Advancements in Civil Engineering and Architecture

Editor: Volkan Kahya



Volume 2: Architecture

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Volkan Kahya
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PRODUCTION OF BANANA WASTE FIBER CEMENT COMPOSITE

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Abstract

Achieving higher strength/weight performance index as a key challenge for new structures necessitates the design of lightweight building materials having adequate properties. However, lightweight materials may weaken in terms of mechanical strength. The thin and lightweight materials are reinforced with fibres to improve tensile strength, impact resistance and decrease brittle fracture behaviour. Fibre-reinforced composites are used in architecture as interior/exterior wall panels, corrugated/plain slabs, roofing tiles, mortars and pre-manufactured components etc. Adobe blocks, reinforced concrete, fibre-reinforced mortars, carbon/glass fibre-reinforced cement/polymer/gypsum wall panels are commonly used in architecture. Glass/steel/carbon and polymeric fibres such as polypropylene/polyethylene/nylon having different tensile strengths (70-3600 MPa) are various fiber types. However, production of these fibers is energy-intensive, expensive, and may cause negative effects on the environment. Thus, in recent years, researchers tend to use natural vegetable/cellulose fibers due to their wide availability at relatively low cost, bio-renewability, biodegradability, non-hazardous nature and allowing the development of more sustainable construction materials.

Over 10 million hectares of banana plantation exist worldwide. There is approximately 50.000 decare of banana plantations exist in Anamur and Bozyazı regions of Turkey, and 350.000 tonnes of bananas are cultivated per year. Banana cultivation produces a huge amount of waste. Only in Anamur and Bozyazı in Turkey, approximately 17.500 tonnes of banana waste is generated in one crop season. Each tonne of this waste have been left to decompose and emits approximately half-tonne of CO_2 per year.

There are several studies regarding with the physical and mechanical properties of banana fiber reinforced cement/polymer composites. These studies reveal that the addition of banana fibres improve the tensile/flexural strengths and the ability to resist cracking and spalling of the composites. Most of these studies are about the influence of various fibre proportions on the properties. However, the experimental investigation of the influence of various banana fibre length on the properties of the banana fibre-reinforced composites are limited. The effects of banana fiber length in epoxy, polyester composites and compressed earth blocks have been studied by the researchers. Hence, to increase the commercial and ecological added value of banana-waste of Turkey and to find out the possibility of banana fibre use as a dispersed phase in a cement composite, this research investigates the influence of the fiber on the behaviour of the cement composite. Strand fibers were reduced by two different mechanical methods and the influence of fibre length was investigated. The matrix consisted only of Portland cement paste so as to have no interference of aggregates on adherence between the fibres and matrix. The fibre content was 4% by dry mass of the cement. The results demonstrated that banana fiber, compared to non-fiber-reinforced cement-based materials, decreased the density, increased the flexural strength and controlled the initiation and growth of the cracks. Because the thickness swelling was lower than 2%, density, flexural strength and modulus of elasticity were higher than 1g/cm^3, 4 MPa and 3000 MPa respectively, the banana fibre-reinforced cement-based composites were found suitable as a building material in architecture.

Keywords: Waste banana; fiber; cement, composite; material; architecture

1. Introduction

Recent innovations in lightweight construction systems necessitate the design of lightweight building materials with adequate properties. However, lightweight building materials may have low mechanical strength. Especially, when a lightweight material is used as a wall panel having the height and length greater than its

thickness, fibre reinforcement is required to improve the tensile strength, impact resistance and to decrease brittle fracture behavior. The main objectives to achieve fibre-reinforced composites with adequate mechanical properties are: obtaining adequate porosity matrix; dispersing the fibres homogeneously in the matrix; providing high adherence between the matrix and the fibers.

Fibre-reinforced composites such as reinforced concrete, carbon/glass fibre-reinforced cement/polymer/gypsum interior/exterior wall panels, corrugated/plain slabs, roofing tiles, fibre-reinforced mortars, and pre-manufactured components are commonly used in architecture. Glass/steel/carbon and polymeric fibres such as polypropylene/polyethylene/nylon having different tensile strengths (70-3600 MPa) are various fiber types. However, production of these fibers depletes natural resources, is energy-intensive, expensive, and may cause negative impact on the environment. Thus, in recent years, there are a lot of efforts to replace the artificial fibers with alternative natural vegetable/cellulose fibers (agricultural by-products) which are annually renewable, abundantly available (Reddy and Yang 2005) without current economic value (Arsène et al. 2003), biodegradable, non-hazardous to the nature and allow the development of more sustainable and low-cost construction materials. The Technology Road Map for Plant/Crop Based Renewable Resources 2020 targets to achieve 10% of basic chemical building blocks from plant derived sources until 2020 and to increase this rate up to 50% until 2050 (The technology roadmap for plant/crop-based renewable resources 2020). Sugarcane, pineapple, banana, coconut, corn, sisal, wheat, sorghum are commonly used plant derived fibres in low-cost construction materials.

Banana is one of the oldest cultivated plants in the world. Having 300 various species, banana belongs to the Musaceae family (Venkateshwaran and Elayaperumal 2010). As a ligno-cellulosic fiber, banana is a bast fiber consisting of cellulose micro-fibrils in an amorphous matrix of lignin and hemicellulose (Mukhopadhyay et al. 2008). It has approximately 0.08 and 0.25 mm diameter (Satyanarayana et al. 1990), 1.35 kg/m^3 density and 600 MPa tensile strength (Murali Mohan Rao and Mohana Rao 2007). Over 10 million hectares of banana plantation exists worldwide (Mostafa and Uddin 2015). There is approximately 50.000 decare of banana plantations exist in Anamur and Bozyazı regions of Turkey, and 350.000 tonnes of bananas are cultivated per year. Banana cultivation produces a huge amount of waste. Only in Anamur and Bozyazı in Turkey, approximately 17.500 tonnes of banana waste is generated in one crop season. Each tonne of this waste which left to decompose emits approximately half-tonne of CO_2 annually (Mostafa and Uddin 2015).

Current reports in the literature refer to the characterization of the banana fibres (Mukhopadhyay et al. 2008; Jústiz-Smith et al. 2008), their performance in polymer-based composites (Pothan et al. 1997; Murali Mohan Rao and Mohana Rao 2007; Venkateshwaran and Elayaperumal 2010; Venkateshwaran et al. 2011), the effects of banana fiber content on the properties of cement-based composites (Zhu et al. 1994; Savastano et al. 2000) and fibre-reinforced concrete (Chacko et al. 2016; Gopinath et al. 2017; Prasannan et al. 2018), curing conditions of banana-fiber reinforced cement mortar (Coutts 1990), and durability of banana-fiber cement composites (Savastano et al. 2001). These studies reveal that the addition of banana fibres improve the flexural strength and the ability to resist cracking and spalling of the composites. However, the experimental investigation of the influence of fibre length on the properties of the banana fibre-reinforced composites is limited. Venkateshwaran et al studied the effects of banana fiber length in epoxy composite (Venkateshwaran et al. 2011). Pothan et al. studied the effects of fiber length on the mechanical properties of the banana-polyester composite (Pothan et al. 1997). Mostafa et al. studied the effects of banana fiber with various fibre length on the compressive and flexural strength of compressed earth blocks (Mostafa and Uddin 2015). The current research investigates the influence of the fiber length on the behavior of the cement-based composite in order to increase the commercial and ecological added value of banana-waste of Turkey and to find out the possibility of banana fibre use as a dispersed phase in cement composites.

2. Materials and Methods

The banana fiber is a waste product of banana cultivation and was obtained from Bozyazı, Anamur region in Turkey. It presents a hydrophilic nature due to its OH^- groups existing in cellulose and hemicellulose. Pectin and waxy substances on the surface of the fibers prevent hydroxyl groups reacting with matrix. The impurities on the surface of the fibers decrease the fiber–matrix adhesion and cause incompatibility in the composite material. Thus, in order to overcome this problem, removing non-cellulosic components on the surface of the fibers is necessary by means of the physical and chemical surface treatments (Erdoğan et al. 2016). Alkali treatment is one of the most effective surface treatment method commonly used in natural fibre-reinforced composites (Rokbi et al. 2011). In the current study, the banana fibers were subjected to alkali treatment in the following steps: (1) immersing the fibers in a container with 5% NaOH aqueous solution for 2 h at ambient temperature;

(2) washing them in tap water to remove the residues; (3) neutralizing with 2% acetic acid solution; (4) washing again in tap water in order to remove the acid traces. After alkali treatment, the fibers were dried up to constant weight in an oven at a temperature of 60°C and cooled to ambient temperature at a cooling rate of 0.5°C/minute in order to avoid thermal shock of the fibers (Frazao et al. 2018).

Banana fibers were processed by two different mechanical methods. In the first method, longitudinal slices were manually scraped from the banana stalks and alkali treatment mentioned above was applied afterwards. After the slices were dried, they were cut with a sharp knife on average 15 mm in length, and 3 mm in width. This dimension complies with the required sizes of the fibrous wood particles in order to produce cement bonded particleboards according to (ISO 8335 1987). The specimens produced by this type of fibers are called as staple-fibre reinforced cement composites and codded as (S-FRCC) in the study.

In the second method, banana stalks were fed to fiber extracting machine consisting of rollers (Fig. 1a). When the fiber extracting machine runs, water of the banana stalk was extracted and the fibers were obtained (Fig. 1b). This method which is called as mechanical treatment (refining) increases the surface area of the fibres (Tonoli et al. 2009). After alkaline treatment, the dry fibers were cut with a guillotine scissor. The dimensions of the fibers were smaller than those of the first method. Moreover, they look like pulp fiber form with their lengths between 0.5-5 mm. The specimens produced by the pulp fibers are called as pulp-fibre reinforced cement composites and codded as (P-FRCC) in the study.



(a) (b)

Figure 1. (a) The fiber extracting machine consisted of rollers; (b) The fibers extracted from the machine

Ordinary Portland cement (OPC) 42.5 conforming to the (TS EN 197-1 2012) was used. Since the addition of pumice aggregate to the gypsum-glass fibre composite affects adversely the fiber-matrix adherence (Ersoy 1985); in the current study, no aggregate was added to the Portland cement-banana fibre composite. The mixture was produced in a room under controlled laboratory conditions (20±2°C, 70±5% RH). The fibre content was restricted to 4% by dry mass of the cement. The water/cement ratio was kept constant as 0.50. All dry components were thoroughly mixed and then the water was added. The consistency of the fresh mortar was measured by flow table test according to the (TS EN 1015-3 2000). The fresh mixture was cast to standard steel prism in the dimensions of 40x40x160 mm. After 24 h, the specimens were demoulded and were sealed in a plastic bag to cure at saturated room temperature for the following seven days. The specimens were then allowed to air cure at 20±2°C (RH=70±5%) until the age of 28 days. The cured specimens are given in Fig. 2.

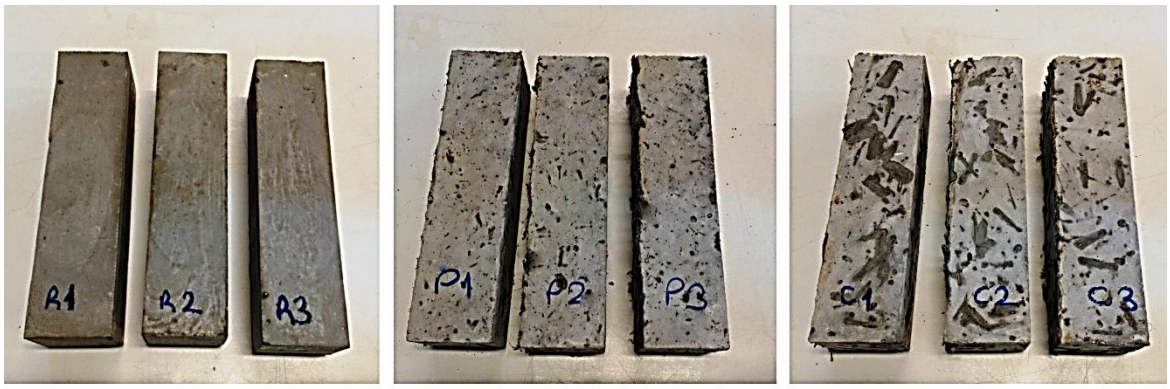


Figure 2. The specimens produced in the current study: (a) reference cement binder; (b) pulp-fiber reinforced cement composite (P-FRCC); (c) staple-fiber reinforced cement composite (S-FRCC)

The specimens were tested for unit weight according to the (TS EN 1015-10 2001), water absorption under the atmospheric pressure according to the (TS EN 13755 2009), dynamic ultrasound velocity/ Young's modulus of elasticity according to the (TS EN 14579 2006), swelling in water according to the (ISO 8335 1987), flexural and compressive strengths according to the (TS EN 196-1 2009). The properties presented in Table 1 are averages of the three specimens.

Table 1. Properties of banana fiber reinforced cement composite

Specimens	Unit Weight (g/cm^3)	Water Absorption by Weight (%)	Thickness Swelling (%)	Ultrasound Velocity (km/s)	Flexural Strength (MPa)	Compressive Strength (MPa)	Young's Modulus of Elasticity (MPa)
ISO 8835	min 1.00	-	max 2.0	-	min 9.0	-	min 3000
Reference	1.89	12.41	0.19	1.81	3.07	24.33	6191
P-FRCC	1.61	20.01	0.32	1.74	9.65	17.28	4874
S-FRCC	1.50	23.12	0.46	1.51	9.01	7.52	3420

3. Results and Discussion

3.1. Physical Properties

The physical properties of each type of banana fibre-reinforced cement composite compared to the reference sample are given in Fig. 3.

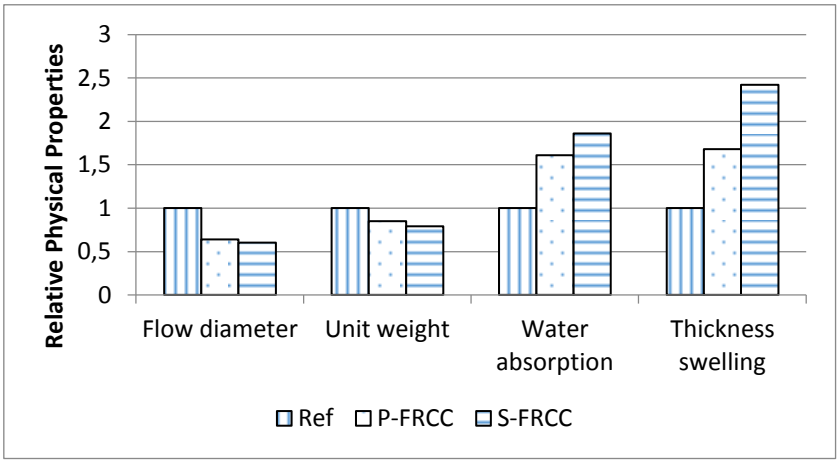


Figure 3. Relative physical properties of banana fibre-reinforced cement composites compared to that of the reference sample

The flow table test value of P-FRCC and S-FRCC decrease 0.64 and 0.60 times, respectively compared to that of the reference sample. Such behaviour is a result of moisture absorption by hydrophilic natural fibres. Due to their hydrophilic character, the fibers absorb some amount of mixing water and the workability of the composites reduce. Similar results were found by other researchers (Onuaguluchi and Banthia 2016; Hospodarova et al. 2017). According to Alvarez et al. the high content of hydroxyl group in cellulose increases the moisture absorption of plant-based fibres (Alvarez et al. 2003). The workability of both types of fibre-reinforced cement composite is close to each other. However, using of pulp fibres facilitates homogeneous distribution of the fibres in the cementitious matrix.

As it can be seen in Table 1 and Fig. 3, densities of P-FRCC and S-FRCC are lower (0.85 and 0.79 times, respectively) in comparison to the control sample. The density of S-FRCC is 0.93 times lower than that of P-FRCC. This result indicates that the density of the composite reduces as fiber length and width increases. Staple fibres lead to the disruption of homogeneous fiber distribution and results in larger and higher void content (Fig. 2c and 4c). Similar results were mentioned by other researchers (Khedari et al. 2001; Zuraida et al. 2011). On the other hand, P-FRCC specimens have more homogeneous fiber distribution and less visible voids than S-FRCC (Fig. 2b and 4b).

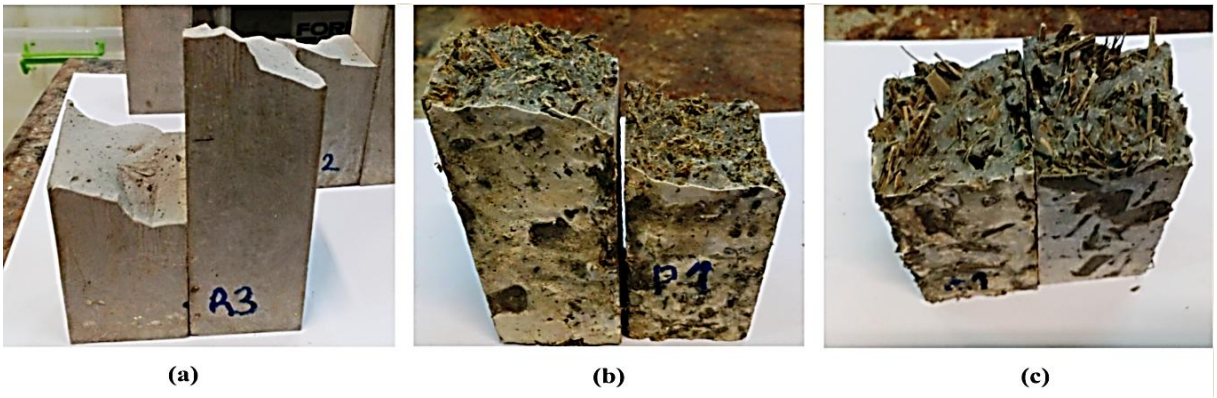


Figure 4. The view of the specimens after flexural strength test: (a) reference cement binder; (b) pulp-fiber reinforced cement composite (P-FRCC); (c) staple-fiber reinforced cement composite (S-FRCC)

The water absorption ratio of the samples is in conformity with the density results. Water absorption increases with decreasing of the density as a result of pore volume increase. The water absorption ratio of P-FRCC and S-FRCC are higher (1.61 and 1.86 times, respectively) than that of the control sample due to the tendency of the hydrophilic character of the natural banana fibres. On the other hand, staple fibers tend to increase the percentage of water absorption compared to pulp fibre reinforced composites. Consequently, the larger the fiber size, the higher the water absorption ratio. This result also conforms with the findings of Li et al. (Li et al. 2000) and Zuraida et al (Zuraida et al. 2011).

Materials having large dimensional change due to their high level of swelling and shrinkage may cause several detrimental effects in a construction. Thus, the amount of swelling of the specimens after 24 hours in water tank should be lower than 2% according to the ISO 8335 (ISO 8335 1987). The swelling thickness values of the Reference, P-FRCC and S-FRCC (0.19, 0.32, 0.46%, respectively) comply with the standard requirement. S-FRCC shows the highest swelling thickness due to the highest water absorption ratio of its fibre shape, which makes it to be used more carefully under relatively high humidity conditions. The water absorption leads to a volume change of the fibers, resulting in the development of internal micro cracks in the matrix (Dhakal et al. 2007). Thus, the moisture absorption of plant-based fibres may have a negative effect on the mechanical characteristics of the final composites.

3.2. Mechanical Properties

The mechanical properties of each type of banana fibre-reinforced cement composites compared to the reference sample are given in Fig. 5.

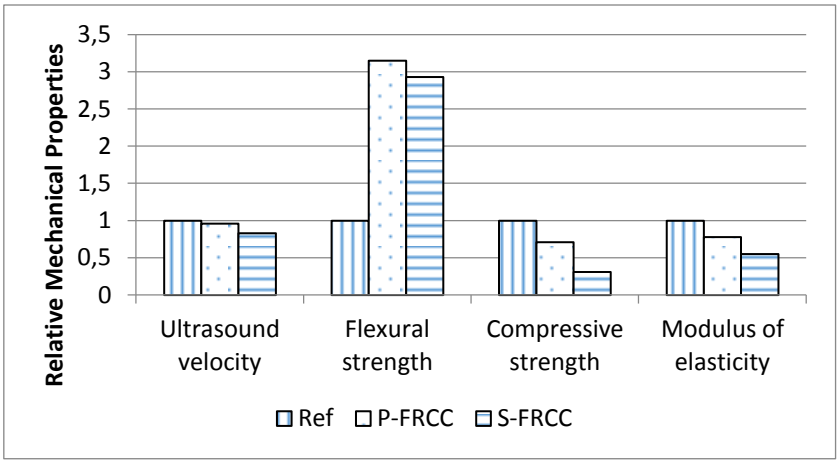


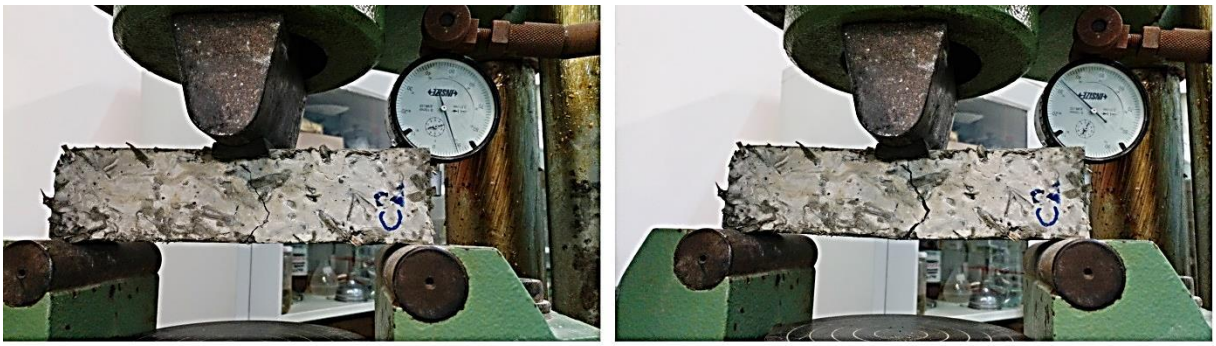
Figure 5. Relative mechanical properties of banana fibre-reinforced cement composites compared to that of the reference sample

The addition of lightweight banana fibres leads to increase the porosity and water absorption ratio which may adversely affect the mechanical properties. The flexural strength of the P-FRCC and S-FRCC are substantially increased (3.15 and 2.93 times, respectively) which is in conformity with the other research results (Khorami and Ganjian 2011). On the other hand, the compressive strengths of P-FRCC and S-FRCC decrease 0.71 and 0.31 times, respectively according to the reference sample as expected. The ultrasound pulse velocity of S-FRCC is 0.86 times lower than that of P-FRCC, which means that S-FRCC have higher porosity in their structure. Moreover, 0.70 times lower modulus of elasticity of S-FRCC compared to P-FRCC means that staple fibers show lower resistance against deformation loads. Likewise, similar changes are seen in the compressive and flexural strength values.

The bonds between the natural fibre and cement result from the mechanical interlocking between the fibre surface and cement hydration products and chemical bonds (mainly hydrogen bonds) (Bentur 2000; Savastano et al. 2005; Tonoli et al. 2013). In order to enhance the bonds among fibre and cement matrix, mechanical treatment (refining) can be applied to the fibres. After mechanical treatment, fibrillation of the fibre surface occurs (Coutts 2005) and the surface area of fibres increase, which make them more reactive with cement (Tonoli et al. 2009). In the current study, the compressive and flexural strengths of P-FRCC have 2.30 and 1.07 times, respectively higher than those of S-FRCC. Indeed, the mechanical properties of the specimens are inversely proportional to the fiber length and width. Similar results have been reported by other researches. (Khedari et al. 2001; Zuraida et al. 2011). The reason of this finding is that the mechanical treatment of banana fibres by fiber extracting machine and guillotine scissor may: (1) increase the specific surface area of the fibres; (2) enhance the physical bonds among fibre and cement matrix; (3) improve the fibre to matrix interface; (4) consequently improve the microstructure and mechanical performance of the composite. In addition, the homogeneous fibre dispersion is the most important factor to enhance the mechanical properties (Amuthakkannan et al. 2013) of the composite materials. So, the lower mechanical properties of S-FRCC compared to P-FRCC is an expected result.

Visual observation during the flexural test revealed that sudden failure behavior was observed in the reference cement paste, in which the material appeared to fail in a brittle manner. For specimens reinforced with banana fibres, after the first crack was observed (Fig. 6a) while the load was gradually increasing, the crack grew slowly while some of the fibers still linked to the two sides of cracks. This finding proved that the resistance to full separation of the material is provided by the fibers bridging across the cracked surface (Fig. 6b).

Table 1 also presents the comparison of the banana fiber reinforced cement composites with cement-bonded particleboards (ISO-8335 1987) in terms of required physical and mechanical properties. According to this comparison, because of thickness swelling is lower than 2%, and density, flexural strength and modulus of elasticity are higher than 1g/cm^3, 4 MPa and 3000 MPa respectively, waste banana fiber reinforced cement composites, either in pulp or staple form, fulfill the requirements of the standard, and thus, it may be used instead of cement-bonded particleboards in the building sector.



(a) (b)

Figure 6. (a) The crack formation on the banana fiber-reinforced specimen at flexural strength test; (b) Bridging effect of fibres against sudden failure of the banana fiber-reinforced specimen

4. Conclusion

Following conclusive remarks can be stated from the obtained results:

- Banana waste fiber extracted from the banana cultivation of Anamur region in Turkey may be used as a reinforcement material in cementitious composites.
- The addition of banana waste fibres considerably increases many of the engineering properties of the cement matrix, especially the flexural strength. On the other hand, especially staple type of banana fibres negatively affects the compressive strength of the matrix because of creating more voids.
- Pulp-fiber reinforced cement composites show better physical and mechanical characteristics than staple-fiber reinforced cement composites due to their higher mechanical interlocking between the fibre surface and cement hydration products.
- Banana waste fibers, either in staple or pulp form, show a satisfactory adherence with cement matrix. The fibers may be used in various cementitious matrix which is more environmentally-friendly compared to cement. The durability properties of the produced composites should be considered as well.
- Banana fiber-reinforced cement composite fulfill the requirements of the ISO-8335, so, it may be inferred that the aforementioned composites could be used as cement-bonded particleboards in architecture.

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