Optimization of Pre-Treatment Process in Spent Bleaching Earth (SBE) on The Characteristics of Pre-Treated SBE as Supplementary Cementitious Material

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Abstract

The palm oil processing industry in Indonesia has experienced significant growth, bringing both positive economic impacts and negative consequences, specifically the generation of spent bleaching earth (SBE), a waste product of bleaching earth. Despite its potential as a substitute material for cement due to its pozzolanic properties, challenges arise from SBE's oil content. Hence, this study introduces pre-treatment methods involving extraction and calcination to optimize the use of SBE, referred to as Pre-treated Spent Bleaching Earth (PSBE). This research aims to analyze the optimized PSBE material through the optimization of the pre-treatment process in the usage of mortar. The optimized PSBE is compared to another supplementary cementitious material, which is fly ash to see the performance of optimized PSBE as supplementary cementitious material. The performance of the mortar was evaluated through tests including slump test, compressive strength test, and mortar hydration temperature analysis. The pre-treatment process of SBE was optimized by combining extraction and calcination methods, which yielded the most effective results from oil content test. One of the performance analysis results showed that the compressive strength test revealed a 28-day compressive strength value of 50,22 MPa for the optimized PSBE mortar, while the fly ash mortar had a compressive strength of 37,36 MPa. In conclusion, the optimized PSBE shows promising potential as a supplementary cementitious material.

Keywords

Palm oil, spent bleaching earth, pre-treatment method, supplementary cementitious material, optimized pre-treated spent bleaching earth

INTRODUCTION

The palm oil processing industry is a strategic industry in Indonesia and is one of the main export commodities and significant foreign exchange earners. Referring to the 2018 palm oil outlook, Indonesia is the world's largest producer of palm oil, accounting for 48,33% of the global palm oil market share [1]. The palm oil processing involves various stages, including the use of bleaching earth for purification. This process helps remove impurities in palm oil. However, the increasing growth of the industry leads to a rise in spent bleaching earth (SBE) waste [2].

The oil content is a significant issue for SBE as supplementary material. Oil has an active polar surface that can affect the hydration process by being absorbed into the hydration particles of portland cement, leading to reduced strength and increased porosity in concrete [3,4]. In addition to the oil content, the particle size of SBE is larger compared to Portland cement, which results in lower compressive strength when SBE is added to mortar mixtures compared to normal concrete without SBE as supplementary cementitious material.

The use of supplementary cementitious material (SCM) has become a common practice in the modern construction industry. SCM is a material used as a partial replacement for cement in concrete mixtures. The use of SCM aims to reduce the reliance on cement, which is a major source of carbon emissions in the construction industry [5,6]. Additionally, the use of SCM can also aid in industrial waste management by utilizing by-products as additional materials in concrete production. There are other commonly used materials in the construction industry other than concrete, namely mortar. Mortar is function is to serve as a binding matrix in various structural and non-structural construction components. Mortar is specifically used for structural applications, such as in stone masonry for building foundation structures. [7]. In non-structural applications, mortar is used for tasks such as bricklaying, plastering, and rapid repairs. Certain building materials like foamed concrete do not include coarse aggregates in their production, and their characteristics similar to mortar [8].

Therefore, this research focuses on optimizing the pre-treatment process of SBE to produce a more environmentally friendly cement replacement material for use in mortar. The pre-treatment process involves extraction and calcination. Extraction is a chemical process that utilizes solvents and has various methods of implementation. On the other hand, calcination is the combustion process of the material, which enhances its pozzolanic activity [9,10].

SBE is not currently categorized as a SCM according to american society for testing and materials (ASTM) regulations. Therefore, there are standards for evaluating alternative SCM, known as alternative supplementary cementitious materials (ASCM) [11]. ASTM C1709 provides guidelines for alternative SCM and emphasizes the need for other SCM materials, such as fly ash, as a comparison. This research aims to contribute to the development of environmentally friendly cement substitute materials for mortar using pre-treated SBE. The performance of this mortar will be compared to mortar using another SCM, namely fly ash, to analyze its suitability for use in the construction industry.

RESEARCH SIGNIFICANCE

This paper investigates the effect of optimized pre-treatment process for SBE, which is turned into optimized pre-treated spend bleaching earth (PSBE) and mixed into mortar. Several pre-treatment processes were carried out to clean the oil in the SBE. Several pre-treatment processes used in this paper were extraction method, calcination method, and a combination of extraction method and calcination method.

METHODOLOGY

A. MATERIAL PREPARATION

This research is an experimental study that aims to optimize the pre-treatment process for SBE and to compare the material from the optimal pre-treatment process with other cement substitute materials, such as fly ash, in the usage of mortar. In conducting a comparison with cement substitutes, the materials used in this study are cement and fly ash. The cement used is PCC (Portland composite cement) according to ASTM C150, and the compound content is tested through XRF test. In addition to cement, fly ash material is used in accordance with ASTM C618, and the compound content is tested through XRF test to compare the pozzolan classification of the material between fly ash and the optimal PSBE [12]. This study utilized SBE from East Java region SBE, which has an oil content ranged from 21% to 24%. In optimizing the pre-treatment process of SBE, there are three types of pre-treatment methods are performed: the extraction method, the calcination method, and a combination of extraction and calcination methods.

B. PRE-TREATMENT METHOD

The extraction method that used in this study is the maceration extraction method using acetone as the solvent. The pre-treatment process with the extraction method begins by stirring a mixture of 5 kilograms of SBE and 5 liters of acetone. The first 15 minutes of stirring are done at a low speed, followed by 15 minutes at a medium speed. Then, the stirred mixture is transferred to a tray and left for 24 hours. Afterward, the liquid in the mixture is discarded, leaving behind the sediment. The sediment is then air-dried until sufficiently dry and oven-dried for 24 hours. The result of the pre-treatment process with the extraction method is referred to as PSBE-E (pre-treated SBE with the extraction method) which contained 1.2% oil content.

The calcination method is a thermal pre-treatment process that involves burning using a furnace. In the pre-treatment process with the calcination method, two variables are considered: temperature and time. The optimal temperature for enhancing the pozzolanic activity of clay is between 540ºC and 900ºC [10]. Therefore, in this study, temperatures ranging from 600 to 900ºC are employed with intervals of 100ºC. The time used in the calcination method ranges from half an hour to one and a half hours, with half-hour intervals. The product of the optimized pre-treatment process with the calcination method is referred to as PSBE-K (pre-treated SBE with the calcination method).

The pre-treatment process using the combination of extraction and calcination methods is obtained from the optimized pre-treatment process using the calcination method on PSBE-E material. The material resulting from the pre-treatment process using the combination of extraction and calcination methods is referred to as PSBE-EK.

In the optimization of the pre-treatment process used, a strength activity index (SAI) test is conducted on PSBE with a 15% cement replacement percentage to analyze the potential of PSBE as a SCM. Previous research on cement substitute materials such as fly ash has shown an influence on compressive strength in mortar with a 15% cement replacement percentage at 28 days old [8]. Therefore, a 15% cement replacement percentage is utilized for three types of PSBE materials to analyze the potential as SCM. Table 1 presents the mix design of the mortar utilized to optimize the pre-treatment process through SAI testing.

The focus of this study is to analyze the differences between the optimal PSBE material and fly ash in the use of mortar. The testing of the mortar for cement mortar, optimal PSBE mortar, and fly ash mortar consists of slump test, compressive strength test, and hydration temperature test. The testing on the mortar aims to analyze the characteristics of the mortar. particularly in terms of the differences in compressive strength testing results for mortar. The percentage of cement replacement used in the mortar is 5%, 10%, and 15% and the tested mortar has ages of 3, 7, 14, and 28 days. The mortar mix design for comparison between fly ash mortar and optimal PSBE mortar can be seen in Table 2.

Table 1 Mix design for cement mortar, PSBE-K mortar, PSBE-E mortar, and PSBE-EK mortar

Mortar	Percentage of cement replacement	Material (Gram)					Water (mL)
		Cement	PSBE-K	PSBE-E	PSBE-EK	Sand	
Cement	0%	500	0	0	0	1375	242
PSBE-K	15%	425	75	0	0	1375	242
PSBE-E	15%	425	0	75	0	1375	242
PSBE-EK	15%	425	0	0	75	1375	242

C. SLUMP TEST

The slump test is conducted to analyze the workability of mortar. The equipment used is a complete set of flow table apparatus according to ASTM C230. The mortar mix design used in this test follows ASTM C109, as shown in Table 2. The slump of the mortar is determined following ASTM C1437. In ASTM C1437, the steps involved are as follows: placing the mold in the center of the flow table, filling the mold with the mortar mixture, compacting and leveling the surface of the mold, lifting and dropping the mold 25 times within a 15-second time span, and finally measuring the diameter of the mortar.

D. COMPRESSIVE STRENGTH TEST

The compressive strength test on mortar aims to obtain the Strength Activity Index (SAI) value for the mortar. The test is conducted on six samples for each type, which include cement mortar, fly ash mortar, and the optimal PSBE mortar and three samples with closely matched compressive strengths were selected. The mortar mix design used in this test follows ASTM C109, as shown in Table 2. Compressive strength is determined by comparing the applied load to the surface area of the mortar, while the SAI value is obtained by comparing the sought SAI value to the SAI of the cement mortar. This SAI test is conducted in accordance with ASTM C311. The compressive strength and SAI value are calculated to analyze and compare the compressive strength and SAI values of the optimal PSBE mortar and the fly ash mortar.

E. HYDRATION TEMPERATURE TEST

The hydration temperature test on mortar aims to analyze the influence of temperature on the setting time of the mortar. The hydration temperature test is conducted to compare the hydration temperatures of cement mortar, optimal PSBE mortar, and fly ash mortar. The percentage of cement replacement used in the mortar is the percentage of cement replacement in the mortar that yields the highest compressive strength. The mortar mix design used in this test follows ASTM C109, as shown in Table 2. In the test, it is important to prepare a stable room temperature. Therefore, in this study, a styrofoam box is used to minimize temperature fluctuations in the measured mortar. Additionally, a bottle with a hole in its cap is needed to insert thermocouple cable through the hole. The steps involved in the test are as follows: first, mix the mortar mixture and then pour it into the bottle. Secondly, insert the thermocouple cable. Finally, begin temperature readings using the thermocouple. Readings are taken at 15-minute intervals until the temperature readings stabilize, and a graph can be created to show the relationship between temperature and time duration. The percentage of cement replacement used in the mortar is the percentage of cement replacement in the mortar that yields the highest compressive strength

RESULTS AND DISCUSSIONS

A. PRE-TREATMENT RESULT

Based on the determination of temperature and time that already mentioned before, several variations can be created for conducting the pre-treatment process with the calcination method, as shown in Table 3. Based on the oil content test results in Table 3, it can be observed that the oil content from the calcination process is not significantly influenced by temperature and time variables, as the results are very close to 0%. In this study, the variation selected will be the burning process at a temperature of 600°C for half an hour to save energy during the calcination process. Therefore, the oil content of PSBE-K contained 1.2% oil content.

Table 3 Variations of temperature and time in the pre-treatment process with the calcination method

Temperatures (ºC)	Durations (Hour)	Oil Content (%)
600	0.5	0.0538
600	1	0.0131
600	1.5	0.0093
700	0.5	0.0571
700	1	0.0862
700	1.5	0.0071
800	0.5	0.0565
800	1	0.0169
800	1.5	0.0312
900	0.5	0.007
900	1	0.0489
900	1.5	0

The pre-treatment process using the combination of extraction and calcination methods is obtained from the optimized pre-treatment process using the calcination method on PSBE-E material. The material resulting from the pre-treatment process using the combination of extraction and calcination methods is referred to as PSBE-EK which contained 0.0063% oil content.

B. OPTIMAL PSBE SELECTION TEST

The Optimization of the pre-treatment process for SBE consists of three materials: PSBE obtained from the extraction method process (PSBE-E), PSBE obtained from the calcination method process (PSBE-K), and PSBE obtained from the combination of extraction method and calcination method process (PSBE-EK). The optimal PSBE material was selected based on the SAI results, which aims to analyze its potential as a substitute material for cement in mortar applications.

As mentioned before, cement substitute materials such as fly ash has shown an influence on compressive strength in mortar with a 15% cement replacement percentage at 28 days old [8]. Hence, in the optimization of the pre-treatment process for SBE, mortar specimens were prepared using a 15% cement replacement material to assess the potential of each type of PSBE. Subsequently, the PSBE exhibiting the highest SAI value was selected as the optimal PSBE candidate. The test results for compressive strength in the optimization of the pre-treatment process for SBE can be found in Table 4 and can be depicted in a graph for better visual analysis, as illustrated in Fig. 1Composition and traffic volume were helpful factors in measuring lane performance [17].

Table 4 Compressive strength results obtained for the optimization of pre-treatment process on SBE

Sample	Mortar type	force (kg)	Area (cm^2)	Compressive strength (*MPa*)	Average Compressive Strength (*MPa*)	SAI (%)
1	Cement	8411.48	25	33.00	32.63	1.00
2		8511.48		33.39		
3		8033.51		31.51		
1	PSBE-E 15%	6751.02	25	26.48	26.14	0.80
2		6465.33		25.36		
3		6771.93		26.56		
1	PSBE-K 15%	6870.70	25	26.95	27.18	0.83
2		7003.09		27.47		
3		6912.51		27.12		
1	PSBE-EK 15%	9191.05	25	36.05	35.58	1.09
2		9267.69		36.35		
3		8752.06		34.33		

Performance obtained from intersection analysis using software SIDRA Intersection 8.0. By knowing the level of service (LOS) and delay (D) at the junction, this program calculates the intersection performance. Knowing the number of cars is the first step in evaluating the performance of a junction. The volume that has to be input is the volume that is distributed based on how each leg moves. Only the volume of light vehicles (LV) and heavy vehicles (HV) may be evaluated due to SIDRA's limitations on the types of vehicles that can be input as traffic volume data. The volume of motorcyclists must thus be multiplied by the comparable number of passenger automobiles at signalized junctions, which is 0.2 for protected conditions and 0.4 for opposed situations.

As mentioned before, cement substitute materials such as fly ash has shown an influence on compressive strength in mortar with a 15% cement replacement percentage at 28 days old [8]. Hence, in the optimization of the pre-treatment process for SBE, mortar specimens were prepared using a 15% cement replacement material to assess the potential of each type of PSBE. Subsequently, the PSBE exhibiting the highest SAI value was selected as the optimal PSBE candidate. The test results for compressive strength in the optimization of the pre-treatment process for SBE can be found in Table 4 and can be depicted in a graph for better visual analysis, as illustrated in Fig. 1.

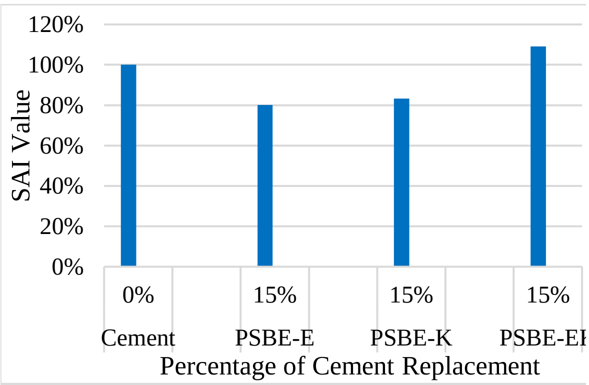

Figure 1 Graph of compressive strength results for the optimization of pre-treatment process on SBE

In accordance with the specifications outlined by ASTM C618, the standard governing the use of supplementary cementitious materials, a minimum SAI value of 75% is deemed necessary for effective performance. The SAI value serves as an indicator of the pozzolanic activity of the material, reflecting its ability to contribute to the strength development and durability of mortar. Figure 1 showcases the results obtained from the experimental investigation on the compressive strength of mortar samples incorporating various types of PSBE materials as cement substitutes. Each PSBE material was subjected to a pre-treatment process to enhance its suitability as a supplementary cementitious material. Remarkably, the graph in Figure 1 reveals that all PSBE materials studied exhibit SAI values that meet or exceed the minimum SAI requirement established by ASTM C618. This suggests that PSBE possess favorable pozzolanic properties, enabling them to effectively replace cement in mortar formulations. To further optimize the pre-treatment process and select the most suitable PSBE material as a cement substitute in mortar, the PSBE material with the highest SAI value was given particular attention. Among the tested materials, PSBE-EK emerged as the frontrunner, boasting an outstanding SAI value of 109%. This value surpasses not only the SAI values of other PSBE but also exceeds the SAI value exhibited by traditional cement mortar.

This can be attributed to the higher pozzolanic activity of PSBE-EK compared to PSBE-E and PSBE-K due to employing two methods for enhancing pozzolanic activity, whereas PSBE-E and PSBE-K underwent only one method for enhancing pozzolanic activity. There are three approaches commonly employed to enhance pozzolanic activity, namely mechanical activation, chemical activation, and thermal activation [13-16]. In this study, chemical activation (through extraction method) and thermal activation (through calcination method) were utilized. The superior performance of PSBE-EK, as indicated by its exceptional SAI value, highlights its potential as an excellent alternative to cement in mortar formulations. The utilization of PSBE-EK in mortar production has the potential to enhance the mechanical properties and overall durability of the resulting mortar, contributing to sustainable and eco-friendly construction practices.

C. COMPARISON TEST OF OPTIMAL PSBE AND FLY ASH FROM POZZOLAN CLASSIFICATION MATERIAL

Pozzolan classification refers to the categorization of materials used as cement substitutes in the construction industry. The american society for testing and materials (ASTM) has established standards, known as ASTM 618, which outline the classification criteria for pozzolans. These criteria are based on different grades, namely Class N, Class F, and Class C. The classification of pozzolans is determined by examining the chemical compounds present in the material. This analysis is typically conducted using a testing method called x-ray fluorescence (XRF). XRF testing allows for the identification and quantification of various chemical elements and compounds within the material, providing valuable insights into its composition. In the current research or study, the material under investigation is PSBE-EK, which is being compared with fly ash. The purpose of this comparison is evaluating their performance as cement substitutes, and assessing their chemical compatibility. Apart from conducting a comparison between PSBE-EK and fly ash, the investigation also includes an analysis of the compound content in the cement to determine its compliance with the ASTM C150 specifications. The XRF test results for the cement, PSBE-EK, and fly ash are presented in Table 5.

Table 5 XRF test results for cement, PSBE-EK, and fly ash

Oxide compounds	Percentage (%)		
	Cement	PSBE-EK	Fly ash
MgO	-	1	-
Al_2O_3	1.9	5	7.5
SiO_2	9.2	41	20
P_2O_5	0.4	6.4	0.5
SO_3	1.5	1	2.2
K_2O	0.65	3.41	1.9
CaO	79.7	14.8	26.9
TiO_2	0.4	2.6	1.5
V_2O_5	0.02	0.14	0.06
Cr_2O_3	-	0.03	0.03
MnO	0.078	0.31	0.32
Fe_2O_3	5.76	23.7	37.9
NiO	-	-	0.03
CuO	0.095	0.15	0.11
ZnO	0.02	0.03	0.083
Rb_2O	0.01	0.059	0.042
SrO	0.081	0.072	0.53
ZrO_2	0.03	0.1	0.076
BaO	0.1	-	0.61
Re_2O_7	0.04	0.04	-
HgO	-	-	0.05

Table 4 presents the XRF analysis results for the cement material, revealing a significant presence of CaO as the highest oxide compound, accounting for 79.7%. Compliance with chemical composition regulations, such as those outlined in ASTM C150, is essential for cement. According to ASTM C150, the maximum allowable percentages for four oxide compounds, namely Al2O3, Fe2O3, MgO, and SO3, are 6%, 6%, 6%, and 3% respectively. The findings in Table 4 indicate that the tested cement material satisfies the specifications defined by ASTM C150.

The XRF analysis results revealed notable distinctions between the fly ash and PSBE-EK materials using ASTM C618. The fly ash material exhibited a combined percentage of SiO2, Al2O3, and Fe2O3 at 64.7%, which falls below the minimum requirement of 70% for both Class N and Class F classifications in accordance with ASTM C618. However, it exceeded the minimum requirement of 50% for Class C classification, indicating its classification as Class C pozzolan material. Additionally, the fly ash contained 2.2% SO3, complying with the maximum requirement of 5% for Class C classification. On the other hand, the PSBE-EK material showcased promising results in comparison. With a combined percentage of SiO2, Al2O3, and Fe2O3 at 70.3%, it surpassed the composition observed in the fly ash material. Furthermore, the PSBE-EK material contained 1.1% SO3. By applying the criteria outlined in ASTM C618, the PSBE-EK material can be categorized as Class N pozzolan material. In summary, the XRF analysis results demonstrate that the fly ash material falls under Class C pozzolan classification, while the PSBE-EK material qualifies as Class N pozzolan, showcasing superior composition compared to the fly ash

E. COMPARISON TEST OF OPTIMAL PSBE AND FLY ASH FROM SLUMP MORTAR TEST

The slump mortar test is a commonly used method to measure the viscosity and workability of mortar. The purpose of the slump mortar test is to analyze the consistency comparison of mortar when incorporating cement replacement materials such as fly ash and PSBE-EK. The testing method is governed by the ASTM C1437 standard, which provides guidelines for conducting the test. The equipment used for the test is a flow table that complies with the specifications outlined in ASTM C230. The slump mortar test is conducted on cement mortar, fly ash mortar, and PSBE-EK mortar specimens to assess their slump characteristics and workability.

The comparison of slump mortar values between cement mortar, fly ash mortar, and PSBE-EK mortar is conducted to analyze the workability of mortar using cement replacement materials compared to normal cement mortar. Cement mortar slump is used as the control slump mortar to serve as a reference in analyzing the slump mortar values. The results of the comparison of slump mortar values can be seen in Table 6.

Table 6 Slump test results for cement mortar, PSBE-EK mortar, and fly ash mortar

Mortar	Percentage of Cement Replacement	Slump (*mm*)
Cement	0%	116.25
Fly ash	5%	116.25
	10%	117.50
	15%	125.00
PSBE-EK	5%	112.74
	10%	105.92
	15%	100.25

The comparison of slump mortar values in Table 6, reveals that cement mortar has different slump mortar values compared to mortar using cement replacement materials. The slump mortar value increases and decreases with the increase in cement replacement materials. In fly ash mortar, the slump mortar value increases with the increase in the percentage of cement replacement compared to cement mortar. On the other hand, in PSBE-EK mortar, the slump mortar value decreases with the increase in the percentage of cement replacement. These slump mortar values significantly impact the workability of the mortar. A higher slump mortar value indicates better workability, and vice versa. Based on this test, it can be analyzed that mortar with fly ash as a cement replacement material shows an increase in slump mortar value, indicating improved workability. However, in PSBE-EK mortar, the slump mortar value decreases with the increase in the percentage of cement replacement, indicating a decrease in workability.

This is due to the consistent water demand of 242 milliliters in the mortar mixture, while the water demand is significantly influenced by the characteristics of the materials utilized. Fly ash, being fine and spherical in nature, exhibits such material characteristics. Conversely, PSBE-EK material possesses less defined and rough characteristics, leading to an elevated water demand as the percentage of cement replacement increases [17-19].

E. COMPARISON TEST OF OPTIMAL PSBE AND FLY ASH FROM COMPRESSIVE STRENGTH TEST

The compressive strength test of mortar is conducted to analyze the strength values of each mortar based on the cement replacement materials used. The mortar mixtures used are in accordance with the mix proportions specified in ASTM C109. The percentage of cement replacement materials used is 5%, 10%, and 15%. The compressive strength test of mortar is conducted at various ages, namely 3 days, 7 days, 14 days, and 28 days. The testing is performed on three types of mortar: cement mortar, fly ash mortar, and PSBE-EK mortar. The results of the compressive strength testing can be seen in Table 7 and The results of the SAI value can be seen in Table 8.

Table 7 Compressive strength test results for cement mortar, PSBE-EK mortar, and fly ash mortar

Mortar	Percentage of Cement Replacement	Compressive Strength (MPa)			
		3 Days	7 Days	14 Days	28 days
Cement	0%	20.05	30.98	31.76	32.63
PSBE-EK	5%	18.51	29.50	32.31	41.04
	10%	15.60	26.41	29.85	37.27
	15%	14.76	18.53	27.00	35.58
Fly Ash	5%	18.27	24.66	28.81	37.36
	10%	14.25	22.86	26.33	35.50
	15%	15.89	23.80	27.70	32.67

Upon analyzing the development of compressive strength in mortar based on the age of the mortar that can be seen in Table 7, Figure 2, and Figure 3, it is found that the cement substitute materials, PSBE-EK and fly ash, exhibit lower compressive strength than cement mortar at early ages, specifically before 14 days. However, at 14 days and 28 days, PSBE-EK mortar and fly ash mortar show an increase in compressive strength compared to cement mortar. This indicates that PSBE-EK mortar and fly ash mortar have the potential to compete with cement mortar at later ages. This can be attributed to the characteristics of the materials used as cement replacements. Several factors can influence the compressive strength of mortar at early ages, including limited initial pozzolanic activity and a slower hydration rate when incorporated into mortar. The limited initial pozzolanic activity can be attributed to pozzolanic materials that require a longer time to react with the calcium hydroxide in cement. Likewise, the slower hydration rate can also impact the early-age compressive strength of mortar as incomplete hydration can result in lower strength development [20-22].

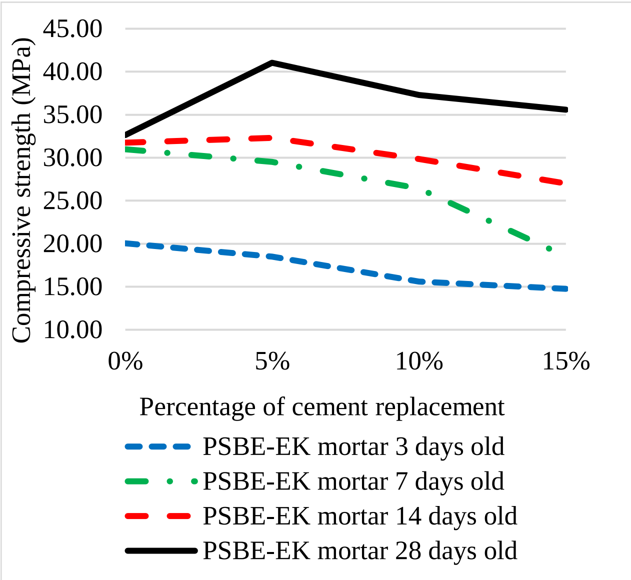

Figure 2 The compressive strength graph of PSBE-EK mortar at 3, 7, 14, and 28 days old

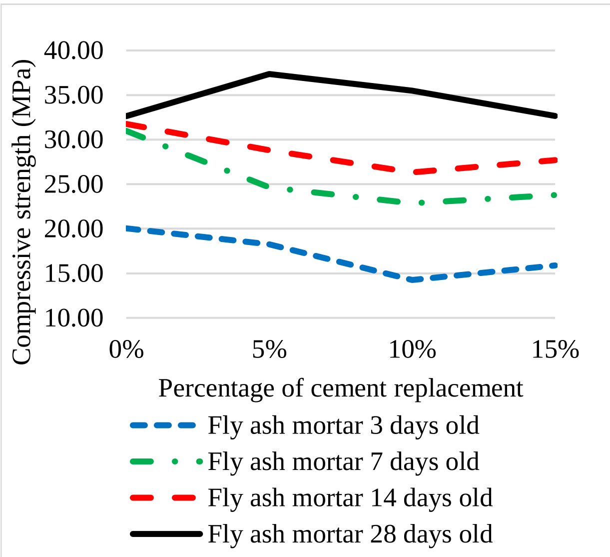

Figure 3 The compressive strength graph of fly ash mortar at 3, 7, 14, and 28 days old

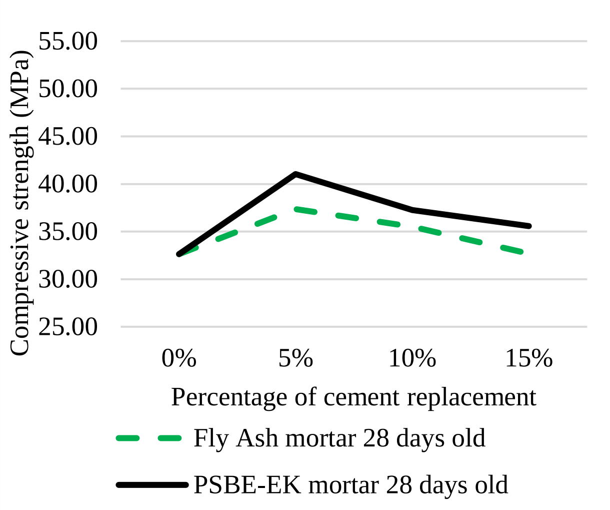

Figure 4 The comparison graph of compressive strength between PSBE-EK mortar and fly ash mortar at 28 days old

Table 8 SAI value for cement mortar, PSBE-EK mortar, and fly ash mortar

Mortar	Percentage of Cement Replacement	SAI Value			
		3 Days	7 Days	14 Days	28 days
Cement	0%	100%	100%	100%	100%
PSBE-EK	5%	92%	95%	102%	126%
	10%	78%	85%	94%	114%
	15%	74%	60%	85%	109%
Fly Ash	5%	91%	80%	91%	114%
	10%	71%	74%	83%	109%
	15%	79%	77%	87%	100%

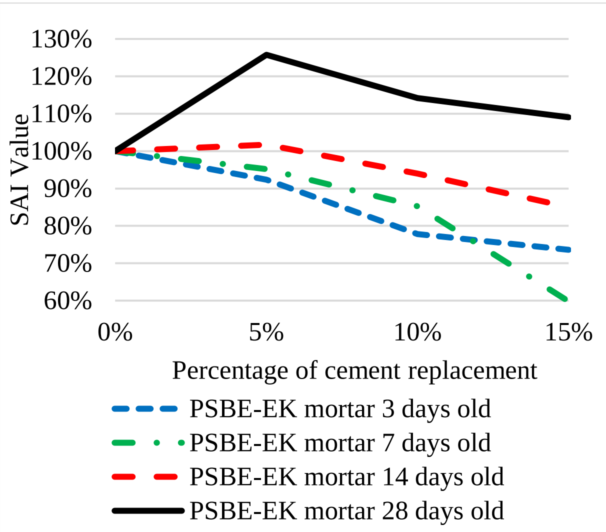

Figure 5 The SAI value graph of PSBE-EK mortar at 3, 7, 14, and 28 days old

When compared to fly ash mortar, PSBE-EK mortar demonstrates similar compressive strength at 3, 7, and 14 days. However, at 28 days, PSBE-EK mortar exhibits higher compressive strength that can be seen in Figure 4. In addition to compressive strength, the SAI value of mortar can also be considered to facilitate the analysis of the potential compressive strength of the mortar. By evaluating the SAI values of various mortar compositions, including those with PSBE-EK or fly ash as cement replacements, we can assess their potential to attain the desired compressive strength.

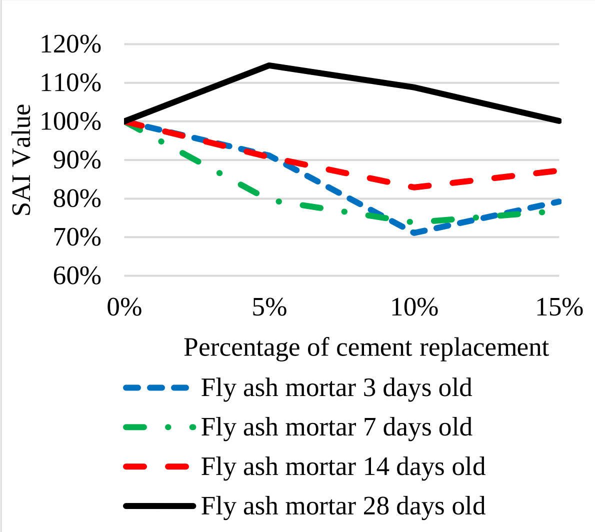

Figure 6 The SAI value graph of fly ash mortar at 3, 7, 14, and 28 days old

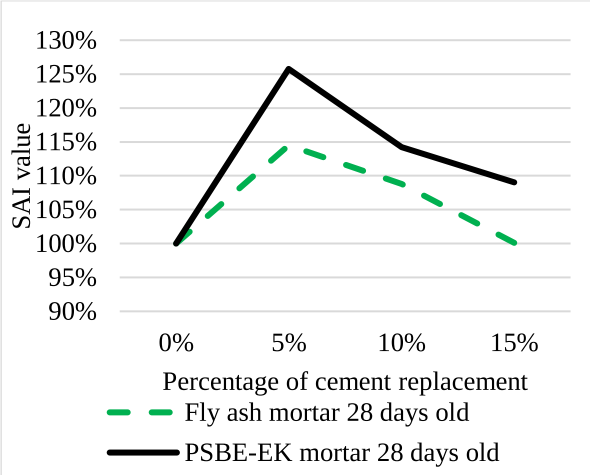

Figure 7 The comparison graph of SAI value between PSBE-EK mortar and fly ash mortar at 28 days old

Higher SAI values indicate a greater overall potential for achieving higher compressive strength in the mortar. According to ASTM C618 standards, there is a minimum requirement for the SAI value in mortar at 28 days old, which is set at 75%. In Table 8 and Figure 5, mortars at 28 days old, it can be observed that PSBE-EK mortar exceeds the SAI value of the control or reference mortar at each percentage of cement substitution, with SAI values of 126%, 114%, and 109% for 5%, 10%, and 15% cement replacement, respectively. Similarly, in Table 8 and Figure 6, fly ash mortar also surpasses the SAI value of the control or reference mortar, with SAI values of 114%, 109%, and 100% for 5%, 10%, and 15% cement replacement, respectively. However, PSBE-EK material shows a higher potential as a cement substitute in mortar, as it achieves higher SAI values compared to fly ash mortar at 28 days old that can be seen in Figure 7. This can be attributed to

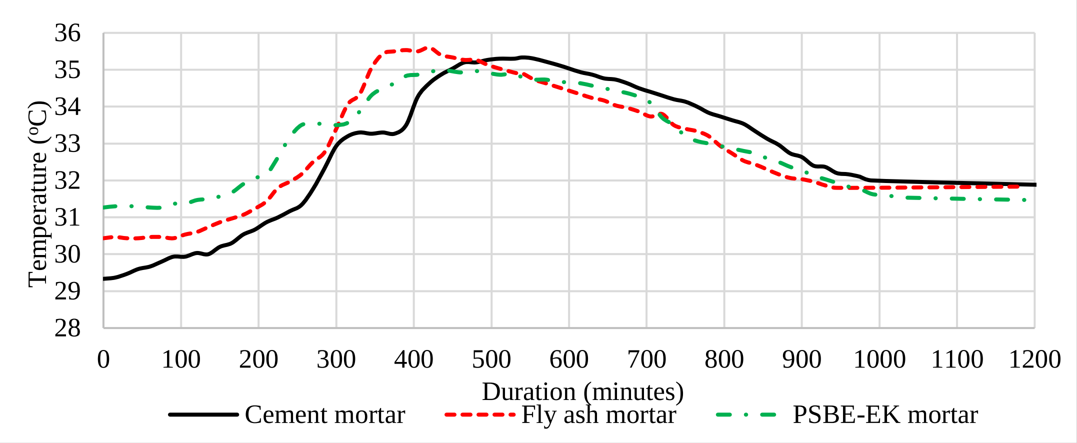

Figure 8 Comparison graph of hydration temperature test on cement mortar, fly ash mortar, and PSBE-EK mortar

Table 9 Comparison results of hydration temperature test

Mortar	Initial temperature (°C)	Maximum Temperature (°C)	Maximum temperature change (°C)	Duration to reach the maximum temperature (minutes)	Duration to reach the stable temperature (minutes)
cement	29.33	35.33	6.00	540	990
Fly Ash	30.43	35.60	5.17	420	945
PSBE-EK	31.27	35.00	3.73	435	1020

the fact that PSBE-EK material exhibits a higher level of pozzolanic activity compared to fly ash.

F. COMPARISON TEST OF OPTIMAL PSBE AND FLY ASH FROM HYDRATION TEMPERATURE TEST

The purpose of conducting hydration temperature test on mortar is to analyze the relationship between temperature and the setting time of the mortar. The purpose of conducting hydration temperature testing on cement mortar, fly ash mortar, and PSBE-EK mortar was to analyze the influence of substitute materials on hydration temperature. The hydration temperature of cement mortar served as a control to compare the effects of hydration temperature on mortars incorporating substitute materials such as fly ash and PSBE-EK. The comparative results of hydration temperature for cement mortar, fly ash mortar, and PSBE-EK mortar can be observed in Figure 8.

Based on the comparison graph in Figure 8, it is evident that there are varying initial temperatures among the different mortars. To facilitate a comprehensive analysis of the comparison results, a table was prepared, which includes the initial temperature, maximum temperature, maximum temperature change, duration to reach the maximum temperature, and duration to reach the stable temperature. The table presenting the comparison results of hydration temperature testing can be found in Table 9.

According to Table 9, the maximum temperatures recorded in each mortar are closely clustered. However, the variations in temperature changes differ among the mortars. Cement mortar demonstrates a higher temperature change compared to both fly ash mortar and PSBE-EK mortar. This discrepancy can be attributed to the differences in characteristics between the substitute materials, fly ash and PSBE-EK, and cement, in addition to the higher cement content utilized [24,25]. Moreover, apart from the higher temperature change, the time required to reach the peak temperature differs between cement mortar and the other two mortars. Cement mortar takes 540 minutes, while fly ash mortar and PSBE-EK mortar reach their peaks in 420 minutes and 435 minutes, respectively. In comparing fly ash mortar to PSBE-EK mortar, notable differences are observed in terms of the maximum temperature change. Fly ash mortar exhibits a significantly higher temperature change compared to PSBE-EK mortar. The highest recorded temperature change for fly ash mortar is 5.17°C, whereas for PSBE-EK mortar, it is 3.73°C. These variations can be attributed to the distinctive characteristics of fly ash and PSBE-EK materials. Upon analyzing the temperature differences, it is evident that fly ash material demonstrates a higher hydration rate than PSBE-EK material. However, the hardening time concludes at approximately the same duration, around 975 minutes. The hydration rate has an impact on the peak temperature and hardening duration of the mortar [25]. This difference in hydration rate can be ascribed to particle characteristics and density, where fly ash particles possessed a spherical shape and denser, while PSBE-EK particles had a rougher and less uniform surface but less dense. The density and smoother particle surface of fly ash facilitates enhanced interaction between cement and water, thereby resulting in a higher hydration rate compared to PSBE-EK mortar [24,25].

CONCLUSIONS

Based on the results of the research that has been conducted, the following conclusions can be analyzed:

1. The pre-treatment process, optimized through a combination of extraction and calcination methods, resulted in the PSBE-EK material with the highest Supplementary Cementitious Material Activity Index

(SAI) value of 109%. This combination approach enhanced the pozzolanic activity of the material and suggests its potential as a cement substitute.

2. PSBE-EK material falls into Class N as a natural pozzolan, while fly ash falls into Class C, based on their distinct chemical compositions. The higher percentage of S_iO_2, Al_2O_3, and Fe_2O_3 in PSBE-EK contributed to its different pozzolan classification.
3. Fly ash mortar showed improved workability with increasing cement replacement, whereas PSBE-EK mortar exhibited reduced workability due to its rough characteristics and increased water demand.
4. PSBE-EK and fly ash mortar exhibited lower early-age compressive strength than cement mortar, but at 28 days, they displayed improved strength, indicating their potential as cement mortar substitutes in the long term. PSBE-EK consistently outperformed fly ash mortar in terms of strength potential, attributed to its enhanced pozzolanic activity through the combination of extraction and calcination methods.
5. Hydration temperature analysis revealed variations in maximum temperature changes among cement mortar, PSBE-EK mortar, and fly ash mortar. Cement mortar showed the highest maximum temperature change, while PSBE-EK and fly ash mortar had lower values. Differences in particle characteristics and density influenced the hydration rates and temperature changes, with fly ash mortar exhibiting a significantly higher temperature change compared to PSBE-EK mortar.

In summary, the optimized pre-treatment process using extraction and calcination methods resulted in PSBE-EK material with enhanced pozzolanic activity and strength potential. It exhibited promise as a cement substitute in mortar, although it showed reduced workability compared to fly ash mortar. The findings also highlighted the influence of material characteristics on hydration rates and temperature changes in mortar.

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