fibres are mixed and cubes, cylinders, beams and slabs are prepared from the mix of standard dimensions. The side dimensions of the cubes are 150 mm. The cylinders are of 150 mm diameter and 300 mm height. The beams are of 150 mm width, 150 mm height and 550 mm span length and slabs are of 750 mm square and 50mm thickness.

The batches are divided as in Table 1 according to the volume fraction of fibres for both rice and wheat straws. The specimens are cured for 56 days until the strength is achieved and tested as per code standards.

For compressive strength tests, [BS EN 12390-3 2009] is followed. Compressive strength is the most common measure of concrete strength. The cubes and cylinders are loaded in compression and the load and the deformation are measured. An extensometer is used to measure the change in side dimension for each specimen to record the strain.

The flexural strength of the beam is measured as per the [TR-34 2013] which describes the standard notched beam test of [BS EN 14651 2007] measuring the flexural tensile strength (limit of proportionality (LOP), residual). Residual strength is an important factor that can be used to assess the effect of the fibre on the flexural performance of the fibre-reinforced concrete beam. It is the level of flexural stress after concrete cracks [Lee 2016].The introduction of fibres in concrete improves the residual tensile strength in the cracked phase and reduces the crack propagation. This provides the ductility in FRC which is the falling branch of the load-deflection curve after the maximum load has been sustained. This ductility is also evident from the load-deflection curve of fibre reinforced concrete and plain concrete which shows the post cracking displacement after the yield stress. Limit of proportionality is the limit until which the deformation remains proportional to the load applied. Beams are tested under central point loading on a span of 500 mm. The specimens are notched (25 mm deep and 5mm wide) in a side face as cast and then tested with the notch in the tension face.

Slabs are tested for strength by resembling a ground floor slab applying loads at the centre. Ground slabs are supported by the soil of specific grade and stiffness. However, to resemble a similar stiffening support, 100 mm thick polystyrene foam is provided below the slab. Displacement of the foam subject to a uniform load which was obtained as 0.011 N/mm^3. Loading was applied at the rate of 0.50 mm/min. LVDTs were used to measure the deflection of the slab. [Overli 2014] also used a Jackofoam 400 XPS which was 100 mm thick and had an average stiffness of 0.15 N/mm^3 to achieve the stiffness of crushed stone used as sub grade for ground floor slabs while studying the bending behaviour of a 3500 mm square slab with a thickness of 120 mm.

Tab. 46: Categorisation of concrete batches

Batch ID	Volume Fraction	Fibre
PC	0%	-
SFRC	0.5%	Steel
PFRC	0.5%	Polypropylene
RSFRC	0.5%	Rice
WSFRC	0.5%	Wheat

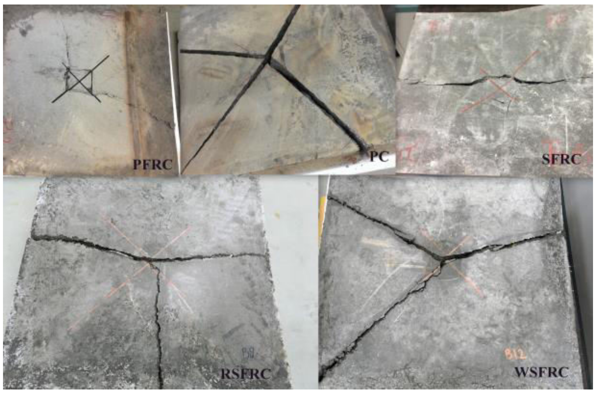

Fig. 89: Crack development in slabs

Similarly in order to avoid excessive edge and corner lifting in smaller scale slabs of 3000 mm, [Alani 2013] tested a full-scale slab of 6000 mm square and 150 mm thickness. [Alani 2013] cast PC, SFRC and PFRC with steel and polypropylene fibre dosages as 40 and 7 kg/m^3 which is around 0.5 % fibre volume. In this experiment the modulus of sub grade reaction (k) varied from 0.044- 0.055 N/mm^3.

Development of cracks and width of these cracks throughout the duration of the load application is critical in understanding the response of FRC. The main aim of this experiment was to determine the failure pattern and understand the bending behaviour of the slab. The slab failure was gradual with the development of wider crack widths and complete failure as the cracks reached the perimeter of the slab thereby disintegrating the whole slab. This phenomenon of failure is shown in Figure 8. From the figure, we can observe that plain concrete has distinct and wide cracks of uniform width extending from the centre of the slab towards the perimeter. For FRC the difference in crack propagation from plain concrete is distinct. For FRC, because of the resistance provided by fibres and the ductile capacity, cracks are not straight and wide as for plain concrete.

4 RESULTS AND DISCUSSIONS

The addition of rice and wheat straw fibres has not shown a detrimental effect onthe concrete compressive strength. The strength of rice straw fibres was 79% and that of wheat straw was 90% of plain concrete. Average stress and strain are plotted in Figure 9 for all the batches of concrete based on the compressive test results of cylinders. The compressive strength of both cubes and cylinders and other mechanical test results are summarised in Table 2. Steel fibre reinforced concrete has the lowest compressive strength for the cubes of 36 MPa whereas rice straw FRC has the lowest cylindrical strength of 26.2 MPa. Polypropylene fibres have shown higher compressive strength compared to all batches of concrete. For both cube and cylinders, polypropylene has exceeded the compressive strength of plain concrete by 13%.

[Nataraja 1999] studied a simple analytical method proposed by [Carreira 1985] for strength fibre reinforced concrete. The equation calculates the stress-strain curve based on peak compressive strength, its corresponding strain and a material parameter **β** which depends on the shape of stress-strain curves. Maximum stress is seen for the uniaxial compression of plain concrete and this is used as a basis to obtain an equation applicable to normal polypropylene fibres and the minimum stress is computed for the rice straw FRC. From the equation and the experimentally drawn stress-strain curves, the analytical stress strain relationship is plotted. It has been observed that the variation in the curve is evident as the strain increases. The analytical equation has a distinction to the experimental plot in the descending portion of the stress. Furthermore, it can be seen that the area under the analytical curve is increased compared to the experimental measurements. Thus this equation helps in obtaining the complete stress-strain curve of FRC to considerable accuracy and within acceptable limits and is validated in our test results.

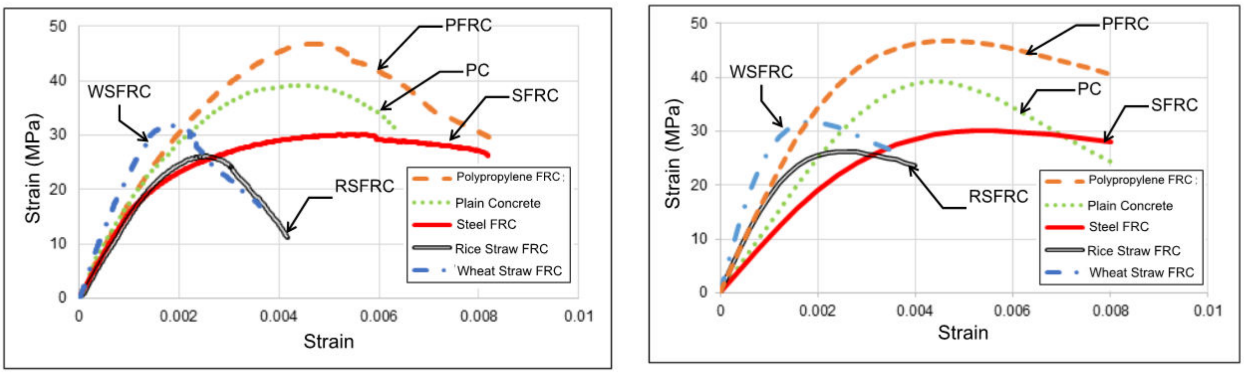

Fig. 90: Average experimental and analytical stress- strain diagrams for cylindrical specimens

Tab. 2: Average mechanical properties of concrete

Properties	PC	PFRC	SFRC	RSFRC	WSFRC
Cube strength (MPa)	47.1	53.2	36.0	37.5	42.3
Cylinder strength (MPa)	39.8	45.1	30.4	26.2	32.8
Beam [Limit of Proportionality (MPa)]	5.6	5.7	6.4	4.9	5.1
Ultimate slab load (kN)	20.3	25.6	20.7	19.6	23.5
Energy absorption capacity (kNmm)	123.7	231.6	246.85	147.0	198.6

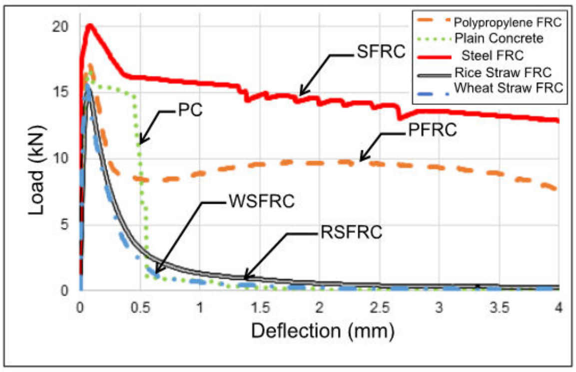

Fig. 91: Average load deflection curves for beams

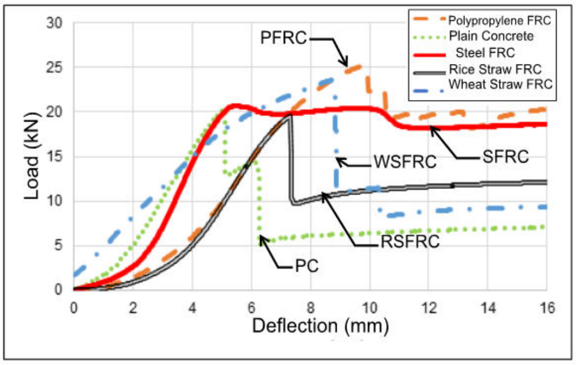

Fig. 92: Average load deflection curves for slab

The average limit of proportionality and residual flexural strength of all five batches of beam specimens are averaged and are tabulated in Tables 2 and 3.

The results are tabulated for equivalent deflections corresponding to CMOD (Crack Mouth Opening Displacements) of 0.5, 1.5, 2.5 and 3.5 mm. The highest residual flexural strength is evident in SFRC of 5.19 MPa compared to 3.77 MPa in plain concrete. Wheat and rice straw fibres had the lowest residual flexural strength in the initial deflection of 0.82 and 1.11 MPa. [Lee 2016] studied the effects in flexural strength of macro high strength polypropylene fibres in concrete. [Lee 2016] summarised that with a fibre content of 0.75% and 1%, there was excellent energy absorption capacity. The fibres helped in improving the residual strength which is more than 4.1 MPa. For polypropylene fibres compared to Lee et al., our residual flexural strength is 3.12 MPa for 2.17 mm displacement. [Pajak 2013] studied the flexural behaviour of self-compacting concrete (SCC) reinforced with straight and hooked end steel fibres at varying percentages of 0.5, 1 and 1.5. In this study, the flexural behaviour of SCC appeared to be comparable to PC, whereas the increase of fibres volume ratio caused the increase in pre-peak and post-peak parameters. The flexural tensile strength of PC and 0.5% straight SFRC was 2.45 MPa and 3.66 MPa at a deflection of 0.05 mm. The residual flexural tensile strength for 0.5% straight SFRC was 1.99, 1.29, 0.89, 0.66 MPa for [Pajak 2013] and 5.19, 4.95, 4.61 and 4.34 MPa at the four different deflections as specified by [BS EN 14651 2007] in our test.

Tab. 3: Average residual flexural tensile strength of beams

Batch ID	Residual Flexural tensile strength (MPa)			
	Deflection (δ) mm			
	0.47	**1.32**	**2.17**	**3.02**
PC	3.77	0.11	0.04	0.03
PFRC	2.72	3.01	3.12	2.98
SFRC	5.19	4.95	4.61	4.34
RSFRC	1.11	0.32	0.16	0.10
WSFRC	0.82	0.15	0.07	0.05

Figure 10 shows the average load-deflection curve for the FRC and plain concrete for the beam. This is crucial in understanding the post yield load carrying capacity of the fibre reinforced concrete. For the plain concrete, the maximum load is 16.6 kN. However, after yielding, the plain concrete shows a sudden drop in load carrying capacity with no residual strength. The steel and polypropylene fibres show remarkable post-cracking strength and undergo large displacement under uniform loading observed from smooth curves with increased displacement. Maximum load is sustained by steel FRC and polypropylene FRC with 20.1 kN and 17.37 kN. The steel and polypropylene fibres are the most ductile FRC and greatly compensate the brittleness of plain concrete with increased flexural strength. Similarly, in the experiment by [Aslani 2015] while comparing the load-deflection curves of SCC beams, SFRC indicated clear deflection-hardening behaviour after cracking and good post-peak properties over the entire deflection range with the first crack at 0.04 mm deflection and load of 18.93 kN. PFRC had 15.84 kN load at 0.2 mm deflection.

For the investigation on ground floor slabs, the ultimate load carrying capacity of the slab has not significantly varied for all batches of concrete. Compared to an ultimate load of 20.3 kN of plain concrete, the rice straw fibres has an ultimate load of 19.6 kN and 23.5 kN for wheat straw fibres. This is an important investigation that signifies that agricultural fibres have huge potential in ground floor slab construction with equal or even increased load carrying capacity compared to steel and polypropylene fibres.

There are several ways of specifying the ductility of the FRC. Energy absorption value can best describe the deformation capacity of concrete under loading. For any given specimen, the area under its load-displacement curve represents the energy dissipated during that loading event [Korol 2012]. For the slab specimens in our experiment, the energy absorption is determined and tabulated in table 2 up to 16 mm. Maximum energy absorption capacity was obtained for the slabs with 0.5% steel fibres. Wheat straw fibres showed energy absorption of 198.6 kNmm compared to 147 kNmm of rice straw fibres. This is the increment of 60% and 18% compared to plain concrete. Steel fibres showed an increase in energy absorption by almost 100% compared to plain concrete. [Korol 2012] investigated the energy absorption of lightweight concrete floors with square concrete slabs Different restraint conditions and loads were applied in the middle of the slab. The results indicate that concrete floor slabs would play an important role in absorbing energy during collapse from an extreme loading event. This implies that concrete floors due to its requirement of high energy absorption capacity, FRC can considerably enhance the ductility of ground floor slabs.

[Sorelli 2006] investigated the structural behaviour of ground floor steel reinforced concrete. Full-scale ground floor slabs were loaded in the centre and the results show that with a relatively low fibre content of steel fibres the load carrying capacity was enhanced. The publication reported 0.38% of steel fibre volume fraction lead to improved ultimate load and ductility. For our research, with 0.5% of polypropylene, the load carrying capacity was 25.6 kN for the polypropylene fibres.

Figure 11 is very beneficial to understand the structural response of ground floor slabs reinforced with fibres. From the average load-displacement curve, it can be seen that plain concrete reaches the peak load with a displacement less than 5mm whereas FRC sustained larger deflections and yielded gradually. The load carrying capacity with only 0.5% volume fraction of fibres is considerably higher compared to ordinary concrete. Compared to [Alani 2013] the slab deformed under the centre loading by 6 mm which is similar to our slab deformations for FRC. [Sorelli 2006] showed that plain concrete had maximum load capacity of 200 kN for a slab of 150 mm under the deformation slightly larger than 1 mm, whereas the maximum load was sustained by steel fibre reinforced concrete by 255 kN under a deformation of 3 mm. So for our experimental results, since the slab is thinner, the load capacity is lower but consistent and the deformation is higher compared to other results. After the yield of slabs, the plain concrete graph shows sudden failure with reduced load under negligible deformation. This brittleness is not observed in fibre reinforced slabs which show large displacements even after the ultimate load due to residual strength provided by fibres.

5 SUMMARY

The cube strength of rice and wheat straw FRC was 79% and 89% respectively. Similarly the compressive strength test done on agriculture fibres showed that the compressive strength was 66% and 83%, respectively. The ultimate slab load slightly decreased to 19.6 kN for RSFRC to 19.6 kN. But there is an increment of 23.5 kN for WSFRC compared to plain concrete ultimate load capacity of 20.3 kN. The energy absorption showed significant improvement by 19% and 60% rise in capacity of RSFRC and WSFRC compared to plain concrete.

This investigation shows that the use of rice and wheat fibres with contents of0.5% by volume of concrete can enhance the load carrying capacity and energy absorption of the concrete. The numerical data from the experimental tests are similar to steel and polypropylene fibres.

The post-cracking behaviour of agriculture fibres was excellent in comparison to plain concrete and has a good post-peak properties over the entire deflection range. The residual flexural tensile strength and energy absorption indicate that agricultural fibres supplement the weakness of concrete well in comparison to other fibres.

These results pave the way for agricultural wastes towards industrial applications in the most economical and sustainable way. The authors present substantial investigation results and the test data for both physical and mechanical properties of fibres and their behaviour with concrete. Although several investigations could be carried out to further verify the fibre properties and enhance their deficiencies, this paper emphasises that rice and wheat can be an excellent replacement of synthetic fibres in fibre reinforced concrete applications.

6 ACKNOWLEDGEMENTS

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