Engineering properties of ancient masonry materials in Thailand and substitution materials for historical structures preservation

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Abstract. This paper presents the engineering properties of ancient masonry materials and substitution materials for the preservation of Thai historical structures. The study was divided into 2 parts. For the first part, the ancient masonry materials including brick and mortar were collected from various historical sites in Bangkok and Ayutthaya provinces. The engineering properties of masonry materials were evaluated in laboratory such as compressive strength, density, chemical compositions, porosity, and water absorption. The second part was investigation to find the suitable substitution materials for historical repair mortars. Fly ash was used as a pozzolanic materials to partial replace slaked lime for making historical repair mortar. The engineering properties of historical repair mortar containing were also evaluated and compared with the ancient masonry materials obtained from the first part. The binder to sand ratio was controlled at 1:3 by weight. The slaked lime was substituted by fly ash in the ranges of 10-30% by weight. The experimental results showed that the use fly ash to a partial replace slaked lime could decrease the setting time of historical repair mortar. The compressive strength of historical repair mortars with fly ash were ranged from 1.54-2.22 MPa, depending on the level of replacement, while that of the ancient masonry materials had the compressive strength of 1.88-2.71 MPa.

1. Introduction

Masonry is a normally used in worldwide historic structures [1]. In Thailand, there are a lot of historic masonry structures that are in risk to be damaged by natural disasters and deteriorate of materials. Structural health monitoring and materials properties assessment are required procedure in historical structure preservation [2-6]. However, the engineering properties of ancient masonry material and substitution materials for Thai historical structures preservation are rarely found. Moreover, the use of fly ash in the substitution material for Thai historical structures has not been reported. Consequently, the objective of this paper is to investigate the engineering properties of ancient masonry material, the common substitution materials used for Thai historical structures preservation, and also the substitution mortar with fly ash.

In this study, the ancient brick and mortar were collected from various historical sites in Bangkok and Ayutthaya provinces. The important engineering properties were evaluated by laboratory testing. Moreover, the engineering properties of suitable substitution materials were investigated in comparison with the ancient materials. In order to improve some engineering properties of the substitution mortar,
the slaked lime was substituted by fly ash in the ranges of 10-30% by weight of the binder. Laboratory investigation was also implemented in order to show the possibility in use of fly ash as the pozzolanic materials for substitution mortar.

2. Materials and mix proportion

2.1 Materials
Substitution bricks, Ancient bricks and ancient mortar were collected from various historical sites in Bangkok and Ayutthaya provinces, which are Wat Chaiwatthanaram, Wat Phrasrisanphet, Werng Nakhon Kasem and Ancient Palace. The bricks from these sites are abbreviated as BS, BC, BP, BW, and BA. Correspondingly, the ancient mortar from these sites are also abbreviated as MC, MP, MW, and MA, respectively. The substitution brick and wet slaked lime used in restoration work were collected from the restoration site in Ayutthaya province. Fly ash was used as a pozzolanic material for this study, which was from the Mae-Moh power plant at the Lampang province.

2.2 Mix proportion of mortar
According to the Fine Art Department specification (FA), the mix proportion of mortar used in historic structures restoration is 1:8:24 by weight of white cement, wet slaked lime, and sand, respectively. In order to investigate the properties of the substitution mortar, the mix proportions of mortar used in this study are listed in Table 1. The flow rate of the mortar was controlled in the range of 65-75%. According to Table 1, it is found that the required mixing water for flow rate control is the highest value for the mortar with 100% slaked lime (DB). The increase in percent of fly ash replacement reduces the required mixing water.

Table 1. Mix proportion of mortars.

| Mix type | Binder:Sand ratio | w/b ratio | Flow (%) |
|----------|-------------------|-----------|----------|
| FA       | Fine Arts Department | 0.66      | 70       |
| DB       | Slaked lime 100% (1:3) | 1.06      | 70       |
| F10      | 10% Fly Ash replacement (1:3) | 0.97      | 70       |
| F20      | 20% Fly Ash replacement (1:3) | 0.91      | 67       |
| F30      | 30% Fly Ash replacement (1:3) | 0.84      | 74       |

3. Experimental results and discussion

3.1 Characteristics of brick and mortar
Figures 1 (a)-(e) show a slightly difference in both color and texture of the brick collecting from each site. It is found that the substitution brick has lighter color than the ancient brick. Moreover, the visual inspection indicates that the ancient brick has a lot of porosity and voids distributed around the surface of specimen.
The color and texture of the collected ancient mortars are shown in figure 2(a)-(d). From the collected specimens, it is found that the slaked lime is clustered around the specimen with a distribution of sand surrounded all the specimens.

![Figure 2. Characteristics of ancient mortar](image)

(a) Wat Chaiwatthanaram (b) Wat Phrasrisanphet (c) Werng Nakhon Kasem (d) Ancient Palace

### 3.2 Chemical compositions of ancient masonry materials

Chemical compositions of the substitution brick (BS), ancient bricks (BC, BP, BW, and BA) and the ancient mortars (MC, MP, MW, and MA) are presented in table 2. The substitution brick and ancient bricks are mainly composed of 60.3-68.2% SiO₂, 16.2-19.3 % Al₂O₃, 7.3-8.7 % Fe₂O₃, and 0.9-5.4% CaO as shown in figure 3(a). For the ancient mortars, they are mainly composed of 51.3-73.9 % CaO, 17.5-32.1% SiO₂, 2.4-4.3 % Al₂O₃, and 0.1-4.1 % Fe₂O₃ as shown in figure 3 (b).

| Chemical composition (%) | Substitution brick | Ancient brick | Ancient mortar |
|--------------------------|--------------------|---------------|---------------|
|                          | BS | BC | BP | BW | BA | MC | MP | MW | MA |
| SiO₂                     | 65.4 | 60.3 | 67.3 | 68.2 | 65.7 | 28.3 | 32.1 | 30.5 | 17.5 |
| Al₂O₃                    | 19.3 | 19.0 | 17.4 | 16.2 | 17.5 | 3.6 | 4.3 | 3.8 | 2.4 |
| Fe₂O₃                    | 8.0 | 8.7 | 8.6 | 7.4 | 7.3 | 0.1 | 2.9 | 4.1 | 3.1 |
| CaO                      | 0.9 | 5.4 | 1.2 | 2.1 | 4.0 | 65.3 | 57.4 | 51.3 | 73.9 |
| MgO                      | 1.1 | 1.1 | 1.0 | 1.0 | 0.8 | 0.9 | 1.2 | 7.2 | 0.6 |
| SO₃                      | 0.0 | 0.2 | 0.1 | 0.1 | 0.1 | 0.2 | 0.3 | 0.2 | 0.3 |
| Na₂O                     | 0.4 | 0.5 | 0.6 | 0.7 | 0.6 | 0.2 | 0.0 | 0.2 | 0.1 |
| K₂O                      | 2.9 | 2.8 | 2.0 | 2.6 | 2.4 | 1.3 | 0.5 | 1.7 | 0.9 |

![Figure 3. Chemical composition: (a) ancient brick (b) ancient mortar](image)

### 3.3 Engineering properties of ancient masonry materials and substitution materials

In this study, the engineering properties including compressive strength, density, porosity, absorption and water vapor transmission of the ancient materials and substituted materials were evaluated by laboratory testing. The testing results are shown in the following sections.
3.3.1 Ancient bricks and Substitution bricks
Table 3 summarizes the engineering properties of substitution brick and ancient bricks used in this investigation. The average compressive strength of substitution bricks is 2.12 MPa. The compressive strengths of ancient bricks are in the range of 2.20-3.70 MPa. So, the compressive strengths of substitution bricks are slightly less than ancient bricks. The density of substitution brick and ancient bricks is in the range of 1,470-1,855 kg/m³. The porosity of substitution bricks and ancient brick is in the range of 29.7-39.2 percent. Water vapor transmission of substitution brick and ancient brick are in the range of 6.8-13.8 g/hr-m². It’s found that water vapor transmission of the substitution brick is less than all those values of the ancient bricks.

Table 3. Engineering properties of substitution brick and ancient bricks in Thailand.

| Types of Brick/Material properties | Compressive strength (MPa) | Density (kg/m³) | Porosity (%) | Absorption (%) | Water vapor transmission (g/hr-m²) |
|------------------------------------|---------------------------|-----------------|--------------|---------------|-------------------------------|
| BS (Substitution brick)            | 2.12                      | 1,664           | 39.2         | 22.2          | 6.8                           |
| BC (Wat Chaiwatthanaram)           | 2.28                      | 1,627           | 31.3         | 18.4          | 8.3                           |
| BP (Wat Phraresanphet )            | 3.70                      | 1,783           | 29.7         | 17.7          | 9.2                           |
| BW (WerngNakhonKasem)              | 3.54                      | 1,470           | 34.9         | 22.9          | 12.3                          |
| BA (Ancient palace)                | 2.20                      | 1,855           | 31.9         | 19.4          | 13.8                          |

3.3.2 Ancient mortars
Table 4 summarizes the engineering properties of ancient mortars used in this study. The compressive strength of ancient mortar is in the range of 1.88-2.71 MPa. The density of ancient mortar is in the range of 1,284-1,639 kg/m³. In addition, the porosity and absorption of ancient mortars are in the range of 37.4-58.7% and 17.2-26.9%, respectively. However, the porosity and absorption of ancient mortar are found with a significant high variation. Water vapor transmission of ancient mortar is in the range of 5.4-29.4 g/hr-m².

Table 4. Engineering properties of ancient mortar in Thailand.

| Types of ancient mortar/Material properties | Compressive strength (MPa) | Density (kg/m³) | Porosity (%) | Absorption (%) | Water vapor transmission (g/hr-m²) |
|-------------------------------------------|---------------------------|-----------------|--------------|---------------|-------------------------------|
| MC (Mortar Wat Chaiwatthanaram)           | 2.36                      | 1,639           | 43.1         | 17.2          | 5.4                           |
| MP (Mortar Wat Phraresanphet )            | 2.71                      | 1,515           | 37.4         | 19.3          | 8.8                           |
| MW (Mortar WerngNakhonKasem)              | 2.39                      | 1,402           | 42.1         | 26.9          | 14.8                          |
| MA (Mortar Ancient palace)                | 1.88                      | 1,284           | 58.7         | 19.9          | 29.4                          |

3.4 Properties of substitution mortars
The slaked lime was substituted by fly ash at the ranges of 10-30% by weight of the binder as shown in figure 4 (a-c). The dark color of substitution materials are increased when the fly ash is increased.

Figure 4. Specimen in laboratory testing for substitution materials. (a) F10 (b) F20 (c) F30
The setting time of all pastes (DB, FA, F10, F20, and F30) is presented in Table 5. The setting times of DB and FA pastes are in the range of 11,460-13,590 min. The setting time of F10, F20, and F30 pastes are 4,820, 2,220, and 1,530 min, respectively. The use of fly ash at 10%, 20%, and 30% decrease the setting time of mortar by 64.5%, 83.66%, and 88.74%, respectively.

**Table 5. Setting time of substitution mortar.**

| Mortar Type | Setting time (hour: minute) |
|-------------|-----------------------------|
| DB          | 226:30                      |
| FA          | 191:00                      |
| F10         | 80:20                       |
| F20         | 37:00                       |
| F30         | 25:30                       |

The compressive strength of substitution mortar was obtained by laboratory testing based on ASTM C109 [7]. The mortar specimens are cube with the size of 50 mm × 50 mm × 50 mm. Compressive strengths of substitution mortar are summarized in Table 6 and Figure 5. According to the results, it is found that the increase in percent replacement of fly ash increases the compressive strength of the mortars. Moreover, the replacement of fly ash at 10% by weight of binder increases the compressive strength of mortar at 60 days up to 83.3% which is about the same as the compressive strength of ancient mortars.

**Table 6. Compressive strength of substitution mortar.**

| Mortar | Compressive strength (MPa) | 7 days | 28 days | 60 days |
|--------|-----------------------------|--------|---------|---------|
| FA     | 0.52                        | 0.68   | 0.83    |
| DB     | 0.53                        | 0.72   | 0.84    |
| F10    | 0.66                        | 1.05   | 1.54    |
| F20    | 0.96                        | 1.04   | 1.85    |
| F30    | 1.03                        | 1.08   | 2.22    |

**Figure 5.** Compressive strength of mortar and age.

**4. Conclusions**

The results of present study can be concluded as follow:

1. The average compressive strength of the substitution brick is 2.12 MPa. The compressive strengths of the ancient bricks are in the range of 2.20-3.70 MPa. The density of substitution bricks and ancient bricks are in range of 1,470-1855 kg/m³. The porosity and absorption of substitution bricks and ancient brick are in the range of 29.7-39.2% and 17.7-22.9%, respectively. Water vapor transmission of substitution bricks and ancient brick is in the range of 6.8-13.8 g/hr-m².
2. The compressive strength of the ancient mortar is in range of 1.88-2.71 MPa. The density of ancient mortar is in the range of 1.284-1.639 kg/m³. The porosity and absorption of ancient mortars are in the range of 37.4-58.7% and 17.2-26.9%, respectively. Water vapor transmission of ancient mortar is in the range of 5.4-29.4 g/hr-m².

3. The use of fly ash at 10%, 20%, and 30% decrease the setting time of mortar by 64.5%, 83.66%, and 88.74%, respectively. The compressive strength of historic substitution mortars with fly ash were ranged from 1.54-2.22 MPa at the ages of 60 days. It is found that the compressive strength of ancient mortars is similar to the compressive strength of substitution mortar.

Acknowledgments
The authors would like to acknowledge the Thailand Research Fund (TRF) and King Mongkut’s University of Technology Thonburi (KMUTT) for their joint support through the Royal Golden Jubilee Ph.D. (RGJ-PHD) Program (Grant No. PHD/0042/2559).

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