Investigation of coal bottom ash and fly ash in concrete as replacement for sand and cement

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HIGHLIGHTS

- Concrete with bottom ash and fly ash added as replacement for sand and cement, respectively.
- Compressive, flexural and tensile strengths of the concrete are determined.
- Pulse velocity, drying shrinkage and micro-structural tests are performed.
- Relationship between mechanical properties and pulse velocity is discussed.

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ABSTRACT

Malaysia produces about 8.5 million tons of coal ash as waste which comprises of bottom ash and fly ash. Reusing such waste which is otherwise sent to landfills is an environment-friendly option. Hence, the major aim of this research study was to investigate their use in concrete to replace sand with bottom ash waste and cement with fly ash. Concrete specimens were prepared incorporating 0, 20, 50, 75 and 100% of bottom ash replacing sand and 20% of coal fly ash by mass, as a substitute for Ordinary Portland cement. Fresh and hardened state properties of the experimental specimens were determined. Results revealed that concrete workability reduced when bottom ash content increased replacing sand. On the other hand, at the early age of 28 d, no significant effect was observed in compressive, flexural and tensile strengths of all concrete samples. After curing at 91 and 180 d ages, compressive strength of both the experimental and control concrete samples increased significantly but remained almost similar. However, flexural and splitting tensile strengths of the experimental mix containing 75% bottom ash and 20% fly ash exceeded much more than the control sample. Moreover, drying-shrinkage of experimental concrete mixtures containing 50%, 75% and 100% bottom ash and 20% fly ash was lower than the control mix. It is concluded that those experimental concrete mixes can be used in several structures (foundations, sub-bases, pavements, etc.) which will minimize the cost, energy and environmental problems to a great extent.

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1. Introduction

Concrete is one of the most important materials in building construction and other infrastructure works. About 2.7 billion m³ of concrete was generated in 2002 worldwide, which is more than 0.4 m³ of concrete generated per person once a year [1]. It is anticipated that the need for concrete will increase further to almost 7.5 billion m³ (about 18 billion tons) a year by 2050 [2]. Such an enormous utilization of concrete calls for higher use of natural aggregates and cement, thus taking toll on the environment. At least three-quarters of the total volume of concrete consists of coarse and fine aggregates. Obviously, natural resources such as river sand are getting depleted [3]. The prohibition on mining in some areas and the growing need for natural environment conservation further exacerbate the problem of river sand availability.

Finding new alternative materials for sustainable development so as to substantially decrease the consumption of natural resources became imperative to safeguard the interests of future generations. High consumption of natural resources led to greater amount of industrial wastes and environmental degradation [4].
Such factors have driven researchers to come up with solutions leading to much needed sustainable development.

Coal fired thermal power plants have created tremendous volumes of coal bottom ash (CBA) and coal fly ash (CFA) (20–80% respectively) for years. CBA and CFA are by-products of pulverized coal combustion. Using them together, increase the use of disposal facilities which can reduce the environmental impact.

The projected forecast for electricity usage in peninsular Malaysia will be produced from coal and gas (58% and 25%) by the year 2024. Even though some difference exists between these figures and those of 2014, it appears that dependence on fossil fuels may be reduced but won’t be eliminated altogether. In fact coal consumption will likely mount from 43% to 58% [5]. As mentioned earlier, electricity production in Malaysia leads to a whopping amount of coal fly ash (CFA) some 6.8 million tons and coal bottom ash (CBA) roughly 1.7 million tons. While CFA is being used to manufacture pozzolanic Portland cement, CBA is not commonly used at all.

The coal ash content depends upon the non-combustible matter present in coal. Rock detritus filled in the fissures of coal becomes separated from the coal during pulverization. In the furnace, carbon and other combustible matter burn, whereas the non-combustible matter results in coal ash. Swirling air carries ash particles out of hot zone where it cools down. CBA displaced from under the furnace accounts for nearly 20% which is directed to suspension ponds that take over several acres of countryside land.

The particle size distribution and appearance of CBA is comparable to that of river sand. CBA is comprised of mostly silica, iron and alumina, trace amount of sulphate, magnesium, and calcium, etc. These chemical constituents in and grading of CBA make it more feasible for the production of concrete. It has been substantiated by previous researchers who came up with quite reassuring results when CBA was used partially or totally replacing sand in concrete because of its fine aggregate quality.

The flue gases carry away the finer and lighter ash particles. In the electrostatic precipitators installed prior to the stack, the ash particles are extracted from the flue gases. The coal ash obtained from the electrostatic precipitators is termed as CFA. It is used in construction industry worldwide as cement substitute in concrete and in the generation of cement as additive mineral in huge quantity. Using different sources of supplementary cementing materials (SCMs), especially CFA could lead to sharp reduction in overall CO2 footprint related to the final concrete production [6]. The use of CFA in concrete has proven to improve long term strength and workability.

There have been a substantial number of studies on concrete production incorporating coal ash either as cement replacements, fine and coarse aggregate. Cherief et al. [7] studied the pozzolanic property of CBA and found that strength activity indexes of CBA with Ordinary Portland cement at 28 d and 90 d of hydration were higher than that specified in European code EN 450 for pozzolanic material to be used in concrete. Their findings confirm that CBA has pozzolanic property and is suitable for use in concrete manufacturing. It was also reported that [8] CBA can be used as aggregates (fine and coarse) in high-strength concrete. They studied the workability and mechanical properties of high-strength concrete and found that CBA had more effect on the flexural strength than compressive strength. Singh and Siddique [9] in their review reported that CBA is a potential substitute material for sand in concrete. Singh and Siddique [10] also investigated the properties of concrete incorporating high volume of CBA as sand replacement. They found that at 28 d of curing, pulse velocity and compressive strength were not affected by CBA used in concrete. Aggarwal and Siddique [11] investigated the microstructure and properties of concrete containing CBA and waste foundry sand as replacement of natural sand in concrete. Singh and Siddique [12] studied the drying shrinkage and compressive strength of concrete containing CBA as total or partial replacement of fine aggregate. They reported that after 90 d of curing period, the compressive strength of CBA concrete outstripped that of normal concrete. Moreover, they found that drying shrinkage of CBA concrete mixtures reduced with increase in CBA content in concrete.

Concrete made with low calcium CBA as a replacement of river sand displayed strength properties comparable to that of conventional concrete [13]. The major gain from CBA as fine aggregate in concrete is reduced dead weight of structure as well as alleviation of environmental hazards. Due to low specific gravity of CBA, concrete made with it has low density as compared to control concrete. Sua-iam and Makul [14] have reported that the use of waste materials either as cement supplementary material or as sand replacement in concrete can result in cost savings and help in reducing the environmental problems. Topçu et al. [15] observed that CBA can be used in production of durable geopolymer concrete without cement.

Limited research studies have been reported on mechanical properties, microstructure, drying shrinkage and pulse velocity of concrete containing both CBA as fine aggregate and CFA as cement replacement.

The objective of current research work was to investigate the effects of using CBA and CFA as replacement of sand and cement, respectively, on the compressive, tensile and flexural strength properties of concrete. They were then compared with those of normal concrete. The materials chosen were carefully studied with respect to their properties such as fineness modulus, specific gravity, particle size distribution and chemical composition. Moreover, the effect of using CBA and CFA on microstructure, drying shrinkage and pulse velocity properties of fly ash-bottom ash concrete mixtures were also investigated in this study. The long-term durability properties of fly ash-bottom ash concrete may be analysed in future study.

2. Experimental program

2.1. Materials

Ordinary Portland cement (OPC) used in this research achieved the requirements of ASTM C150-07 [16]. The chemical compositions of OPC, CFA and CBA are given in Table 1. OPC used had a blain surface area, specific gravity, soundness, initial and final setting times of 3980 cm2/g, 3.15, 1.0 mm, 125 min and 210 min, respectively. A single source of CFA conforming to ASTM C618-15 [17] was obtained from Tanjung Bin coal power plant located in Johor, Malaysia. CFA was used as 20% replacement of OPC in all fly ash-bottom ash concrete mixtures with specific gravity, blain fineness and soundness of 2.45, 3450 cm2/g and 1.0 mm, respectively.

The FESEM image shows that CFA has spherical and regular shape and smaller particles compared to CBA (Fig. 1). Chemical analysis showed that CFA is mostly composed of Silica, Iron, and Alumina. The percentage sum of SiO2, Al2O3 and Fe2O3 in CFA is about 78.82% showing that it is a Class F according to ASTM C618-15 [17].

Sand was collected from Sungai Sayong River quarry near Johor, Malaysia. The sand used in this research was as per the specification of ASTM C778-13 [18] and was graded in accordance with the specification of ASTM C33/C33M-13 [19]. The results of fineness modulus, water absorption and specific gravity of this River sand are presented in Table 2.

Coal bottom ash (CBA) was collected from Tanjung Bin coal power thermal plant Johor, Malaysia. Particle size distribution of CBA and river sand are shown in Fig. 2. CBA was graded in accordance with the specification of ASTM C33/C33M-13 [19]. In this research, CBA was sieved through 4.75 mm sieve before use as replacement of sand. The chemical properties of CBA are presented in Table 1. The chemical analysis of CBA was carried out using XRF. The chemical analysis shows that CBA is mostly comprised of Silica, Iron and Alumina with small quantities of Sulphate, Magnesium and Calcium etc. Summation of the percentage of SiO2, Al2O3 and Fe2O3 present in CBA was 83.24%. Loss on Ignition (LOI) of CBA was less than 0.1%. The physical properties of CBA are shown in Table 2.

Fig. 3 shows the FESEM image of CBA. The FESEM image shows that CBA has irregular and spherical shaped, porous particles and complicated texture. Fig. 4 presents three different sizes of CBA; coarse, fine and ultrafine CBA. The crushed stone aggregate was obtained from Bukit Namu quarry. The physical properties of coarse aggregate are mentioned in Table 2 below. The maximum size of coarse aggregate was 20 mm.
2.2. Mix proportions

Initially, sixteen batches of concrete with different percentages of CBA as fine aggregate and CFA as cement were prepared. As a result of initial samples’ compressive strength and workability, concrete with 20% of CFA as cement replacement and different percentage of CBA as fine aggregate were selected for further analysis. Saturated Surface Dry (SSD) CBA and river sand was used and fixed quantity of water to cement ratio (w/c) was added in all of the concrete mixtures. The CBA was used by mass in concrete as river sand replacement. The effective w/c was 0.55 for all cases. The amount of cement (375 kg/m³) and the range of slump (6–18 cm) were the same for all manufactured concretes. The British (DOE) [20] method was used to calculate the mixture proportions shown in Table 3.

2.3. Casting and curing of specimens

Concrete cubes of 100 mm × 100 mm × 100 mm sizes were cast to determine the compressive strength, water absorption, density and pulse velocity. Cylindrical specimens of size 100 mm × 200 mm were cast to determine the flexural strength of concrete. The specimens were demoulded after 24 ± 1 h of adding water to concrete mixture and were water cured at room temperature up to a specified age of the test. The casting and curing of samples were performed in accordance with the specification of BS EN 12390-02 [21].

2.4. Testing procedure

Compressive strength of concrete samples was determined at 7 d, 28 d, 91 d and 180 d curing age as per BS EN 12390-03 [22]. The dry cubes with well saturated surface were subjected to 3000 kN compression testing machine. A consistent load was then applied to all the experimental specimens without any shock, thereby adding more at the rate of 5.0 kN/s till the samples couldn’t take it. Flexural strength under four point loading was assessed at 7 d, 28 d, 91 d and 180 d curing as per BS EN 12390-05 [23] using beams of 100 mm × 100 mm × 500 mm.

Splitting tensile strength of cylinders (100 mm × 200 mm), at the age of 7 d, 28 d, 91 d, and 180 d was determined as per ASTM C496-11 [24]. Pulse velocity through concrete was determined at 7 d, 28 d, 91 d and 180 d of curing age as per procedure ASTM C597-09 [25]. Battery operated Portable Ultrasonic Non-destructive Digital Indicating Tester was used to measure the pulse velocity through concrete. The pulse velocity (V) is calculated by dividing the length of the specimen (L) by transit time (T). Shrinkage due to drying of concrete mixtures was evaluated as per ASTM: C157/C157M-08 [26]. It was measured on 75 mm × 285 mm prism specimen in one direction; using stainless steel pins fixed over 100 mm gauge length on two opposite long sides. Test specimens were kept in upright position in the drying storage room. The comparator readings were acquired after curing of 7 d, 14 d, 21 d, 28 d, 60 d, 91 d, 120 d, 150 d and 180 d of air storage.

3. Results and discussions

3.1. Workability

The workability of fresh concrete is a multiple issue which includes the diverse requirements of compatibility, stability, and mobility. Using industrial by-products in concrete as total or partial substitute of sand by CBA mixed with a partial substitute of cement paste by CFA could affect the fresh concrete properties of the mix. Slump is a measure indicating the consistency or workability of concrete. The effect of CFA as cement replacement and CBA as replacement of sand in concrete mixtures on slump values with similar w/c, are tabulated in Table 3.

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**Table 1**

<table>
<thead>
<tr>
<th>Material</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>CaO</th>
<th>MgO</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>TiO₂</th>
<th>P₂O₅</th>
<th>MnO</th>
<th>SO₃</th>
<th>BaO</th>
<th>LOI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>20.4</td>
<td>5.20</td>
<td>4.19</td>
<td>62.39</td>
<td>1.55</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.005</td>
<td>–</td>
<td>2.11</td>
<td>–</td>
<td>2.36</td>
</tr>
<tr>
<td>CFA</td>
<td>47.6</td>
<td>23.8</td>
<td>7.42</td>
<td>10.7</td>
<td>1.50</td>
<td>–</td>
<td>1.68</td>
<td>2.92</td>
<td>1.16</td>
<td>0.120</td>
<td>0.759</td>
<td>0.154</td>
<td>–</td>
</tr>
<tr>
<td>CBA</td>
<td>45.3</td>
<td>18.1</td>
<td>19.84</td>
<td>8.70</td>
<td>0.969</td>
<td>–</td>
<td>2.48</td>
<td>3.27</td>
<td>0.351</td>
<td>0.248</td>
<td>0.352</td>
<td>0.311</td>
<td>–</td>
</tr>
</tbody>
</table>

**Table 2**

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific gravity</th>
<th>Water absorption</th>
<th>Fineness modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBA</td>
<td>2.62</td>
<td>11.61</td>
<td>3.44</td>
</tr>
<tr>
<td>River sand</td>
<td>2.69</td>
<td>7.4</td>
<td>2.67</td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>2.69</td>
<td>0.61</td>
<td>6.48</td>
</tr>
</tbody>
</table>

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**Fig. 1.** FESEM image of CFA.

**Fig. 2.** Grading curve of CBA and sand.
Slump values of control mix C0, FBC1, FBC2, FBC3 and FBC4 were 73 mm, 92 mm, 76 mm, 53 mm and 37 mm, respectively. Since the CBA is known to possess much higher water absorption ratio in comparison to river sand particles, some water is absorbed internally by the porous CBA particles. Up to 50% replacement level of CBA, fly ash-bottom ash concrete mixtures FBC1 and FBC2 displayed more increase in slump values as compared to that of control mix C0. It may be because of existence of CFA with low percentage of CBA (less than 50%) in these concrete mixtures. On the other hand, by increasing CBA content in fly ash-bottom ash concrete mixtures FBC3 and FBC4, considerable decrease occurred in slump values as compared to C0 mix control concrete. Moreover, Fig. 2 shows that particles of CBA carry rough texture and irregular shape. Use of CBA as fine aggregate actually enhances the concrete's texture with many more irregular and fine-shaped, porous particles that are usually very rough. Hence, it enhances the inter particle friction which is responsible for obstructing the flow of fresh concrete. Therefore, for fixed w/c, the workability of concrete reduces with increasing use of CBA as replacement of river sand. These results are comparable to those reported by Singh and Siddique [13]. Bong et al. [27] also obtained similar trend showing reduced workability of concrete containing CBA.

3.2. Compressive strength

Compressive strength test results are illustrated in Fig. 5. It is evident that compressive strength development pattern for fly ash-bottom ash concrete after curing, is almost the same as that of control concrete. At curing period of 7 d, compressive strength of FBC mixtures reduced with increase in CBA content as substitute of sand. At curing period of 7 d, fly ash-bottom ash mixture FBC1 (25% CBA – 20% CFA) achieved 90.1%, FBC2 (50% CBA – 20% CFA) achieved 81.4%, FBC3 (75% CBA – 20% CFA) achieved 77.2% and FBC4 (100% CBA – 20% CFA) achieved 74.2% compressive strength of control concrete mix C0. With increase in curing age, compressive strength of control concrete increased at a slower rate than the experimental mixtures. At 28 d curing age, compressive strength of the experimental mixtures namely, FBC1, FBC2, FBC3

<table>
<thead>
<tr>
<th>Codes</th>
<th>Mix proportions (Kg/m³)</th>
<th>Slump (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cement</td>
<td>Fine aggregate</td>
</tr>
<tr>
<td></td>
<td>% of CFA</td>
<td>CFA</td>
</tr>
<tr>
<td>Control</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>FBC1</td>
<td>20</td>
<td>75</td>
</tr>
<tr>
<td>FBC2</td>
<td>20</td>
<td>75</td>
</tr>
<tr>
<td>FBC3</td>
<td>20</td>
<td>75</td>
</tr>
<tr>
<td>FBC4</td>
<td>20</td>
<td>75</td>
</tr>
</tbody>
</table>
and FBC4 was lower than that of control concrete. Compressive strength of fly ash-bottom ash concrete mixtures FBC1, FBC2, FBC3 and FBC4 was 26.49 MPa, 26.33 MPa, 25.01 MPa and 24.59 MPa respectively, as compared to 31.03 MPa of control concrete mixture. At curing period of 91 d, fly ash-bottom ash concrete mixture FBC1 gained 96.98%, FBC2 gained 100.2%, FBC3 gained 99.18%, and FBC4 gained 98.17% compressive strength of the control specimen. It can be easily deduced that significant compression increase of 24.07% and 12.68% for the mixes FBC3 and FBC4 in comparison to the control mix C0.

**Fig. 5.** Variation of compressive strength with age for C0 and FBC mixes.

As shown in Fig. 6, fly ash-bottom ash concrete mixtures FBC1, FBC2, FBC3 and FBC4, C-S-H gel is not as monolithic and compact as in control concrete mixture. Formation of an imprecise C-S-H gel and higher percentage of voids in fly ash-bottom ash concrete mixtures might have affected their compressive strength at early curing age. At curing period of 91 d and 180 d, the fine spread of C-S-H gel and formation of extra C-S-H gel due to consumption of portlandite by pozzolanic action of CBA and CFA resulted in higher compressive strength of fly ash-bottom ash concrete at earlier ages. At curing period of 91 d, fly ash-bottom ash concrete mixtures FBC1, FBC2, FBC3 and FBC4 gained compressive strength 99.73%, 100.27%, 101.92% and 100.49% respectively of control concrete mix C0. The decrease of 2.88% and 4.09% for FBC1 and FBC2 mixes is ascribed to the fine spread of C-S-H gel and formation of extra C-S-H gel due to consumption of portlandite by pozzolanic action of CBA and CFA at early curing period. The delay in hydration and slow pozzolanic activity of CFA and CBA at early curing age may be the possible explanation for decrease in flexural strength of fly ash-bottom ash concrete at earlier ages. At curing period of 91 d and 180 d, the fine spread of C-S-H gel and formation of extra C-S-H gel due to consumption of portlandite by pozzolanic action of CBA and CFA resulted in higher flexural strength of fly ash-bottom ash concrete mixtures with high amount of CBA as fine aggregate.

The outcomes of present research work are comparable to that reported by Singh et al. [29]. The results of splitting tensile strength of fly ash-bottom ash mixes are summarized in Fig. 8. The decrease of 3.55%, 8.87%, and 5.32% in tensile strength was observed for the mixes FBC1, FBC2 and FBC4 and increase of 1.99% was observed for the mix FBC3 at 7 d age curing time with regards to control mix C0. Similarly, at age of 28 d curing period, the decrease of 9.76%, 14.88% and 2.48% for mixes FBC1, FBC2 and FBC4 was observed with increase of 4.96% for the mix FBC3 in comparison to the control mix C0. The decrease of 2.88% and 4.09% for mixes FBC1 and FBC2 mixes was observed at age of 91 d curing period, with increase of 23.67% and 11.21% for the FBC3 and FBC4 mixes in comparison to the control mix C0. Similarly, at age of 180 d curing time, the decrease of 1.29% and 2.51% for mixes FBC1 and FBC2 was observed with increase of 24.07% and 12.68% for the mixes FBC3 and FBC4 in comparison to the control mix C0.

### 3.4. Tensile strength

The results of splitting tensile strength of fly ash-bottom ash mixes are summarized in Fig. 8. The decrease of 3.55%, 8.87%, and 5.32% in tensile strength was observed for the mixes FBC1, FBC2 and FBC4 and increase of 1.99% was observed for the mix FBC3 at 7 d age curing time with regards to control mix C0. Similarly, at age of 28 d curing period, the decrease of 9.76%, 14.88% and 2.48% for mixes FBC1, FBC2 and FBC4 was observed with increase of 4.96% for the mix FBC3 in comparison to the control mix C0. The decrease of 2.88% and 4.09% for mixes FBC1 and FBC2 mixes was observed at age of 91 d curing period, with increase of 23.67% and 11.21% for the FBC3 and FBC4 mixes in comparison to the control mix C0. Similarly, at age of 180 d curing time, the decrease of 1.29% and 2.51% for mixes FBC1 and FBC2 was observed with increase of 24.07% and 12.68% for the mixes FBC3 and FBC4 in comparison to the control mix C0.
Fig. 6. Scanning Electron Micrographs (SEM) of concrete mixtures FBC1, FBC2, FBC3 and FBC4 at 90 d of curing age.
At 7 d and 28 d, all fly ash-bottom ash mixes showed the tensile strength lower than C0 mix except FBC3. However, as the age increased to 91 d and 180 d, all mixes showed almost comparable tensile strengths to that of control mix C0. It could have been a result of fine spread of C-S-H gel and extra C-S-H gel due to consumption of portlandite by pozzolanic action of CFA and CBA in concrete with high amount of CBA as sand replacement. The outcome of present study corroborated with Aggarwal and Siddique [11] and Singh and Siddique [13].

3.5. Pulse velocity

Table 4 illustrates the effect of CFA and CBA on pulse velocity through fly ash-bottom ash concrete mixtures evaluated on the basis of percentage decrease/increase over that of control mix. At curing period of 7 d, the pulse velocity values of all experimental concrete mixtures were surely found to be lower than that of control concrete mix. The pulse velocity values through the concrete mixtures FBC1, FBC2 FBC3 and FBC4 were lower by 1.19%, 1.34%, 0.15% and 0.62% respectively in comparison to the control mix C0. At 28 d of curing age, the pulse velocity of mixtures FBC1 and FBC2 when compared to the control mix C0, decreased by 3.61% and 3.16% respectively. Whereas, the pulse velocity through the concrete mixtures FBC3 and FBC4 over that of control mix C0 were 0.12% and 0.55% respectively. Pulse velocity of bottom ash concrete mixtures increased with age as well as with the increase in CBA content.

Comparing pulse velocity values obtained in this study with pulse velocity values given in Neville [30], the quality of concrete made with CBA and CFA can be graded as good. The difference in pulse velocity values for all ages of maturing were less than 3.61%. Higher values of pulse velocities obtained in this study indicated that the quality of fly ash-bottom ash concrete mixtures was good in terms of density, homogeneity and uniformity. At curing period of 91 d, the pulse velocity values for concrete mixtures FBC1, FBC2 and FBC4 were lower by 2.20%, 1.16% and 0.28% respectively when compared to the control mix C0. On the other hand, the pulse velocity values for FBC3 were higher by 0.60% compared to that of control mix C0. Significant decrease in permeable pore space in fly ash-bottom ash concrete mixtures resulted in higher values of pulse velocities. At curing period of 180 d, the pulse velocity values for fly ash-bottom ash concrete mixture FBC1,
FBC2 and FBC3 increased by 6.63%, 6.82% and 5.09% respectively. In case of FBC4 the values increased by 4.85% over pulse velocity values at curing period of 28 d as compared to 4.22% increase seen for control mix C0.

Fig. 9 shows the relationship between compressive strength and ultrasonic pulse velocity of concrete obtained in the study. The equation showing the relationships between compressive strength ($f_{cu}$) and the ultrasonic pulse velocity ($V$), together with the coefficients of determination ($R^2$) derived is given below. The empirical parameters of the equation obtained from the present research work are almost similar to that reported by Singh and Siddique [10] for CBA concrete and P. Turgut [31] for normal concrete. However, the coefficient of determination $R^2$ is higher than the one reported by them. Higher value of coefficient of determination indicates good relevance between the regression curve and data points.

$$f_{cu} = 0.0111e^{1.8593V} \quad R^2 = 0.8556 \quad \text{(Author)}$$

$$f_{cu} = 1.0741e^{0.8102V} \quad R^2 = 0.9493 \quad [10]$$

$$f_{cu} = 1.146e^{0.77V} \quad R^2 = 0.80 \quad [31]$$

where  
$V$ = Pulse velocity in km/s.  
$f_{cu}$ = Compressive strength of cube in MPa.

Fig. 10 shows the relationship between flexural strength and ultrasonic pulse velocity of concrete. The equation showing the relationships between flexural strength ($f_f$) and the ultrasonic pulse velocity ($V$), together with the coefficients of determination ($R^2$) derived is given below.

$$f_f = 0.0525e^{1.0297V} \quad R^2 = 0.953$$

where  
$V$ = Pulse velocity in km/s.  
$f_f$ = Flexural strength of concrete in MPa.

Fig. 11 shows the relationship between tensile strength and ultrasonic pulse velocity of concrete. The equation showing the relationships between tensile strength ($f_t$) and the ultrasonic pulse velocity ($V$), together with the coefficients of determination ($R^2$) derived is given below.

$$f_t = 0.0048e^{1.4882V} \quad R^2 = 0.9331$$

where  
$V$ = Pulse velocity in km/s.  
$f_t$ = Tensile strength of concrete in MPa.

3.6. Drying shrinkage

The result of drying shrinkage performance of control concrete and fly ash-bottom ash concrete mixtures are shown in Fig. 12. At constant w/c, the amount of porous particles in concrete increases with the increase of CBA quantity, that gradually allows the water content to flow during the drying process of concrete and therefore, cause decreased drying shrinkage. It has been surmised that the porosity of CBA results in decreased drying shrinkage of concrete. Hence it exerted reduced shrinkage strain on the drying process of experimental mixtures. The shrinkage strains of concrete mixtures FBC1, FBC2, FBC3 and FBC4 were $361.38 \times 10^{-6}$, $324.77 \times 10^{-6}$, $334.32 \times 10^{-6}$ and $222.88 \times 10^{-6}$ respectively at 28 d of maturity. Nevertheless, shrinkage strain of control mix C0
was $369.97 \times 10^{-6}$ at the same curing age. At 91 d drying age, the shrinkage strains of fly ash-bottom ash concrete mixtures FBC1, FBC2, FBC3 and FBC4 were $469.64 \times 10^{-6}$, $450.54 \times 10^{-6}$, $394.02 \times 10^{-6}$ and $296.11 \times 10^{-6}$ respectively. On the other hand, the control mix C0's shrinkage was $462.75 \times 10^{-6}$. At 180 d of drying period, fly ash-bottom ash concrete mixtures FBC2, FBC3 and FBC4 experienced 4.26%, 15.77%, and 37.89% respectively lower shrinkage strain as compared to control mix C0. Moreover, the experimental mixture FBC1 containing 25% CBA as replacement of sand and 20% CFA as cement replacement experienced 1.54% more shrinkage than that of control mix C0. In fact, the drying shrinkage of all experimental mixtures, with the exception of FBC1 mixture, were recorded lower than the control concrete mix C0 during all the tests’ drying age. These results are comparable to Singh and Siddique [12], Ghafoori and Bucholc [28,32] and Kou and Poon's [33] work. All of them have reported that in the given slump range, drying shrinkage standards of all the experimental mixes were lower than the control concrete.

4. Relationship between compressive, flexural and tensile strength

Fig. 13 demonstrates the relation between flexural and compressive strength of fly ash-bottom ash concrete mixtures. The equation showing the relationship between compressive and flexural strength together with the coefficients of determination $R^2$ obtained from the present research is given below.

$$f_f = 2.2335e^{0.0202f_c} \quad R^2 = 0.9337$$

where

- $f_f$ = Flexural strength in MPa.
- $f_c$ = Compressive strength of cube in MPa.

The elevated coefficient of determination $R^2$ points to favourable relationship between regression curve and data points.

Fig. 14 demonstrates the association of compressive and splitting tensile strength of fly ash-bottom ash concrete mixtures. The equation showing the relationship between compressive and split tensile strength together with the coefficients of determination $R^2$ derived from test results of the present research is given below.

$$f_f = 1.1231e^{0.0283f_c} \quad R^2 = 0.8579$$

where

- $f_f$ = Splitting tensile strength in MPa.
- $f_c$ = Compressive strength of cube in MPa.

Fig. 15 demonstrates the relation between flexural and splitting tensile strength of fly ash-bottom ash concrete mixtures. The equation showing the relationship between split tensile and flexural strength together with the coefficients of determination $R^2$ is given below.

$$y = 2.2335e^{0.0202x} \quad R^2 = 0.9337$$

5. Conclusions

The outcome of present experimental research work led to the following conclusions:

1. CBA shows low density, high water absorption, irregular and spherical shaped and complicated texture. On the other hand, due to suitable particle size distribution of CBA it can be concluded that it is possible to utilize CBA as a fine aggregate substitute for natural sand.

2. The workability of fly ash-bottom ash concrete was reduced due to the utilization of CBA as total or partial substitute of fine aggregate in concrete. The descending values of experimental concrete mix showed a downswing at fixed w/c, with increase in CBA content as substitute of sand in concrete. The CBA particles are found to have rough texture and irregular shape. Use of CBA as fine aggregate actually enhances the concrete’s texture with many more irregular and fine-shaped, porous particles that are usually very rough. It, therefore, enhances the inter particle friction which is responsible for obstructing the flow of fresh concrete.

3. The phenomenon of compressive strength development of fly ash-bottom ash concrete with curing period is almost similar to that of control concrete. At curing age of 7 d there was considerable reduction in compressive strength in all fly ash-bottom ash concrete mixtures compared with that of control concrete. With progress in curing period, considerable increase in compressive strength of fly ash-bottom ash concrete mixtures was noticed. It can be concluded with some certainty that notable increase in compressive strength of fly ash-bottom ash
References


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