การใช้เถ้ากากตะกอนน้ำตาลเป็นวัสดุในการผลิตคอนกรีตมวลเบาระบบเซลลูล่าร์

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บทคัดย่อ

งานวิจัยนี้เป็นการศึกษาสมบัติของคอนกรีตมวลเบาระบบเซลลูล่าร์ (Cellular Lightweight Concrete) โดยการใช้เถ้ากากตะกอนน้ำตาล (Incinerated Sugarcane Filter Cake (FC)) แทนที่ปูนซีเมนต์ปอร์ตแลนด์ประเภทที่ 1 ที่อัตราส่วนร้อยละ 0, 5, 10, 15 และ 20 โดยน้ำหนัก ทั้งนี้กำหนดความหนาแน่นของอัตราส่วนผสมเท่ากับ 1,000 ± 50 กิโลกรัมต่อลูกบาศก์เมตร และอัตราส่วนน้ำต่อวัสดุประสาน (ปูนซีเมนต์และเถ้ากากตะกอนน้ำตาล) เท่ากับ 0.50 ในทุกส่วนผสม ทำการทดสอบสมบัติของคอนกรีตสด อันประกอบไปด้วย ความหนาแน่น การไหล และระยะเวลาการก่อตัว และทดสอบสมบัติทางกลของคอนกรีตที่แข็งตัว อันประกอบไปด้วย กำลังอัด กำลังดัด การหดตัวแห้ง และการดูดซึมน้ำ จากผลการทดสอบพบว่าเถ้ากากตะกอนน้ำตาลมีแคลเซียมออกไซด์ (CaO) เป็นองค์ประกอบหลัก อนุภาคมีลักษณะเป็นเหลี่ยมมุมผิวเรียบและขรุขระปนกัน การผสมเถ้ากากตะกอนน้ำตาลในปริมาณที่เหมาะสมช่วยเพิ่มความสามารถในการไหลของคอนกรีตมวลเบาระบบเซลลูล่าร์ให้ดีขึ้น เมื่อปริมาณการแทนที่เถ้ากากตะกอนน้ำตาลในปูนซีเมนต์เพิ่มมากขึ้น กำลังอัดและกำลังดัดมีแนวโน้มลดลง ในขณะที่การหดตัวแห้งและการดูดซึมน้ำมีแนวโน้มเพิ่มขึ้น เถ้ากากตะกอนน้ำตาลสามารถนำมาใช้ร่วมในการผลิตคอนกรีตมวลเบาระบบเซลลูล่าร์ได้ เมื่อพิจารณาตามข้อกำหนดมาตรฐานผลิตภัณฑ์อุตสาหกรรม มอก. 2601-2556 (คอนกรีตบล็อคมวลเบาแบบเติมฟองอากาศ)

คำสำคัญ : คอนกรีตมวลเบาระบบเซลลูล่าร์ / เถ้ากากตะกอนน้ำตาล / การแทนที่ปูนซีเมนต์ / กำลังอัด / การดูดซึมน้ำ

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Use of Incinerated Sugarcane Filter Cake as a Material in Producing Cellular Lightweight Concrete

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Abstract

This study investigated the properties of cellular lightweight concrete (CLC) incorporating incinerated sugarcane filter cake (FC) as a substitute for Type I Portland cement (OPC) at replacement percentages of 0%, 5%, 10%, 15%, and 20% by weight. CLC was maintained at a density of 1,000 ± 50 kg/m^3 and a constant water–binder ratio of 0.5 was used for all mixes. Tests for density, flow behavior and setting time were carried out on fresh concrete mixes and tests for compressive strength, flexural strength, drying shrinkage and water absorption were investigated for the hardened concrete mixes. The test results indicated that calcium oxide (CaO) is the main component of sugarcane filter cake (FC). The particles of FC are irregular in shape and most particles have both rough and smooth surfaces. CLC containing suitable amount of FC exhibited increased flowability. The compressive strength and flexural strength of CLC decreased, whereas its shrinkage and water absorption increased as a result of increasing the percentage at which FC was used to replace OPC. The results suggested that it is possible to use FC in the production of CLC according to the Thailand Industrial Standard TIS-2601-2556 (cellular lightweight concrete).

Keywords : Cellular Lightweight Concrete (CLC) / Sugarcane Filter Cake (FC) / Cement Replacement /Compressive Strength / Water Absorption

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1. Introduction

Sugarcane is a source of 65–70% of the world's sugar, and developing countries are the main sites of sugar production [1]. World production of sugarcane increased from 1,342 million tons in 2004 to 1,728 million tons in 2008 and 1,842 million tons in 2012 [2]. In particular, opportunities to supply sugar to growing markets in Asia have encouraged Thailand to expand its sugar production capacity. Thailand is home to ~100,000 sugarcane farmers working on 10 million rai of dedicated land. Currently, 51 mills are in operation, with an estimated annual crushing capacity of 100 million tons [3]. The main inputs and outputs of the production process of sugar from sugarcane are represented in Fig. 1.

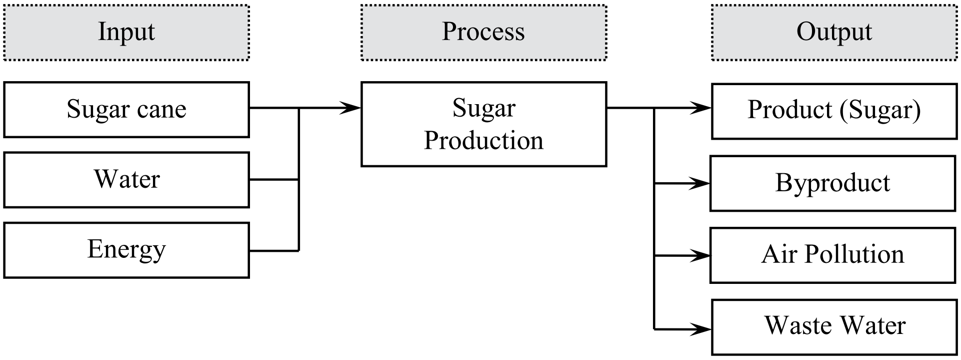

Figure 1 Inputs and outputs of the production process of sugar derived from sugarcane [1]

Bagasse, molasses, and filter cake are the main economically important byproducts of the cane sugar industry. For every 1,000 kg of sugarcane harvested, approximately 231 kg of bagasse, 26 kg of molasses, and 33 kg of filter cake are produced. Table 1 estimates the amount of sugarcane and byproducts produced in Thailand in 2004-2013. To reduce the negative impact of the sugarcane industry on the environment, filter cake is frequently used as fertilizer in the cultivation of sugarcane and as animal feed [1, 4].

Table 1 Estimated amounts of sugarcane and byproducts in Thailand in 2004–2013

Year	Sugarcane [2] (Million tons)	Bagasse (Million tons)	Molasses (Million tons)	Filter cake (Million tons)
2013	100.10	23.12	2.60	3.30
2012	98.40	22.73	2.56	3.25
2011	95.95	22.16	2.49	3.17
2010	68.81	15.89	1.79	2.27
2009	66.82	15.43	1.74	2.20
2008	73.50	16.98	1.91	2.43
2007	64.37	14.87	1.67	2.12
2006	47.66	11.01	1.24	1.57
2005	49.59	11.45	1.29	1.64
2004	65.00	15.01	1.69	2.14

A recently developed and innovative technology, cellular lightweight concrete (CLC), is a cement paste or mortar that contains entrapped air voids. The air entrapment procedure utilizes a mechanical process, rather than the one based on any chemical reactions. Pores are formed by mixing a suitable foaming agent with part of the mixing water (known as "preformed foaming") or with the mortar (known as "mix foaming") [5, 6]. A number of studies have evaluated the potential of using byproduct or waste material as an alternative to pozzolanic and/or siliceous material in the production of CLC [6]. Fly ash (FA) and ground granulated blast furnace slag have been used in the range of 30–70% and 10–50%, respectively, as a replacement for cement in order to reduce costs, improve the consistency of the mix, and reduce heat of hydration while contributing to long term strength [5]. Further, Jitchaiyaphum et al. [7] reported that compared to FA, natural zeolite (NZ) is slightly more reactive and that the latter also strengthens CLC. The optimum replacement level for NZ is 10wt%, which results in a 140% increase in 28-d compressive strength. A replacement level of 20wt% results in decreased strength; however, even at this replacement level, the CLC was still stronger than the control mix. Also, crushed clay brick, unprocessed low-lime coal fly ash and andesite-dusty rock were used as alternative fine aggregates [6, 8-9].

Cement blocks or concrete blocks with hollows can be produced to reduce CLC weight and/or to improve its transport properties [10-11]. In contrast, as a porous material with a homogeneous cellular structure, satisfactory workability, and self-flowing properties, CLC has many advantages. Its good thermal properties and acoustic performance make CLC a natural choice as a building construction material [7]. Indeed, the use of foamed concrete has rapidly expanded worldwide. Applications for foamed concrete range from house foundations to geotechnical uses, to highway, bridge abutment, and backfill uses, and even fire protection, the latter of which utilizes foamed concrete's high thermal insulation ability [8].

The objective of the present study is to evaluate the fresh and hardened properties of CLC mixtures that include incinerated sugarcane filter cake (FC) as a partial replacement for cement. The use of a replacement for cement can reduce the quantity of primary materials necessary and provide a way to recycle waste materials.

2. Experimental investigation

2.1. Constituent materials

2.1.1 Cement

Type I Portland cement (OPC) that complied with ASTM C150 [12] was used in this study. The chemical compositions and physical properties of this kind of cement are presented in Table 2. The morphologies of OPC were examined using scanning electron microscopy (SEM), as shown in Fig. 2.

2.1.2 Sugarcane filter cake

Sugarcane filter cake (FC) was used as a mineral admixture, which was produced as by-products during sugar production from a local sugar mill located in the Suphanburi province of central Thailand. Filter cake combustion was performed in an electrical furnace, with the temperature held constant at 1,200 °C for 3 h with a heating rate of 10 °C/min. The chemical compositions and physical properties of sugarcane filter cake are presented in

Table 2. The morphologies of FC were examined using scanning electron microscopy (SEM), as shown in Fig. 2.

2.1.3 Aggregate

Natural river sand fine aggregate was used in this study. The particle size distribution met the concrete aggregate specifications of ASTM C33 [13].

2.1.4 Foaming agent

A commercially available protein-type surfactant was used to produce the pre-formed foam.

2.1.5 Water

Mixing water was discharged into the mixer from the municipal water supply.

Table 2 Chemical compositions and physical properties of CLC components

Oxides	Type I Portland cement	Sugarcane filter cake
Chemical composition (% by mass)		
Silicon dioxide (SiO_2)	19.61	2.01
Alumina oxide (Al_2O_3)	4.13	0.26
Ferric oxide (Fe_2O_3)	3.21	0.25
Magnesium oxide (MgO)	1.17	2.56
Calcium oxide (CaO)	63.01	80.58
Sodium oxide (Na_2O)	0.27	0.03
Potassium oxide (K_2O)	0.42	0.31
Sulfur trioxide (SO_3)	3.69	1.50
Physical properties		
Loss on ignition (% by mass)	1.74	12.19
Median particle size (μm)	19.07	13.17
Specific gravity	3.15	1.90
Specific surface area, BET method (cm^2/g)	10,400	12,700

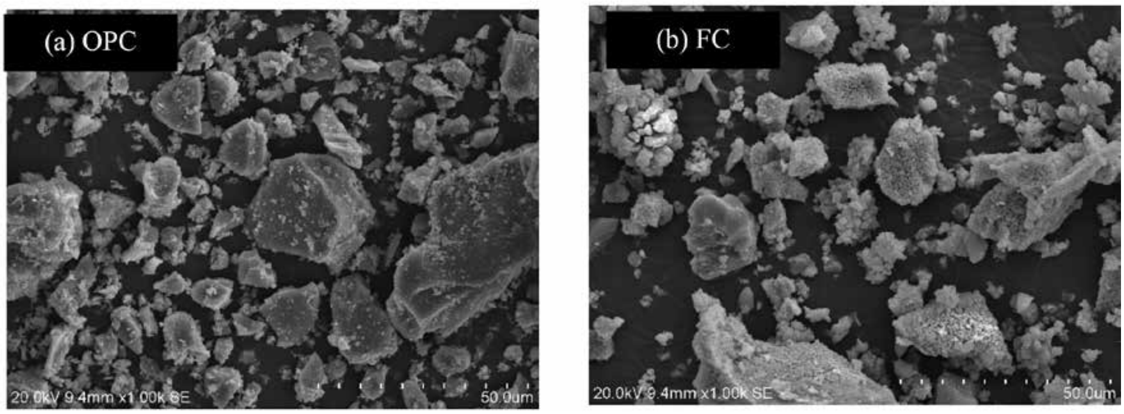

Figure 2 SEM images of (a) OPC and (b) FC (magnification ~1000×)

2.2 Mix proportions

Five CLC mixtures were prepared by progressive incorporation of FC, with binder contents of 400 kg/m^3. OPC was replaced with incinerated FC at 0%, 5%, 10%, 15%, and 20% by weight. The binder to sand ratio was 1:1. A water to binder (W/B) mass ratio of 0.5 was used for all the mixtures. The foaming agent was diluted with water at a mass ratio of 1:30. This diluted foaming agent was added and mixed until a uniform CLC was obtained.

The density of the control mixture was ~1,000 kg/m^3, with a variation of ±50 kg/m^3 [14]. This fresh density was chosen on the basis of trials. Each mixture was designated by the form FCx, where x is the weight percentage of cement replaced by incinerated FC. The concrete mix proportions are provided in Table 3. The pre-foaming method was applied in order to achieve the desired density. This method comprises the production of a base mix and performing foam separately and then thoroughly blending the foam into the base mix, as shown in Fig. 3.

Table 3 Mixture proportions of CLC mixtures

	Cement replacement (wt%)	Material (kg/m^3)				W/B
		Cement	Filter cake	Fine aggregate	Water	
FC0	0	400	0	400	200	0.5
FC5	5	380	20	400	200	0.5
FC10	10	360	40	400	200	0.5
FC15	15	340	60	400	200	0.5
FC20	20	320	80	400	200	0.5

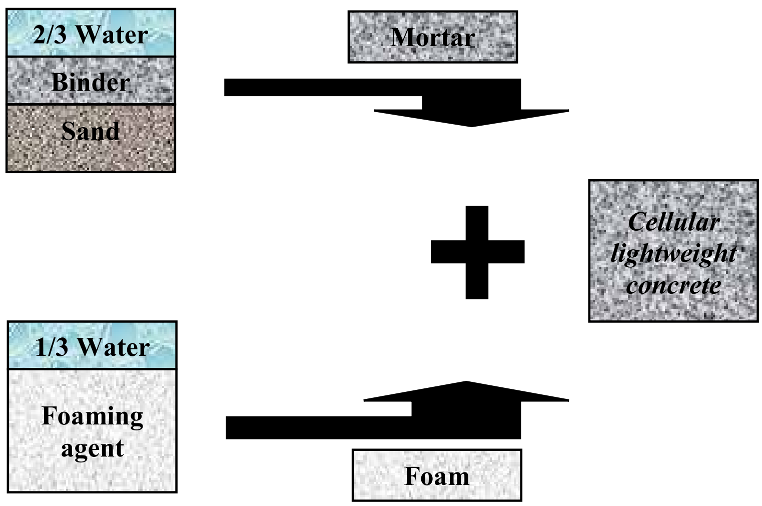

Figure 3 Pre-foaming method diagram for foamed concrete [6]

2.3 Testing procedures

For each mix, the density, slump flow, setting time, compressive strength, flexural strength, drying shrinkage, and water absorption were determined as follows:

1. The density of freshly prepared CLC was measured as specified in ASTM C138 [15].

2. The slump flow was determined in accordance with EFNARC guidelines [16].

3. The setting time was measured as specified in ASTM C807 [17].

4. Flexural strength is one measure of the tensile strength of concrete, expressed as the modulus of rupture. This test method determines the flexural strength of a concrete specimen by using a simple beam with center-point loading. Moreover, tests to determine compressive strength, drying shrinkage, and water absorption were conducted according to the standards given in Table 4.

Table 4 Tested specimens and age of testing

Properties	Standard of testing	Dimension of specimen	Age of testing
Compressive strength	BS EN 12390-3 [18]	100×100×100 mm cube	3, 7, 14, 28 days
Flexural strength	ASTM C293 [19]	75×75×250 mm prismatic	3, 7, 14, 28 days
Drying shrinkage	ASTM C596 [20]	75×75×250 mm prismatic	7, 14, 21, 28 days
Water absorption	ASTM C642 [21]	100×100×100 mm cube	28 days

2.4 Criteria

The typical volume density, compressive strength, and water absorption acceptance criteria for CLC mixtures according to TIS standards [14] are listed in Table 5.

Table 5 General acceptance criteria for CLC mixtures according to TIS standard

Type of CLC	Density	Compressive strength	Water absorption
C10*	1,000±50 kg/m^3	>25.5 kg/cm^2	<23 % by mass

Note : *Class C10 defined as density of 901–1,000 kg/m^3

3. Results and discussion

In this study, the fresh and hardened properties of CLC were investigated by using incinerated sugarcane filter cake (FC) at four replacement rates for cement. The consistency indices of 1,000 kg/m^3 CLC, which comprise measurements of practical density, flow behavior and setting time, are summarized in Table 6.

Table 6 Properties of fresh CLC mixtures

Materials	Density (kg/m^3)		Slump flow (cm)	Setting time (hour:minute)	
	Design	Measured		Initial	Final
FC0	1,000	1,000	23.5	14.45	17.30
FC5	1,000	1,010	24.0	13.30	16.30
FC10	1,000	990	25.0	12.50	16.00
FC15	1,000	990	25.0	12.30	15.15
FC20	1,000	1,000	24.0	12.00	14.45

3.1 Density

Density can be determined in the fresh or hardened state. A value of fresh density is required for mix design and casting control purposes. However, a theoretical equation for fresh density may not be applicable, because there can be scatter in the results due to numerous factors (e.g., foam expansion after discharge, foam loss during mixing [5]). Therefore, the actual mix density was measured by filling a pre-weighed standard container of known volume with foam concrete, and then weighing the filled container. The density of the design mixture was ~1,000 kg/m^3. The acceptable variation between the design and the achieved densities was fixed at ±50 kg/m^3, which was within the defined tolerance limit [14].

3.2 Flow behavior

The slump flow ranged from between 23.5 and 25 cm. The slump flow increased with increasing FC content of up to 10%, and then decreased with increasing FC content (Fig. 4). Compared to the control CLC (FC0), all the CLC mixtures had higher slump flow values. This was because of the addition of fine particles to the latter together with the improved packing of the solid phase and the adsorption of the mixing water to the FC particles, which reduced the interparticle friction [8]. The characteristics of FC ensured greater cohesiveness of the CLC mixtures.

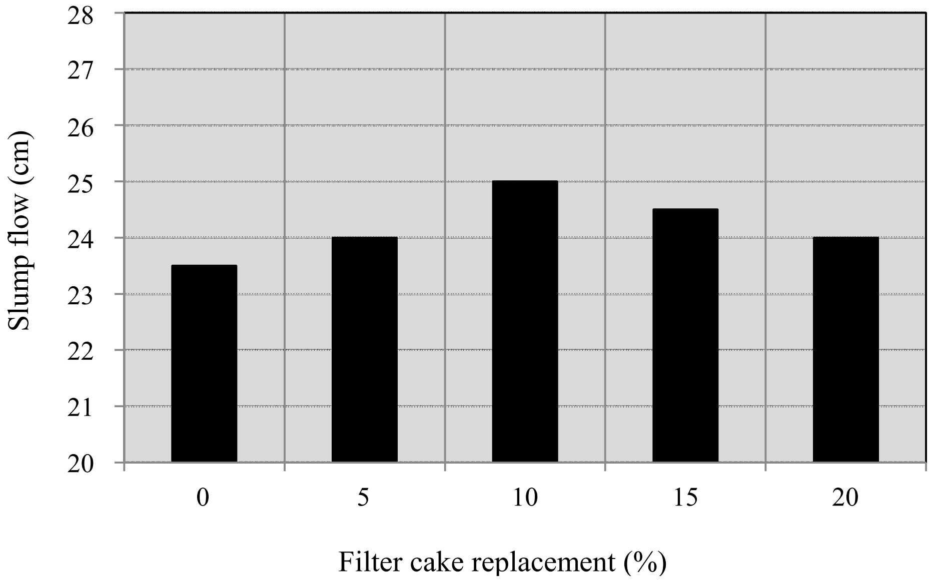

Figure 4 Slump flow for CLC mixtures

3.3 Setting time

The initial and final setting times of the CLC mixtures containing FC are presented in Fig. 5. The setting times increased as the FC content decreased, and vice versa. As the FC replacement was increased from 0% to 5%, 10%, 15%, and 20%, the initial (final) setting time decreased from 14.45 to 13.30 , 12.50, 12.30, and 12.00 h:m, respectively, whereas the final setting time decreased from 17.30 to 16.30, 16.00, 15.15, and 14.45 h:m, respectively. These increases in the setting time of the CLC mixtures is due to the fillers acting as a nucleation site and thus promoting chemical reactions and cement hydration. Fine FC with a high surface area (12,700 cm2/g) produces a greater reaction than does comparatively coarser OPC with a low surface area (10,400 cm2/g) [7].

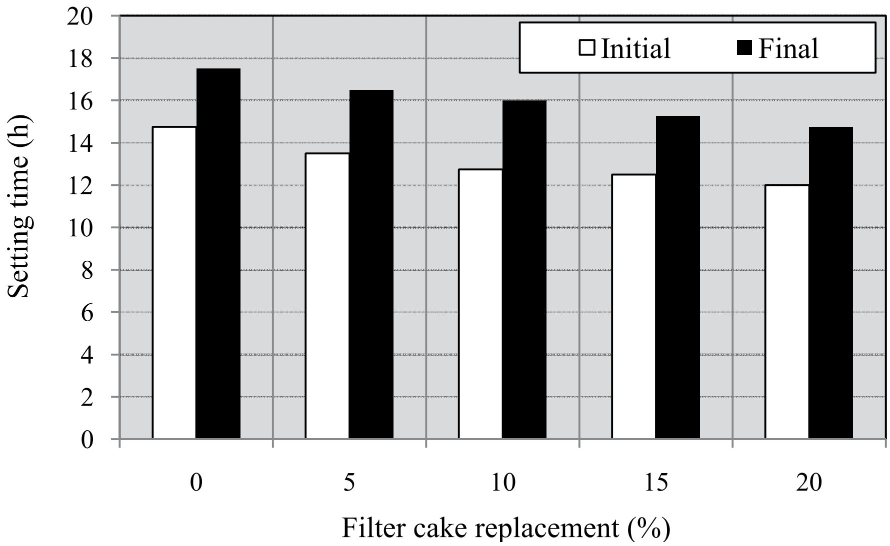

Figure 5 Setting time for CLC mixtures

3.4 Compressive strength

The compressive strength of a sealed-cured 100-mm cube continued to increase over the 28-day curing period, as presented in Fig. 6. Compressive strength ranged from 10.0 to 4.5 kg/cm^2 at 3 days, from 16.5 to 8.0 kg/cm^2 at 7 days, from 22.0 to 11.5 kg/cm^2 at 14 days, and from 29.0 to 16.0 kg/cm^2 at 28 days the FC replacement increased from 0% to 20%, respectively. The compressive strength of the CLC increased as the curing time increased because the hydration reaction increases the calcium silicate hydrate (C-S-H) product [7]. As increasing FC was used to replace cement in the concrete mixture, the decreasing amount of cement resulted in a lower $Ca(OH)_2$ content, which, in turn, reduced the compressive strength of the concrete [5]. For example, after 28 days, compared to the control mix, the concrete mixtures with FC replacements of 5%, 10%, 15%, and 20% exhibited reductions in compressive strength of 10%, 22%, 33%, and 45%, respectively. The compressive strength was within the acceptable range when the FC percentage was 5%.

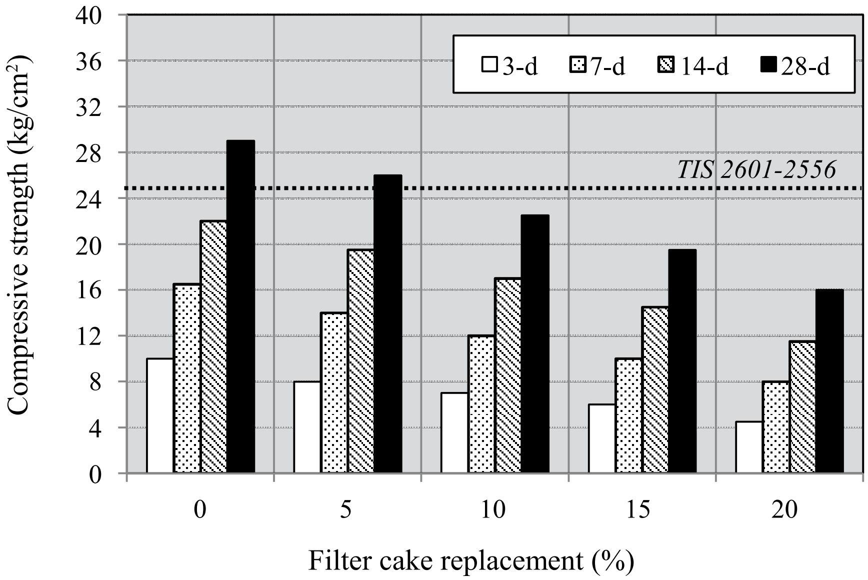

Figure 6 Compressive strength development of CLC mixtures as a function of time

3.5 Flexural strength

Flexural strength continued to increase over the 28-day curing period (Fig. 7). For most of the mixes, the flexural strength results showed a trend of development similar to that of the compressive strength results. Flexural strength ranged from 5.61 to 2.29 kg/cm^2 at 3 days, from 8.16 to 3.82 kg/cm^2 at 7 days, from 10.20 to 5.35 kg/cm^2 at 14 days, and from 12.24 to 6.88 kg/cm^2 at 28 days as the FC replacement increased from 0% to 20%, respectively. The increasing flexural strength with aging may have been due to the hydration reaction of OPC and the filling effects of the FC [6]. As increasing FC was used to replace cement in the concrete mixture, the reduced flexural strength of the concrete may have been due to the FC weakening the paste formed by the cement and the FC. This may have resulted in a weak bond between the paste and the sand grains [22]. For example, compared to the control mix, the reductions in concrete flexural strength after 28 days were 12%, 23%, 33%, and 46% at the 5%, 10%, 15%, and 20% replacement levels, respectively.

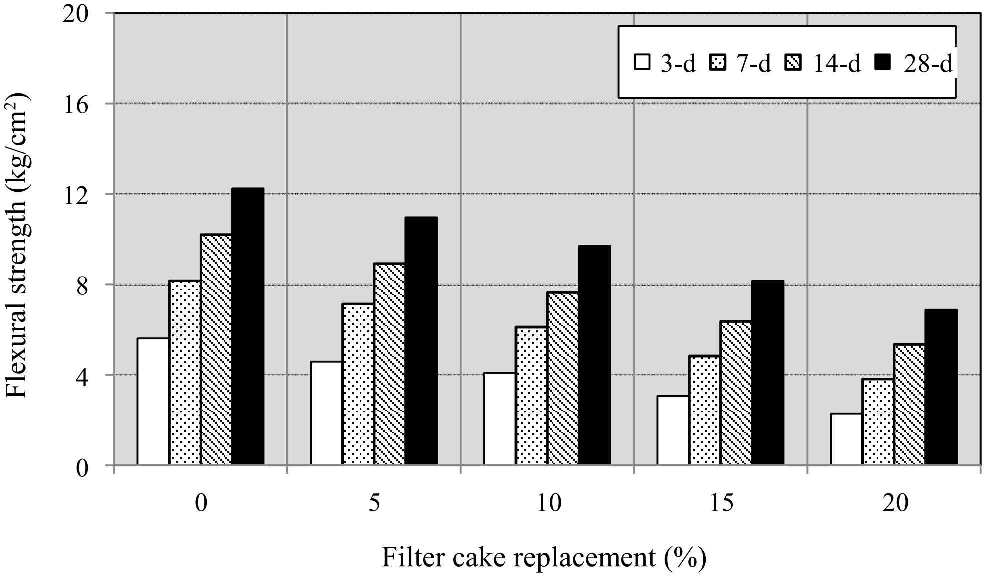

Figure 7 Flexural strength development of CLC mixtures as a function of time

The relationship between compressive strength and flexural strength for all the mixtures is shown in Fig. 8. The correlation between compressive strength and flexural strength of CLC using the best fit can be expressed as follows:

$$F = 0.3902fc - 1.081 \quad \textbf{(1)}$$

where fc is the compressive strength in kg/cm^2 for values from 4.5 kg/cm^2 to 29.0 kg/cm^2 and F is the flexural strength in kg/cm^2. It is clear that the compressive strength of concrete is proportional to its flexural strength; the greater the compressive strength, the greater the flexural strength. Flexural strength development possesses linear relationship with the compressive strength development. The ratio of flexural strength to compressive strength of CLC containing incinerated FC was of 0.39 (Fig. 8). It is higher than the previous studied ranging from 0.25 to 0.35 [5, 23]. These results further proved that the densification of CLC microstructure due to a filler effect of the FC increased the flexural behavior of the prismatic specimens.

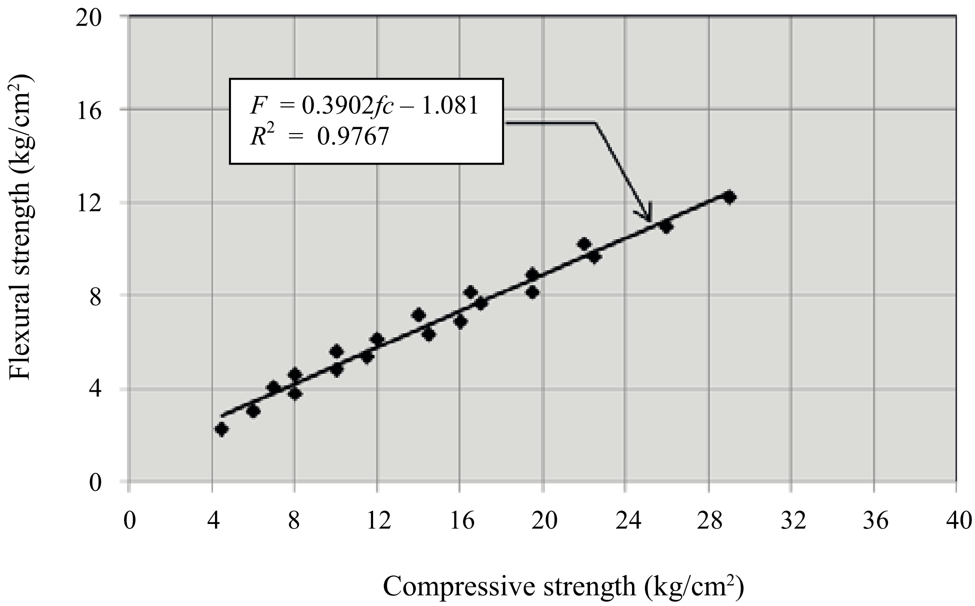

Figure 8 Relationship between the compressive strength and flexural strength

3.6 Drying shrinkage

The results of the drying shrinkage of the CLC are shown in Fig. 9. The use of FC as a replacement for OPC increased the shrinkage compared with the control CLC (FC0). Drying shrinkage ranged from 0.0696% to 0.0757% at 7 days, from 0.0700% to 0.0764% at 14 days, from 0.0703% to 0.0769% at 21 days, and from 0.0709% to 0.0781% at 28 days as the FC replacement increased from 0% to 20%, respectively. The rates of shrinkage of the CLC mixtures containing FC were very high at the early age. At early test ages, the shrinkage of all the specimens exhibited a very steep development. At this stage, there was very little difference between the amount of the drying shrinkage of the control CLC (FC0) and of the mixtures containing FC. But after about 4 weeks, a clear difference in this regard was observed: the shrinkage of concrete with FC increased as the amount of FC used to replace OPC increased. Thus, it can be concluded that the addition of microfine particles to concrete increases the drying shrinkage. According to Mehta and Monteiro [24], concrete that incorporates pore refinement additives will have higher shrinkage and higher creep values than will concrete without such additives.

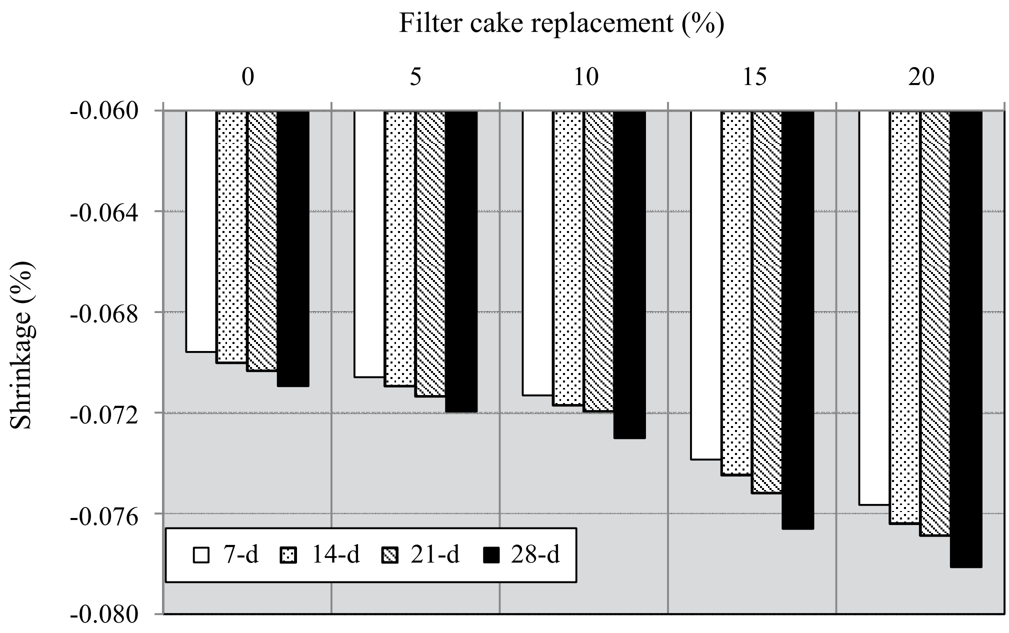

Figure 9 Shrinkage of CLC mixtures as a function of time

3.7 Water absorption

The results of CLC water absorption at 28-day curing are presented in Fig. 10. The water absorption of the control CLC (FC0) was 16% by mass at 28 days, whereas the water absorption of CLC with FC5, FC10, FC15, and FC20 were 19%, 22%, 25% and 29%, respectively. The water absorption of CLC containing FC increases as the FC content increases. The results may be related to porosity, as a small increase in capillary pores in CLC causes a small increase of water absorption. It was observed that replacing a high amount of cement with a corresponding amount of FC in CLC results in an increased number the pores get bigger [6]. The water absorption in concrete after 28 days compared to the control mix increased by 19%, 38%, 56%, and 81% at the 5%, 10%, 15%, and 20% replacement level, respectively. The water absorption was within the acceptable range when the FC percentage was 10% or less.

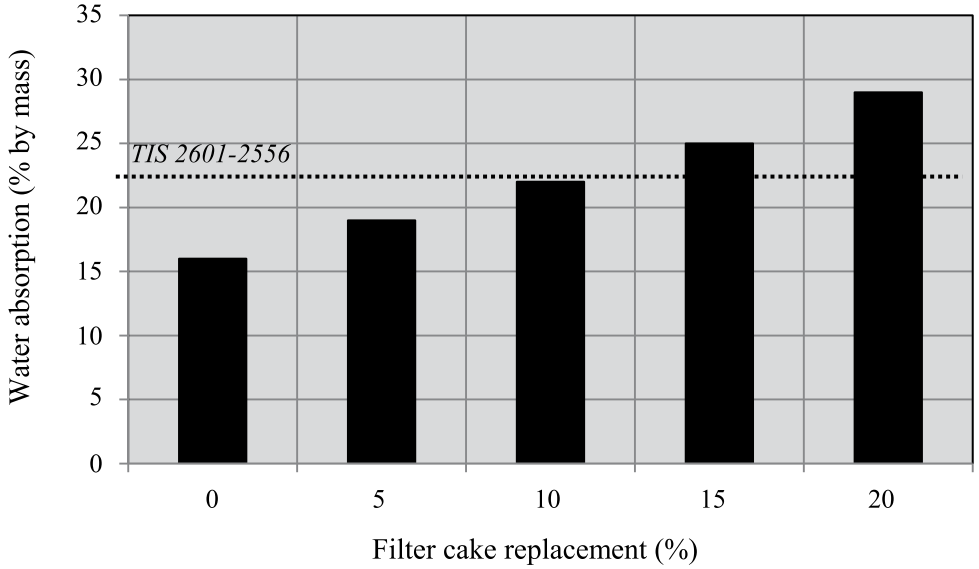

Figure 10 Water absorption of CLC at 28 days

4. Conclusion

Based on the work undertaken here, the following conclusions can be drawn:

1. For the combustion of sugarcane filter cake using an electrical furnace, conditions whereby the temperature was held constant at 1,200 °C for 3 h with a heating rate of 10 °C/min produced the highest content calcium oxide (CaO) ash, i.e., 80.58%. The median particle size of FC is smaller than those of OPC.

2. The FC mixes exhibited enhanced flowability with increasing FC content of up to 10%, and then decreased with increasing FC content. The setting time reduced as increasing FC content compared to those the control mixture.

3. The incorporation of incinerated FC as a cement replacement decreased the compressive and flexural strength values, which increased with age in all the mixtures. After 28 days, compressive strength decreased by 10%, 22%, 33%, and 45% compared to the control mixture in mixtures at the 5%, 10%, 15%, and 20% FC replacement level, respectively.

4. Increased incinerated FC content increased the drying shrinkage and water absorption of the CLC. Compared to the control mix, the CLC's water absorption after 28 days increased by 19%, 38%, 56%, and 81% at the 5%, 10%, 15%, and 20% replacement level, respectively.

5. It is possible to use FC to manufacture CLC that is acceptable according to TIS standards. Further research is needed, however, especially in regard to long-term conditions and microstructural analysis.

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