Effect of ground granulated blast furnace slag (GGBS) in coconut shell concrete as partial cement replacement

Muhammad Fiqree Ali[1], *Noor Aina* Misnon[1*], *Faridah Hanim* Khairuddin[1], *Nadia* Zulkarnaen[1], *Hidayu Murni* Abu Hussain[2], and *Gunalaan* Vasudevan[2]

[1] Department of Civil Engineering, Faculty of Engineering, Universiti Pertahanan Nasional Malaysia, Kem Sungai Besi, Sungai Besi, 57000, Malaysia
[2] Tunku Abdul Rahman University of Management and Technology, Jalan Genting Kelang, Setapak, 53300 Kuala Lumpur, Malaysia

Abstract. The continual removal of aggregates to produce concrete led to an alarming rate of resource depletion resulting in environmental issues. Meanwhile, the use of cement, the main constituent in concrete production, contributes significantly to global carbon dioxide (CO_2) emissions during its manufacturing process. This study explores the potential of crushed coconut shells (CS) as an alternative solution to aggregate to produce lightweight aggregate concrete (LWAC) namely coconut shell concrete (CSC). The effect of the utilization of ground granulated blast furnace slag (GGBS) as cement replacement in CSC is also studied. This study aims to determine the mechanical properties, chemical composition, and microscopic examination of CSC with GGBS. Three different samples were cast and tested i.e., normal concrete (NC) as control samples, CSC, and CSC with 10% GGBS. The incorporation of 10% GGBS in CSC as cement replacement improved the compressive strength, splitting tensile strength and flexural strength up to 20.2 N/mm^2, 2.2 N/mm^2, and 3.1 N/mm^2, respectively. RAMAN spectroscopy test offers important findings in phase detection of cement hydration products at the observed white and dark regions in the concrete samples. The white region denotes possible early strength growth of calcium silicate hydrates (CSH) that contribute to the strength of the concrete samples.

1 Introduction

Concrete is the most commonly used material in construction because of its excellent strength properties. It is produced by mixing cement, fine and coarse aggregates, and water. The aggregates, which occupy the majority of the concrete volume, primarily contribute to its strength, with the cement paste acting as a binder. The high demand for aggregates not only in the construction industry but also in infrastructure, electronics, and cosmetics has led to extensive mining and extraction activities, causing environmental conflicts [1-2].

---

* Corresponding author: nooraina@upnm.edu.my

Additionally, the cement industry is a significant source of global carbon dioxide (CO_2) emissions, accounting for approximately 5% of the total CO_2 emissions worldwide [3].

Numerous studies have been conducted to identify sustainable materials that can serve as alternative aggregate fractions in concrete production, including agricultural wastes such as palm kernel shells, corn cobs, and coconut shells [4 -6]. Crushed coconut shell (CS) has been used as an aggregate replacement due to its hardness, which is comparable to hardwood, and its promising mechanical properties [6]. Research on the mechanical properties of concrete incorporating CS, known as coconut shell concrete (CSC), has shown encouraging results, with the compressive strength of CSC meeting the minimum requirements for lightweight aggregate concrete in structural applications [7]. However, achieving the desired strength in CSC necessitates a high cement content [6]. To address this, substituting cement with pozzolana has been proposed to reduce cement content while enhancing CSC's strength. Ground granulated blast-furnace slag (GGBS) has been identified as a reactive pozzolan with advantages in improving concrete strength [8 -9].

To date, the use of GGBS as cement replacements in CSC has not been extensively studied particularly in the investigation of the chemical compound of the CSC. It is important to understand the bonding between the concrete matrix to produce high-quality concrete. Thus, this research was carried out to determine the mechanical properties of the CSC with GGBS and to examine the chemical compound using RAMAN spectroscopy.

2 Sample preparation and testing

In this study, crushed CS was used as a whole replacement of gravel in normal concrete to produce lightweight aggregate CSC. The crushed CS was collected from the wider region of Kuala Lumpur, Malaysia with sizes ranging from 10 mm to 13 mm. 10% GGBS was incorporated in the CSC design mix as a partial cement replacement. The design mix ratio used was 1: 1.6: 0.7 (cement: sand: coarse particles) with water cement ratio (w/c) of 0.42 which was adopted from Gunasekaran et al. [6]. The cement content used was 480 kg/m^3 to increase the reactivity of cement during the hydration process [6]. The crushed CS was soaked in water before the concrete mixing to ensure the saturated surface dry (SSD) condition of the crushed CS [10]. This step minimizes the water absorption during the concrete mixing by the crushed CS. Table 1 shows the design mix of the samples for 1m^3 concrete volume. A total number of 36 samples were cast and were plastic wrapping cured up to 28 days before the testing. The fresh and hardened state of testing was carried out consisting of a slump test, compression test, splitting tensile test, and flexural strength test. Microscopic examinations were carried out to observe the bond between the cement paste and coarse particles.

Table 1. Design mix of the samples for 1 m^3 concrete volume.

Sample/Component	Cement	Sand	Gravel	CS	GGBS	Water
Normal concrete	480	768	336	-	-	201.6
CSC			-	336	-	
CSC + 10% GGBS			-	336	48	

** All units in kg*

Slump test was carried out to assess the workability and consistency of fresh concrete following BS EN 12350-2. The compressive strength, splitting tensile strength and flexural strength tests were conducted according to BS EN 12390 using the universal testing machine (UTM) with a maximum capacity of 3000 kN. The hydration of cement pastes during setting and characterization of hydration products were analyzed in real-time using Raman spectroscopy (Figure 1). A near-ultraviolet, visible, or near-infrared laser is typically used in a Raman spectroscopy system to illuminate the sample [11]. In this study, the type of laser 532 nm was selected since it easily penetrates solid material like concrete. The penetration depth, laser power, and source are 0.7μ, 50 mW, and green, respectively with a grading of 1800.

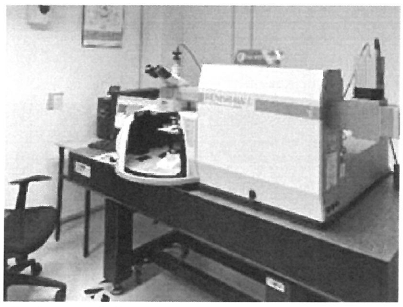
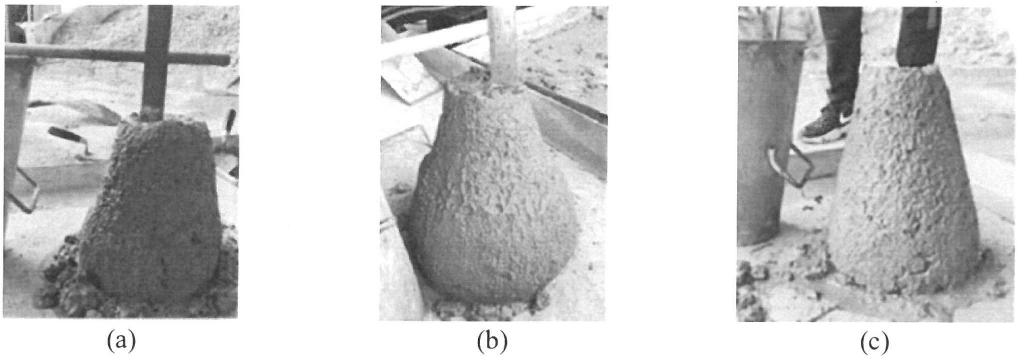


Fig. 1. RAMAN spectroscopy apparatus and machine.

3 Results and discussion

3.1 Slump test and density

All the samples showed true slump type (Figure 2) as stated in BS EN 12350-2 with a slump value of less than 100 mm (Figure 3). The smooth surface and high-water absorption capacity of crushed CS led to reduced workability with a lower slump value (67 mm) when compared to the NC (70 mm). The incorporation of 10% GGBS in CSC also reduced the workability since more water consumed for GGBS interacts with calcium hydroxide to produce more cementitious compounds [12].



(a) (b) (c)

Fig. 2. True slump of (a) Normal concrete (b) CSC (c) CSC + 10% GGBS.

Figure 4 shows the density of the samples at 7 and 28 days of curing. All samples showed a similar pattern with density reduction between the age of 7 days and 28 days age of curing due to the loss of water for the hydration process until the samples achieved matured age at 28 days. Both CSC samples can be categorized as LWAC since the ρ were less than 2000 kg/m^3 at the age of 28 days of curing [10]. The mass reduction of CSC was expected since the crushed CS has a lower bulk density when compared to the gravel [13]. Adding 10% GGBS to the CSC sample showed a slight reduction in density at both 7 and 28 days of curing as a result of replacing the cement content because GGBS has lower specific gravity and bulk density than cement [9].

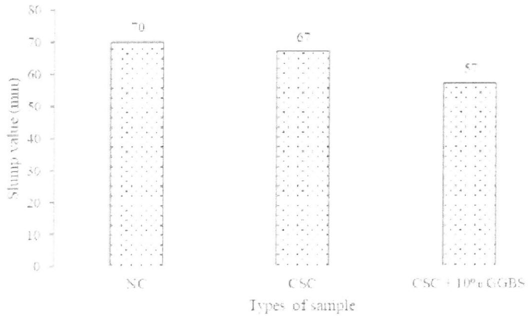


Fig. 3. Slump value of different samples.

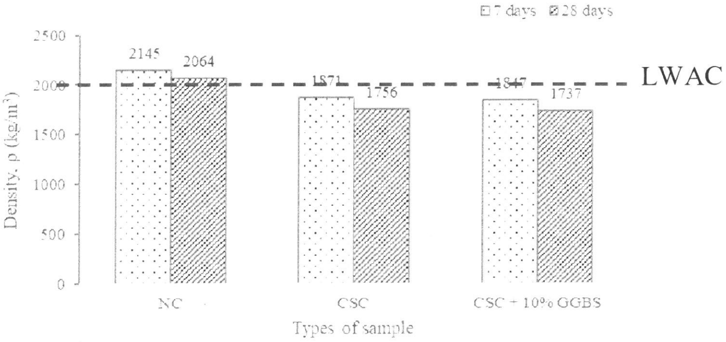


Fig. 4. The density of the samples at 7 and 28 days.

3.2 Mechanical properties of samples

The mechanical properties of the samples were determined by conducting compressive strength test, splitting tensile strength test, and flexural strength test of the samples at 28 days of curing. Table 2 summarizes the mechanical properties results for all the samples.

Table 2. Summary of mechanical properties of the samples at 28 days

Samples	Average CST (N/mm^2)	*n*	COV	Average STS (N/mm^2)	*n*	COV	Average FS (N/mm^2)	*n*	COV
NC	20.8	3	0.051	2.2	3	0.008	4.1	3	0.017
CSC	19.4	3	0.023	2.1	3	0.033	2.6	3	0.067
CSC + 10% GGBS	20.2	3	0.013	2.2	3	0.018	3.1	3	0.065

**CST= compressive strength; STS = splitting tensile strength; FS = flexural strength; n = no of samples; COV = coefficient of variance*

Figure 5 shows a comparison of CST between all the samples at 7 and 28 days. All the samples showed that the CST at 7 days achieved at least 70% of the ultimate strength at 28 days which agreed with the conventional concrete strength development. At the maturity age of the samples at 28 days, the CST of CSC slightly decreased up to approximately 7% when compared to the NC. The CST reduction was anticipated since the crushed CS has a lower specific gravity [13] and led to the weakening of the concrete samples. However, the substitution of 10% cement with GGBS successfully improved the CST of CSC approximately 20.2 N/mm^2 comparable to the NC. Notably, GGBS possesses a pozzolanic reaction by creating a compact and dense microstructure [14]. All the samples satisfy the minimum requirement for CST i.e., 17 N/mm^2 to be used as structural lightweight concrete as stated in ASTM C330/C330M-14.

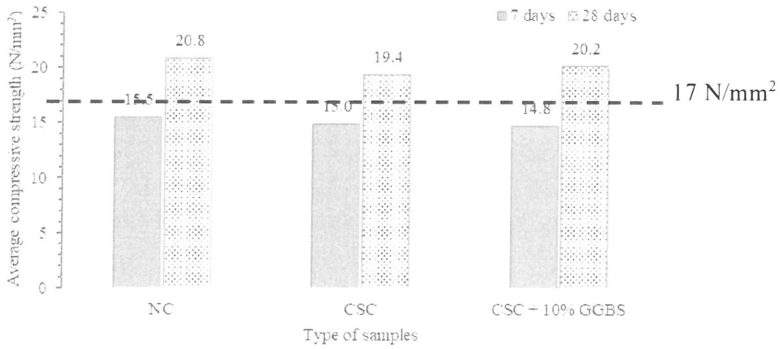


Fig. 5. Compressive strength of the samples at 7 and 28 days.

STS and FS of the samples are shown in Figure 6. Since the STS has a close relationship with CST [15] the finding showed that the STS of CSC samples was slightly lower than NC samples with only 5% strength reduction. Replacing 10% cement with GGBS in CSC, successfully enhanced the STS similar to NC. According to ASTM C330/C334 M-14, the CSC+10% GGBS fulfills the minimum STS requirement for structural application i.e., 2.2 N/mm^2. The linear relationship between STS and CST can be proposed using equation (1),

$$STS = 0.0721\,(CST) + 0.7143 \qquad (1)$$

This relationship has a close value of STS with the formulation proposed in CEB-FIP where,

$$STS = 0.3(CST)^{(2/3)} \qquad (2)$$

A comparison between the equations and experimental results is presented in Table 3 and the relationship between STS and CS is plotted in Figure 7.

Table 3. Comparison relationship between STS and CS

Samples	Experimental CST (N/mm^2)	Experimental STS (N/mm^2)	Equation (1) (N/mm^2)	Error (%)	Equation (2) [17] (N/mm^2)	Error (%)
NC	20.8	2.2	2.22	+0.8	2.27	+3.3
CSC	19.4	2.1	2.12	+0.8	2.17	+3.3
CSC + 10% GGBS	20.2	2.2	2.17	-1.5	2.22	+1.0

The FS of concrete provides fundamental information regarding the behavior of the concrete material under flexural stress. Figure 6 shows the results of FS for all the samples tested under the three-point bending test. It is remarked that the replacement of crushed coconut shell significantly reduced the FS up to -40% when compared to NC. The addition of 10% GGBS improved the FS of CSC up to +20% and only reduced -24% relative to the NC samples.

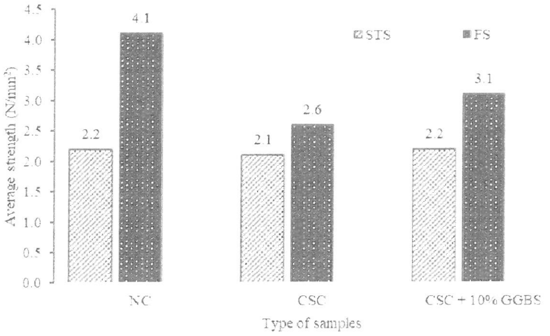


Fig. 6. Splitting tensile and flexural strength of the samples at 28 days.

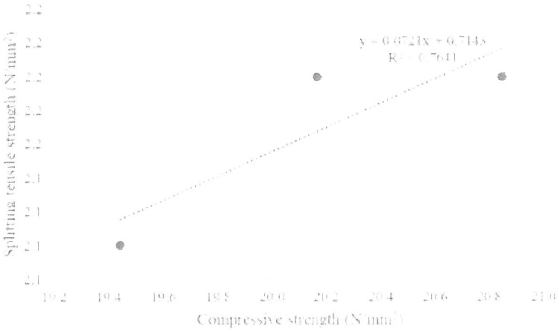
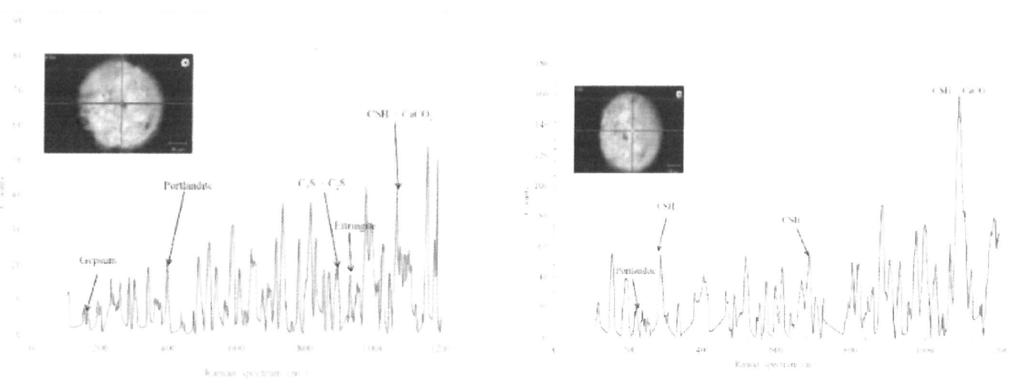


Fig. 7. Relationship between STS and CST of the samples.

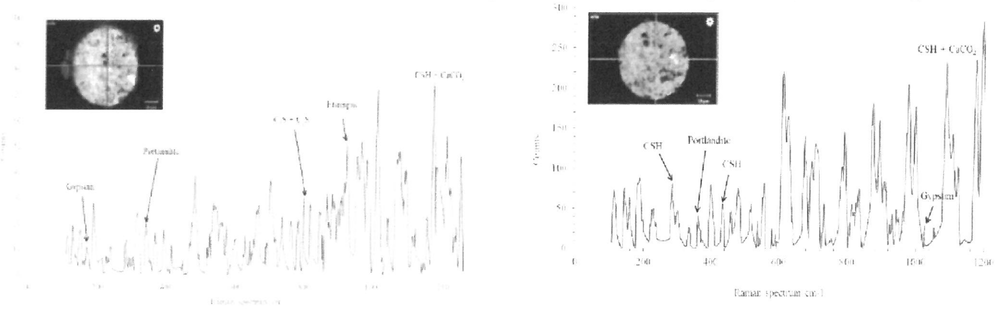
3.3 RAMAN spectroscopy

RAMAN spectroscopy provides valuable insight into the cement hydration process including the detection of the presence of different cement hydration products such as calcium silicate hydrate (CSH), ettringite, tricalcium silicate (C_3S), dicalcium silicate (C_2S), calcium hydroxide (CH), etc. In this study, the phase detection of cement hydration products was observed in dark and white regions of the samples. The identification of the Raman peaks was referred to Liu et al. [11]. Figure 8 – Figure 10 show the Raman shift in dark and white regions for all the samples. At the white region, the presence of CSH was detected at the early phase (Raman shift of 250 cm^{-1}) suggesting that the region was completely hydrated. The existence of gypsum component at Raman shifts around 1150 cm^{-1}, which controls the rate of reaction, was a sign that there might be unreacted gypsum in the region [11] yet the count is still lesser than in the dark region. Early development of concrete strength denoted by the Portlandite peak at Raman shift of as early 384 cm^{-1}. At the dark region, the hydration process is still slowly developing with the presence of C_3S +C_2S observed at Raman shift of 853 cm^{-1}, which are the major chemical compounds in cement and responsible for the strength of hydrated cement paste. The detection of ettringite at peak Raman shift of 976 cm^{-1} confirmed the ongoing hydration occurred at the region since ettringite is commonly exhibited during the early hydration product [10]. The existence of CSH was only detected at the Raman shift of 1186 cm^{-1}.



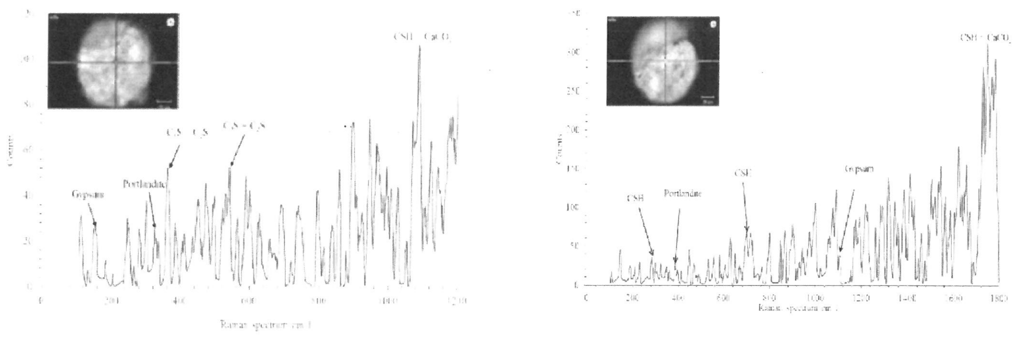
(a) (b)

Fig. 8. Raman spectrum of NC sample on (a) dark region (b) white region.



(a) (b)

Fig. 9. Raman spectrum of CSC sample on (a) dark region (b) white region.



(a) (b)

Fig. 10. Raman spectrum of CSC + 10% GGBS sample within (a) dark region (b) white region.

4 Conclusion

This study investigates the potential of using crushed CS as coarse particles in the concrete mix to produce lightweight aggregate concrete (LWAC). Additionally, the mechanical properties of CSC with a 10% replacement of cement by GGBS were examined. RAMAN spectroscopy was conducted to gain a deeper understanding of the chemical composition. From the study, it can be concluded that:

i. Replacement 10% of cement with GGBS in CSC assists in strength improvement while reducing approximately 2% of the CSC density.
ii. The presence of CSH as the main binding component in concrete was detected as early as at Raman shift 284 cm^{-1} suggesting strength development in the CSC mix.

This project was funded by Tunku Abdul Rahman University of Management and Technology (TARUMT) under grant number UC/I/G2022-0091. The authors gratefully acknowledge the assistance of the technical staff of the structural and heavy material laboratory of Universiti Pertahanan Nasional Malaysia.

References

1. M. Bendixen, L. L. Iversen, J. Best, D. M. Franks, C. R. Hackney, E. M. Latrubesse, L. S. Tusting. *Sand, gravel, and UN Sustainable Development Goals: Conflicts, synergies, and pathways forward*. One Earth 4, no. **8** (2021)
2. I. Sallehan, K. W. Hoe, M. Ramli. *Sustainable aggregates: The potential and challenge for natural resources conservation*. Procedia-Social and Behavioral Sciences **101** (2013)
3. P. Jouni, *Climate change: the ultimate tragedy of the commons*. Property in land and other resources (2011)
4. F. N. A. A. Aziz, N.A. Al-Ghazali, L. K. Min, K. Aramugam, N. A. Mohd Nasir, T. H. Law. *Properties of Sustainable Concrete Containing Different Percentages and Particles of Oil Palm Ash as Partial Sand Replacement*. Pertanika J Sci Technol **31**, no. 4 (2023)
5. J. Pinto, B. Vieira, H. Pereira, C. Jacinto, P. Vilela, A. Paiva, S. Pereira, V. M. C. F. Cunha, H. Varum, *Corn cob lightweight concrete for non-structural applications*. Constr Build Mater, **34**, (2012)
6. K. Gunasekaran, P. S. Kumar, M. Lakshmipathy. *Mechanical and bond properties of coconut shell concrete*." Constr Build Mater **25**, no. 1 (2011)
7. N. A. Misnon, S. Shahidan, F.H. Khairuddin, N. L. Rahim, S.K. Che Osmi, H.Husen. *Effect of Coconut Fibre on Coconut Shell Concrete*. In Advances in Civil Engineering Materials: M. M. F. Meor Razali, M. Awang, and S. S. Emamian, Eds., Springer (2021)
8. R. Siddique, Rachid Bennacer. *Use of iron and steel industry by-product (GGBS) in cement paste and mortar*." Resources, Conservation and recycling **69** (2012)
9. P. Shafigh, M. Z. Jumaat, H. B. Mahmud, U. J. Alengaram, *Oil palm shell lightweight concrete containing high volume ground granulated blast furnace slag*. Constr Build Mater **40** (2013)
10. A. M. Neville, *Properties of concrete* (vol. **4**): Longman London." (1995).
11. F. Liu, S. Zhihui, Q. Chengqing. *Raman spectroscopy study on the hydration behaviors of Portland cement pastes during setting*. J Mat in Civil Eng **27.8** (2015)
12. A. Agnihotri, P. V. Ramana. *GGBS: fly-Ash Evaluation and Mechanical properties within high strength concrete.* Materials Today: Proceedings **50** (2022).
13. P. Shafigh, H. B. Mahmud, M. Z. Jumaat, M. Zargar, *Agricultural wastes as aggregate in concrete mixtures–A review*. Constr Build Mater, **53**, (2014)
14. Kumar, VR Prasath, K. Gunasekaran, T. Shyamala. *Characterization study on coconut shell concrete with partial replacement of cement by GGBS.* J Building Eng **26** (2019)
15. Y. Choi, L. Y. Robert. *Experimental relationship between splitting tensile strength and compressive strength of GFRC and PFRC*. Cement and Conc Res **35.8** (2005)