Research Article

Effects of Sand Powder on Sulfuric Acid Resistance, Compressive Strength, Cost Benefits, and CO₂ Reduction of High CaO Fly Ash Concrete

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This article studies the efficiency of sand powder as a supplementary cementitious material (SCM) in improving the sulfuric acid resistance of concrete incorporated with high CaO fly ash. Besides, the effects of sand powder on compressive strength development, mitigation of carbon dioxide emission, and cost-effectiveness are addressed. Paste mixtures with W/B ratios of 0.25 and 0.40 were used in this study for the performances of sulfuric acid resistance and long-term compressive strength development. The test results indicated that sand powder could reduce the weight loss of the tested paste specimens in sulfuric acid solution with a pH of 1, compared to the control specimens, especially for the specimens incorporated with high CaO fly ash. The sand powder addition could also increase the compressive strength of cement pastes at the age of 90 days by 26.27% and 43.80% for W/B ratios of 0.25 and 0.40, respectively. The use of sand powder in the evaluated concrete mixture could also reduce CO₂ emission by 23.23% and lower the cost of the mixtures by 8.05%, compared to the control mixture. The addition of sand powder could significantly increase the sulfuric acid resistance, compressive strength, and economic benefits and reduce the CO₂ emission of high CaO fly ash-cement-based materials.

1. Introduction

Concrete is one of the most widely used construction materials. It offers satisfactory strength for constructed structures. The cost and the durability of concrete in aggressive environments should be considered. Currently, many researchers have found that the use of supplementary cementitious materials (SCMs) such as fly ash, blast furnace slag, and silica fume could improve several performances of concrete effectively [1–6]. A disadvantage of most SCMs, especially fly ash, is that they result in low early age compressive strength of the concrete. Filler materials such as limestone powder, granite dust, and ground sand or sand powder were found to be effective in combination with SCMs, to enhance compressive strength [7–9].

By designing the concrete mix proportion properly and reasonably, concrete with satisfactory mechanical and durability properties, low cost, and low environmental impact features can be produced. The designed concrete mixtures should satisfy the short-term and long-term strength and durability requirements. The mixtures should also be economical and result in low CO₂ emission. These have been successfully achieved for the past few decades in Thailand via the application of fly ash concrete. In Thailand, two main
kinds of fly ash are commonly used in the concrete industry. The first kind is the fly ash with a high CaO content (Mae Moh fly ash), while the other is the one with a low CaO content (BLCP fly ash). The use of Mae Moh fly ash in concrete generally results in a higher early strength than the BLCP one [10–12]. Because of this reason, the Mae Moh fly ash is more popular in the concrete industry in Thailand than the BLCP fly ash. It should be noted that the amount of Mae Moh fly ash is approximately 80% of the total fly ash production in Thailand. The Mae Moh fly ash is the main supply of fly ash for the concrete industry, whereas the production of BLCP fly ash is much lower at less than 15% of the total Thai fly ash production. The demand of fly ash in Thailand has recently surpassed the supply, making the price of fly ash higher than before. The high CaO Mae Moh fly ash is more common and more popular than other low CaO fly ashes in Thailand, so its price is higher. In addition, the transportation distance from Lampang province in the north of Thailand to Bangkok and other central regions of Thailand, where a majority of the construction projects are concentrated, is far, causing a large amount of CO2 emission from transportation activity. It is known that fly ashes with different chemical compositions have different advantages and disadvantages, in terms of concrete properties. Fly ashes with a low CaO content have been studied and known to significantly improve the resistance to some aggressive environmental attacks [13, 14], especially an acid attack. However, the amount of low CaO fly ash in Thailand is limited. The low CaO fly ash in Thailand also shows disadvantages in many other performances when used in concrete, as compared to the high CaO Mae Moh fly ash. Considering the abovementioned problems, more benefits can be achieved if there exists an additional cement-replacing material. This material could be used in combination with the high CaO Mae Moh fly ash to improve the acid resistance, reduce the mixture cost, and reduce the CO2 emission of the concrete mixtures. Many researchers studied the use of cement-replacing materials (CRMs) with high SiO2 contents such as silica fume, which can improve both the strength and acid resistance of concrete [6]. However, the use of silica fume in Thailand significantly increases the concrete cost [15]. It also increases the transportation-related CO2 emission, as it must be imported from foreign countries. In this study, a new alternative filler material is selected for this purpose, sand powder.

Sand powder is a filler material that has a high SiO2 content. A study has found that, though not as reactive as other pozzolans, SiO2 in sand powder can react with Ca(OH)2 from cement hydration to produce new C-S-H bonds [16]. In addition, the small sand particles can help cement to react more completely in the hydration process.

The purpose of this research is to study the possibility of using sand powder to improve the acid resistance of concrete incorporated with high CaO Mae Moh fly ash. This research can help reduce the cost and total CO2 emission of the sand powder-incorporated high CaO fly ash concrete mixtures when compared to the respective mixtures without the sand powder. Mixtures in which cement was partially replaced by the high CaO Mae Moh fly ash, low CaO BLCP fly ash, and by combined high CaO fly ash with sand powder were studied and compared for the acid resistance, cost, and CO2 emissions. The results of this study will be useful in the future for mix proportion optimization of acid-resisting concrete with the use of the most typical fly ash type (high CaO fly ash) and sand powder.

2. Materials

2.1. Portland Cement. The Portland cement used in this study is an ordinary Portland cement type I, following ASTM C 150 [17] and the Thai Industrial Standard (TIS 15) [18].

2.2. Cement-Replacing Materials

2.2.1. Fly Ash. Two different types of fly ash were used in this study: one from the Mae Moh electric power plant of the Electricity Generating Authority of Thailand (EGAT) in Lampang Province, north of Thailand, which produces a high CaO content fly ash and the other one from the BLCP Power Co., Ltd., in Rayong province, east of Thailand, which produces a low CaO content fly ash. Properties of the fly ashes follow the Thai Industrial Standard (TIS 2135–2545) [19]. The BLCP fly ash (FAR), containing a low calcium oxide (CaO) content of 2.32%, is classified as Class 2a according to TIS 2135–2545 (Figure 1(a)). In contrast, the Mae Moh fly ash (FAM), containing a high calcium oxide (CaO) content of 13.63%, is classified as Class 2b conforming TIS 2135–2545 (Figure 1(b)).

2.2.2. Sand Powder. The sand powder used in the tests has a mean particle size of 15.18 μm. It was produced by grinding river sand sourced from Ayutthaya province by a planetary ball mill (Figure 2).

The chemical compositions and physical properties of the materials used in this study are given in Tables 1 and 2, respectively.

3. Experiment

3.1. Specimen Preparation. Ten mix proportions of paste specimens (as shown in Table 3) were prepared with water to binder ratios of 0.25 and 0.4. The ten mix proportions consist of three systems of mixtures: single binder, binary binders, and ternary binders. The single binder system consists of Portland cement type I as the only binder. For binary binders, mixtures with 10% replacement by sand powder, mixtures with 30% replacement by high CaO fly ash (FAM), and mixtures with 30% replacement by low CaO fly ash (FAR) were prepared. In the case of ternary binders, only one mixture was used for this study: 10% sand powder with 20% replacement by high CaO fly ash (FAM). All of the mixtures were cast to obtain cube specimens (50 × 50 × 50 mm), following ASTM C109 [20] for the compressive strength test and acid corrosion test. Each test specimen was removed from the mold one day after casting and cured in lime water until 28 days of age. After curing, the specimens were exposed to a sulfuric acid solution with a pH
of 1 for 240 days. It is noted that the acid resistance test was conducted on paste samples in order to accelerate the degradation of the tested specimens in acid solution.

3.2. Acid Solution Preparation and pH Maintenance. Acid solutions were prepared using sulfuric acid (95–97%) dissolved in reverse osmosis water, to obtain a solution with a

![Figure 1: The fly ashes used in this study. (a) BLCP fly ash (FAR). (b) Mae Moh fly ash (FAM).](image1)

![Figure 2: Sand powder (GS).](image2)

| Chemical compositions (%) by weight | Portland cement type I (OPC) | Sand powder (GS) | Fly ash Mae Moh (FAM) | BLCP (FAR) |
|------------------------------------|-----------------------------|------------------|-----------------------|------------|
| SiO₂                               | 19.70                       | 98.51            | 40.93                 | 61.91      |
| Al₂O₃                              | 5.19                        | —                | 22.42                 | 20.35      |
| Fe₂O₃                              | 3.34                        | —                | 13.64                 | 5.20       |
| CaO                                | 64.80                       | —                | 13.63                 | 2.32       |
| MgO                                | 1.20                        | —                | 2.93                  | 1.35       |
| Na₂O                               | 0.16                        | —                | 0.89                  | 0.79       |
| K₂O                                | 0.44                        | —                | 2.39                  | 1.36       |
| SO₃                                | 2.54                        | —                | 1.93                  | 0.28       |
| Free lime                          | 0.87                        | —                | 0.22                  | 0.19       |
| LOI                                | 2.10                        | —                | 0.46                  | 5.68       |

| Physical properties               | Portland cement type I (OPC) | Sand powder (GS) | Fly ash Mae Moh (FAM) | BLCP (FAR) |
|-----------------------------------|-----------------------------|------------------|-----------------------|------------|
| Specific gravity                  | 3.13                        | 2.60             | 2.26                  | 2.16       |
| Blaine fineness (cm²/g)           | 3,660                       | 3,590            | 2,460                 | 3,400      |
| Mean diameter (µm)                | 15.41                       | 15.18            | 17.74                 | 15.91      |
pH of 1. The prepared cement paste specimens with different mix proportions were immersed in the sulfuric acid solutions. The pH of the acid solutions was measured daily by using a pH meter. A pH of 1 was maintained by the addition of acid throughout the test period.

3.3. Test Procedures

3.3.1. Compressive Strength. The compressive strength of the paste specimens was tested at 3, 7, 28, and 90 days in accordance with ASTM C109 [20]. Each compressive strength value was the average of the values obtained from three tested specimens.

3.3.2. Mass Loss by Acid Attack. Mass loss by sulfuric acid attack of paste specimens was measured following the method applied by Banchong et al. [12] and Sirisawat et al. [21]. After curing the cement paste samples in lime water for 28 days, the samples were weighed to find their initial weights. During submersion in the acid solution, the paste samples were routinely brought out of the acid solution and weighed to find the weight change every week. Before weighing, the paste samples were washed with water and brushed with a soft brush to eliminate the unsound surface, which was the result of the acid attack. They were then dried by a clean towel. After that, the weights of the specimens were measured. The mass loss or weight change (in percent) can be calculated by the following equation:

\[
\text{mass loss, in percent} = \left( \frac{w_i - w_f}{w_i} \right) \times 100\%,
\]

where \( w_i \) is the initial weight of a specimen after 28-day curing before immersion in the sulfuric acid solution (g) and \( w_f \) is the weight of the specimen after immersion in the sulfuric acid solution (g).

3.3.3. Porosity Test. Pore size distributions of paste specimens C100 and C90GS10 with a W/B of 0.25 were determined by Mercury Intrusion Porosimetry (MIP) using a Micromeritics AutoPore V 9600 (U.S.A.) with a maximum 414 MPa intrusion pressure. This MIP instrument is able to detect the pores with the diameter ranging from 3 nm to 500 μm. The cube samples with dimensions of 10 mm × 10 mm × 10 mm were cut out using a diamond saw from the midportion of the paste specimens after curing in lime water until 90 days of age. After that, the small cube samples were submerged in acetone for 24 h and subsequently dried in an oven at 50°C for 24 h to stop the hydration. Two samples were used for each MIP test.

4. Inventory Data for Calculating Carbon Dioxide Emission of Concrete Mixtures

Figure 3 shows the processes that were considered for the CO₂ emissions in obtaining a cubic meter of a concrete mixture. They include raw material production (cement, coarse aggregate, fine aggregate, and fly ash), transportation of raw materials, and concrete production. Hence, to compute the CO₂ emissions of all mix conditions in this research, the inventory data of the concrete’s raw materials and the other essential processes were collected from several sources, such as cement companies, ready-mixed concrete companies, and a literature survey. Chemical admixtures are not considered in the CO₂ emission calculation in this study, as the amount of a chemical admixture used is usually small when compared to other concrete ingredients. The calculation to obtain CO₂ emissions of a mixture is given by the following equation [22]:

\[
EF_{\text{mix}} = (W_C \times EF_C) + (W_G \times EF_G) + (W_S \times EF_S)
+ (W_{FA} \times EF_{FA}) + (W_{GS} \times EF_{GS}) + EF_{\text{plant}},
\]

where \( EF_{\text{mix}} \) is the CO₂ emission of a produced concrete mixture (t-CO₂), \( W_C \) is the weight of cement per 1 m³ of concrete (kg), \( W_G \) is the weight of coarse aggregate per 1 m³ of concrete (kg), \( W_S \) is the weight of fine aggregate per 1 m³ of concrete (kg), \( W_{FA} \) is the weight of fly ash per 1 m³ of concrete (kg), \( W_{GS} \) is the weight of sand powder per 1 m³ of concrete (kg), \( EF_C \) is the emission factor of cement (kg-CO₂/t-cement), \( EF_G \) is the emission factor of coarse aggregate (kg-CO₂/t-coarse aggregate), \( EF_S \) is the emission factor of fine aggregate (kg-CO₂/t-fine aggregate), \( EF_{FA} \) is the emission factor of fly ash (kg-CO₂/t-fly ash), \( EF_{GS} \) is the emission factor of sand powder (kg-CO₂/t-sand powder), and \( EF_{\text{plant}} \) is the emission factor of the concrete plant (kg-CO₂/t-concrete plant).

Table 3: Mix proportions of tested paste specimens.

| No. | Mix designation | W/B | Portland cement type I (ratio by weight) | Cement-replacing materials (ratio by weight) |
|-----|----------------|-----|-----------------------------------------|---------------------------------------------|
|     |                |     | C | GS | FAM | FAR |
| 1   | C100           | 0.25| 1.00 |     |     |     |
| 2   | C90GS10        | 0.25| 0.90 | 0.10 |     |     |
| 3   | C70FAM30       | 0.25| 0.70 |     | 0.30 |     |
| 4   | C70FAR30       | 0.25| 0.70 |     |     | 0.30 |
| 5   | C70FAM20GS10   | 0.25| 0.70 | 0.10 | 0.20 |     |
| 6   | C100           | 0.40| 1.00 |     |     |     |
| 7   | C90GS10        | 0.40| 0.90 | 0.10 |     |     |
| 8   | C70FAM30       | 0.40| 0.70 |     | 0.30 |     |
| 9   | C70FAR30       | 0.40| 0.70 |     |     | 0.30 |
| 10  | C70FAM20GS10   | 0.40| 0.70 | 0.10 | 0.20 |     |

C is cement; GS is sand powder; FAM is high CaO (Mae Moh) fly ash; FAR is low CaO (BLCP) fly ash.
factor of sand powder (kg-CO₂/t-sand powder), and EF_plant is the emission factor for manufacturing a cubic meter of concrete by an industrial batching-mixing plant (kg-CO₂/m³-concrete).

4.1. Emission Factors of Raw Materials

4.1.1. Emission Factor of Cement (EFC). The CO₂ emission inventory data used in this research for ordinary Portland cement were obtained from the report of the Thailand Greenhouse Gas Management Organization (Public Organization). The data were collected from 2001 to 2014 from the top five cement manufacturers in Thailand [23, 24]. The CO₂ emissions of cement production mainly come from 2 parts. The first is the direct emission of CO₂ from calcination and fuel combustion. The second is the indirect emission from the electricity used for external production. Moreover, the methodology for calculating CO₂ emissions was from the Cement Sustainability Initiative (CSI) method Version (B1) [25]. From 2001 to 2014, The Thailand Greenhouse Gas Management Organization (Public Organization) reported that the average value of CO₂ emission is about 0.7935 t-CO₂/tonne (direct emission of CO₂ = 0.7330 t-CO₂/tonne and indirect emission of CO₂ = 0.0605 t-CO₂/tonne).

4.1.2. Emission Factor of Fine Aggregate (EFS). The emission factor of fine aggregate production (EFS) used in this study was derived from previous research that studied the CO₂ emission of sand production for concrete works in Thailand [22]. The CO₂ emission per tonne of sand is 0.0046 t-CO₂/tonne.

4.1.3. Emission Factor of Coarse Aggregate (EFG). The data for estimating the CO₂ emission due to the production of coarse aggregate were from previous studies [26]. The coarse aggregate used in our analysis is limestone aggregate, which is usually obtained from a typical mining process. The data obtained were based on typical aggregate mining and production processes. They considered the processes starting from the use of explosives to blast the rock from a quarry into medium-sized boulders and rocks, applying diesel-powered excavators and haulers, removing the rubble and dumping it into electric crushing and screening equipment, and moving the final graded products into stockpiles by diesel-powered haulers. This information was taken from fuel, electricity, and explosives invoices and site sales figures. The fuel, electricity, and explosives data were used to calculate the amount of CO₂ produced per tonne of aggregate, produced at each site. The CO₂ emission per tonne of coarse aggregate (EFG) is 0.029 t-CO₂/tonne.

4.1.4. Emission Factor of Fly Ash (EFFA). As mentioned, there are two main sources of fly ash that are practically used in the concrete industry in Thailand, Mae Moh and BLCP fly ashes. It is commonly accepted that fly ash does not have direct emissions of CO₂ from their production, as they are by-products from electric power plants. However, indirect emissions caused by additional processes for managing the fly ash at the power plants, such as transportation to the stockpiles, quality control processes, and consumer-related processes, should be considered. In this research, the emission factor of fly ash production is estimated to be about 0.0196 t-CO₂/tonne [26].

4.1.5. Emission Factor of Sand Powder (EFGS). The emission factor of the sand powder (EFGS) in this research is calculated by considering two parts (emission factor of raw materials and emission factor of grinding sand). For the first part, the original sand used for preparing the sand powder was river sand obtained from a sand source in Ayutthaya province. The emission factor data for this part are from Section 4.1.2. For the second part, to prepare the sand powder in the
laboratory, the original sand was ground to obtain the sand powder with a mean particle size of about 15 microns. In the laboratory, the river sand was ground for about 45 min at a speed of 400 rpm by using a planetary ball mill. However, in real mass production, the CO₂ emission from the energy used for grinding sand was assumed in this study to be similar to that for grinding limestone to a similar size. The data were obtained from Siam City Concrete. The electricity used was around 51 kWh/tonne [27]. The average CO₂ emission per 1 kW of electricity is equal to 0.545 kg-CO₂/kW [28]. So, in this research, the calculated emission factor of sand powder (EF_{GFS}) is approximately 0.0324 t-CO₂/tonne. All emission factors that are used for the CO₂ emission calculation of material production in this study are summarized in Table 4.

4.2. Emission Factor for Transportation. Inventory data of energy and transportation are used for the concrete materials in Thailand. The values of CO₂ emissions by the combustion of fuels (diesel) are estimated at 0.0714 t-CO₂/ km for 20t trucks [23]. The distance considered for the calculation of CO₂ emissions by transportation is the distance from the source of the materials to the Bangkok metropolitan area. The CO₂ emission calculations for material transportation to the Bangkok metropolitan area are summarized in Table 5.

4.3. Emission Factor for Concrete Manufacturing in Batching and Mixing Plants (EF_{plant}). The data on power usage for manufacturing ready-mixed concrete were collected from several ready-mixed concrete plants around Bangkok that were reported by Sukontasukkul [22]. The report shows that the CO₂ emission for manufacturing 1 m³ of ready-mixed concrete is about 0.0012 t-CO₂/m³.

The reference mix proportion of concrete used for evaluating CO₂ emission and cost is a typical mix proportion used in ready-mixed concrete companies (Table 6). This mix proportion was obtained from the Concrete Products and Aggregate Co., Ltd. (CPAC), the leading ready-mixed concrete company in Thailand. In this research, the CO₂ emissions from water and the chemical admixture were neglected due to their insignificant values.

5. Cost of Concrete Ingredients

The cost-effectiveness of the use of sand powder to improve acid resistance performance of the concrete with the high CaO fly ash was also evaluated. The unit price of the concrete and the mix proportions are shown in Table 7. The mix proportions in Table 7 were obtained based on the reference mix proportion in Table 6 (C100 in Table 7 is the same mixture as the mixture in Table 6).

The unit prices of the materials used in the concrete mixtures were collected from various sources as follows.

5.1. Price of Cement. The unit price of bulk-delivered OPC, typically used for ready-mixed concrete, was used for the calculation of the unit price of cement. The price was averaged from the five major cement manufacturers in Thailand, i.e., Siam Cement Group Co., Ltd., Siam City Cement Public Co., Ltd., TPI Polene Public Co., Ltd., Asia Cement Public Co., Ltd., and Jalaprapathan Cement Public Co., Ltd.

5.2. Price of Aggregates. The prices of fine and coarse aggregates were collected from the Economic and Trade Indices Database (ETID), Ministry of Commerce 2018 [29]. The prices were the annual average prices during 12 months in 2018.

5.3. Prices of Fly Ashes. The prices (in 2018) of the Mae Moh and BLCP fly ashes were collected from several ready-mixed concrete plants in Bangkok.

5.4. Price of Sand Powder. The price of sand powder was estimated by adding the price of sand in Section 5.2 with the cost of the grinding process, which was obtained from the Siam City Concrete Co., Ltd.

A summary of the unit prices of concrete ingredients is given in Table 8. The unit prices of the ingredients listed in Table 8 include the transportation cost from their sources to the Bangkok area.
6. Results and Discussion

6.1. Effects of Fly Ashes and Sand Powder on Compressive Strength. Compressive strength measurements of the specimens were carried out at the ages of 3, 7, 28, and 90 days. The compressive strength of a mixture was calculated from the average of 3 tested specimens. The test results are shown in Figure 4. The compressive strengths of the mixtures with a W/B of 0.25 and 0.40 show a similar tendency. The compressive strength of the mix with 10% GS replacement is higher than that of the control cement-only specimen and also higher than both fly ash mixtures (FAM and FAR mixtures) during the first 28 days. The improvement of compressive strength of the mixtures with 10% replacement by sand powder at an early age is because it serves as an activator to increase hydration and pozzolanic reactions [30]. When 30% fly ash was used in the mixtures, the compressive strengths were lower than that of the control specimen at the ages of 3, 7, and 28 days due to the nature of the pozzolanic material and cement dilution effects. However, the fly ash can improve the compressive strength to be even higher than that of the control at 90 days. This is due to the continued pozzolanic reaction at a later age. When comparing the effects of different fly ash types on the compressive strength, the mix with 30% FAM replacement shows a higher strength than the mix with 30% FAR. This is due to the higher CaO content of the FAM, compared to FAR. The sand powder improves the compressive strength of the tested pastes at an early age, especially when it is used in combination with fly ash in the mixtures. The ternary binder mixtures (cement + fly ash + sand powder) show a higher compressive strength at all tested ages, compared to the control specimen. This indicates that the sand powder can be used to improve the compressive strength of the mixtures, both with and without fly ash.

Results obtained from MIP test of a control cement paste (C100) and a paste with 10% sand powder (C90GS10) at the age of 90 days are illustrated in Figure 5. Cumulative pore size distribution curves of the pastes are shown in Figure 5(a). It is observed that the use of sand powder decreases the volume of pores when compared with the control cement paste. It also decreases the proportion of large capillary pores (sizes from 50 nm to 10 μm) and increases the proportion of the medium capillary pores (sizes from 10 nm to 50 nm). It is noted that the pore size classification was adopted from Mindess et al. [31]. The most probable pore sizes of pastes can be obtained from the peak of the differential distribution curves [32–36] as illustrated in Figure 5(b). It is seen that the most probable pore sizes of C100 and C90GS10 are 54.3 nm and 32.5 nm, respectively. These MIP test results indicate that the sand powder can reduce pore volume and refine the pore structures in pastes effectively, resulting in the compressive strength improvement of the mixtures incorporated with the sand powder.

6.2. Effects of Mineral Admixtures on Mass Loss. The results of mass loss were obtained in terms of the loss of weight of paste specimens after immersion in the sulfuric acid solutions with a pH of 1. As shown in Figures 6(a) and 6(b), the control paste specimens (C100) for both tested W/B ratios show the highest weight loss after immersion. In contrast, the resistance to sulfuric acid attack was improved, indicated by a decrease in mass loss, when using fly ashes in the mixes. For the binary binder case, the mix with 30% FAR fly ash replacement showed the lowest weight loss, which was followed by the mix with 10% sand powder and the mix

### Table 6: Mix proportion for the compressive strength of concrete, 28 MPa at an age of 28 days.

| Compressive strength (MPa) cylinder | Mix proportion (kg/m³) | Cementitious materials | Water | Fine aggregate | Coarse aggregate | Admixture (cc) | W/B ratio | Slump (cm) |
|-----------------------------------|------------------------|------------------------|-------|----------------|-----------------|---------------|-----------|-----------|
| 28                                | 298                    | 180                    | 930   | 1,050          | 700–800         | 0.60          | 5–10      |

### Table 7: Mix proportions of concrete that are used to compare the unit price.

| Mixtures          | Cement (OPC) (kg/m³) | Fly ash (FAM) (kg/m³) | Fly ash (FAR) (kg/m³) | Sand powder (GS) (kg/m³) | Coarse aggregate (kg/m³) | Fine aggregate (kg/m³) |
|-------------------|----------------------|-----------------------|-----------------------|--------------------------|--------------------------|------------------------|
| C100              | 298                  |                       |                       |                          | 1,050                    | 930                    |
| C90GS10           | 268.2                |                       |                       |                          | 1,050                    | 930                    |
| C70FAM30          | 208.6                | 89.4                  |                       |                          | 1,050                    | 930                    |
| C70FAR30          | 208.6                |                       | 89.4                  |                          | 1,050                    | 930                    |
| C70FAM20GS10      | 208.6                | 59.6                  |                       | 29.8                     | 1,050                    | 930                    |

### Table 8: Unit prices of concrete ingredients.

| Type     | Ingredient   | Prices (Baht/tonne) |
|----------|--------------|---------------------|
| Binders  | Cement (C)   | 1,920               |
|          | Fly ash (FAM)| 1,600               |
|          | Fly ash (FAR)| 639                |
|          | Sand powder (GS)| 180               |
| Aggregates| Coarse aggregate | 260               |
|          | Fine aggregate | 145               |
with 30% FAM fly ash that were almost equivalent. The results confirm that using the tested cement-replacing materials, which are fly ash and sand powder, can improve the resistance to sulfuric acid of the pastes. This is probably because of its ability to reduce the amount of calcium hydroxide, which is vulnerable to sulfuric attack. For the

|          | C100 | C90GS10 | C70FAR30 | C70FAM30 | C70FAM20GS10 |
|----------|------|---------|----------|----------|--------------|
| W/B = 0.25 |      |         |          |          |              |
| 3 days    | 45.06| 54.07   | 30.44    | 40.55    | 49.96        |
| 7 days    | 48.5 | 57.23   | 35       | 41.23    | 51.94        |
| 28 days   | 69.00| 79.35   | 41.00    | 57.27    | 75.74        |
| 90 days   | 82.00| 83.00   | 90.56    | 100.04   | 103.54       |

|          | C100 | C90GS10 | C70FAR30 | C70FAM30 | C70FAM20GS10 |
|----------|------|---------|----------|----------|--------------|
| W/B = 0.40 |      |         |          |          |              |
| 3 days    | 12.2 | 14.64   | 10.98    | 14.00    | 14.00        |
| 7 days    | 19.1 | 21.97   | 18.00    | 21.23    | 21.23        |
| 28 days   | 26.70| 32.04   | 24.03    | 29.00    | 29.00        |
| 90 days   | 35.00| 38.50   | 45.75    | 50.33    | 50.33        |

**Figure 4:** Compressive strength of specimens, before immersion in sulfuric acid solution. Compressive strength of mixtures with a W/B of (a) 0.25 and (b) 0.40.

**Figure 5:** Porosity of specimens with a W/B of 0.25 at 90 days. (a) Cumulative intrusion curve showing the cumulative pore size distribution. (b) Differential pore size distribution, identifying the most probable pore sizes.
ternary binder mixture, the mixtures with 20% FAM and 10% GS show a lower weight loss than the binary mixture with 30% FAM and the binary mixtures with 10% GS. This shows that the sand powder can improve the acid resistance of a mixture with high CaO fly ash (FAM).

The weight losses of the mixtures incorporating FAR30 with a lower CaO/SiO2 ratio (1.42) are lower than the mixtures incorporating FAM30 with a high CaO/SiO2 ratio (1.90) because the C-S-H bonds produced by the pozzolanic reaction of lower CaO/SiO2 ratio fly ash have a higher capacity to resist acid attack than the C-S-H bonds produced by the higher CaO/SiO2 ratio fly ash [13, 14, 37]. In addition, the C70FAM20GS10 mixtures show higher performance than the C70FAM30 mixtures because the inclusion of sand powder increases the silica content (SiO2) in the mixtures. This reduces the amount of CaO, which is the main component that reacts with sulfuric acid to cause deterioration in the mixture [38].

### 6.3. Cost-Effectiveness and Mitigation of Carbon Dioxide Emissions

In this research, the mix proportion received from a ready-mixed concrete supplier (C100, as shown in Table 6) is used as the reference mixture for the evaluations of CO2 emission and cost-effectiveness of the tested binary and ternary binder systems.

Table 9 shows the cost-effectiveness and mitigation of CO2 emission of each mix proportion.

| Mixtures | Cost (Bath/m³) | Relative cost* (%) | CO2 emission (t-CO2/m³) | Relative emission* (%) |
|----------|----------------|--------------------|-------------------------|------------------------|
| C100     | 1,040.17       | 100                | 0.2880                  | 100                    |
| C90GS10  | 978.92         | 94.11              | 0.2652                  | 92.08                  |
| C70FAR30 | 859.91         | 82.67              | 0.2192                  | 76.13                  |
| C70FAM30 | 1,006.38       | 96.75              | 0.2218                  | 77.04                  |
| C70FAM20GS10 | 956.39 | 91.95        | 0.2211                  | 76.77                  |

*Compared to the C100 mixture.

Figures 4(a) and 4(b) show a compressive strength at an age of 90 days for mixture C70FAM20GS10 at 3.50 MPa higher (3.54% higher) and 4.58 MPa higher (10.01% higher) than mixture C70FAM30 for a W/B of 0.25 and 0.40, respectively. For the performance of resistance to sulfuric acid attack after 240 days of submersion, it was found that the weight loss of the C70FAM20GS10 mixture was 1.45% lower and 14.66% lower than the C70FAM30 mixture for a W/B of 0.25 and W/B of 0.40, respectively, as shown in Figure 6.

Relative performances of all mixtures, compared to the cement-only (C100) mixture, and relative performances of the ternary binder mixture with sand powder (C70FAM20GS10), compared to the binary FAM mixture (C70FAM30), are summarized in Figures 7 and 8, respectively. The smaller values on each axis indicate better performances on that axis. Therefore, all evaluated performances of mixture C70FAM20GS10 are better than mixture C70FAM30, as shown by the inner diamond of fly ash FAR while other performances, i.e., cost, acid resistance, and CO2 emission, are worse. However, the results in this research indicate that the sand powder (GS) can improve the performance of the mixture with FAM (comparing mixtures: C70FAM20GS10 with C70FAM30).
mixture $C_{70FAM20GS10}$ in all four performance axes, as illustrated in Figure 8. Therefore, we successfully utilize the sand powder to improve the $H_2SO_4$ acid resistance of concrete with FAM (the major type of fly ash in Thailand) by achieving three other additional superior performances, i.e., cost, CO$_2$ reduction, and compressive strength. The results of this study will be useful for the sustainable mix design of $H_2SO_4$ acid-resisting multibinder concrete in Thailand.

7. Conclusions

(1) Using sand powder (GS) to partially replace fly ash as a ternary binder cementitious system can improve the compressive strength of a tested paste, both at an early age and long term.

(2) The ternary binder mixtures with high CaO fly ash and sand powder ($C_{70FAM20GS10}$) demonstrate higher sulfuric acid resistance, compared to the binary binder mixtures with the high CaO fly ash ($C_{70FAM30}$).

(3) High CaO fly ash from Mae Moh (FAM) is more popular and its price is high in Thailand. The use of sand powder to partially replace fly ash as a ternary binder mixture ($C_{70FAM20GS10}$) can reduce the cost of the concrete mixture, compared to the binary mixture with high CaO fly ash ($C_{70FAM30}$).

(4) The ternary binder mixture with sand powder ($C_{70FAM20GS10}$) can mitigate more carbon dioxide emissions than the binary mixture with FAM ($C_{70FAM30}$).

From the above conclusions, we successfully utilize the sand powder to improve sulfuric acid resistance of concrete with high CaO Mae Moh fly ash (FAM), which is the major type of fly ash in Thailand. Three other superior performances, i.e., cost, CO$_2$ reduction, and compressive strength, are also achieved.
Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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