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An experimental study on the flexural performance of agro-waste cement composite boards

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Abstract

Worldwide, asbestos fibers utilized in fiber cement boards, have been recognized as harmful materials regarding the public health and environmental pollutions. These concerns motivate the researchers to find the appropriate alternatives to substitute the asbestos material towards the sustainability policies. In this paper, the applicability of asbestos replacement with three types of agricultural waste fibers, including bagasse, wheat and eucalyptus fibers were experimentally investigated. To this end, the flexural behaviour and microstructure of cement composite boards made by addition of 2 % and 4 % of waste agricultural fibers in combination with and without 5 % replacement of silica fume by mass of cement were evaluated. The results of this study attested the applicability of utilized waste agricultural fibers in production of cement composite boards by improving the flexural and energy absorption characteristics, more or less, depending on the type of fibers. Moreover, it is found that application of silica fume in production of cement composite boards led to an increase in flexural strength.

Keywords: *Cement composite board, Waste agricultural fibers, Flexural strength, Toughness.*

1. Introduction

The most common use of asbestos was within asbestos-cement pipe, flat and corrugated asbestos cement roof sheets typically used for outbuildings, warehouses, garages and so on. Most of the rest was used in brake linings and pads. Asbestos dust exposures from the use, disposal and replacement of these products can be quite significant from the public health anxieties. Considering the injurious effects of asbestos and environmental pollutions, in the early 1970s, a global effort was initiated to legislate regarding the emission of asbestos from a wide range of products. The leading countries inhibit the application of asbestos materials in their construction related industries are the ones trying to reach the most top levels of sustainable development [1-4].

Many research studies demonstrated the suitability of cellulose fibres as one of well candidates for asbestos fibre replacement in production of the cement composite using the Hatscheck process.

These findings are supported by their appropriate individual properties, accessibility of such fibers and economical aspects [5-8].

From the sustainability viewpoints, environmental and social-heath concerns, replacing the asbestos with vegetable waste fibers have multi-aspect advantages. The reduction of asbestos usage is the most important advantage and on the other hand, the possible application of agricultural-waste fibers as reinforcing component could be efficiently reduced the by-product wastes. Besides, the revolution in the agricultural sector has resulted in substantial increases in the quantities of agricultural by-products and wastes of different types. In addition to reed, straw, corn cob and stalk, many other non-traditional materials, such as coir, bagasse, and wheat fiber, ground nut husk, rice husk and jute sticks, are obtained as agro-wastes. They are mostly disposed by incineration or used as fuel, although their calorific value is much lower than that of coal [9]. Accordingly, the application of the aforementioned agro-wastes fibers could be beneficial in this view.

Nowadays, there can be found many research works which have been examined the application of such waste fibers in construction products. An attempt has been made by Aggarwal [9] to convert bagasse by-product into useful eco-friendly cement-bonded composites, which can be used for various internal and external applications in buildings.

Coutts and Ridikas [10] conducted a relatively comprehensive study on the evaluation of refined wood fiber to produce asbestos-free cement sheets. The modulus of rupture, toughness, moisture effect, and effect of refining were studied on the produced samples. They found that the asbestos can be replaced totally for modified

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wood fibers in commercial production of fiber -cement sheeting.

Savastano et al. [11] evaluate the compressive strength and modulus of rupture of furnace slag based cement composites reinforced by eucalyptus pulp fiber, coir, and sisal fiber. The results of the study emphasized that the performance of tiles of size 487×263×7 mm made with these composites is in accordance with the requirements of international building codes, with maximum load higher than 450 N, in wet conditions.

Thermal properties of cement composites reinforced by vegetable bagasse fibers were studied by Onésippe et al. [12]. The results revealed that adding refined bagasse fibers reduces the thermal conductivity of produced composites and yields a weaker specific heat in comparison with composites made with unrefined bagasse fibers. Moreover, they found that the more fibers, the lighter specimen; lower its thermal conductivity and lower its specific heat.

The effects of laboratory scale accelerated aging exposures on changes in physical and mechanical properties of commercially produced cellulose fibers reinforced cement composites were investigated by MacVicar et al [13]. The results of the study showed that the aging test based on artificial carbonation was more effective in simulating natural aging performance of the composites, while the freeze-thaw cycling method failed to induce significant aging effects on the composites even after 21 cycles.

Karade [14] reviewed the properties of various kinds of lignocellulosic wastes generated from different sources such as agriculture, construction, wood and furniture industries. He attempted to give details about the various restraints like compatibility of these wastes with cement, their toxicity, and limitation of composite strength. He underscored the use of pre-treatment or application of chemical accelerators to enhance the properties of the mentioned fibers. Moreover, the results clarified the similar performance of the mentioned lignocelluloses in the cement matrix which promoted by their dosage.

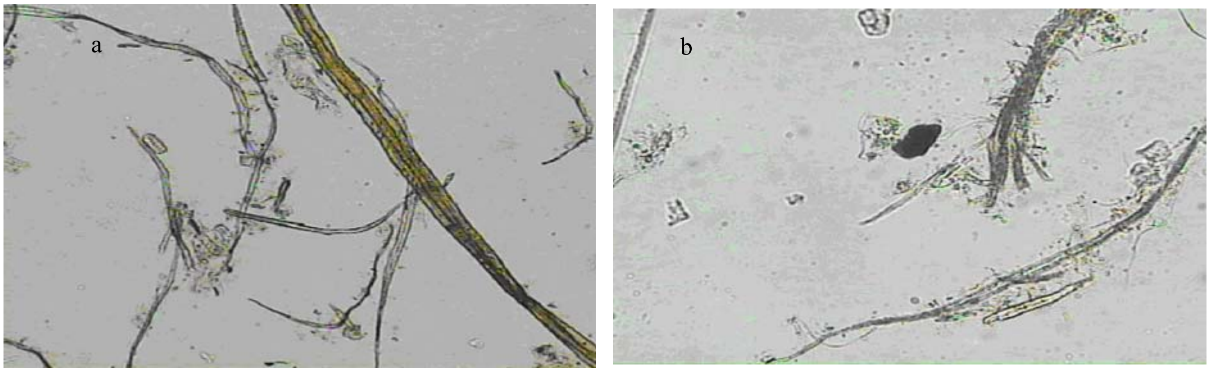
Considering the published research works, reveals the importance of flexural response of composite cement boards reinforced by natural fibers and also their consistencies with cement matrix. To this means, the paper is dealt with finding an appropriate proportion to produce cement composite boards (CCBs) with blending of cement, silica fume, and natural fibers including wheat, bagasse, and eucalyptus.

2. Materials and Methods

2.1. Pre-processing of fibers

As the major parts of the fibers obtain from original agricultural wastes, they should be pre-proceeded and refined. It should be noted that refinement or beating of the fibers, fibrillates the fiber surface [15] which leads to increase of the surface of fiber and thus fiber–cement bonding will be enhanced. Accordingly the fibers were subjected to refinement process to ensure a good fibrillation on their surface.

Fibrillation of fibers can be divided into two parts, external and internal fibrillation. External fibrillation which is related to surface treatment for bagasse fibers is shown in Figure 1 as microscopic pictures of fibers before and after refinement process.



(a) (b)

Fig. 1 Surface treatment effects on bagasse fiber surfaces (b); (a) before and (b) after refining

The fibrils attached to the surface of fibers widely vary in size and shape. The fibrils formed on the outer surface of the fibers, have significant role in developing the mechanical bonds. In contrary to external fibrilation, internal fibrillation effects are difficult to observe with a microscope, but they can be considered like a piece of rope. Rope is a helical wrap of strands which themselves are helical wraps of fibers. If one twists a rope in the direction of the helical wrap the rope becomes stiffer; likewise if the twist is in the opposite direction the rope unwinds (or delaminates) to open up the structure and becomes 'floppy'; such is the case with internal fibrillation. The main effect of internal fibrillation is to increase the flexibility of fiber and swelling. The last stage of external fibrillation is the peeling off of the fibrils from the fiber surface with the formation of fines. Depending on the forces acting on the fiber during refining process, some amounts of the fibrils will be removed from the surface of the fiber. Due to unfavourable effects of these substances, the fibers should be sieved before use. Further refining leads to fiber shortening which should be avoided. An indication for shortening of the fiber is observable changes in the particle size distribution, which is a result of the cutting action of the blades or discs in the machinery on the single fiber.

2.2. Materials

Physical properties of used agro-waste fibers are summarized in Table 1. All fibers submerged in water for 24 hours before using in the mixture and then were refined. The refining process fibrillated them as demanded. After then, the prepared fibers were sieved by sieve No. 100 (150 micron) to separate fines and dust which were less than 150 micron in dimensions (Figure 2). The fibers retained on the sieve were used to make the specimens.

Table 1 Physical properties of utilized fibers

Type	Average length$^+$ (mm)	Average diameter (mm)	Aspect ratio
Bagasse	1.303	0.348	3.744
Eucalyptus	1.12	0.480	2.3
Wheat	1.238	0.345	3.588

+ Average length and diameter of 50 fibers.

Fig. 2 Preparation of fibers for specimens

Locally available Type II Portland cement conforming ASTM C150 [16] and silica fume (SF) were used as supplementary cementitious materials (SCM). The chemical and physical properties of these materials are presented in Table 2. As seen, the aspect ratios of fibrillated fibers are in an approximate range of 2.3 to 3.7 which are very low ratio. It was known [15,17] that the fiber aspect ratio (l/d) plays a significant role in the performance of randomly distributed fiber composites. However, in this research, due to the manual fibrillation, this ratio remained in the aforementioned range.

Table 2. Chemical and physical properties of cementitious materials

Compound/property	Cement	Silica fume
Calcium oxide (CaO)	61.32	2.25
Silica (SiO_2)	21.68	85.86
Alumina (Al_2O_3)	4.85	2.0
Iron oxide (Fe_2O_3)	4.40	0.80
Magnesia (MgO)	2.60	
Sulfur tri oxide (SO_3)	--	0.11
Tri calcium silicate (C_3S)	40.57	--
Di calcium silicate (C_2S)	31.55	--
Tri calcium aluminate (C_3A)	1.90	--
Insoluble residue, %	0.72	5.48
Autoclave expansion, %	0.3	--
Loss on ignition, %	1.74	1.53
3 days compressive strength, kg/cm^2	14.4	--
7 days compressive strength, kg/cm^2	21.9	--
28 days compressive strength, kg/cm^2	32.1	--
Initial setting time, min	146	--
Final setting time, min	242	--
Specific surface, cm^2/g	2800	--
Moisture content, %	--	0.50

2.3. Mix proportion

The major parameters considered to study were the type and percentage of fibers for reinforcing the CCBs. The effect of silica fume as supplementary cementitious material, were also studied in this research.

In order to recognize the effect of increasing fibre content on flexural performance of the specimens, preliminary, many trial specimens were made with different amounts of fibre content (i.e. 1, 2, 3 and 4% by mass of cement). This preliminary study reveals that the application of more than 4% of fibres, lead to non-uniformity of product and on the other hand, as the effect of increasing fibre content followed an special trend as would be discussed in this paper and to avoid confusing and cluttered the graphs, just the results of specimens reinforced by 2 and 4 percent fibres were reported in this paper.

Table 3 Mix proportions*

Fiber type	Code	Cement (g)	Silica fume (g)	Fiber (g)	Combination
--	Reference	200	--	--	No fiber used
Bagasse	BCCB2	200	--	4	2% Bagasse
	BCCB4	200	--	8	4% Bagasse
	BCCB4-M5	190	10	8	4% Bagasse +SF
Wheat	WCCB2	200	--	4	2% Wheat
	WCCB4	200	--	8	4% Wheat
	WCCB4-M5	190	10	8	4% Wheat +SF
Eucalyptus	ECCB2	200	--	4	2% Eucalyptus
	ECCB4	200	--	8	4% Eucalyptus
	ECCB4-M5	190	10	8	4% Eucalyptus +SF

*Amount of water in slurry for all specimens was 450 gr.

Table 3 shows the mixture constituents and proportions used for the study. As it can be observed, in three mixtures, silica fume, 5% by mass of cement was replaced.

2.4. Experimental procedure

Water to cement ratio of 2.25 was used to prepare the CCBs. A rotary mixer with horizontal blades was used. Initially, in order to unravel the fibers from each other for better dispersion in the cement paste, they were subjected in a mixer with high speed (2000 rpm) for 5 min. Then the cement, water and fibers (if applicable) were added to mixture and stirred for another 5 min. The prepared homogeneous mixture poured into the mould to form sheets of size 70×800×180 mm for all mix proportions (Figure 3).

Fig. 3 Equipments for preparing the specimens

Excessive water was sucked from the specimens using a vacuum pump (0.9 bar power). During this procedure, a 10 kg load was applied on specimens for better drainage and compaction. Then, the specimens were demoulded, dried for 1 hour in Laboratory environment and finally cured in steam cabinet (RH=100%) for 28 days.

3. Tests

3.1. Tests on fibers

The tensile strength of agro-waste fibers was measured and reported in Table 4.

Table 4 Tensile strength of fibers

Type	Tensile strength* (MPa)			
	Min	Max	Average	Standard deviation
Eucalyptus	7	12	8	2.84
Bagasse	9	14	13	2.15
Wheat	4	8	6	2.65

* Average tensile strength of 20 fibers.

3.2. Tests on the cement boards

3.2.1. Flexural strength

Flexural strength of the flat CCB specimens of size 180×80×7 mm (Figure 4) were measured using three-point test setup according to BS EN 12467 [18]. This standard suggests five classes for flexural strength. According to this standard, minimum required flexural strength for cement composite board of group 2 is 7 MPa.

Fig. 4 Some prepared samples according to the EN12467 test method.

4. Results and Discussions

4.1. Flexural behaviour

According to EN 12467, the results of flexural strength test (or MOR: Modulus of Rapture) should be interpreted by calculating flexural stress as follow:

$$\sigma = \frac{3PL}{2BH^2} \tag{1}$$

where σ is flexural stress/modulus of rapture (MPa), P is the breaking load (N), L is the span of the simple supports (mm), B is the width of the specimen (mm), H is the thickness of the specimen (mm).

Flexural strength of each group is only a number that can be calculated by the average of all specimens in each group, while flexural behaviour contains more details of loading stages and clarify function of fibers in matrix. For this reason, flexural behaviour of some selected specimens is investigated and at the end of this section, flexural strength of specimens will be illustrated.

In each group, the flexural behaviour of a specimen being nearest to the average of the flexural strength (with the difference less than 10% through the mean and standard deviation less than 0.6 MPa) was selected as a representative of that group. Figures 5 and 6 are associated with different groups and compare the flexural behaviour of representative of each group with others. It should be noted that in these graphs, the deflection in the central point of the specimen were plotted versus flexural stress calculated with Eq. (1).

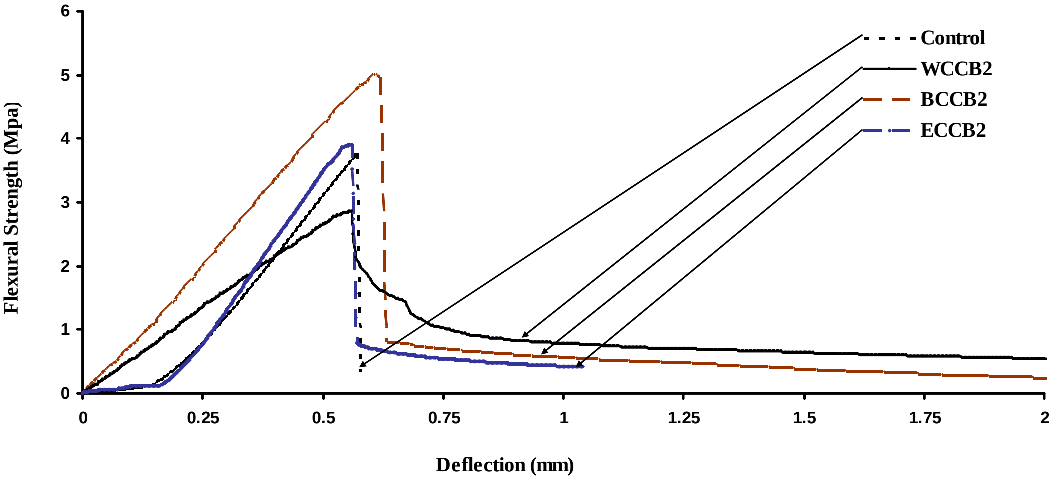


Fig. 5 Flexural behaviour of CCB with 2% fibers and compare with control specimen

Figure 5 presents the flexural behaviour of fiber cement boards for all groups with 2% agro-waste fiber content. As it can be observed, addition of 2 percent fibers leads to some changes in maximum flexural strength (MFS); however, ductility of the specimens is almost similar to each other and also they are still brittle as well as control specimen. MFS for the control specimen was measured as 3.7 MPa and for the specimens incorporating 2 % of bagasse, eucalyptus and wheat fibers were measured as 5 MPa, 3.9 MPa and 2.9 MPa respectively. It is considerable that except the specimen include wheat fiber, other specimens; in particular specimen with bagasse has experienced an increase in its flexural strength.

In order to identify the effect of increasing fiber content on flexural behaviour, similar graphs are plotted for the specimens reinforced by 4 % fibers as shown in Figure 6.

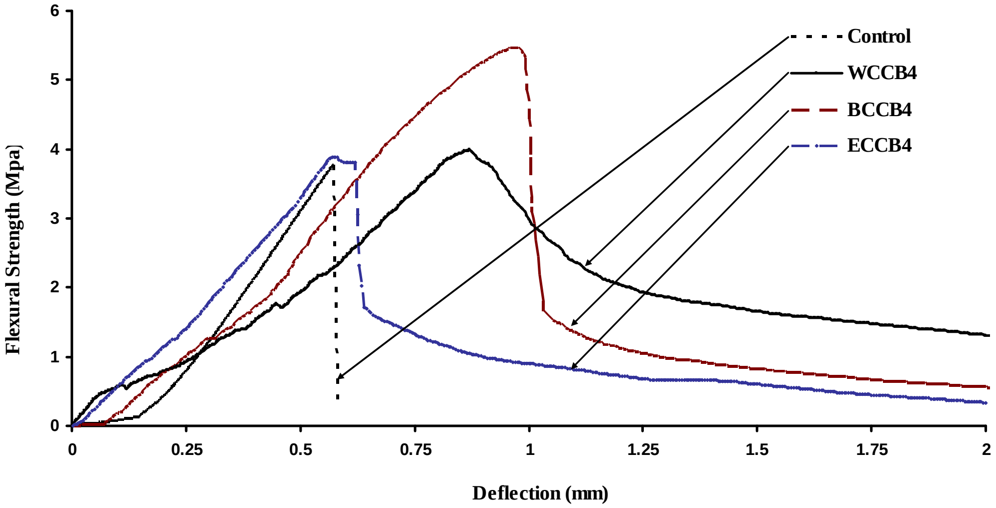


Fig.6 Flexural behaviour of CCB reinforced by 4% fibers and compare with control specimen

Utilizing 4 % of all types of fibers in production of CCBs, led to a significant improvement in flexural response as shown in Figure 6. Not only all groups have the MFS more than control ones but also their ductility has been also improved. Addition of 4 % of bagasse, eucalyptus and wheat fibers increased the MSF up to 5.46 MPa, 3.88 MPa, and 3.98 MPa respectively.

In comparison to the control specimen, increasing bagasse fibers content from 2 up to 4 percent enhanced the MFS up to around 33 and 45 percent respectively;

however, when utilizing similar content of eucalyptus led to only an improvement around 3.7 and 3.2% respectively. This trend for the case of wheat fiber is quietly different so that utilizing 2% of wheat fiber decreased the MFS up to around 24%, whereas application of 4% of wheat fiber led to 5.7 % increase in flexural response.

It can be deduced that the flexural strength and the ductility of CCB containing bagasse are more than other groups. After bagasse, the best flexural respond is related to eucalyptus and wheat incorporated specimens respectively.

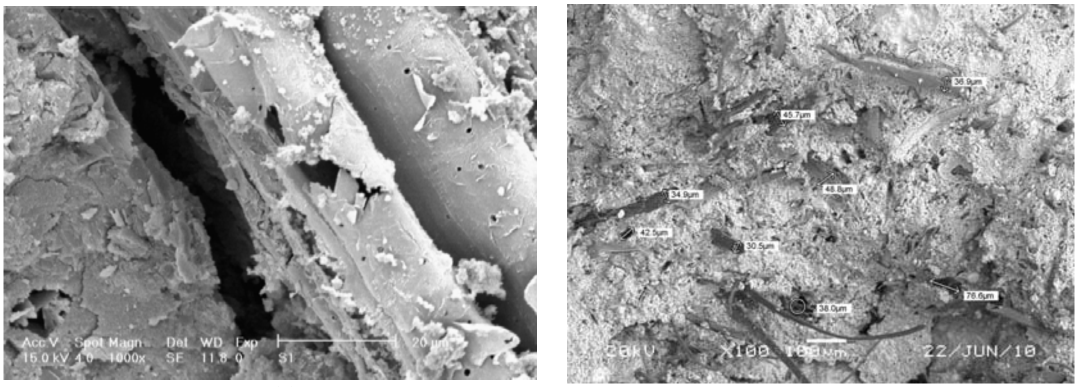
Increasing fibers content more than 4 percent creates disruption. Due to the lower specific gravity the fibers float on top surface of the slurry and this phenomena leads to insufficient homogeneity of the composite in a manner that the top surface of the composite fills with accumulated fibers. Therefore, making specimens with excess of 4% fiber content was ceased.

Better performance of the bagasse fiber can be attributed to the high tensile strength and high aspect ratio of the bagasse fiber rather than wheat and the eucalyptus fibers. High aspect ratio of the fiber leads to an increase in lateral surface area of the fibers contacting with the cement, hence bonding between the cement and the fibers increases. Also, the high tensile strength of the fibers causes a change in the mechanism of rupture from breaking fibers to pulling out the fibers from the matrix. This means that the bonding strength between the cement and the fibers controls the mechanism.

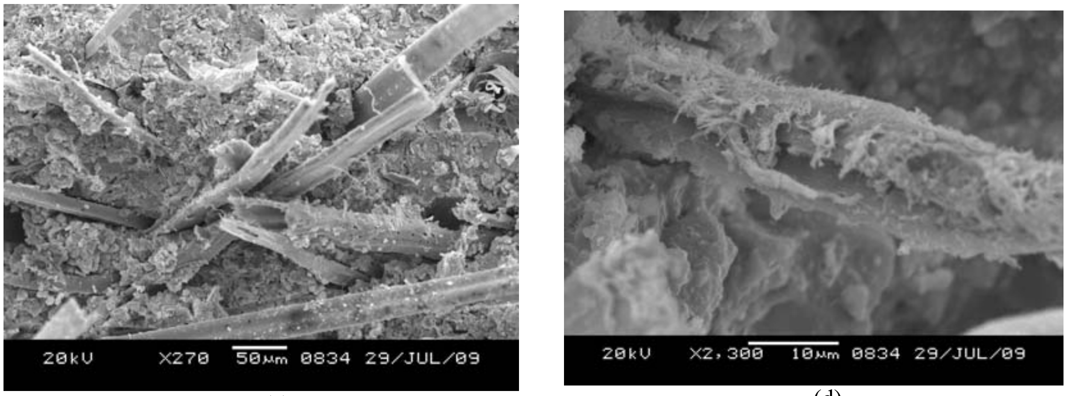
Flexural behaviour of the composite containing the wheat fibers illustrated in Figures 5 and 7 shows that adding 2 % of the fibers causes a reduction in the flexural strength (round 24%) compare to the control specimen, while increasing 4 % of these fibers enhance the flexural strength a bit more than control specimen (roughly 5.8%). Analyzing the broken pieces of the wheat-CCB specimens, showed that some parts of the wheat fibers couldn't disperse uniformly in the matrix and some of these fibers clamped together and accumulated in some points of the specimen. It means some areas of the specimens were left without fibers. This situation could promote the growing the initial cracks in these areas. When the amount of the fibers reached up to 4 percent, the fibers covered the whole of the composite, however; the "balling effect" still observed in some points of the composite. This means, a minimum amount of the fibers dispersed in whole areas of the composite.

Another point that can be deduced from Figure 6 is that applying 4% fiber content of the wheat or eucalyptus fibers causes an insignificant raise in MFS compare to the control specimen, however; its effect on energy dissipation (ductility) is considerable that will be dealt with in 4.3.

SEM pictures depicted in Figure 7, propose different mechanisms for rupture of wheat-CCB, eucalyptus-CCB and bagasse-CCB specimens. In the case of wheat-CCB specimens, a fiber breaking mechanism is governed while in the case of eucalyptus-CCB specimens fibers pulling out are mainly observed. The average and minimum tensile strength of the wheat fibers are 6 and 4 MPa respectively (Table 4). As it can be observed from Figure 6, as MFS of specimens reinforced by 4 percent wheat approaches to around 4 MPa, the specimens start gently to break. This behaviour might be attributed to some weak fibers with minimum tensile strength of 4MPa placed in the matrix which they reach to their maximum tensile strength and then break and the initial cracks appear in the specimen. Once some parts of the specimen are experienced the cracks, the applied stress for the rest parts of the specimen increases. Since there are some strong fibers (with 8 MPa tensile strength) in the specimen, loading can continue and breaking would be subsided. Observation of the broken specimens in Figure 7 emphasises that most of the wheat fibers had been broken rather than pulling up from the matrix. This type of behaviour for the wheat fibers can also be led to more ductility as shown in Figure 6. This behaviour can be related to the gradual breaking of the fibers which eventually leads to increase in ductility of the specimens reinforced by wheat fibers.



(a) (b)



(c) (d)

Fig. 7 SEM micrographs of: a) Fibers breaking rupture mechanism in the wheat-CCB specimens, b) Fibers pulling out rupture mechanism in the Eucalyptus-CCB specimens, c) Both fibers breaking and pulling out rupture mechanism of bagasse fibre in the cement paste, d) Bagasse fibre covered by cement hydration products

Figure 7(c) and (d) present SEM micrographs of bagasse fibers in the matrix. Figure 7(c) shows a relatively strong bond with hydrated cement paste where leaf surrounded by hydration products. This figure demonstrates both fibers breaking and fiber-pulling out rupture mechanism. Combination of these two mechanism lead to an enhancement of flexural strength and toughness of CCB. As mentioned before, Table 4 indicates a high level of tensile strength for bagasse fibres which lead to delayed tearing of these fibers. Moreover, Figure 7(d) shows a single bagasse leaf with magnification of 2300X. In this micrograph, rough surface of fibers covered with hydration products could be easily distinguished. Owing high aspect ratio contribute a large surface area for better bonding with cement paste in comparison with two other types of fibers under study. Thus as expected, bagasse-CCB exhibited a relatively better flexural behaviour than wheat and eucalyptus ones.

In spite of wheat-CCB, the reason for breaking the eucalyptus-CCB specimens seems not to be related to the weak tensile strength of the eucalyptus fibers. As it can be seen in the Figures 5 and 6, applying 2 or 4 percent fibers doesn't have any significant effect on the flexural behaviour of the composites. The flexural behaviour for the both groups are similar to each other. In the case of eucalyptus-CCB, the aspect ratio might be the governing factor. The aspect ratio for the eucalyptus fibers is 2.3 while for the wheat and the bagasse fibers are 3.5 and 3.7 respectively. So there is a little amount of lateral surface area ready for the eucalyptus fibers to form bond between the cement and the fibers. Observation of the broken specimens (Figure 7) shows that most of the eucalyptus fibers were slipped and pull out rather than breaking. As sliding of the fibers occurs suddenly and rapidly, so it is not expected these specimens show a great ductility or energy dissipation as it can be attested in Figures 5 and 6.

4.2. Effect of micro silica

Silica fume consists primarily of amorphous (non-crystalline) silicon dioxide (SiO_2), with individual particles being extremely small. Due to these fine particles, large surface area and the high SiO_2 content, silica fume is a very reactive Pozzolanic.

Figure 8 compares the flexural behaviour of the specimens containing silica fume for each group. As it can be observed, replacing of silica fume, 5% by mass of cement, lead to an increase of flexural strength of cement composite boards around 20% compared to those specimens without silica fume incorporated, i.e. bagasse-CCB4, wheat-CCB4 and eucalyptus-CCB4. Such incensement can be attributed to the silica fume particles being extremely smaller than that of the cement particles (approximately twice smaller).

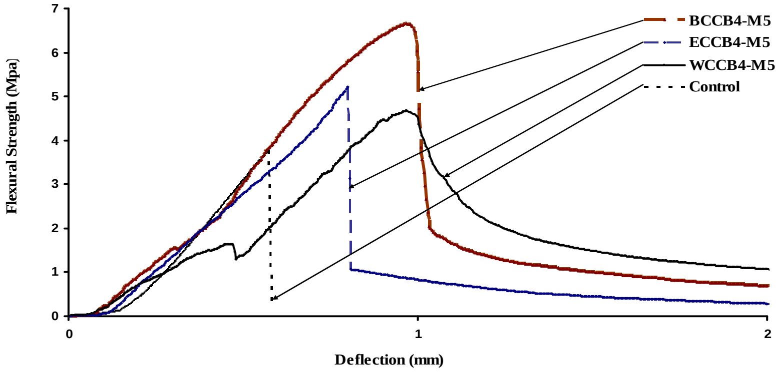


Fig. 8 Effect of replacing 5% micro silicate for cement for all groups

The silica fume particles act as filler materials within the cement matrix, reducing the porosity of the CCB. Also due to Pozzolanic reaction of silica fume, calcium hydroxide (C-H) is converted to calcium silicate hydrate (C-S-H). Application of silica fume in CCB reinforced by cellulose fibers can also further enhance the flexural strength because these very fine Pozzolanic materials decrease alkaline environment of cement matrix. Indeed, cellulose fibers have a little lignin which can be attacked by alkaline cement; hence it leads to degradation in strength of composite. It seems use of these Pozzolanic materials leads to reduction in alkaline matrix.

In Figure 8, the highest flexural strength belongs to the specimens containing bagasse, eucalyptus, and wheat fibers, respectively. For the supplement of 5% silica fume, the flexural strength of the CCB specimens containing 4% of bagasse, eucalyptus, and wheat fibers improve up to 76.3 %, 38.5 % 23.9% respectively in comparison with the reference specimens.

MFS for different groups with considering control specimen is shown in Figure 9.

As it can be observed, except specimen wheat-CCB2, other specimens have strength higher than control one. Generally, when fiber content increased from 2 to 4%, the flexural strength of specimens increased with an exception for eucalyptus-fiber contained specimens.

Replacing 5 percent of cement by silica fume led to approximately 20 percent increasing in flexural strength for all groups because of Pozzolanic and filler effects of silica fume. The highest flexural strength belongs to bagasse-CCB specimens that might be attributed to high tensile strength and high aspect ratio of these fibers.

According to EN12467 [18], minimum required flexural strength for CCB is 4 MPa. Therefore only some mixtures shown in Figure 9 could be accepted by En 12467. Also, based on this standard, minimum required flexural strength of class 2 is 7MPa.

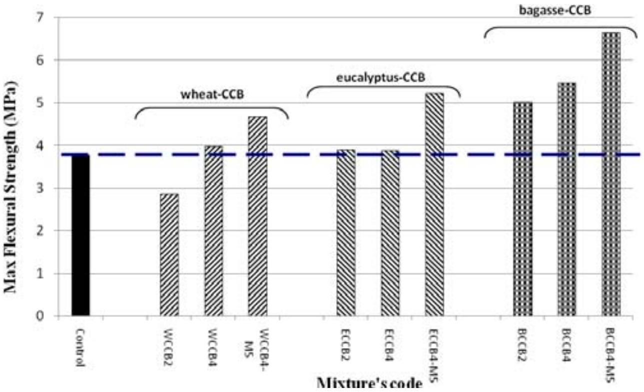


Fig. 9 Effect of silica fume on the maximum flexural strength

4.3. Toughness (Energy absorption)

Toughness is the ability of a material to absorb energy and plastically deform before rupturing. Toughness can be determined by measuring the area covered under stress strain curve. In this research, the flexural strain was not measured, so the area underneath the flexural stress-deformation which is proportional to the energy absorption is calculated and considered as an alternative measure of CCB's toughness.

Table 5 presents toughness measure for various mixtures of CCBs. As it can be seen, the Toughness Measure (TM) of cement boards is increased by applying fibers and also by replacing silica fume.

Table 5 Toughness measures (N/mm) of specimens ($\times 10^{-3}$)

Control	Bagass-CCB2	Bagass-CCB4	Bagass-CCB4-M5	Eucalyptus-CCB2	Eucalyptus-CCB4	Eucalyptus-CCB4-M5	Wheat-CCB2	Wheat-CCB4	Wheat-CCB4-M5
0.929	3.17	5.17	5.95	1.44	3.10	3.42	2.53	4.33	4.47

To provide an illustrative explanation tool, toughness improvement ratio (*TIR*) is defined as follows:

$$TIR = (TM_{\upsilon-\lambda} - TM_r) \times 100 / TM_r \tag{2}$$

where $TM_{\upsilon-\lambda}$ is the toughness measure of CCB incorporating υ% of fiber and λ% of silica fume, TM_r is the toughness measure of reference cement board. In fact, *TIR* compares the toughness of CCBs with control specimen. *TIR* for various mixtures of CCB specimens is shown in Figure 10.

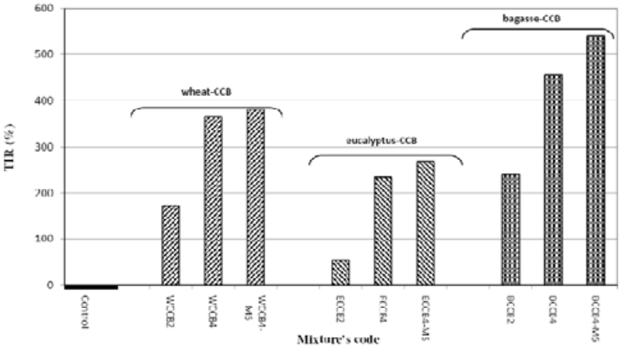


Fig.10 Toughness improvement ratio of vegetable CCB mixtures.

As it can be deduced from Figure 10, the highest improvement of toughness characteristic belongs to the CCB made by bagasse fibers, whereas eucalyptus fibers was seen to have the lowest and wheat fibers have intermediated improving effects on the energy absorption properties of CCBs. It is considered that by increasing the amount of fiber from 2 to 4 %, the toughness of CCBs experienced an increasing trend. By doubling the fiber content of bagasse, TIR increased about 1.9 times. This trend for eucalyptus and wheat corresponds to increase about 4.24 and 2.12 times respectively. It can be perceived that in the case of eucalyptus, the highest improvement gained by doubling the fiber content application from 2 to 4%.

Moreover, as it can be illustrated in Figure 10, using silica fume increased the TIR of CCBs containing 4% of fibers in all mixes.

These observations proved the capabilities of fibers in improvement of flexural strength after crack initiation begins. In other words, this process could improve the energy absorption properties of composites by delaying the sudden failure.

Figures 5, 6 and 9 reveal the brittle fracture mechanism for control specimen as non-reinforced sample, whereas specimens reinforced by vegetable fibers exhibited more or less ductile behaviour depending on the content of utilized fibers.

Figure 11 shows a schematic representation of crack propagation inside the fiber reinforced matrixes. The diagram proposes several possible local failure events occurring before fracture of the composite.

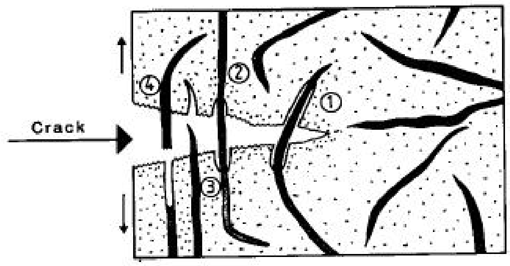


Fig. 11 Schematic of crack propagation inside the cement matrix with fibers.

At some distance ahead of the crack, which has started to travel through the section, the fibers are intact. In high-stress regions close to the crack tip, fibers may be debonded from the matrix (i.e. form 1 in Figure 11). This rupture at the interface absorbs energy from the stressed system. Ample stress may be transferred to a fiber (i.e. form 2) to enable the fiber to be ultimately fractured (as in form 4). When total debonding occurs, the strain energy in the debonded length of the fiber is lost to the material and is dissipated as heat. A totally debonded fiber can then be pulled out from the matrix and considerable energy lost from the system in the form of frictional energy (i.e. form 3). These processes are called crack bridging. As it can be attested, it is also possible for a fiber to be left intact as the cracks propagate.

For bagasse-CCB, as demonstrated in Figure 12, the pull-out mechanism was observed during the loading process.

Fig.12 Fracture surface of BCCB.

Following the full-pulling out of the fiber from the cement paste, the strain energy would be propagated across the length of fibers in the form of thermal energy. On the other hand, in pull-out mechanism of the fibers, a considerable energy would be released in the form of frictional energy. Also a fiber may be slipped and remained intact during the crack propagation. In this case, the intact fiber would be bridged between two fractured surface parts of composite that eventually led to more improvement. If the bonding is stronger, then the sample bears more loads until tearing of the fibers.

The experimental observation (Figure 9 and 10) shows that application of wheat fibers increases the energy absorption up to about 3.6 times whereas; the flexural enhancement was seen about 6%. Namely, it might be proposed that wheat fibers play as a crack controller in CCB and then it could not enhance the flexural strength.

According to the Figures 9 and 10, it can be seen that the maximum effect of eucalyptus fibers on the flexural strength and toughness were about 3% and 2.3 times respectively. Regarding to these results and SEM observations depicted in Figure 7, it might be said that larger diameter of eucalyptus fibers in contrast to the others (Table 1), would decrease the lateral surface which leads to a reduction in bonding strength.

In wheat-CCB and eucalyptus-CCB specimens, increasing of the fiber content from 2 to 4 % lead to an increase in energy absorption characteristics about more than 2 and 4 times respectively. This would be due to the proper dispersion and possible contribution of more fibers in load bearing process. Hence, by increasing the demand of frictional energy, the energy absorption would be increased as a consequence.

It seems that the energy absorption of developed CCBs was mainly influenced by physical characteristics of fibers like the aspect ratio and tensile strength.

5. Conclusion

This paper addressed an experimental study to explore the applicability and flexural response of asbestos-free cement composite boards made by waste vegetable fibers including bagasse, eucalyptus and wheat. From the results obtained in this investigation, the following conclusions can be drawn:

1- Results of this study attested the applicability of utilized natural cellulous fibers in production of cement composite boards by improving the flexural and energy absorption characteristics, more or less, depending on the type of fibers.

2- Utilized bagasse fibers have the most beneficial effects on flexural strength and energy absorption characteristics of cement composite boards. Using 2 and 4% of bagasse fibers, flexural strength and fracture toughness increased about between 33-45% and 2.4-4.5 times respectively in comparison with reference specimen; however, in the case of eucalyptus fibers, these values were about 3% and 0.5-2.3 times. When utilizing wheat fibers up to 2 %, the flexural strength reduced up to 24% but its toughness was improved up to 1.7 times. However, the application of 4% of wheat fibers led to a little bit improvement in flexural strength (5.8%) and toughness increased up to 3.7 times in comparison with the reference specimen. Generally all samples containing fibers except WCCB, fulfilled the group 2 strength grade of EN12467 standard.

3. Replacing 5 % of Silica Fume (SF) by mass of cement led to an increase in both flexural strength and fracture toughness. Comparing to the reference specimen, the flexural strength of BCCB, ECCB and WCCB increase about 76, 38.5 and 24% respectively and toughness raised about 5.4, 2.7 and 3.8 times respectively.

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