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RECYCLING OF WASTE INCINERATION BOTTOM ASH IN THE PRODUCTION OF INTERLOCKING CONCRETE BRICKS

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Abstract

This study presents an experimental investigation on the recycling of waste incineration bottom ash (IBA) as a fine aggregate in the production of interlocking concrete bricks (ICB). Before being used, the concentration of heavy metal in IBA was determined to confirm it is a non-toxic material. In this study, the IBA was used to replace crushed sand (CSA) in the brick mixtures at different replacement levels of 0%, 25%, 50%, 75%, and 100% (by volume). The ICB samples were checked for dimensions, visible defects, compressive strength, bending strength, water absorption, and surface abrasion in accordance with the related Vietnamese standards. The test results demonstrated that the IBA used in this study was a non-toxic material, which can be widely used for construction activities. All of the ICB samples prepared for this study exhibited a nice shape with consistent dimensions and without any visible defects. The incorporation of IBA in the brick mixtures affected engineering properties of the ICB samples such as a reduction in the compressive strength and bending strength and an increment in water absorption and surface abrasion of the brick samples. As a result, the compressive strength, bending strength, water absorption, and surface abrasion values of ICB samples at 28 days were in the ranges of 20.6 – 34.9 MPa, 3.95 – 6.62 MPa, 3.8 – 7.2%, and 0.132 – 0.187 g/cm^2, respectively. Therefore, either partial or full replacement of CSA by IBA, the ICB with grades of M200 – M300 could be produced with satisfying the TCVN 6476:1999 standard in terms of dimensions, visible defects, compressive strength, water absorption, and surface abrasion. These results demonstrated the high applicability of the local IBA in the production of the ICB for various construction application purposes.

Keywords: interlocking concrete brick; waste incineration bottom ash; visible defect; compressive strength; bending strength; water absorption; surface abrasion.

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1. Introduction

Brick is the most commonly used material in masonry construction due to its ease of production, low cost, and useful structural characteristics [1, 2]. It has reported that the increasing demand for

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housing and infrastructure worldwide promotes the non-stop growth in the brick industry [2–4]. Numerous types of bricks are employed in construction relying on methods of production and types of raw materials used. For example, traditional bricks were produced utilizing clay and shale under high temperature (900–1000°C) kiln firing, or concrete bricks were manufactured using ordinary Portland cement (OPC)-based methods. Another type of brick is a non-fired brick produced from recycled materials from industrial and construction wastes and does not require heat treatment. However, the consumption of large amounts of natural clay and cement for the production of traditional brick led to the depletion of natural resources, energy-intensive, adversely affect the environment [1, 5, 6]. In contrast, the development of non-fired brick utilizing friendly materials has been considering a topical solution in the construction industry [1, 5].

In developing countries, the accumulation of industrial waste such as fly ash and bottom ash has been becoming an urgent environmental problem. Re-utilization of these kinds of wastes as usable construction materials is an effective approach and also further brings economic benefits. In Vietnam, for instance, several studies have carried out to investigate the application of various industrial wastes such as unground rice husk ash [7], fly ash and residual rice husk ash [8], ground granulated blast-furnace slag, and circulating fluidized bed combustion ash [9] as construction materials. However, the use of waste bottom ash from incineration plants (IBA) as source material for producing construction materials has been limited.

IBA is one of the major wastes of the combustion of the domestic solid waste in waste treatment plants. It usually accounts for about 10% in volume compared to the total volume of the original waste [10]. Currently, there are about 1.3 billion tons of domestic solid waste discharged to the environment each year and about 130 million tons are incinerated in the world, accounting for 10 – 15% of the total domestic waste [10]. Particularly in Vietnam, the total amount of domestic solid waste generated in the Hanoi capital city in 2017 was about 7,500 tons/day [11]. Meanwhile, in Ho Chi Minh City, the total volume of domestic solid waste generated in 2017 was 3,175,500 tons, an average of 8,700 tons/day [11]. Thus, the amount of IBA is increasing rapidly and leading to the negative environmental impact and lack of storage space and facilities. In the trend of sustainable development, IBA should be re-used as a construction material to solve the abovementioned problems. In Vietnam, many incineration plants have been built and put into operation [12]. Therefore, the IBA treatment is currently a major concern of many agencies, departments, and researchers.

The objective of this study is, therefore, to investigate the engineering performance of the interlocking concrete brick (ICB) utilizing locally and abundantly source of IBA as fine aggregate in the brick mixtures. The heavy metal concentration in leachates of the IBA was first checked to ensure this material can be used as non-toxic wastes by using the toxicity characteristic leaching procedure (TCLP). The compressive strength, bending strength, water absorption, and surface abrasion tests were then conducted on the ICB samples produced using IBA replacement of 0%, 25%, 50%, 75%, and 100% by volume as fine aggregate. The obtained results were discussed and compared to the requirements following the current Vietnamese standards.

2. Materials and experimental methods

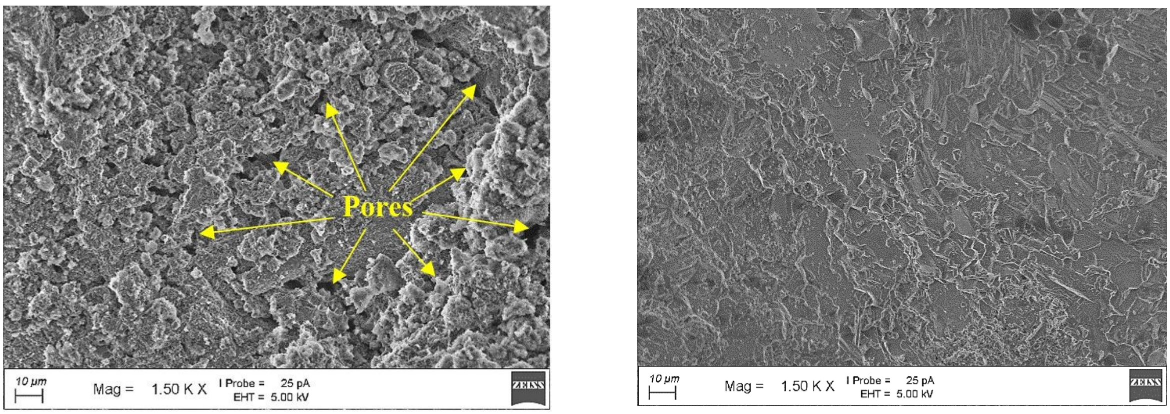
2.1. Materials

In this study, the proposed ICB samples were produced utilizing a mixture of widely available blended Portland cement (PCB) of grade 40 and fly ash (FA) from a thermal power plant in Southern Vietnam as binder materials. The specific gravity of cement and fly ash was 2.84 and 2.14, respectively. CSA and crushed stone (CST) were used as fine and coarse aggregates for the preparation of

ICB samples, respectively. Especially, IBA was employed as a substitution of fine aggregate in the brick mixtures. Physical properties of the used aggregates including density, water absorption, fineness modulus (FM), and maximum diameter (D_{max}) are provided in Table 1. Moreover, the scanning electron microscope (SEM) morphologies of the IBA and CSA particles are displayed in Fig. 1. It could be said that the morphology of the IBA particle possesses the porous structure, resulting in a lower density and a higher value of water absorption (see Table 1) in comparison with the CSA.

Table 1. Physical properties of aggregates used in this study

Materials	Density (kg/m^3)	Water absorption at 24h (%)	Remarks
IBA	2243	7.76	FM = 2.76
CSA	2747	1.48	FM = 3.56
CST	2764	0.47	D_{max} = 9.5 mm



(a) IBA particles

(b) CSA particles

Figure 1. SEM micrographs of aggregates used in this study

Prior to being used, the toxicity characteristic leaching procedure (TCLP) was conducted to check the heavy metal concentration in leachates of the used IBA. The TCLP test results (Table 2) showed that the heavy metal concentrations in leachates of the IBA were much lower than the thresholds for hazardous waste indicated as per QCVN 07:2009/BTNMT [13]. In other words, the used IBA was a non-toxic waste and can be employed as fine aggregate for the preparation of ICB samples in this study.

Table 2. Heavy metal concentration in TCLP leachates for the incineration ash

Materials	Level of toxicity leached of heavy metals (mg/L)					
	Cu	Cr (VI)	Cd	Pb	Ni	Zn
IBA	< 0.01	< 0.003	0.0003	< 0.0007	< 0.001	< 0.015
Limitation [13]	-	≤ 5	≤ 0.5	≤ 15	≤ 70	≤ 250

2.2. Mixture proportions

This study applied the idea of densified mixture designed algorithm (DMDA) technology [14] to design the mixture proportions for the preparation of ICB samples. In DMDA, the maximum density of brick can be obtained by well-packing all solid particles with different sizes to a dense structure. In which, the smaller particles are used to fill the voids between the larger particles to create a highly compact and dense system. Under this idea, this study used FA to fill the voids between the CSA particles and then used the mixture of FA and CSA to fill the voids between the CST particles to obtain the least void mixture. As a result, both the pozzolanic and filling effects can be achieved. By the way, the cement paste was reduced efficiently. The amount of each ingredient in the brick mixtures (as shown in Table 3) was calculated following the guidelines of Chen et al. [14].

Table 3. Mixture proportions of ICB samples

Mix designation	Cement (kg/m^3)	FA (kg/m^3)	IBA (kg/m^3)	CSA (kg/m^3)	CST (kg/m^3)	Water (kg/m^3)
IBA00	385	124	0	1118	466	231
IBA25	385	124	228	838	466	231
IBA50	385	124	456	559	466	231
IBA75	385	124	684	279	466	231
IBA100	385	124	913	0	466	231

To investigate the influence of IBA on the properties of bricks, five different ICB mixtures were prepared. In which, the amount of CSA was either partially or fully replaced by IBA at 0%, 25%, 50%, 75%, and 100% by volume, namely IBA00, IBA25, IBA50, IBA75, and IBA100, respectively. It is important to note that the IBA, CSA, and CST used for the preparation of the ICB samples were in saturated surface dry (SSD) condition. Additionally, based on the pre-trials in the laboratory, a constant water-to-binder ratio of 0.42 was used for all of the five brick mixtures. Detailed proportions of the ICB mixtures are presented in Table 3.

2.3. Preparation of ICB samples

A pan-type mixer was used to prepare the ICB samples in the laboratory with the following procedures: All of the ingredients were firstly prepared based on their proportions as shown in Table 3. These materials were then dry mixed for about 2 minutes to get a uniform mixture. Next, water was

Figure 2. Overview of ICB samples produced in this study

gradually added to the dry mixture, and mixing was continued for additional 3 minutes to obtain a homogenous mixture. Then, the ICB samples with a size of 216 × 216 × 60 mm (Fig. 2) were cast using plastic molds. Right after that, the ICB samples were vibrated at a controlled frequency of 8 Hz for 15 seconds using a vibration table. Finally, the brick samples were stored uncovered in room conditions (temperature of 27 ± 2 °C and relative humidity of 65 ± 5%). All of the brick samples were removed from the molds 24 hours after casting and cured in the open air until subjecting to various test programs.

2.4. Test methods

To evaluate the performance as well as the effect of using IBA as a CSA replacement on the engineering properties of ICB samples, the brick samples were subjected to different tests including dimensions and visible defects, compressive strength, bending strength, water absorption, and surface abrasion following the guidelines of the Vietnamese standards. Particularly, the dimensions and visible defects of the ICB samples at 28 days were checked according to the TCVN 6476:1999 [15]. Additionally, the compressive strength and bending strength of the brick samples were measured at 7, 14, 28, and 56 days under the TCVN 6476:1999 [15] and TCVN 6355-2:1998 [16], respectively. Besides, the water absorption and surface abrasion of the ICB samples were tested at 28 and 56 days in compliance with the TCVN 7744:2013 [17] and TCVN 6065:1995 [18], respectively. Five groups of ICB samples were used for each testing age and the average value was reported.

3. Results and discussion

3.1. Dimensions and visible defects

Table 4 presents the dimensions of the newly developed ICB samples. It can be seen that the obtained dimensions of all of the brick samples met the requirements outlined in TCVN 6476:1999 [15]. The variations of dimensions of brick were negligibly small (± 1 mm) compared to their designs and these variation were majorly caused by the deformation of the plastic mold during the manufacturing stage. Also, in terms of visible defection, all of the ICB samples showed consistency of shape and dimensions without any cracks, curvature, indentation on the brick's surface, and the deformations through the naked eye examination (see Fig. 2).

Table 4. Dimensions of brick samples

Mix designation	Dimensions (mm)		
	Length	Width	Height
IBA00	216.0	215.8	58.7
IBA25	216.9	216.7	58.5
IBA50	217.0	216.6	60.0
IBA75	216.8	216.6	59.4
IBA100	216.6	216.4	59.6
Allowable tolerance [15] (mm)	216 ± 2	216 ± 2	60 ± 3

3.2. Compressive strength

Compressive strength plays a primary role in the mechanical properties of brick and is a crucial index for evaluating the quality of this material. The development in compressive strength of the ICB samples is presented in Fig. 3. In general, the compressive strength of the proposed brick samples increased with the curing age. The increase could be explained by the cement hydration products [19, 20]. Accordingly, during the hydration process, the presence of hydration products gradually increases, resulting in a denser microstructure, and hence increasing the compressive strength [21, 22]. At the age of 28 days, the ICB samples containing 50-75% IBA were classified as the brick grade of M200 while the brick samples incorporating 0-25% IBA met brick grade of M300 in terms of compressive strength as stipulated in TCVN 6476:1999 [15].

Moreover, the influence of IBA on the development of compressive strength of all brick samples was also observed: the compressive strength reduced with the increase in the amount of IBA replacement. For instance, at the ages of 28 days, the compressive strength of brick samples contained 0%, 25%, 50%, 75%, and 100% IBA were 34.91 MPa, 32.19 MPa, 26.46 MPa, 24.49 MPa, and 20.6 MPa, respectively. It indicated that the compressive strength values of the ICB samples containing 25%, 50%, 75%, and 100% IBA were reduced by an approximate 7.8%, 24.2%, 29.8%, and 41.0% in comparison with the IBA-free bricks, respectively. Herein, the reduction in brick strength could be explained by the slow pozzolanic reaction of IBA [23]. Also, the high porosity in nature (Fig. 1) of the used IBA with high absorption capacity (Table 1) as compared to CSA could be considered as another possible reason to explain the reduction in the compressive strength of the ICB samples [24–26].

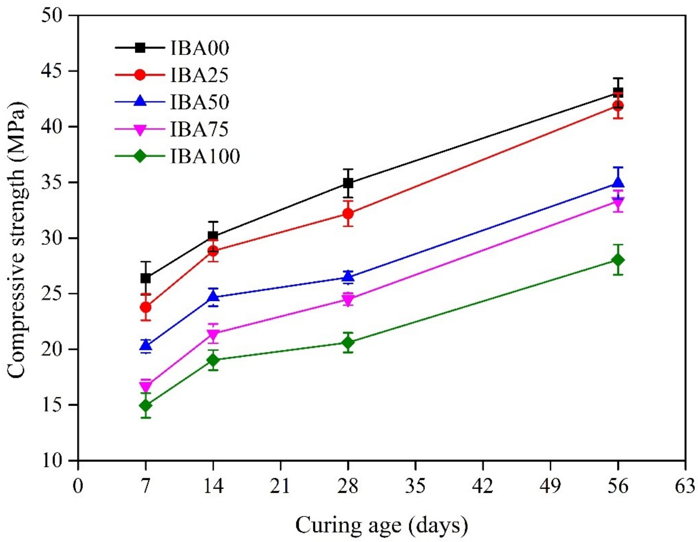


Figure 3. Compressive strength development of brick samples

However, it is interesting to found that the compressive strength of all ICB brick samples kept developing further (after 28 days) at a high rate of strength increment. In fact, at the age of 56 days, the compressive strength values of brick samples containing 0%, 25%, 50%, 75%, and 100% IBA were 46.03 MPa, 41.88 MPa, 34.92 MPa, 33.31 MPa, and 28.05 MPa, respectively. The significant strength increment at the later ages of the ICB samples could be attributed to the internal curing effect of the IBA [22] and/or pozzolanic reaction of the fine IBA particles [21, 22].

3.3. Bending strength

The development of bending strength for the brick samples is displayed in Fig. 4. Overall, the bending strength of the brick samples increased with the curing age. Similar to the increment in the compressive strength values as above-mentioned, the increased bending strength values could be attributed to the presence of cement hydration products [19, 20]. In detail, the presence of hydration products gradually increases, leading to a denser microstructure, and hence increasing the bending strength of the brick sample [21, 22]. At the age of 28 days, the average bending strengths of IBA100, IBA75, IBA50, IBA25, and IBA00 were 3.95 MPa, 4.86 MPa, 5.22 MPa, 5.89 MPa, and 6.62 MPa, respectively. The results indicated that the types of the IBA100 and IBA75 bricks were Type-3 and Type-2, respectively, while this was Type-1 for the IBA50, IBA25, and IBA00 bricks compared to requirements in terrazzo tiles for external use [17].

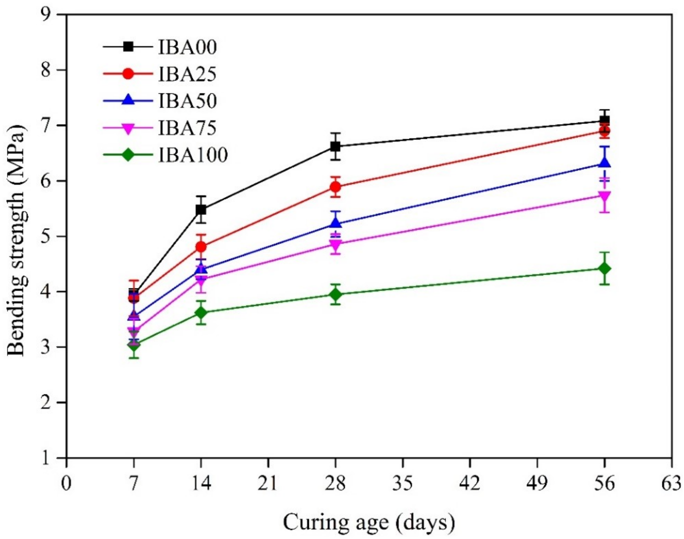


Figure 4. Bending strength development of brick samples

Fig. 4 also illustrates the influence of IBA on the bending strength of the brick samples. Accordingly, the bending strength of the bricks was reduced with an increase in the amount of IBA replacement. For example, at the ages of 28 days, the bending strengths of brick samples contained 25%, 50%, 75%, and 100% bottom ash led to approximate 11.0%, 21.1%, 26.6%, and 40.3% reduction of bending strength in comparison with the IBA-free brick, respectively. Similar to the compressive strength, the slow pozzolanic reaction [23] and the high natural porosity of the used IBA (Fig. 1) could be reasonable reasons for the reduction in the bending strength of the brick samples [24–26]. Furthermore, as can be seen from Fig. 4, the bending strength of all of the ICB samples kept raising after 28 days of age. In which, the IBA-brick samples exhibited a higher rate of increase as compared to the no IBA bricks. This phenomenon could be explained by the internal curing effect of the IBA and/or pozzolanic reaction of the fine IBA particles as aforementioned.

3.4. Water absorption

Water absorption is an important index that can provide useful information relating to the pore structure and permeation characteristic of brick structure [27–29]. Fig. 5 presents the water absorption of the ICB brick samples at the ages of 28 and 56 days. As a result, the water absorption of the brick samples ranged from 3.1% to 7.2%. These values are all below 8%, which is the maximum level for M300 and M400 brick grades stipulated by TCVN 6476:1999 [15]. This result indicated that the proposed ICB samples satisfy the requirement in terms of water absorption for the classified interlocking concrete brick.

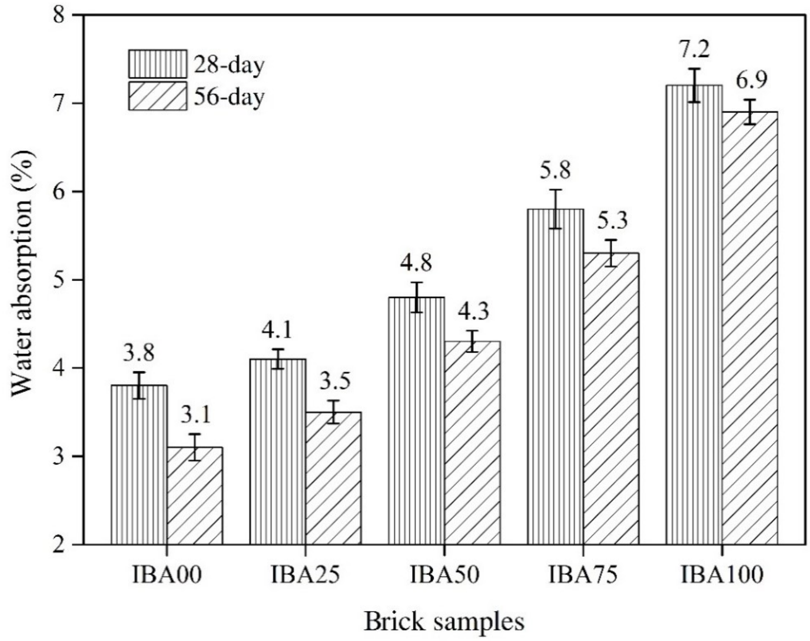


Figure 5. Water absorption of brick samples

In addition, the water absorption of all brick samples decreased with curing age (from 28 to 56 days). It is believed that the reduction in water absorption values was mainly due to the reduced total porosity within the brick samples [27, 30, 31]. Accordingly, the generation of more hydration products with curing time resulted in a denser microstructure (lower porosity), and hence reduced the water absorption of the bricks at later ages. Moreover, it should be noted that the water absorption capacity gradually increases during the drying process due to the reduction of moisture content in the brick samples [27, 32, 33]. This phenomenon, however, could be dominated by the hydration processes within the system (i.e., the evolution of total porosity), as observed in this study.

The influence of IBA replacement on the water absorption of the brick samples was also observed in Fig. 5. It was clear that replacing CSA with IBA significantly increased the water absorption of ICB samples. In other words, a higher amount of IBA replacement in the mixtures contributed to a higher water absorption value of the bricks. Here, with the porous structure of the IBA particles (Fig. 1), the significantly higher water absorption capacity of the used IBA compared to that of the CSA (Table 1) could be considered as the main reason to explain the increase in water absorption of the brick samples [24–26].

3.5. Surface abrasion

Surface abrasion is a crucial index for evaluating the quality of the surface layer characteristics of interlocking concrete brick during its service life. Fig. 6 shows the surface abrasion of the proposed ICB samples at the ages of 28 and 56 days. The surface abrasion values of all ICB samples were in the ranges of 0.132 – 0.187 g/cm^2 and 0.081 – 0.144 g/cm^2 at 28 days and 56 days, respectively. Thus, the surface abrasion of the brick samples was lower than 0.5 g/cm^2, which is the maximum level outlined in TCVN 6476:1999 [15] regardless of the brick grade.

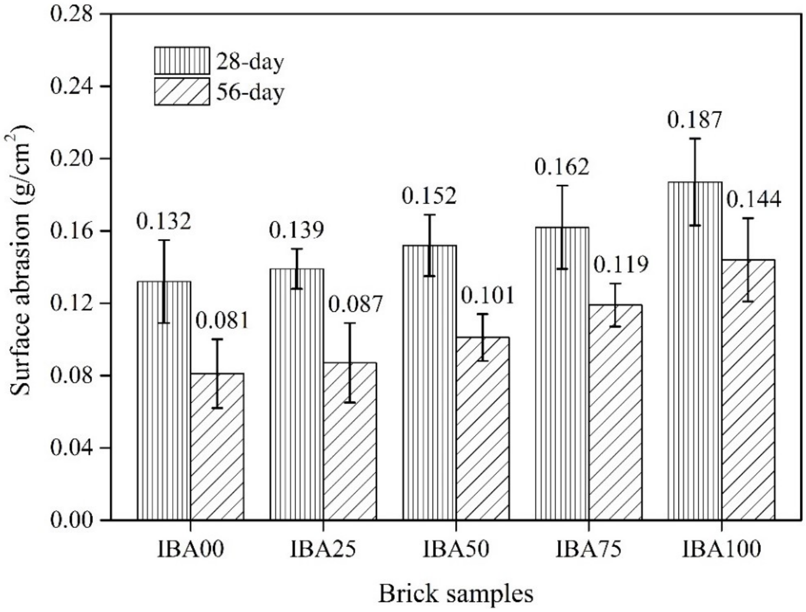


Figure 6. Surface abrasion of brick samples

On the other hand, the influence of IBA on the surface abrasion of the brick samples is also observed in Fig. 6. As expected, the obtained results indicated that the surface abrasion of the bricks increased with increasing in IBA replacement level. For example, the ICB samples containing 25%, 50%, 75%, and 100% IBA at 28 days had surface abrasion values of about 5.3%, 15.2%, 22.7%, and 41.7% higher than that of the reference sample without IBA, respectively. This phenomenon could be explained through the compressive strength of the bricks [34, 35]. Accordingly, the reduction in compressive strength leads to a lower surface abrasion resistance of the brick samples [22, 35]. Therefore, the development in brick's strength at later ages (after 28 days) was associated with the enhancement in surface abrasion resistance of the ICB samples at the corresponding ages.

3.6. Correlation between compressive strength and water absorption or surface abrasion

Fig. 7 shows the correlation between compressive strength and water absorption of the ICB samples at 28 and 56 days, whereas the correlation between compressive strength and surface abrasion of the ICB samples at the same ages was presented in Fig. 8.

As can be seen in Figs. 7 and 8, the approximate linear fitted curves were validated with a very high coefficient of determination ($R^2 \geq 88\%$), indicating closed correlations between compressive strength and water absorption/ surface abrasion of the ICB samples. The correlations greatly supported the above discussion as a higher water absorption value (higher porosity) was associated with a lower strength (Fig. 7) and hence lower strength was attributable to the lower surface abrasion resistance of the bricks (Fig. 8).

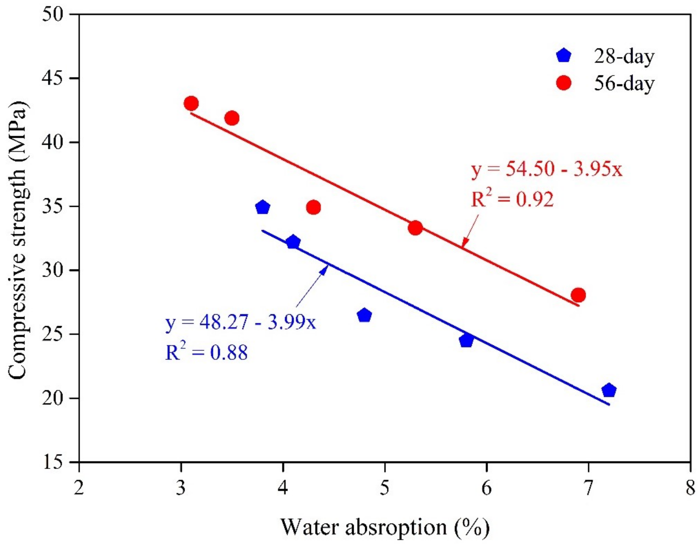


Figure 7. Correlation between compressive strength and water absorption of brick samples

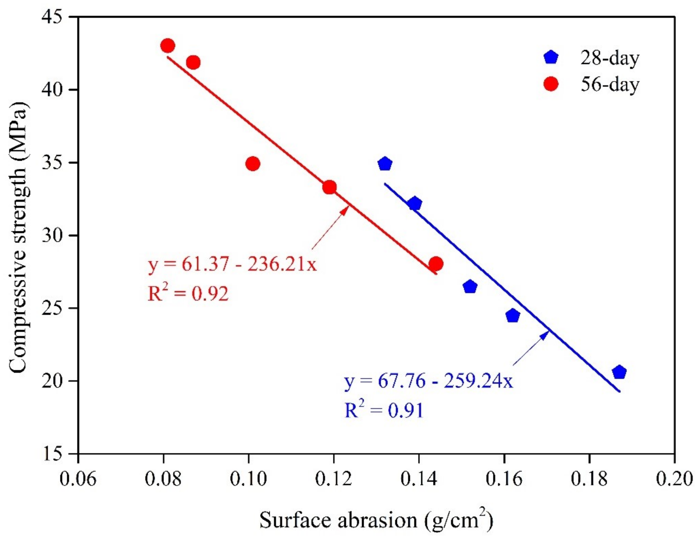


Figure 8. Correlation between compressive strength and surface abrasion of brick samples

4. Conclusions

This study investigates the possible application of IBA to manufacture interlocking concrete brick. The influence of IBA as replacement material on the engineering properties of the bricks is evaluated. On the basis of the experimental results, the following conclusions can be drawn:

- The TCLP test results confirmed that the IBA used in this study can be re-utilized in construction activities as a non-toxic material.

- All of the ICB samples prepared for this study exhibited a nice shape with consistent dimensions and without any visible defects. The influence of IBA could be observed as an increase in IBA replacement level led to a reduction in compressive strength and bending strength, but an increment in water absorption and surface abrasion of the newly developed brick samples.

- The ICB samples achieved compressive strength, bending strength, water absorption, and surface abrasion values at 28 days in the ranges of 20.6 – 34.9 MPa, 3.95 – 6.62 MPa, 3.8 – 7.2%, and 0.132 – 0.187 g/cm^2, respectively. Thus, either partial or full replacement of CSA by IBA, the brick grades of M200 – M300 could be produced with satisfying the TCVN 6476:1999 standard in terms of dimensions, visible defects, compressive strength, water absorption, and surface abrasion. Based on a specific application and requirement, a suitable brick mixture was selected for the production.

- The results of this study further contributed to clarifying the influence of IBA on the properties of ICB samples. In practice, this study provides an experimental investigation to clarify the applicability of the locally and highly available IBA source in the production of the non-fired concrete brick in Vietnam. However, the experimental results should be monitored at the long-term ages (after 56 days). Other properties of the proposed ICB samples such as bulk density and void volume also need to investigate. Thus, the mentioned aspects should be further investigated and addressed in the next studies.

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