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Development of an External Rubber-Clay Plaster Stabilized with Alkaline Sodium Silicate to Improve Adobe Wall Rain Resistance

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ABSTRACT

An external clay plaster stabilized with blended prevulcanized rubber latex and sodium silicate was developed to enhance the poor water resistance of adobe walls. Sodium silicate was added to act as a pH stabilizer maintaining the pH and liquidity of the rubber latex during the manufacturing process. The study characterized the adobe plasters using an accelerated spray test, capillary absorption and microstructure investigation in terms of surface morphology, chemical analysis and porosity. The results showed that adding 3–5% sodium silicate could preserve the liquidity of 5–10% rubber latex during the mixing process. The newly developed sodium silicate + rubber-clay substrates had the highest water resistance in term of both rain resistance and water tightness, when compared with traditional clay plaster, rubber-clay plaster and stabilized rubber-clay plasters with a low sodium silicate content. The microstructure investigations confirmed that the alkaline-stabilized rubber latex could distribute throughout the substrate, was bound to most of the soil particles and filled capillary pores when dried. The stabilized-clay plaster with blended 10% rubber and 5% sodium silicate performed best, eroding only 1.2 cm after a spray test that approximated 50 yr of 1,800 mm annual rainfall, an above average annual amount for Thailand.

Keywords: adobe, water resistance, rubber latex, sodium silicate, pH stabilizer

INTRODUCTION

Adobe, typically a mix of sand and clay, is one of the oldest building materials, and remains common with Dethier (1986) indicating that at least 50% of the world's population lived in dwellings made of earth construction. The service life of adobe walls can be extended by improving their water resistance and strength, especially in regions where there is heavy rain such as Thailand, where the average rainfall is 1,572.5 mm per year (Thai Meteorological Department, 2007) and reached 1,824 mm in 2011 which resulted in severe flooding in many areas (Hydro and Agro Informatics Institute, 2011). While the rain resistance and strength can be improved by incorporating high embodied energy materials, such as cement, asphalt, and lime as adobe stabilizers, recent studies have found that natural rubber latex has an ability to improve the mechanical properties and water resistance of adobe (Laokomain, 2004; Ruthankoon *et al*., 2006; Hinchiranan *et al*., 2008, Banjongkliang *et al*., 2015). In Thailand, latex from the rubber

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tree (*Hevea brasiliensis*) is readily available as a sustainable resource (Rubber Research Institute of Thailand, 2010) and has lower embodied energy than cement, asphalt, and lime which are common additives (Ancorn and Wood, 1998; Department of Alternative Energy Development and Efficiency, 2007). Moreover, rubber latex forms a water-insoluble film when dried. However, the rapid agglomeration of rubber latex during the adobe manufacturing process causes problems in the molding process (Ruthankoon *et al.*, 2006) and reduces the quality of the rubber-stabilized adobe brick when dried (Laokomain, 2004).

Previous research (Banjongkliang *et al.*, 2015), proposed using sodium silicate as a rubber pH stabilizer to solve the problems caused by the rapid agglomeration of rubber latex during the adobe manufacturing process. Their results found that adding 3–5% sodium silicate could maintain the pH and liquidity of rubber latex during the adobe manufacturing process, with the alkaline-stabilized rubber latex being able to fully disperse throughout the adobe matrix, bind soil particles, fill the capillary pores when dried and significantly increase its compressive strength and flexural strength. Moreover, their results also showed the possibility of sodium silicate as a secondary binder and rubber reinforcement. However, the rain resistance of sodium silicate + rubber-clay adobe was not mentioned in that study.

The current research sought to improve the rain resistance of adobe walls by optimizing the proportions of blended rubber latex and sodium silicate in external clay plaster. The developed stabilized plasters were studied using a new approach—a University Technology of Sydney (UTS) spray test, capillary absorption test and microstructure analysis. A rubber latex content of up to 30% and a sodium silicate content of up to 5% by weight of soil and sand were investigated. Importantly, the improvement in rain resistance due to the characteristics of sodium silicate as a pH stabilizer in the rubber-clay plaster were also analyzed.

MATERIALS AND METHODS

Materials

As described in Banjongkliang *et al.* (2015), sandy clay loam soil was collected from the field in Mae-Rim-Tai sub-district, Mae-Rim district, Chiang Mai province in northern Thailand. Dried soil lumps were ground and the soil that passed through an American Society for Testing and Materials (ASTM) sieve number 10 was used. The soils had the properties shown in Tables 1 and 2. Fine river sand, following ASTM C778 (American Society for Testing and Materials, 2011), was collected from the Ping River in Chiang Mai province. The soil to sand ratio was fixed at 1:1 by weight.

Table 1 Properties of soil and sand (Banjongkliang *et al.*, 2015).

Textural composition of Mae-Rim soil	Percentage (by weight)
Sand (0.02–2 mm)	50.74
Silt (0.002–0.02 mm)	22.73
Clay (<0.002 mm)	26.53
pH of soil	6
Atterberg limits of soil	%
Liquid limit	45.00
Plastic limit	28.45
Plastic index	16.55
Shrinkage limit	22.41
Linear shrinkage	7.40

Hevea brasiliensis rubber latex was used as a commercial casting compound–prevulcanized rubber latex (R) with the common formula shown in Table 3. The sodium silicate (SS) was commercial 90% industrial graded sodium silicate (Na_2SiO_3) with 4% water content and a pH value of 13. Tap water with a pH value of 7 was used.

Specimen preparation and investigation of fresh mixture

The mix proportions are summarized in Table 3. Soil and sand were mixed in a dry state for 5 min at low speed in a mortar mixing machine, and then mixed with water at medium speed for 3 min. The clay plaster was stabilized using sodium silicate which was mixed with water before pouring into the soil-sand dry mix. The rubber latex was added last. Water (about 0.16–0.25% by weight of soil and sand) was added to produce an pliable fresh plaster with an initial flow of 60–70%, according to ASTM C1437 (American Society for Testing and Materials, 2011). During mixing, any film formation of the rubber latex was observed by visual inspection.

Once mixed, the pH was measured and the fresh mixture was poured immediately into molds in two layers and manually compacted-tamped 32 times per layer to ensure uniform filling of the molds.

Table 2 Chemical composition of soil and sand (Banjongkliang *et al.*, 2015).

Chemical composition	Percentage (by weight)	
	Mae-Rim soil	Ping sand
CaO	1.21	0.87
SiO_2	62.50	80.48
Al_2O_3	21.50	11.22
Fe_2O_3	7.98	2.08
MgO	1.77	-
K_2O	3.24	5.27
SO_3	0.22	-
MnO	0.18	0.08
TiO_2	1.37	-
-	-	-

Table 3 Ingredients of casting compound-prevulcanized rubber latex (Banjongkliang *et al.*, 2015).

Type	Weight (g)	Function
Concentrated rubber latex (60% dry rubber content)	167	Rubber
50% Sulphur dispersion	5	Vulcanizing agent
50% ZnO dispersion	3	Activator
50% ZDEC dispersion	3	Accelerator
50% ZMBT dispersion	2	Accelerator
10% Teric 16 A16	2	Non-ionic Wetting Agent (surfactant)
50% TiO_2	5	Filler & pigment
50% $CaCO_3$	20	Filler
50% Wingstay-L	2	Antioxidant
pH		10

The plaster specimens were sun dried in the molds for 1–2 d before the molds were removed. The specimens were sun dried an additional 3 d and then oven dried at 60 °C for 4–7 d until their weights were constant. The final moisture content of the specimens was around 2%, within the 2–5% equilibrium moisture content of adobe materials (Morton, 2008). A flow chart of the research methodology is shown in Figure 1a.

University of Technology, Sydney spray test (UTS)

The UTS spray test was developed by Heathcote and Moore (2010) at the University of Technology, Sydney, NSW, Australia, as a new accelerated spray test to enhance the limitations of the Bulletin 5 accelerated spray test (Schneider, 1981) for rainfall simulation in different climates. The UTS spray test can also predict wall thickness loss over a 50 yr period. Heathcote (2002) stated that "On balance it appears that a spray test offers the best alternative for an accelerated test. It is easy to perform, simulates the actions of driving rain, and acts over a reasonable area of a specimen, thus reducing the chance of testing minor weak spots".

Heathcote and Moore (2010) used the following UTS spray test conditions: a Fulljet 1550 spray nozzle (Spraying Systems Co.; Wheaton, IL, USA), water pressure of 70 kPa, water discharge of 9.3 L.min^{-1}, stream velocity of around 9 m.s^{-1} and the specimen block placed at a right angle 35 cm from the nozzle. The erosion depth was determined by placing a straight rod across the block face and measuring the deepest erosion depth with a pencil as a depth gauge. The time of exposure for the specimens can be determined using Equation 1 (Heathcote and Moore, 2010):

$$T = (R/10) \times W \quad (1)$$

where T is the time of exposure (minutes). R is the average rainfall intensity (millimeters per year) and W is 0.5 where the average wind speed during the rain period is less than 4 m.s^{-1}.

The predicted average loss of wall thickness over 50 yr (Loss_{50}) can be determined using Equation 2 (Heathcote and Moore, 2010):

$$\text{Loss}_{50} = 2 \times \text{Measured erosion depth} \quad (2)$$

where the Loss_{50} and measured erosion depth are expressed in centimeters.

In this study, the test consisted of spraying water onto the face of a 10 × 10 × 10 cm clay stabilized block for a period of 90 min, as shown in Figure 1b. The calculation of the time of exposure was based on Thailand's average rainfall intensity in 2011 (an extreme year) of around

Table 3 Mix proportions of plastering mortar components.

Component	Contents (% by weight of soil and sand)	Notation
Traditional clay plaster	-	R0
Rubber	R = 0, 5, 10, 20, 30 %	R0, R5, R10, R20, R30
Sodium silicate	SS = 0, 0.5, 0.8, 3 %	R0, SS0.5, SS0.8, SS3
5% Rubber + Sodium silicate	R = 5% with SS = 0, 0.5, 1, 3%	R5_SS0, R5_SS0.5, R5_SS1, R5_SS3
10% Rubber + Sodium silicate	R = 10% with SS = 0, 0.5, 1, 3, 5%	R10_SS0, R10_SS0.5, R10_SS1, R10_SS3, R10_SS5

1,800 mm, when 65 of Thailand's 77 provinces were declared flood disaster zones. The average wind speed was generally lower than 4 m.s^{-1} (Energy Policy and Planning Office, Ministry of Energy, Thailand, 2012). Inputting these values in Equation 1, the spraying time, *T*, was (1800/10) × 0.5 = 90.0 min. In fact, the water volume sprayed onto the 10 cm diameter face for 90 min approximated the rain intensity equivalent of 59 yr of 1,800 mm annual rainfall in Thailand. The erosion depth was measured at 90 min or when the samples were punctured, whichever came first. The average of the results of at least two specimens was obtained.

Capillary absorption

The capillary absorption values of specimen discs (diameter =70 mm and depth = 30 mm) were investigated using the sponge capillary absorption test, following the methodology of Ren and Kagi (1994), as shown in Figures 1c and 1d. The weight increase over the area of the surface of the specimen at different periods up to 7 d was measured. The capillary absorption was determined using Equation 3 (Ren and Kagi, 1994):

$$\text{Capillary absorption} = (w_t - w_0)/A \quad (3)$$

where w_0 is the initial weight of the specimens (in kilograms), w_t is the weight of specimen (in kilograms) at time *t*, and *A* is the area of the specimen surface (in square meters).

Each capillary absorption value was based on the average value of at least two test results (Kagi and Ren, 1995)

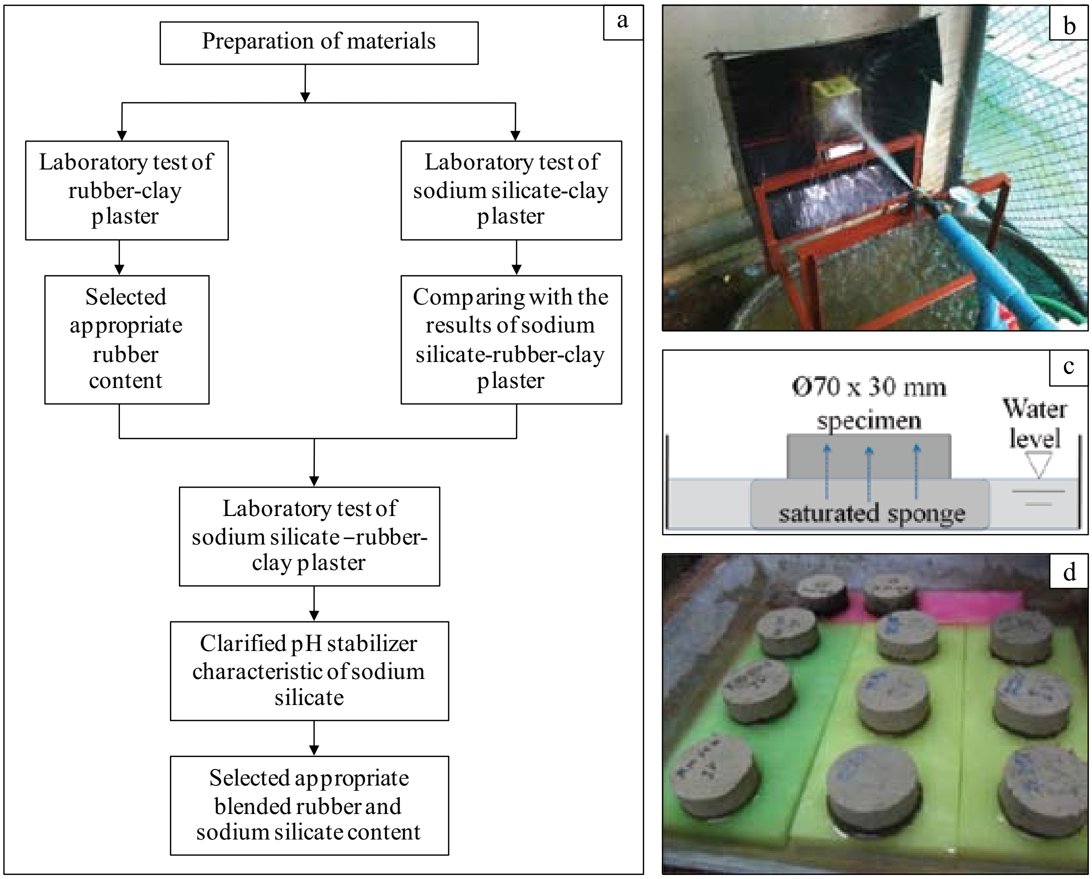


Figure 1 Testing procedure (a) flow chart for research methodology, (b) UTS spray test and, (c and d) capillary absorption test, where specimen discs have diameter 70 mm and depth 30 mm.

Scanning electron microscopy, energy dispersive X-ray spectrometry and porosimetry

The morphology of the samples was observed using a scanning electron microscope (JSM 5910 LV; JEOL Ltd.; Tokyo, Japan) with gold coating of samples. The energy dispersive X-ray spectrometer (EDX; INCA PentaFETx3; Oxford Instruments Plc; Abington, UK) attached to the scanning electron microscope was used for semi-quantitative chemical analysis.

The porosity and pore size distribution of the samples (brick fragments weighing less than 1 g) were measured using an Hg Porosimeter (PO2000 with macropore unit; Carlo Erba; Milan, Italy). The maximum pressure reached during the analysis was 800 bars.

RESULTS AND DISCUSSION

Investigation of fresh adobe plasters

The pH values and rubber film formation of the fresh plaster were investigated. The fresh clay plaster was weakly acidic (pH values of about 6). The sodium silicate + rubber latex were alkaline solutions with pH values of 13 and 10, respectively. When the rubber latex was added to the fresh clay plaster, the rubber film rapidly formed a fine rubber aggregate, which was a similar result to that found by Ruthankoon *et al.* (2006), Laokomain (2004), and Banjongkliang *et al.* (2015). The segregation increased as the rubber latex content increased. These rubber-clay plasters had a pH of 6. The decreasing pH value of rubber latex was one reason for this early film formation (Subsathaphol, 2004). Moreover, the results of fresh sodium silicate + rubber-clay plasters with sodium silicate below 3% were the same.

When 3% or more sodium silicate was added to the clay plaster, the fresh sodium silicate-clay plaster was strongly alkaline, with a pH value of 10 or higher. When the rubber latex was added last, the pH of the fresh sodium silicate + rubber-clay plasters (R5_SS3, R10_SS3 and R10_SS5; see Table 3 for notation description) remained above 10. During the mixing and molding process, the rubber latex did not form a film or fine rubber aggregate because the alkalinity of the rubber latex was maintained by the presence of 3–5% sodium silicate (Banjongkliang *et al.*, 2015). When fresh, these rubber-clay substrates with 3% or more of sodium silicate were easier to apply to a wall than the agglomerated rubber-clay plaster.

Water resistance results of rubber-clay plasters

The erosion depth of the rubber-clay plasters after 90 min spraying was far less than for the traditional clay plaster; the plaster with 20% rubber eroded the least (Figure 2). After the spray test simulating 50 yr of 1,800 mm annual rainfall, the rubber-clay plaster eroded 2.4 to 8.1 cm, according to Equation 2. The rubber-clay plasters were far more durable than the traditional clay plaster, which lost more than 19.5 cm of thickness. These results agreed well with those reported by Laokomain (2004). Moreover, increasing the proportion of rubber up to 20% in the plaster reduced its capillary absorption compared to clay plaster over 1–7 d, as shown in Figure 3a; these results agreed with Hinchiranan *et al.* (2008). The plaster with 20% rubber yielded the most optimal capillary absorption, similar to the rain resistance results.

Adding rubber latex up to 20% improved the water resistance of the plasters, while adding more than that reduced the water resistance, as the rubber latex tended to form a larger rubber aggregate, rather than distributing throughout the substrate. Even though adding 20% rubber latex was the most water resistant, adding 5–10% rubber latex was more economical, while still being more water resistant than traditional clay plaster. As such, the 5–10% rubber latex formulation was selected for the next phase in this study.

Water resistance results of sodium silicate-clay plasters

Adding sodium silicate to the plaster improved its rain resistance, as shown in Figure

4. This was due to the binding ability of inorganic siloxane or the condensation of sodium silicate (Ren and Kagi, 1994). However, adding sodium silicate did not reduce the capillary absorption of the substrate. In contrast, it tended to increase capillary absorption, as shown in Figure 3b. This occurred, in part, because the sodium silicate bonds are soluble in water (Ren and Kagi, 1994).

Water resistance results of sodium silicate-rubber-clay plasters

Figure 4 shows the improvement in the

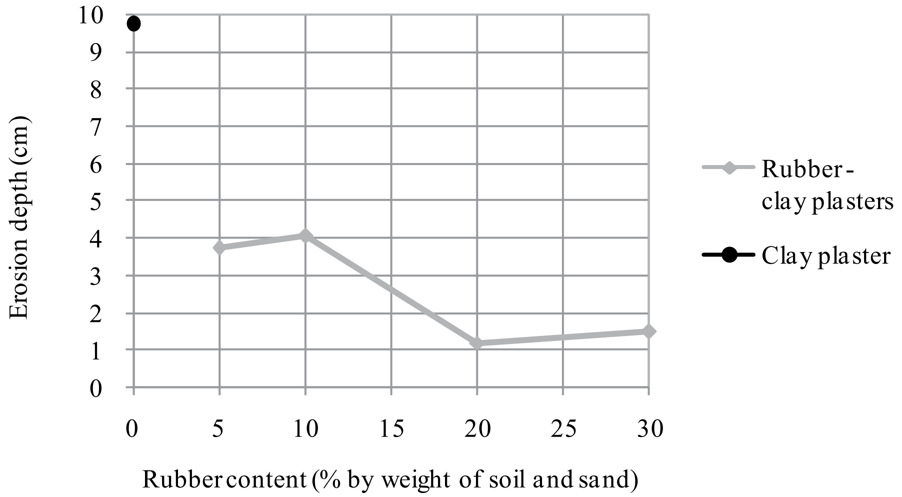


Figure 2 Erosion depth of rubber-clay plasters after 90 min University of Technology, Sydney spray test.

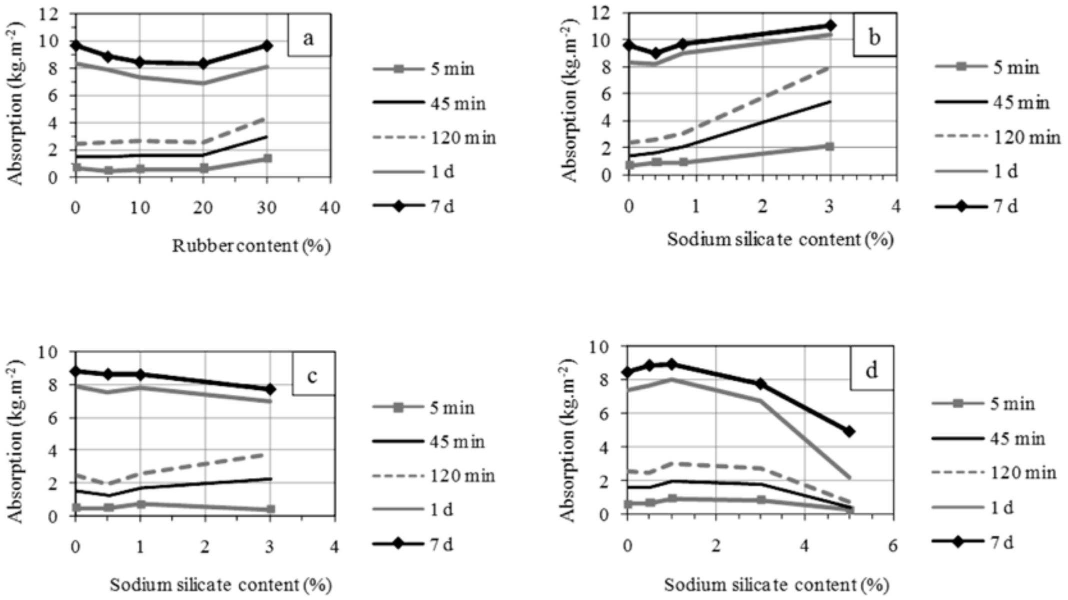


Figure 3 Capillary absorption results of adobe plasters: (a) Rubber-clay plaster, (b) Sodium silicate + clay plaster, (c) 5% Rubber + sodium silicate (R5_SS_) clay plaster, (d) 10% Rubber + sodium silicate (R10_SS_) clay plaster

rain resistance of the plaster when sodium silicate was added as a pH stabilizer in fresh 5–10% rubber-clay plaster. Increasing the sodium silicate content significantly decreased the erosion depth of sodium silicate-rubber-clay plasters after the 90 min UTS spray test. The erosion depth results of the R5_SS_and R10_SS_ series were similar and lowest when 3–5% sodium silicate was added. The 90 min erosion depth of traditional clay, R5_SS3, R10_SS3, and R10_SS5 were >9.75, 0.93 (1.61% weight loss), 0.77 (1.36% weight loss) and 0.60 cm, respectively. The predicted average loss of plaster thickness of R5_SS3, R10_SS3 and R10_SS5 was only 1.9, 1.5 and 1.2 cm over 50 yr, respectively. These (3–5%) SS–(5–10%) rubber-clay plasters were much more rain resistant than the traditional clay plaster. In fact, the rain resistance of the sodium silicate + rubber-clay substrates increased continuously with increasing sodium silicate content, even though the sodium silicate content was too low to act as a pH stabilizer. This was due to the binding ability of sodium silicate (Hinchiranan *et al*., 2008)

Increasing the level of sodium silicate up to 1% in the sodium silicate + rubber-clay plaster tended to slightly increase its capillary absorption (Figures 3c and 3d). The results conformed to the results from the sodium silicate + clay plasters. However, capillary absorption substantially decreased when the sodium silicate was increased up to 3–5% (Figures 4c and 4d). These results contradicted the result of the 3% sodium silicate-clay plaster (without rubber). From these results, it was assumed that the alkaline stabilized rubber latex, which was evenly distributed throughout the substrate during mixing, filled the voids in the matrix when hardening.

Figure 5 shows the capillary absorption results of traditional clay plaster, rubber-clay plasters, sodium silicate-clay plasters and sodium silicate + rubber-clay plasters. Capillary absorption remained relatively constant after 1 d (1,440 min) of testing. The 1–7 d absorption of the SS3 plaster was highest (11.11 kg.m^{-2}), followed by the traditional clay plaster (9.63 kg.m^{-2}). The R10_SS5 was lowest (4.93 kg.m^{-2}), followed by the R10_SS3 (7.76 kg.m^{-2}) and R5_SS3 (7.70 kg.m^{-2}) plasters.

Scanning electron microscopy energy dispersive X-ray spectrometry analysis results

As shown in Figure 6a (Banjongkliang *et al*., 2015), the morphology of R10SS1 was a large and thick rubber film wrapping only some groups of soil particles. While the morphology of R10SS3 and R10SS5 (Figures 6b and 6c) clearly presented a better dispersion of thin and smooth-surface rubber films wrapping most of the soil particles in the substrates. In the energy dispersive X-ray spectrometry analysis (Figure

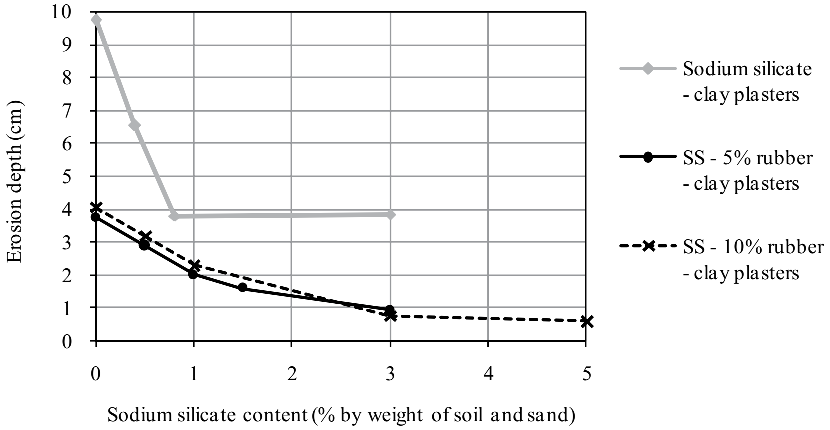


Figure 4 Erosion depth of sodium silicate + rubber-clay plasters after the 90-minute UTS spray test.

6a and 6b), the presence of a significant amount of C (22.2–70.0% for R10SS1 and 22.8–31.6% for R10SS3) confirmed the evidence of rubber film in the substrate (Banjongkliang *et al.*, 2015). The ranges of C of R10SS3 were narrower than of R10SS1 due to the more uniform distribution of alkaline-stabilized rubber films (Banjongkliang *et al.*, 2015).

Porosimetry analysis results

This study only considered the capillary porosity (0.01–10 µ). The porosity results of small pores (<0.01 µ) were too small (<0.32%) and could be neglected (Banjongkliang and Stitmannaithum, 2006). The porosity results of the bulk pores were too variable to study comparatively because bulk pores are usually isolated and cannot be

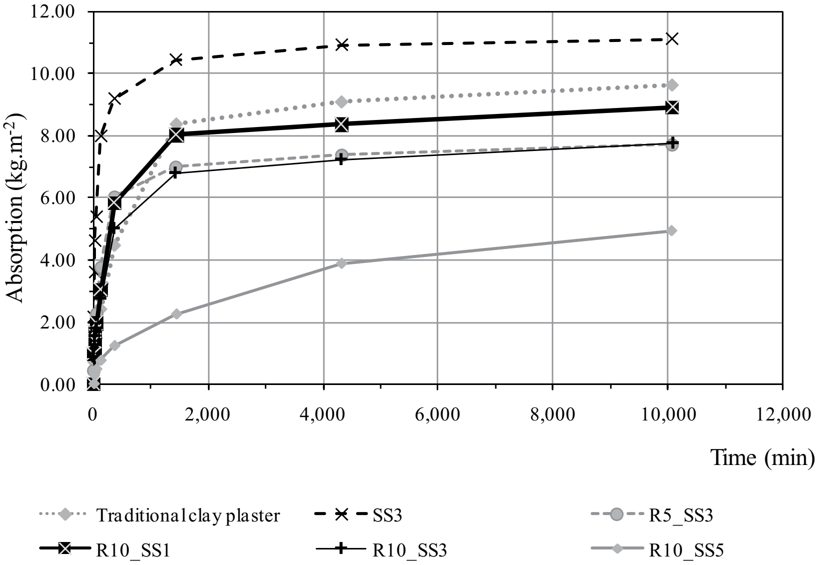
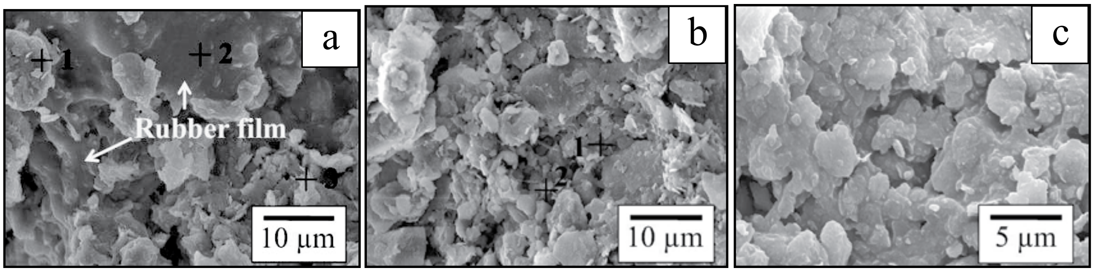


Figure 5 Capillary absorption results of plasters over time (SS3 = 3% Sodium silicate; R5_SS3 = 5% Rubber + 3% sodium silicate; R10_SS1 = 10% Rubber + 1% sodium silicate; R10_SS3 = 10% Rubber + 3% sodium silicate; R10_SS5 = 10% Rubber + 5% sodium silicate.



No.	C	O	Na	Mg	Al	Si	K	Ca	Fe	Total
1	70.0	17.4	-	-	4.0	7.6	1.1	-	-	100
2	22.2	39.5	-	-	12.4	18.7	2.7	0.0	4.4	100
3	38.1	25.6	-	-	5.5	23.7	1.2	1.1	4.9	100

No.	C	O	Na	Mg	Al	Si	K	Ca	Fe	Total
1	31.6	37.8	-	-	7.2	19.0	1.7	-	2.7	100
2	22.8	44.0	0.6		7.1	19.9	4.1		1.5	100

Figure 6 Scanning electron micrographs (×2,500) and energy dispersive X-ray spectrometry analysis of: (a) 10% rubber + 1% sodium silicate (Banjongkliang *et al.*, 2015); (b) 10% rubber + 3% sodium silicate; (c) 10% rubber + 5% sodium silicate.

entirely detected by the porosimetry method (Banjongkliang and Stitmannaithum, 2006).

Figure 7 shows the consistency between the capillary porosity and capillary absorption of the plasters as the capillary absorption decreased with decreasing capillary porosity. R10_SS5 had the lowest capillary porosity (1.99%) with the lowest capillary absorption (4.93 kg.m^{-2}) on the seventh day. R10_SS3 had the second lowest capillary porosity (13.81%) with the second lowest capillary absorption (7.76 kg.m^{-2}) on the seventh day. The capillary porosities of the traditional clay plaster (R0), R10 and R10_SS1 were similar (between 20.49–21.93%) and were higher than that of R10_SS3 and R10_SS5. The capillary absorption values of the traditional plasters, R10 and R10_SS1 were the same and higher than those of R10_SS3 and R10_SS5. Finally, SS3 had the highest capillary porosity (23.23%) with the highest capillary absorption (11.11 kg.m^{-2}) on the seventh day. The results conformed well with the previous study by Banjongkliang *et al.* (2015) who reported that when the level of sodium silicate increased from 3%, the sodium silicate-stabilized rubber latex (pH more than 10) distributed better within the fresh substrate and that the alkaline-stabilized rubber films filled and reduced the number of pores in the substrate, thus significantly decreasing its water permeability.

CONCLUSION

Adding prevulcanized rubber latex to traditional clay plaster improved its water resistance in terms of both rain resistance and capillary absorption. However, a fine rubber aggregate formed during mixing that only held some clusters of soil particles and would likely cause some difficulty in plastering.

Sodium silicate at 3–5% acted as a pH stabilizer maintaining an alkaline pH value of 10 for the rubber latex and preserving the liquidity of the rubber latex when mixed with other ingredients. When the sodium silicate + rubber-clay substrates that had been stabilized with 5–10% rubber latex and 3–5% sodium silicate dried, these alkaline-stabilized rubber films tended to bind most of the soil particles throughout the substrate. These newly developed sodium silicate + rubber-clay substrates had the highest rain resistance and water tightness, compared with the traditional clay plaster, rubber-clay plaster and stabilized rubber-clay plasters with low sodium silicate content.

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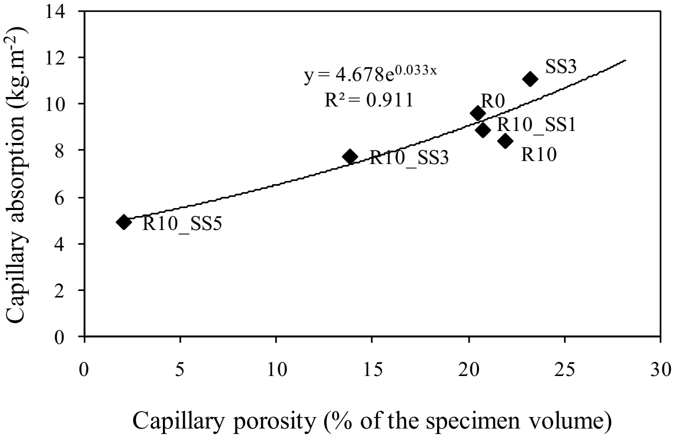

Figure 7 Relation between capillary porosity and capillary absorption of adobe plasters. Numbers in labels indicate the percentage of rubber (R) and sodium silicate (SS).

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