Research Article

Influence of Bottom Ash Replacements as Fine Aggregate on the Property of Cellular Concrete with Various Foam Contents

Patchara Onprom, Krit Chaimoon, and Raungrut Cheerarot

Concrete and Computer Research Unit, Field of Civil Engineering, Faculty of Engineering, Mahasarakham University, Mahasarakham 44150, Thailand

Correspondence should be addressed to Raungrut Cheerarot; raungrut@hotmail.com

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This research focuses on evaluating the feasibility of utilizing bottom ash from coal burning power plants as a fine aggregate in cellular concrete with various foam contents. Flows of all mixtures were controlled within $45 \pm 5\%$ and used foam content at 30%, 40%, 50%, 60%, and 70% by volume of mixture. Bottom ash from Mae Moh power plant in Thailand was used to replace river sand at the rates of 0%, 25%, 50%, 75%, and 100% by volume of sand. Compressive strength, water absorption, and density of cellular concretes were determined at the ages of 7, 14, and 28 days. Nonlinear regression technique was developed to construct the mathematical models for predicting the compressive strength, water absorption, and density of cellular concrete. The results revealed that the density of cellular concrete decreased while the water absorption increased with an increase in replacement level of bottom ash. From the experimental results, it can be concluded that bottom ash can be used as fine aggregate in the cellular concrete. In addition, the nonlinear regression models give very high degree of accuracy ($R^2 > 0.99$).

1. Introduction

In recent years, cellular concrete has increasingly been used in construction because it has an advantage of reducing the sizes of structures. Cellular concrete or foam concrete is a lightweight material consisting of Portland cement paste or cement filler matrix (mortar) with homogeneous voids or pore structures created by introducing air in the form of small bubbles. Introduction of pores is achieved through mechanical means either by preformed foaming or mix foaming. Preformed foaming is preferred to mix-forming technique due to the following advantages: (1) a lower foaming agent requirement and (2) a close relationship between amount of foaming agent used and air content of mix [1–3]. Generally, cellular concrete can be classified into two types: autoclave and nonautoclave cellular concrete. High-pressure steam curing makes the autoclave cellular concrete to improve the quality in lighter weight, low thermal conductivity, high heat resistance, and low drying shrinkage. The cellular concrete is widely used in the construction industry due to its lightweight

and favorable insulation properties which are suitable for materials of sound barriers, fire walls, and building panels [4].

The use of industrial waste and byproduct materials is now widely recognized as one of the preferred options towards the achievement of sustainable development [5]. Bottom ash (BA) is a byproduct of the combustion of pulverized coal in the power plants. From the previous studies, BA was used mainly on concrete block and road constructions and it was applied as lightweight aggregate in mortar and concrete [6], where the results indicated that BA can be applied as a construction material. Some studies had progressed slowly focusing on the possibility of BA as sand replacement in normal concrete [7–9]. In addition, it was used as fine and coarse aggregate in high-strength concrete [10]. The results indicated that the slump flow of fresh concrete was slightly decreased when coarse BA was replaced at 100% of normal coarse aggregate. In Thailand, Mae Moh power plants produce BA approximately 2,000 tons a day or about 20% by volume of the total ash [11]. Most of the BA has been disposed in landfills because its uses are

TABLE 1: Physical and chemical properties of materials.

	Cement	Sand	Bottom ash
Physical properties			
Specific gravity	3.14	2.56	2.10
Absorption (%)	—	1.21	6.18
Moisture content (%)	—	0.47	0.43
Voids (%)	—	34.6	46.8
Fineness modulus	—	2.76	2.10
Blaine fineness (cm^2/g)	3,270	—	—
Median particle size (micron)	13.0	—	290
Retained on sieve number 325 (%)	10.8	—	94.5
Chemical composition (%)			
SiO_2	20.62	92.86	46.02
Al_2O_3	5.22	3.17	22.31
Fe_2O_3	3.10	0.27	10.64
CaO	65.00	0.55	11.48
MgO	0.91	0.49	3.45
K_2O	0.07	0.32	2.37
Na_2O	0.50	0.42	0.07
SO_3	2.70	0.55	1.76
LOI	1.13	0.67	4.03

limited, leading to increases of landfills results in greater air and environment pollution problems. In addition, these are several advantages of use of BA in the cellular concrete, that is, cost saving and reduction in the use of natural sand, disposal of wastes, prevention of environmental pollution, and energy saving. Moreover, high porous BA particles may reduce the shrinkage which was found in using lightweight aggregate in foam concrete [12].

2. Experimental Program

2.1. Materials. The physical properties of materials were shown in Table 1. Ordinary Portland Cement (OPC) with specific gravity of 3.14 and Blaine fineness of $3,270 \text{ cm}^2/\text{g}$ was used in all cellular concrete mixtures. Local river sand (SA) having a specific gravity of 2.56 and BA specific gravity of 2.10 from Mae Moh power plant in the north of Thailand were used in this research as fine aggregate. Both SA and BA were sieved through sieve number 16 and retained on sieve number 100.

Figure 1 shows the scanning electron microscope (SEM) of BA. The particle shape of BA is irregular and porous. However, the particle size distributions of the combinations of SA and BA in this research indicated by the gradation curves meet most of the requirement of ASTM C 33 (in Figure 2). The chemical properties of both materials are also reported in Table 1. The major chemical compositions of Portland cement, SA, and BA were CaO (65.00%), SiO_2 (92.86%), and SiO_2 (46.02%), respectively.

2.2. Mix Proportions. The mix proportions of cellular concrete are given in Table 2. Different mixes of cellular concrete were made by use of foam content (V) at 30%, 40%, 50%,

TABLE 2: Mix proportions of cellular concrete.

Mixture	Mix proportions (by volume, m^3)				
	Cement	Sand	Water	Foam content	Bottom ash
30V0BA	0.175	0.215	0.310	0.3	0
30V25BA	0.166	0.161	0.318	0.3	0.054
30V50BA	0.158	0.108	0.327	0.3	0.108
30V75BA	0.150	0.054	0.335	0.3	0.161
30V100BA	0.142	0	0.343	0.3	0.215
40V0BA	0.151	0.185	0.264	0.4	0
40V25BA	0.144	0.139	0.271	0.4	0.046
40V50BA	0.136	0.093	0.278	0.4	0.093
40V75BA	0.129	0.046	0.285	0.4	0.139
40V100BA	0.123	0	0.292	0.4	0.185
50V0BA	0.127	0.155	0.218	0.5	0
50V25BA	0.121	0.116	0.224	0.5	0.039
50V50BA	0.115	0.078	0.229	0.5	0.078
50V75BA	0.110	0.039	0.235	0.5	0.116
50V100BA	0.104	0	0.241	0.5	0.155
60V0BA	0.103	0.126	0.172	0.6	0
60V25BA	0.097	0.095	0.177	0.6	0.032
60V50BA	0.092	0.063	0.182	0.6	0.063
60V75BA	0.087	0.032	0.187	0.6	0.095
60V100BA	0.083	0	0.191	0.6	0.126
70V0BA	0.079	0.097	0.126	0.7	0
70V25BA	0.074	0.073	0.130	0.7	0.024
70V50BA	0.069	0.049	0.134	0.7	0.049
70V75BA	0.066	0.024	0.137	0.7	0.073
70V100BA	0.062	0	0.141	0.7	0.097

Note: 30, 40, 50, 60, 70: percentage of foam content, V: foam content, 0, 25, 50, 75, 100: percentage of bottom ash, and BA: bottom ash.

FIGURE 1: SEM of original bottom ash observed at magnification 50x.

60%, and 70% by volume of mixture and the aggregate to binder ratio at 1:1 by weight and original BA replacement for SA at the rates of 0, 25, 50, 75, and 100% by volume of sand. Foam was produced by aerating an organic based foaming agent. The foaming agent was diluted with water in ratio of 1:30 by volume and then poured into an indigenously fabricated foam generator to produce foam with a density of 50 kg/m^3 . Cellular concrete was produced in laboratory by using a paddle mixer with adding of foam into a mortar mix

FIGURE 2: Particle size distributions of SA, BA, and combinations.

(cement-sand or cement-sand-bottom ash). The sequence of mixing starts with combining the cement and fine aggregate with water and keep mixing until a homogeneous mortar is obtained. After that, foam volume was added in the mortar and mixed for a minimum duration until foam was uniformly distributed.

2.3. Testing Details. Based on several trails, the percent flows (consistency), measured in a standard flow table and in accordance with ASTM C 230 (without raising/dropping of the flow table as it may affect the foam bubbles entrained in the mix), were arrived at as $45 \pm 5\%$. Earlier studies showed that, within this range, it gives a good stability and consistency [13, 14]. After that, the specimens were removed from the mold after 24 hours. The compressive strength, water absorption, and density at specific ages were determined.

The compressive strength was measured by three 50 mm cubes at 7, 14, and 28 days, in accordance with ASTM C 109. Water absorption is usually measured by drying the specimen to constant mass, immersing it in water and measuring the increase in mass as a percentage of dry mass. Density is defined as mass divided by volume. All testing was measured on 3 cube specimens with size of 50 mm for each mix of cellular concrete after moist curing. An average of the three values at each age was calculated.

The morphology and microstructure analysis of cellular concrete were characterized using scanning electron microscope (SEM) images and electron dispersive X-ray (EDX) spectrum with 15 kV, respectively. Gold-coated samples were used to examine fracture surfaces.

3. Results and Discussion

3.1. Water Requirements. The water requirements for achieving a stable and workable of cellular concretes are also shown in Table 2. It was found that the water requirement increases

FIGURE 3: Water content of cellular concrete.

with an increase in the level of sand replacement by BA. For example, the water content of 50V0BA, 50V25BA, 50V50BA, 50V75BA, and 50V100BA was 0.218, 0.224, 0.229, 0.235, and 0.241 m^3 , respectively. This was due to the increase of porosity in cellular concrete. Similar results have been reported on a study of concrete using bottom ash as sand in literature [15]. And some literature explained that this was due to the high porosity of BA which absorbed water and resulted in high water requirements [11]. In contrary, the increase of foam content resulted in a decrease of water content because of its lower solid content which can be seen in Figure 3.

3.2. Compressive Strength. Compressive strength is one of the most important properties of concrete. Many researches showed that the compressive strength inversed the density of cellular concrete [12–14]. Table 3 tabulates the compressive strength of cellular concrete and Figure 4 presents some of the relationship among compressive strength and important parameters. The compressive strength of 30V0BA, 40V0BA, 50V0BA, 60V0BA, and 70V0BA at 28 days were 5.2, 4.0, 2.8, 2.0, and 1.7 MPa, respectively. It was found that compressive strength depended on foam content, percent sand replacement by BA, and curing age where the cellular concretes with the higher foam gave the lower compressive strength. The cellular concrete with foam content less than 50% gave the compressive strength more than 2.5 MPa (as TIS 1505-1998 specification). The replacement of SA by BA decreased cement content in cellular concrete, thus resulting in lower compressive strength the same as the results of cellular concrete using higher foam content. For example, the compressive strength at 28 days of cellular concretes 50V0BA, 50V25BA, 50V50BA, 50V75BA, and 50V100BA was 2.8, 2.8, 2.3, 1.9, and 1.7 MPa, respectively. It can be seen that the use of 25% of sand replacement by BA gave similarly compressive strength of 0% of sand replacement (not use BA). For mixes with BA, compressive strength decreases with increasing of BA content because increasing of water content and pore number in cellular concrete will induce a decrease

TABLE 3: Compressive strength, water absorption, and density of cellular concretes.

Mixture	Compressive strength (MPa)			Water absorption (%)			Density (kg/m ³)		
	7 days	14 days	28 days	7 days	14 days	28 days	7 days	14 days	28 days
30V0BA	4.4	4.8	5.2	20	20	19	1336	1332	1296
30V25BA	4.2	4.5	5.0	22	23	22	1270	1280	1165
30V50BA	3.5	3.8	4.2	25	26	25	1248	1244	1241
30V75BA	2.9	3.2	3.4	27	28	27	1180	1178	1171
30V100BA	2.6	2.9	3.1	31	31	30	1141	1138	1142
40V0BA	3.6	3.8	4.0	21	21	20	1184	1180	1176
40V25BA	3.3	3.6	4.1	24	24	23	1151	1148	1142
40V50BA	2.6	3.0	3.2	28	27	27	1112	1121	1118
40V75BA	2.2	2.4	2.6	32	31	31	1065	1072	1068
40V100BA	2.0	2.5	2.6	35	36	35	1012	1010	1008
50V0BA	2.5	2.6	2.8	23	23	23	1064	1034	999
50V25BA	2.5	2.7	2.8	28	27	28	1032	995	984
50V50BA	1.8	2.0	2.3	35	34	34	1000	984	968
50V75BA	1.6	1.7	1.9	37	35	36	924	883	856
50V100BA	1.5	1.6	1.7	39	38	38	904	884	840
60V0BA	1.7	1.8	2.0	26	26	27	960	892	832
60V25BA	1.7	1.9	2.1	32	33	33	885	861	855
60V50BA	1.4	1.4	1.6	38	38	37	832	835	827
60V75BA	1.2	1.3	1.4	42	43	43	804	811	798
60V100BA	1.1	1.1	1.2	45	46	46	766	755	762
70V0BA	1.4	1.6	1.7	40	38	38	816	818	808
70V25BA	1.5	1.5	1.7	42	42	44	795	791	797
70V50BA	1.2	1.4	1.5	48	49	49	774	765	761
70V75BA	0.9	1.0	1.0	52	53	53	740	738	735
70V100BA	0.8	0.9	1.0	56	55	56	711	708	704

of compressive strength. Similar results have been reported on a study of compressive strength of lightweight concrete in literature [16, 17]. However, BA is one of pozzolanic materials and thus it can react $\text{Ca}(\text{OH})_2$ from hydration reaction to produce CSH and CAH which can enhance compressive strength of concrete [11].

3.3. Water Absorption. From Figure 5, it was found that an increase in the level of replacement of SA by BA and foam content leads to increase of water absorption. For example, the water absorptions at 7 days of cellular concretes 30V0BA, 30V25BA, 30V50BA, 30V75BA, and 30V100BA were 20, 22, 25, 27, and 31% while the water absorptions at 7 days of cellular concretes 70V0BA, 70V25BA, 70V50BA, 70V75BA, and 0V100BA were 40, 42, 48, 52, and 56%, respectively. A relatively higher water-solids ratio produces a weaker and pervious matrix, leading to higher capillary porosity which is in turn responsible for the increase in water absorption of mixes with BA. Similar results have been reported on water absorption of foam concrete using fly ash as sand in the literature of Nambiar and Ramamurthy [18].

3.4. Density. Figure 6 indicates that an increase of BA content leads to decrease of density of cellular concrete due to its low specific gravity (2.10) compared with SA (2.56). As a result, BA replacement for SA at 100% by volume reduced density approximately 15% by weight. Use of foam content more than 50% gave the density lower than $1,000 \text{ kg/m}^3$. However, it can be seen that when the compressive strength and density are higher, the water absorption is lower (as Table 3). From Table 3, it showed that the mixes that had the compressive strength more than 2.5 MPa and the water absorption less than 30% and the density less than $1,000 \text{ kg/m}^3$ were cellular concretes 50V0BA and 50V25BA where cellular concrete 50V25BA was selected as the optimum mix because it had the lower density.

With the current results, it could be concluded that 25% of the BA as SA and 50% of foam content (50V25BA) were the optimum of BA content due to the compressive strength, density, and water absorption comparable to that of the control cellular concrete. In addition, it was found that the compressive strength of cellular concrete is equal to class 2 of aerated lightweight concrete by Thai Industrial Standards

FIGURE 4: The compressive strength of cellular concrete.

(TIS) 1505 and 2601 [19, 20]. However, the density of BA cellular concrete is higher than that of the TIS standard. Although the density obtained from cellular concrete containing 50V25BA is higher than for TIS standard, nevertheless, the density of this study is lower than typical clay brick in Thailand's Construction Industry. Furthermore, its compressive strength in this research meets most the required clay brick strength. These comparisons are summarized in Table 4.

3.5. Microstructural Analyses. The typical SEM-EDX at magnitude of $\times 50$ and $\times 2000$ of cellular concrete is shown in Figure 7. At $\times 50$ of SEM, it showed that at fractured surface of cellular concrete had many spherical bubbles with 150–500 μm in the matrix of cellular concrete. Figure 7(a) showed the SEM image of cellular concrete after 28 days of 50V0BA

(without BA) and Figures 7(b)–7(e) showed the SEM image of cellular concrete containing BA, where it can be observed that cellular concrete had many air voids from foam agent. Size and number of air voids in 50V0BA had close to BA cellular concrete because it used the same foam content. Use of BA did not change the shape and the size of artificial air pores. Cellular concretes incorporating with BA were inconsistently formed of particle and were more porous than the control cellular concrete. It can be seen that the porous cellular concrete increases with an increase in the BA content. It can be explained that the porous behavior is relatively reduced in density of cellular concretes [21]. At $\times 2000$ of SEM, it can be seen that the microstructure morphology of fracture surface of cellular concretes was rough surface due to hydration products (CSH, $\text{Ca}(\text{OH})_2$, and ettringite). The 50V0BA had the denser surface than that of BA cellular concrete because BA had high porous particle.

FIGURE 5: The water absorption of cellular concrete.

According to Ordinary Portland Cement (OPC), BA from Mae Moh power plant contained large amount of CaO and SiO₂ [22]. Therefore, the results of the EDX analysis of cellular concrete confirm the presence of Ca and Si as major elements and the elements of Fe and Mg are present as minor elements. In addition, it was found that the increasing of the BA content had a little effect on the chemical reaction of cellular concrete because BA had large particle for reaction with Ca(OH)₂ and it was also used as fine aggregate [11]. A ratio of CaO and SiO₂ (Ca/Si) was often used to characterize the CSH in concrete where the higher Ca/Si ratio gave the higher compressive strength. From Table 1, it was found that CaO and SiO₂ of Ordinary Portland Cement (OPC) and BA were 65.00% and 20.62% and 11.48% and 46.02%, respectively. Thus the Ca/Si ratios of 50V0BA, 50V25BA, 50V50BA, 50V75BA, and 50V100BA were 3.15, 1.91, 1.15, 0.63, and 0.25, respectively. It

can be seen that use of higher BA replacement decreased the Ca/Si ratio and compressive strength of cellular concrete was related to the decrease in Ca/Si ratio too.

3.6. Predicting the Compressive Strength, Water Absorption, and Density Using Multiple Regression Techniques. The non-linear regression models were performed under SPSS version 15 as (1). The best fit of the data was determined to predict compressive strength, water absorption, and density of cellular concretes containing bottom ash. Classical statistical method was employed for nonlinear regression models and the various possible equations were tried to find the appropriate equation based on the absolute fraction of variance (R^2) results that estimates the proportion of the total variation in the series using (2). In addition, the root mean square (RMS) error and mean absolute percentage (MAPE) error were

FIGURE 6: The density of cellular concrete.

used to measure the variation using (3) and (4), respectively. Consider

$$\begin{aligned}
 Y = & a + a_1x_1 + a_2x_2 + a_3x_3 + a_4x_4 + a_5x_5 + a_6x_6 \\
 & + a_7x_1^2 + a_8x_2^2 + a_9x_3^2 + a_{10}x_4^2 \\
 & + a_{11}x_5^2 + a_{12}x_6^2 + a_{13}x_1x_2 + a_{14}x_1x_3 \\
 & + a_{15}x_1x_4 + a_{16}x_1x_5 + a_{17}x_1x_6 \\
 & + a_{18}x_2x_3 + a_{19}x_2x_4 + a_{20}x_2x_5 \\
 & + a_{21}x_2x_6 + a_{22}x_3x_4 + a_{23}x_3x_5 \\
 & + a_{24}x_3x_6 + a_{25}x_4x_5 + a_{26}x_4x_6 \\
 & + a_{27}x_5x_6,
 \end{aligned} \tag{1}$$

$$R^2 = \frac{\sum_{i=1}^N (P_i - \bar{P}_i)(M_i - \bar{M}_i)}{\sqrt{\left[\sum_{i=1}^N (P_i - \bar{P}_i)^2\right] \left[\sum_{i=1}^N (M_i - \bar{M}_i)^2\right]}}, \tag{2}$$

$$\text{RMS} = \sqrt{\frac{1}{N} \sum_{i=1}^N |P_i - M_i|^2}, \tag{3}$$

$$\text{MAPE} = \frac{1}{N} \sum_{i=1}^N \frac{|P_i - M_i|}{P_i} \times 100, \tag{4}$$

where P_i is the predicted value of i th pattern, $\bar{P}_i$ is the average predicted value of i th pattern, M_i is the actual value of i th pattern, $\bar{M}_i$ is the average actual value of i th pattern, and N is the number of patterns.

In this study, the volume of cement (x_1), sand (x_2), water (x_3), foam content (x_4), bottom ash (x_5), and age (x_6)

FIGURE 7: SEM image and EDX spectrum of cellular concrete after 28 days.

TABLE 4: Comparison between cellular concrete and other materials.

Description	Compressive strength (MPa)	Density (kg/m ³)	Water absorption (%)
Aerated lightweight concrete			
(TIS 1505-1998) class 2	2.5	300–500	30
(TIS 2601-2013) class 8	2.0	701–800	25
(TIS 2601-2013) class 9	2.5	801–900	23
(TIS 2601-2013) class 10	2.5	901–1000	23
(TIS 2601-2013) class 12	2.5	1001–1200	23
(TIS 2601-2013) class 14	5.0	1201–1400	20
Commercial clay brick (in Thai)	2.0–3.0	1650	40

TABLE 5: The input variables used in nonlinear regression models.

Input variables	Minimum	Maximum
Cement (by volume), x_1	0.062	0.175
Sand (by volume), x_2	0	0.215
Water (by volume), x_3	0.126	0.343
Foam content (by volume), x_4	0.3	0.7
Bottom ash (by volume), x_5	0	0.215
Age (day), x_6	7	28

TABLE 6: Statistical performance of proposed regression models.

Nonlinear regression models	R^2	RMSE	MAPE
Compressive strength	0.99493	0.08151	3.33669
Water absorption	0.99670	0.56786	1.50650
Density	0.99348	14.73598	1.07225

had significant influence on the compressive strength, water absorption, and density of cellular concrete. Therefore, these six important input parameters were taken into account in the proposed nonlinear regression models. The limit values of input variables used in regression models are listed in Table 5. The details of the best expression equations for the compressive strength, water absorption, and density of cellular concrete using nonlinear regression techniques are given as (5), (6), and (7), respectively.

The nonlinear regression models were evaluated via statistical parameters as seen in Table 6. Based on absolute fraction of variance (R^2), it was found that the nonlinear regression technique gives a high degree of accuracy where R^2 of the nonlinear regression models are higher than 0.99. In addition, the root mean square (RMS) error and mean absolute percentage (MAPE) error of compressive strength, water absorption, and density of cellular concrete were 0.08151, 0.56786, 14.73598 and 3.33669%, 1.50650%, and 1.07225%, respectively. Figures 8–10 demonstrated that the nonlinear regression was reasonably highly capable of generalizing between the input parameters variables and the output response. Consider

Compressive strength (MPa)

$$= 17218.66 - 272213x_1 - 246505x_2 + 242078.9x_3 \\ - 28700.7x_4 - 327519x_5 - 0.21929x_6$$

$$+ 56701.74x_1^2 + 186147.4x_2^2 - 396672x_3^2 \\ + 11435.29x_4^2 + 209709.4x_5^2 - 0.00063x_6^2 \\ + 335143.9x_1x_2 + 318630.6x_1x_3 \\ + 272458.9x_1x_4 + 308200.1x_1x_5 \\ + 0.730102x_1x_6 + 110436.4x_2x_3 \\ + 243536.3x_2x_4 + 410634.9x_2x_5 \\ + 7.434676x_2x_6 - 253026x_3x_4 + 280612.4x_3x_5 \\ - 4.78157x_3x_6 + 326210x_4x_5 + 0.110857x_4x_6 \\ + 8.228497x_5x_6, \quad (5)$$

Water absorption (%)

$$= 302875.2 - 936182x_1 - 2667696x_2 + 978052x_3 \\ - 568808x_4 - 2962800x_5 + 0.466288x_6 \\ + 512554x_1^2 + 3055733x_2^2 - 287101x_3^2 \\ + 266562.2x_4^2 + 4053092x_5^2 + 0.000225x_6^2 \\ + 4887007x_1x_2 - 1780599x_1x_3 + 867523.8x_1x_4 \\ + 5326411x_1x_5 - 22.3514x_1x_6 - 915991x_2x_3 \\ + 2588109x_2x_4 + 7054651x_2x_5 - 15.2013x_2x_6 \\ - 968535x_3x_4 - 1138688x_3x_5 + 21.40973x_3x_6 \\ + 2870581x_4x_5 + 0.083734x_4x_6 - 21.8526x_5x_6, \quad (6)$$

Density (kg/m³)

$$= -161981 - 7568416x_1 + 5710310x_2 \\ + 794080.4x_3 + 268847.1x_4 + 5422624x_5 \\ - 585.922x_6 + 15649.19x_1^2 + 15173410x_2^2 \\ + 16463903x_3^2 - 96259.7x_4^2 + 28294298x_5^2 \\ + 0.022099x_6^2 + 27792847x_1x_2 - 1647790x_1x_3$$

FIGURE 8: Performance of the compressive strength by nonlinear regression model.

FIGURE 10: Performance of the density by nonlinear regression model.

FIGURE 9: Performance of the water absorption by nonlinear regression model.

$$\begin{aligned}
 &+ 7307366x_1x_4 + 27585862x_1x_5 - 223.943x_1x_6 \\
 &- 6611945x_2x_4 + 42750751x_2x_5 \\
 &+ 626.9418x_2x_6 + 95381.23x_3x_4 \\
 &+ 999.1555x_3x_6 - 6533201x_4x_5 \\
 &+ 591.7785x_4x_6 + 450.7238x_5x_6,
 \end{aligned} \tag{7}$$

when x_1 is cement (by volume), x_2 is sand (by volume), x_3 is water (by volume), x_4 is foam content (by volume), x_5 is bottom ash (by volume), and x_6 is age (day).

4. Conclusions

From the experimental results on evaluating the feasibility of utilizing BA from Mae Moh power plant as a fine aggregate in cellular concrete, it can be concluded as follows:

- (1) The cellular concrete containing the BA exhibited higher porosity than those of the control concrete and resulted in higher water requirement for achieving workability of cellular concrete. Compressive strength, absorption, and density depended on foam content, percent sand replacement by BA, cement content, and curing age.

- (2) The optimum replacement of BA in cellular concrete was 25% by volume of sand and used 50% of foam content, where it gave compressive strength, density, and water absorption of 2.8 MPa, 984 kg/m³, and 28%, respectively. In addition, it was closed to class 10 of TIS standard. Moreover, the resultant properties of the optimum mix are greater than typical clay brick in Thailand's construction industry.

- (3) The nonlinear regression technique can be used to predict the compressive strength, water absorption, and density of cellular concrete because it gave a high absolute fraction of variance with a low mean absolute percentage error and root mean square error.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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