Emirati Journal of Civil Engineering and Applications
Vol 2 Issue 2 (2024)
Pages (19 - 30)

Available at www.emiratesscholar.com

Developing greener concretes from spent bleaching earth and sugarcane bagasse ash

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ARTICLE INFO

Published on 5th of October 2024
Doi:10.54878/jvggwe15

KEYWORDS

Concrete, spent bleaching earth, sugarcane bagasse ash, compressive strength, split tensile strength, shrinkage

HOW TO CITE

Developing greener concretes from spent bleaching earth and sugarcane bagasse ash. (2024). *Emirati Journal of Civil Engineering and Applications*, *2*(2), 19-30.

ABSTRACT

Concrete is by far the most widely utilized construction material due to its excellent mechanical and durability properties. However, the concrete industries are notorious for their anthropogenic activities that contribute to climate change. Cement production alone consumes immense amounts of energy and trails a significant CO2 footprint. One solution that researchers have deemed promising over the last couple of decades is the substitution of cement with agricultural waste products, which subsequently serves to alleviate waste disposal problems. This study investigates the suitability of spent bleaching earth (SBE) and sugarcane bagasse ash (SCBA) as partial replacement of ordinary Portland cement (OPC) in increments of 0, 5, 10 and 15% by mass. Tests were conducted in accordance to British Standards to assess the consistence, compressive strength, split tensile strength and drying shrinkage strain of SBE and SCBA based concretes. Results indicated that while these concretes displayed similar degrees of consistency, the SCBA concretes exhibited superior compressive and tensile strengths. Optimum SCBA dosages were revealed to be about 5-10%, yielding a 7-12% and 3-8% increase in compressive and tensile strengths, respectively, as compared to OPC concrete. Drying shrinkage behavior was also improved in the SCBA concretes. Further, comparisons of the mechanical and durability performances of the concretes with British and American codes suggest that up to 10% replacement of cement with SCBA may be a viable approach to developing sustainable materials for the concrete industry.

1. Introduction

Concrete is the second commonly utilized material on earth after water due to its excellent mechanical and durability properties. As cement is the key ingredient of concrete, its production process requires extensive energy and excessive use of natural aggregates and other natural sources, apart from the significant carbon dioxide (CO2) production. Cement manufacturing consumes about 3.2 to 6.3 GJ of energy and 1.7 tons of raw materials (mainly limestone) per metric ton of clinker produced [1], which today accounts for 30-40% of the global energy consumption [2]. These activities generate approximately 5-7% of the total CO2 anthropogenic emissions [3], all of which can result in ecological imbalance, and environmental degradation and pollution [4]. The two primary sources for the CO2 emissions are the combustion of fossil fuels and the thermal decomposition of calcium carbonate to produce the cement clinker [5].

Over the last few decades, researchers have explored the use of supplementary cementitious materials in an attempt to develop sustainable construction materials and reduce the negative impact of concrete production on the environment. Fly ash, ground granulated blast-furnace slag and silica fume are among the most commonly utilized supplements in the market due to their low embodied CO2 (eCO2) [6]. However, as these materials are mainly by-products from industrial processes, their availability in different countries cannot always be guaranteed [7], depending on the prosperity of the country's industrial sector. In such cases, utilizing agricultural waste materials that are more readily available could be an alternative option for concrete production [4]. Agriculture sectors worldwide are known to generate significant quantities of solid wastes that contribute to environmental pollution as well as human health and waste management concerns, particularly in developing nations. It has further been reported that the deposition of agricultural solid wastes is increasing at a rate of 7.5% annually, contributing about 21% of greenhouse gas emissions [8].

There are very few published studies on the use of agricultural wastes to reduce the cement proportion in concrete production and mitigate its negative environmental impact. Spent bleaching earth (SBE) is one example of a solid waste material that has been considered as a cement substitute in recent literature due its pozzolanic property [9]. Adding pozzolanic materials to cement will form additional calcium silicate hydrate (CSH) due to the reaction between the silicon dioxide (SiO2) with the free lime released during the hydration stage. Most of the studies that were done using SBE as a cement substitute in foamed concrete or non-fired wall tiles. SBE is essentially derived from the refining process of palm oil in order to remove (physical traces) color, residue gums or any metal. It is estimated that about 600,000 tonnes of SBE is generated in refining more than 60 million tons of oil [10]. Disposing mass amounts of SBE can also potentially pose fire and pollution hazards as it contains 20-40% residual oil [11]. The durability performance of SBE based foamed concretes under acidic conditions can also be increased by increasing the curing age [11]. Although, the workability of foamed concrete may decrease as the amount more SBE content is added [11]. Up to 50-60% SBE can be used to replace cement to produce both strong and lightweight concrete using either air or water curing techniques [12]. Similarly, 30% processed SBE has been shown to improve the strength characteristics of foamed concrete [11] and enhances the durability by effectively decreasing the porosity of the concrete [13]. However, for normal concrete the optimum SBE content has been suggested to be about 5%, in addition to about 2% rice husk ash, which can increase the strength and elasticity properties [14]. SBE can also be utilized in small quantities (~3.4%) in casting non-fired wall tiles to significantly reduce cost of the raw materials [15]. Further, SBE could be used as a filler construction material to improve the characteristics (e.g. CBR) of a limestone landfill mixture [16] or to serve as fine aggregates in producing lightweight bricks without considerable loss in strength or water absorption [17].

Another agricultural waste product that is widely acknowledged as a pozzolanic material is sugarcane bagasse ash (SCBA) [18]. SCBA is a by-product of burning sugarcane bagasse under controlled conditions, and while they may potentially valuable as a fertilizer, the frequent disposal of SCBA in landfills in countries like China and India have led to escalated environmental issues [19]. A notable alternative explored in research is the combination of agricultural wastes as replacements for both the cement and aggregate components of concrete. Singh et al. [4] conducted a study investigating the impact of using SCBA as a partial replacement for cement and coal bottom ash as a partial replacement for the fine aggregate. The study found that a combination of 10% SCBA and 10% coal bottom ash enhanced both the workability and strength characteristics of concrete. It has also been found that the fineness of the SCBA content in concrete tends to increase the retention of water molecules due to more voids being formed in comparison to conventional fine aggregates, thus reducing the workability [20, 21]. On the other hand, the compressive strength, split tensile strength, flexural strength and water absorption can all be optimized at quantities of 5-10% SCBA [18, 22-25]. At higher % SCBA content however the increased porosity and weak intergranular bonding of SCBA particles allow easier penetration of moisture and carbonation [26, 27]. About 5-10% SCBA can also be added in mixes to control cracks in concrete slabs by reducing both length and width [28], while the bond strength between concrete and reinforcement steel bars can be improved with addition of 5-25% SCBA [29].

Despite the fact that the incorporation of SBE and SCB as cementititous substitutes appears to be an attractive option to create sustainable concretes, the research in this area has been limited [9, 23]. Most of the works on SBE have been concerning its use in foamed concrete or non-fired wall tiles. Also, no studies have made a comparison in the performance between SBE and SCBA based concretes. Durability results of these concretes are also less commonly examined and hence there is still some ambiguity on its behavior in the long term. Furthermore, the applicability of such concretes within the regimes prescribed by international codes have yet to be considered. To address these issues, this study investigates the potential of utilizing locally sourced agricultural wastes in Oman to produce concrete, contributing to the effort to reduce cement content in the country's concrete industry. Green concretes were produced by supplementing ordinary Portland cement (OPC) with either SBE or SCBA, in quantities of 0 to 15% by mass and at 5% increments. A series of mechanical and durability experiments were then conducted in accordance to British Standards to measure the consistence, compressive strength, splitting tensile strength and drying shrinkage strain of the concretes. The results were evaluated against an OPC concrete mix as well as other acknowledged references. The proximity of the concretes performance to current British and American design codes was also assessed. The outcomes and significance of this research aim to contribute to efforts in several key areas: reducing cement content in concrete, minimizing energy consumption in cement production, lowering greenhouse gas emissions from cement manufacturing, and managing and reusing agricultural wastes in Oman.

2. MATERIALS

2.1. Cement and Water

For this study, ordinary Portland cement (OPC) of type CEM I 42.5N was selected from the Oman Cement Company, which conforms to BS EN 197-1:2011 [30]. The water used for the design mix of concrete samples, and during the curing stages, was ensured to be free from organic matter, silt, oil, sugar, chloride, and acidic material.

2.2. Fine Aggregates

Fine aggregates comprised of alluvial sand with a maximum size of 4.75 mm, which were commercially available and conformed to BS EN 12620:2002 [31]. The sand was washed and screened to remove any impurities.

2.3. Coarse Aggregates

Crushed limestone of maximum size 20 mm was used as coarse aggregates. The aggregates were also commercially available, predominantly angular in shape and conformed to BS EN 12620:2002 [31].

2.4. Spent bleaching earth

Spent bleaching earth (SBE) was sourced from the Omani Vegetable Oils & Derivatives Company. The raw SBE was firstly oven-dried at a temperature of 120ºC to remove oil content and other contaminants. The final product of the SBE is shown in Fig. 1a.

2.5. Sugarcane bagasse ash

Sugarcane bagasse was collected from a local Omani sugarcane mill. The sugarcane was sourced from Dhofar and Ad Dakhiliyah Governorate of Oman, which is generally used for sugar juice extraction or red sugar production. The bagasse was further crushed and oven-dried at a temperature of 120ºC to remove moisture content, then burnt at a controlled temperature 600ºC for three hours to obtain the sugarcane bagasse ash (SCBA), as shown in Fig. 1b.

(a)

(b)

(c)

Fig 1. (a) Spent bleaching earth (SBE); (b) Sugarcane bagasse ash (SCBA); (c) Seiving of SBE and SCBA.

2.6. Physical tests of materials

The processed spent bleaching earth (SBE) and sugarcane bagasse ash (SCBA) were carefully prepared for use as cementitious substitutes. Initially, the SBE was passed through a No. 100 ASTM sieve, while the SCBA was passed through a No. 10 ASTM sieve (Fig. 1c). The material retained in the pan from each sieving process was collected and used as the cementitious substitute.

To ensure the quality and suitability of the materials, specific gravity and water absorption tests were conducted. For the fine aggregates, SBE, and SCBA, the ASTM C128 [32] method was employed, which is commonly used in the literature for determining the specific gravity and absorption of fine aggregates. For the coarse aggregates, the ASTM C127 [33] method was applied for testing the properties. The results of these tests are presented in Table 1.

Furthermore, a comprehensive sieve analysis was performed on all materials using the ASTM C136/C136M [34] procedure. This allowed the particle size distribution of aggregates to be determined, as well as the gradation and fineness of the materials, ensuring they met the required specifications for use in concrete production.

TABLE 1. PHYSICAL ATTRIBUTES OF MATERIALS

Parameter	OPC	FA[a]	CA[b]	SBE	SCBA
Specific gravity	3.11	2.63	2.71	2.17	1.94
D10 (μm)	2.3	256.2	1888	47.6	95.5
D90 (μm)	52.5	853.1	17743	113.5	945.7
Water absorption	-	0.71%	1.92%	-	-

[a]Fine aggregates (FA); [b]Coarse aggregates (CA)

TABLE 2. MIX PROPORTIONS OF THE CONCRETE SPECIMENS

Notation	Mix proportion (kg/m^3)				
	OPC	FA[a]	CA[b]	SBE	SCBA
OPCC	409	785.7	960.3	-	-
SBE5	388.5	785.7	960.3	20.5	-
SBE10	368.1	785.7	960.3	40.9	-
SBE15	347.6	785.7	960.3	61.4	-
SCBA5	388.5	785.7	960.3	-	20.5
SCBA10	368.1	785.7	960.3	-	40.9
SCBA15	347.6	785.7	960.3	-	61.4

[a]Fine aggregates (FA); [b]Coarse aggregates (CA)

3. EXPERIMENTATION

3.1. Design mix

The mix proportions for the concrete mixes are outlined in Table 2. The control mix (OPCC) was prepared following the BRE method [35] with a water-to-cement (w/c) ratio of 0.55 and a target characteristic strength of 30 N/mm2. The ingredients of concrete were mixed thoroughly in a concrete mixer until the required consistency is achieved. Prior to casting, the relevant molds were prepared and oiled, following which the fresh concrete mixture was poured uniformly into the molds

The green concrete mixes were created by replacing the cement content with SBE and SCBA material at 5, 10 and 15% by mass while maintaining the same w/c ratio and quantities of aggregates. All specimens were water cured until the specified ages of testing. For each test, the average result of at least three specimens was obtained.

3.2. Consistency

The consistence of all fresh concrete mixes was evaluated based on the true slump value in accordance to the procedure of BS EN 12350-2:2019 [36].

3.3. Compressive strength

The compressive strength of concrete specimens were measured using the BS EN 12390-3:2019 [37] test on 100 mm cubic specimens at 1, 3, 7 and 28 days of the cube age. Loading was applied through an IMPACT® hydraulic machine with a load range of 0-3000 kN at a constant load rate of 0.5 MPa/s until failure of the specimens. The compressive strength was determined by $fck = F/Ac$, where F is the maximum load at failure, and Ac is the cross-section area of the specimen.

3.4. Splitting tensile strength

Splitting tensile strength tests were conducted on 150 (d) × 300 (L) mm cylindrical concrete specimens at 28 days of age using a standard jig apparatus in accordance with BS EN 12390-6 [38]. The cylinders were laid horizontally in the IMPACT® machine with hardboard packing strips pressed along the bottom and top surfaces. Loading was transferred through a curved steel loading piece at a constant rate of 0.05 MPa/s. The splitting tensile strength was then computed by $fct,sp = 2F/(\pi Ld)$, were F is the failure load.

3.5. Drying shrinkage strain

In measuring the drying shrinkage strains of the 75 × 75 × 285 mm prismatic concrete specimens, ASTM C490 [39] was adopted. A comparator device was used to record the change in length of the specimens at weekly intervals up to 15 weeks, starting at 7 days after curing. During each reading, a reference steel bar was also measured in the comparator apparatus to minimize changes in reading due to differences in contact surfaces. The drying shrinkage strain was obtained as $\varepsilon ds = [(Lt - Lr) - (Li - Lr)]/G$, where Lt and Lr are the comparator readings of the specimen and reference bar at the specific age, respectively, Li is the initial comparator reading of the specimen, and G is the gauge length of the specimen (250 mm). Following each reading, the samples were allowed to air cure at 20°C and 65% relative humidity.

4. RESULTS AND DISCUSSIONS

4.1. Particle Size Distribution

Fig. 2 provides valuable insights into the particle size distributions (PSD) of the ordinary Portland cement (OPC), spent bleaching earth (SBE), and sugarcane bagasse ash (SCBA). Based on the PSD, the OPC exhibits the finest particles (1-100 µm), followed by SBE (10-200 µm), and SCBA with the coarsest particles (10-1000 µm). This variation in particle sizes influences their potential use as sustainable concrete materials. OPC exhibits the finest particle size distribution, with 90% of its particles below 52.5 µm. SBE and SCBA have coarser distributions, with D90 values of 113.5 µm and 945.7 µm, respectively. OPC's finer particles contribute to its higher reactivity and strength development in concrete. While SBE and SCBA have potential as sustainable cementitious substitutes, their coarser particle sizes may require additional processing to enhance reactivity.

Utilizing these materials can reduce CO2 emissions associated with cement production and address waste disposal issues. Optimizing the particle sizes of SBE and SCBA through grinding and blending with OPC in appropriate proportions can help achieve a balance between sustainability and performance in concrete applications. Blending could potentially improve the packing density and reducing porosity. SBE's finer particles may show higher pozzolanic activity compared to SCBA, which might require additional processing to enhance reactivity.

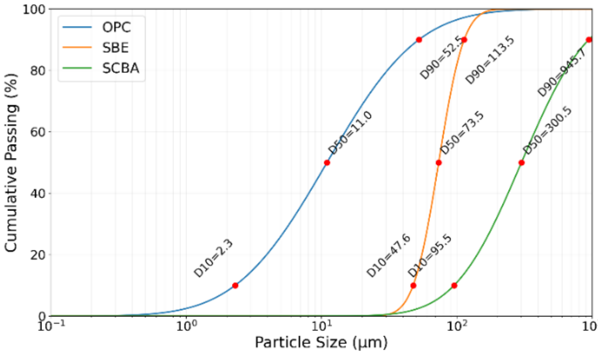

Fig. 2. Particle size distribution for OPC, SBE and SCBA.

4.2. Consistence

The slump values of the fresh concrete mixes are presented in Fig. 3. Firstly, the control OPCC mix achieved a slump of about 65 mm, which classifies it in the S2 slump zone (50-90 mm) according to BS EN 206:2013 [40]. This degree of workability is generally appropriate for normal reinforced concrete structures, providing a balance between ease of placement and minimal segregation.

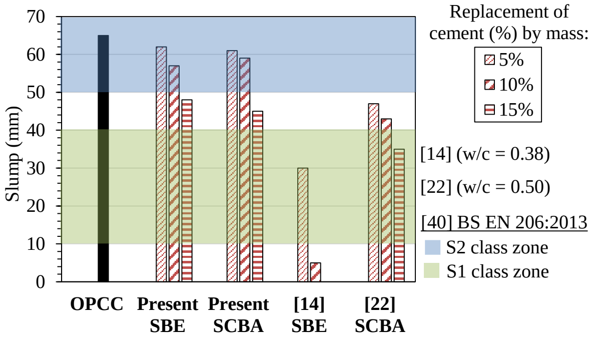

Fig. 3. Slump values of the fresh concrete mixes

For the present results in the figure (w/c = 0.55), the supplement of 5 to 10% SBE or SCBA with cement did not affect this workability significantly, as the slump values of the corresponding mixes were similar to the OPCC, and also remained in the S2 zone. With 15% SBE and SCBA replacement, however, the slump value fell below the S2 category and hence lost much of its original workability. This reduction indicates a threshold beyond which the inclusion of these materials begins to significantly influence the mix's plasticity, likely due to increased surface area and the pozzolanic activity of the ash, which could lead to greater water demand. Further, it can be deduced that the consistence of both the SBE and SCBA mixes were fairly comparable with each other at equal content from 5 to 15%. This may suggest that the rate of water absorption by the SBE and SCBA material in the respective mixes is similar.

When the w/c ratio is reduced, the slump values of the SBE and SCBA also reduce according to previous studies [14, 22]. At w/c = 0.5 and for M30 grade concrete, the slump of SCBA mixes tend to fall below the S2 zone and towards the S1 zone (10-40 mm) with increasing content [22]. Hence, at this range of workability these mixes would be more suitable for lightly reinforced foundations and pavements where lower slump values can be tolerated or even preferred for preventing excessive bleeding and ensuring better compaction. It is also interesting to note that the rate of loss in slump of the SCBA mixes from 5-15% is similar to the present results. However, when the w/c is reduced further to 0.38 for the same M30 grade concrete [14], the slump of SBE mixes seems to drop well in to the S1 zone. Further, an increase from 5% to 10% SBE replacement with cement causes a significant loss in workability even below the S1 zone. This may indicate that such mixes could be relatively dry and would require a sufficient level of compaction even for application as plain cement concrete below shallow foundations.

4.3. Compressive Strength

Fig. 4 illustrates the progress in compressive strength (fck) of the hardened concrete specimens at days 1, 3, 7 and 28. As expected, the OPCC concrete maintained adequate strengths from early age until day 28 when it attained a strength of 44.10 MPa. It is apparent that the SBE concretes displayed weaker strengths compared to the OPCC at all ages. At day 1, the strengths of the SBE5, SBE10 and SBE15 concretes were in close range, with a reduction of about 24 to 30% compared to the OPCC. At later ages, however, the strengths of these concretes reduce considerably with increasing SBE content. By day 28, the strength reduction is about 13%, 25% and 40% of the respective concretes compared to the OPCC. In addition, the gain in strength of the SBE concretes from day 7 to day 28 seems to be decreasing with the more SBE content that is added to the concrete. These observations suggest that the optimum SBE replacement in concrete should be between 0 to 5% in order to maintain strengths closer to the OPCC concrete.

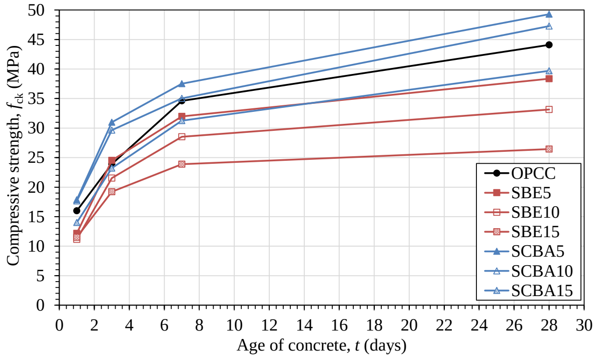

Fig. 4. Compressive strength development of the SBE and SCBA concretes

In contrast SCBA5 and SCBA10 concretes exhibited higher strengths at all ages compared to the OPCC. Particularly at day 28, these concretes were at least 7-12% stronger than the OPCC, indicating a potential for SCBA to enhance the long-term compressive strength of concrete. The early-age strength development of these mixes suggests a more efficient pozzolanic reaction, leading to a denser microstructure. With addition of 15% SCBA content, however, the strength development seems to fall below the OPCC. It is also interesting to note that the development of the SCBA15 and SBE5 concretes from days 1 to 28 are very similar, which may imply that

5% SBE or 15% SCBA replacement of cement results in a similar density of microstructure, although further tests would need to be performed to confirm this deduction. Nevertheless, the results indicate the optimum quantity of SCBA replacement for cement should be about 5-10% to obtain increased strengths, which also agrees with former studies [22-25]. Furthermore, given that the density of SCBA is lower than OPC, SCBA concretes also present as a lightweight and high-strength alternative to 100% cement-based concretes. This characteristic could prove beneficial in structural applications where both weight reduction and strength are critical considerations.

The effect of the % replacement of SBE and SCBA material with cement on the 28-day compressive strength is shown in Fig. 5. The present results correspond to w/c = 0.55. The OPCC data represents the strength of the concrete at 44.10 MPa, without any addition of SBE or SCBA content (i.e. 0%). The SBE concretes clearly display a linear depreciation in strength as the % SBE is increased. Particularly, at 10% SBE content the strength loss in the present results is at about 25%. If the w/c ratio is lowered slightly to 0.5 for CEM I 42.5N based concrete [11], the reduction in strength is much higher at 40%. Similarly, a relatively low w/c of 0.38 for M30 grade concrete [14] results in a further degradation of strength of about 56%. Hence, both the present and referenced results infer that the minimum w/c of SBE concrete mixes should be about 0.5 and the % SBE should be kept to less than 5% to avoid loss of significant strength. This may be due to the SBE material requiring adequate amounts of water to undergo the necessary degree of pozzolanic reaction to form a stable cementitious matrix in the concrete. Moreover, it's important to consider that high percentages of SBE could also affect the workability and setting times of the concrete, potentially leading to complications during the mixing and placing processes. This trade-off between strength and workability highlights the need for careful balance when incorporating supplementary materials like SBE.

With regards to the SCBA concretes, it is evident that both the present and referenced results reflect an improvement in strength from 0-10% SCBA replacement with cement. This may be because within this range of SCBA content the hydration reaction in the cementitious mix is enhanced, thus prompting he formation of calcium silicate hydrate (C-S-H) gels and increasing the mechanical strength. Also, note that when comparing a M30 grade concrete made from Pozolona Portland cement (PPC) (w/c = 0.45) [21] and a M20 grade concrete made from ordinary Portland cement (OPC) (w/c = 0.52) [23], the strengths appear to be similar for equal % SCBA content. Together with the present results, this further validates that the type of cement, w/c ratio and grade of concrete are important factors to consider in the development of SCBA concretes to a desired strength. It underscores the necessity of optimizing mix designs and understanding the interactions between different types of cementitious materials to achieve the best performance. This approach could lead to more sustainable concrete solutions with enhanced properties and reduced environmental impact.

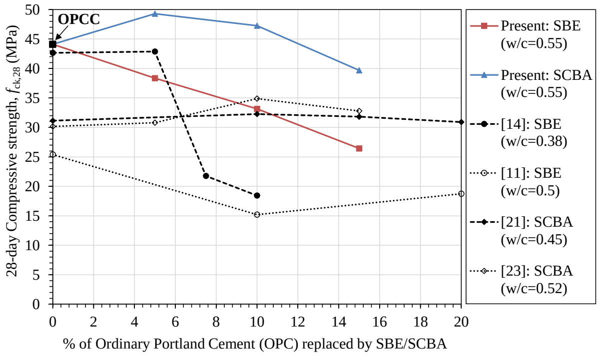

Fig. 5. 28-day compressive strengths for varying % SBE and % SCBA.

Fig. 6 depicts the ratio of the compressive strength (fcm(t)) of the concretes at any age (t) with respect to the 28-day strength (fcm), where subscript 'm' denotes the mean value. According to the Eurocode 2 (EC2) [41] and American Concrete Institute (ACI) [42], this ratio is referred to as β(t) and are defined by, respectively,

EC2:2004 $\beta(t) = fcm(t)/fcm,28 = \exp\{s[1 - (28/t)1/2]\}$ (1)

ACI 209.2R:2008 $\beta(t) = fcm(t)/fcm,28 = t/(a + bt)$

(2)

where the constants s = 0.25, a = 4 and b = 0.85 for Class N (EC2) and Type-1 (ACI) cements. Judging from the EC2 and ACI curves, there is a noticeable difference in the strength ratios during the early ages (< 14 days), with EC2 predicting higher strength development compared to ACI. At more mature ages (> 14 days), the two curves converge. The strength ratios of the reference OPCC concretes also follow closely to the EC2 curve, while the ratios of the SCBA concretes lie somewhat in between the EC2 and ACI curves. The strength ratios of the SBE concretes, however, are relatively higher compared to both the EC2 and ACI predictions. This highlights the fact that the SBE concretes had developed its 28-day strength at a faster rate than OPCC or the SCBA concretes, although the magnitudes of the strengths are much lower as shown in Fig. 4. In addition, the ratios appear to deviate higher above the EC2 and ACI curves with increasing % SBE content. Hence, concretes which are produced greener with 0-15% SBE may yet be appropriate for practices where high early strength is required, such as in high-speed in-situ or cold-weather concrete construction.

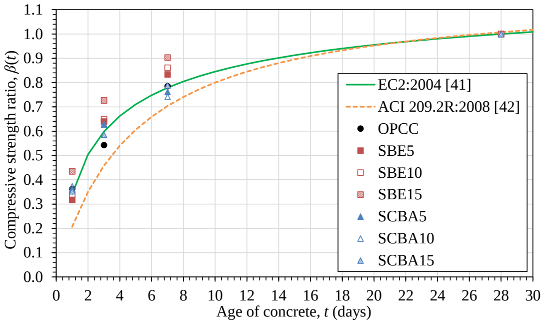

Fig. 6. Experimental compressive strengths compared to EC2 and ACI.

This observation suggests that while SBE concretes may not reach the ultimate strength of traditional OPCC or SCBA concretes, their rapid early strength development could be advantageous in specific applications where early load-bearing capacity is critical. Furthermore, this rapid early strength gain might also indicate a more efficient pozzolanic reaction at early ages, potentially due to the finer particle size or specific chemical properties of SBE. The trade-offs between early strength gain and overall strength development should be considered when designing concrete mixes for specialized construction scenarios.

4.4. Splitting Tensile Strength

The experimental results of the 28-day splitting tensile strengths (fct,sp) of the concretes for varying % replacement of cement are displayed in Fig. 7. The tensile strength of the reference OPCC concrete (with 100% cement) was measured to be 3.82 MPa. For 5% SBE replacement with cement, the tensile strength decreased by 26%, which is very similar to the loss of 29% obtained from the study on M30 grade concrete with w/c = 0.38 [14]. This observed reduction aligns with expectations, as higher replacement percentages of SBE can dilute the cement matrix, weakening the concrete's ability to resist tensile forces. With further % SBE replacement, the strength reduces linearly as shown through the present data, which supports the finding in Fig. 5 concerning the compressive strength. Hence, it may feasible to state that the mechanical strengths of the present SBE concrete mix design decrease at a linear rate with respect to the % SBE replacement for cement.

The SCBA concretes, however, exhibited better tensile strengths than the OPCC or SBE concretes from 0-10% replacement, which is also in agreement with the outcomes of tests conducted on M30 grade concretes composed of PPC (w/c = 0.45) [24] and OPC (w/c = 0.5) [25]. Combining the present and referenced results, it is intriguing to note that the lowering the w/c content could potentially result in a higher gain in tensile strength. For example, at 5% SCBA replacement the tensile strength improves by about 8%, 13% and 20% corresponding to w/c = 0.55, 0.50 and 0.38, respectively. These findings imply that an optimum content of 0-10% SCBA and w/c ratio of 0.4-0.5 could potentially achieve high tensile strengths, which is particularly beneficial in applications where cracking and other serviceability limit states need to be controlled.

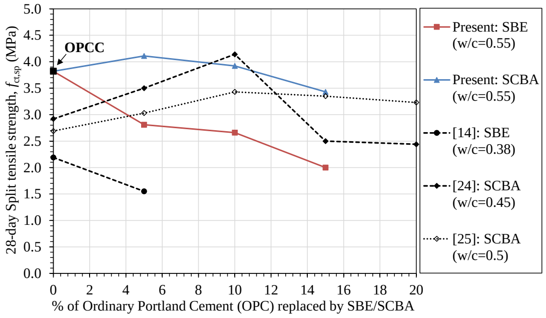

Fig. 7. Splitting tensile strength for varying % SBE and % SCBA.

Fig. 8 outlines the relation between the experimental 28-day compressive strength (fck,28) and splitting tensile strengths (fct,sp) of the concretes, along with the predictions from the EC2 [41] and ACI [43] codes, which are stipulated as:

$$\text{EC2:2004 } f_{ct,sp} = 0.7\times0.3\times(f_{ck,28})^{2/3}/0.9 \qquad (3)$$

$$\text{ACI 318:2014 } f_{ct,sp} = 0.56\times(f_{ck,28})^{1/2} \qquad (4)$$

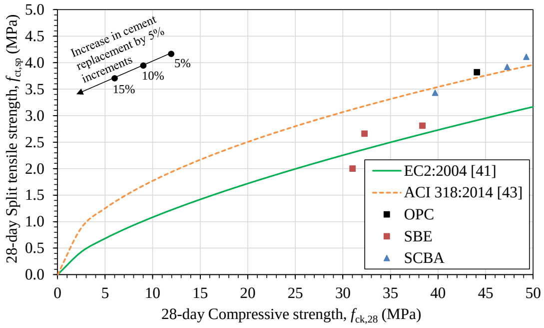

Fig. 8. Relation between tensile and compressive strengths of the concretes.

As shown in the figure, the data points shifting downwards-left represent the strengths corresponding to increases of 5% increments in cement replacement. It is clear that the EC2 curve provides lower estimates of tensile strengths compared to the ACI 318. This discrepancy suggests that the EC2 code might be more conservative in predicting tensile strengths, potentially accounting for a broader range of material variations or safety factors. Furthermore, the strengths of the OPCC and SCBA concretes coincide well with the ACI 318, while the strengths of the SBE concretes seem to align more with the EC2.

Moreover, since the functions of two codes are relatively parallel for the majority of strength ranges, it may dictate that the rate of increase in tensile strength with respect to compressive strength is similar for both the SBE and SCBA concretes. Although, further data points are perhaps needed to verify this conjecture. This observation highlights the potential for both codes to be applicable in estimating tensile strengths for various concrete mixes, though adjustments may be necessary depending on the specific mix design.

4.5. Drying Shrinkage Strain

The development of the drying shrinkage strain of the tested concretes are expressed in Fig. 9 for a period of 15 weeks after curing. Upon inspection of the figure, the OPCC concrete experienced a moderate strain development relative to the other concretes. The final shrinkage strain achieved by the OPCC concrete was about 6.1(10-4) at 80-90 days of age. It is also observable that as more % SBE or SCBA content was added, there was an inflation in shrinkage strains suggesting that the available free water for evaporation in the concretes increased. This increase in shrinkage can be attributed to the higher porosity or reduced binding capacity of the cement paste with higher percentages of supplementary materials.

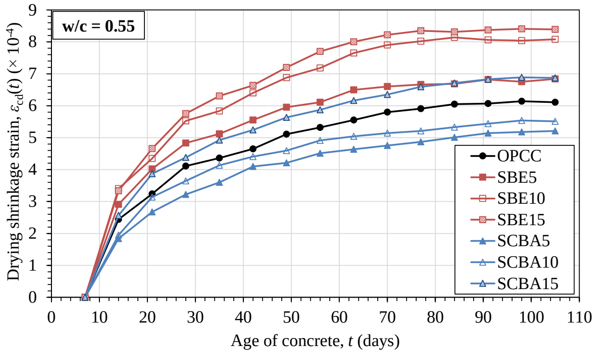

Fig. 9. Development of drying shrinkage strain of the tested concretes.

The SBE5, SBE10 and SBE15 concretes, however, demonstrated higher strains throughout the testing period, with a final strain value that was 10%, 30% and 40% higher than the OPCC, respectively. This signifies that that these concretes were more susceptible to shrinkage cracks. Furthermore, the SBE concretes developed its final strain earlier than the OPCC concrete, at about 70-80 days, which would suggest that the dormant period of the SBE concretes began earlier. On the contrary, the SCBA5 and SCBA10 concretes revealed lower strains than both the OPCC and SBE concretes, with a final strain that was 15% and 10% lower than the OPCC, respectively.

In addition, the dormant period of the SCBA concretes appeared to be later at about 90-100 days. This delayed onset of significant shrinkage could provide advantages in construction practices, particularly where extended curing periods are feasible. Incidentally, the SCBA15 concrete exhibited a similar shrinkage behavior to the SBE5, which is also supported by the compressive strength development of the two concretes in Fig. 4. Hence, it is possible that a greener concrete composed of either 15% SCBA or 5% SBE demonstrates similar mechanical and durability properties.

In the EC2 [41] and ACI [42] codes, the drying shrinkage strain of concrete at any age (t) is defined as εcd(t) = βds(t,ts)βRHεcd,∞, where βRH and εcd,∞ are the relative humidity factor and final shrinkage strain, respectively (see [41, 42]), and βds(t,ts) is a drying shrinkage coefficient expressed as:

EC2:2004 βds(t,ts) = (t-ts)/[(t-ts)+0.04h3/2)
(5)

ACI 209.2R:2008 βds(t,ts) = {(t-ts)/[350B2+(t-ts)]}1/2
(6)

where ts is the age at beginning of drying, h = 2A/u is a notional cross-section size and B = (V/S)/50 is volume to surface area ratio. As illustrated in Fig. 10, βds(t,ts) describes the relative development of the shrinkage strains over time. At early ages up to about 15 days, the EC2 and ACI predictions are similar. Beyond this age, however, there is a significant disparity between the two codes, with the EC2 yielding higher shrinkage coefficients. This divergence may reflect differing approaches in accounting for factors such as moisture loss or internal curing effects in the concrete mix.

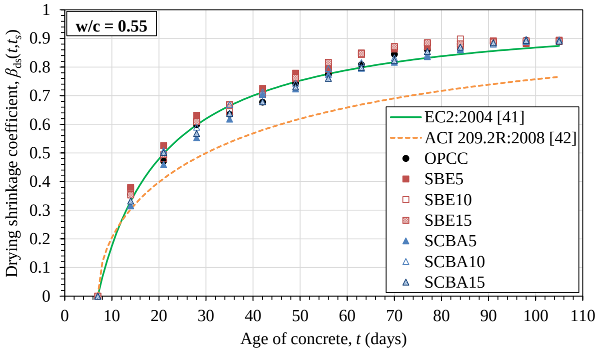

Fig. 10. Drying shrinkage coefficient of the tested concretes as compared to EC2 and ACI.

Overall, the shrinkage development pattern for all the concretes were more in coherence with the EC2 rather than ACI. This consistency with the EC2 model might indicate that its approach to calculating drying shrinkage is more suited to the concrete mixes tested, possibly due to its consideration of different parameters or empirical data that better align with the experimental results. Further investigation into why the EC2 code predicts higher shrinkage coefficients could provide valuable insights into optimizing concrete formulations to mitigate shrinkage-related issues. Additionally, understanding the underlying reasons for the code differences could help refine prediction models and improve the accuracy of shrinkage forecasts in various concrete applications.

CONCLUSIONS

The objective of this study was to investigate the performance of green concretes formulated from agricultural waste products, specifically spent bleaching earth (SBE) and sugarcane bagasse ash (SCBA). After testing both fresh and hardened mixes containing 0-15% SBE and SCBA as cementitious substitutes, the following results are highlighted:

- The consistence of fresh mixes incorporating equal quantities of SBE or SCBA are comparable. Up to 5-10% substitution can be employed with w/c = 0.55 to maintain the same S2 class slump as an OPC concrete.

- Based on present and referenced results [21, 22-25], an optimum dosage of 0-10% SCBA can achieve increased compressive and split tensile strengths and perform better than OPC and SBE based concretes.

- EC2 [41] code can reasonably predict the compressive strength development of the 0-15% SCBA concretes, but may underestimate for the SBE concretes, especially at early ages and at high % quantities.

- The relation between compressive and split tensile strength of the 0-15% SCBA concretes was forecasted accurately by the ACI [43], but for the SBE concretes the EC2 [41] appeared to yield closer estimates.

- For equal mix quantities, the SBE concretes attained significantly higher drying shrinkage strains than the SCBA concretes, which may have induced more shrinkage cracks, comparatively.

- The shrinkage coefficients of the 0-15% SBE and SCBA concretes displayed a better correlation to the EC2 [41] as compared to the ACI [42].

Agricultural wastes generated in large quantities worldwide pose serious environmental and health concerns. Concurrently, the cement industries are receiving increasing demands to stem the release of CO2 that is accelerating global warming. Based on the outcomes, this study recommends a possible solution to these problems by producing sustainable concretes using 0-10% cement substitution with SCBA, at a w/c ratio of 0.55. A stronger justification could be established through further investigations on the durability properties of these concretes, such as resistance to carbonation penetration and performance under acidic environments.

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