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Properties of Alkali-Activated/Cement Paste as Coating Material

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Abstract – This paper presents the properties of an alternative coating material produced from alkali-activated/cement powder (AACP) paste, including setting time, strength development, and bond strength of AACP paste-coated reinforcing steel bars in concrete. The AACP paste was prepared by activating a mixture of dry geopolymer powder (GPP), Portland cement (PC), and silica fume (SF) with tap water and 2M sodium hydroxide solution. The effect of PC replacement and sodium silicate-to-sodium hydroxide solution (SS-to-SH) ratio in the production of GPP on the properties of AACP paste were also investigated. Test results exhibited that the incorporation of FA and PC activated with an SS-to-SH ratio of 2.0 in the production of GPP decreased their setting time of fresh AACP pastes while marginally increasing their strength development. In addition, AACP paste-coated reinforcing steel bars positively affected the bond strength of reinforced concrete, especially for the GPP produced by FA without PC. The increased reaction products at the contact zone could contribute to a strengthening of their bonds. It can be recommended that the use of FA without PC activated with a low SS-to-SH ratio in the production of GPP would be beneficial for improving bond strength.

Keywords**:** Novel coating material, Dry geopolymer powder, Alkali-activated/cement powder, AACP paste, coating material

1. Introduction

Reinforcing steel bars in reinforced concrete structures can corrode over time due to various environmental and operational factors, causing corrosion issues. Some of the factors that contribute to corrosion issues in reinforcing steel bars include exposure to moisture, carbonation of concrete, chloride ion ingress, and alkaline attack [1, 2]. Carbonation of concrete occurs when carbon dioxide (CO_2) reacts with calcium hydroxide from the hydration product in the concrete, resulting in a decrease in alkalinity [3]. The use of corrosion-resistant steel or coatings, proper concrete mix design, and regular maintenance and inspections have been implemented to prevent rust problems in reinforcing steel bars.

The current method of preventing such problems includes epoxy-coated steel bars to increase their resistance to chemical corrosion, water opacity, and concrete adhesion [1]. However, the prices of these products are quite high. Consequently, alternative coating materials with comparable properties and lower costs are desirable. In recent years, alkali-activated binders (AAB) have been developed and have demonstrated excellent properties as repair and coating materials for concrete structures due to their excellent mechanical properties, durability, and good adhesion to the concrete substrate [4, 5]. Additionally, they offer advantages such as low cost, environmental friendliness, and the ability to utilize industrial by-products and waste materials as raw materials [6, 7]. In general, AAB can be divided into two types based on their calcium content: low-calcium and high-calcium contents [8, 9]. The formation of sodium aluminosilicate hydrate (N-A-S-H) gel is the main reaction product of low-calcium AAB. While the formation of calcium silicate hydrate (C-S-H) and/or calcium aluminosilicate hydrate (C-A-S-H) coexisted with N-A-S-H gel is the main reaction product of high-calcium AAB [9].

Currently, the use of AAB as coating materials has been extensively studied. For example, Aguirre-Guerrero et al. [10] studied a novel coating material derived from fly ash-metakaolin geopolymers to prevent corrosion in reinforced concrete. Kretzer et al. [11] carried out a pioneering work on hybrid geopolymer-cement coating mortar optimized based on metakaolin, fly ash, and slag. All researchers reported that the use of AAB as a coating for reinforced concrete structures is as promising as the use of epoxy resin. This method of AAB production is commonly referred to as "two-part alkali-activated binder" However, the production process of "two-part alkali-activated binder" is difficult to apply in real construction. Therefore, there is a need and desire to develop "one-part alkali-activated binder" that is easier to use in real construction with the concept "just add water" [12-14]. Recently, Phiangphimai et al. [14] and Lv et al. [15] attempted to develop the one-part AAB produced by drying powder inorganic and alkali-activated/cement powder for use as a coating material. They reported that drying powder inorganic-coated decorative walls were extremely effective and long-lasting, with no surface cracking.

Therefore, this research aims to investigate the properties of alkali-activated/cement powder (AACP) paste derived from geopolymer powder as a potential coating material. In addition, the effect of AACP paste-coated reinforcing steel bars on bond strength were also investigated. The obtained test results would help to understand the preliminary behavior of one-part AACP pastes and provide guidelines for the future development of AACP paste as a coating material.

2. Materials and experimental procedures

2.1. Staring materials and alkaline solutions

High-calcium fly ash (FA) and Portland cement type 1 (PC) were used as the starting materials for the production of geopolymer paste. 10M sodium hydroxide (SH) solution and sodium silicate (SS) solution with 28.66% SiO_2, 11.67% Na_2O, and 59.67% H_2O were used as the alkaline solutions in the mixture. Note that the silica modulus (SiO_2/Na_2O molar ratio) and total Na_2O+SiO_2 content were based on the previous studies [14].

Table 1 shows the chemical compositions of FA, PC and silica fume (SF) whereas their physical properties are illustrated in Tables 2. It should be noted that the SF was used as the reactive SiO_2 in the mixture and the reaction of SiO_2 and calcium oxide is needed in order to improve its strength development [14].

Table 1 : Chemical compositions of FA, PC, and SF (by weight)

Materials	Chemical compositions (%)										
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	TiO_2	P_2O_5	SO_3	LOI
SF	92.00	0.70	1.20	0.20	0.20	0.40	0.10	-	-	-	-
FA	36.93	18.10	11.91	21.41	2.78	2.28	1.42	0.36	0.20	2.90	1.54
PC	20.80	4.70	3.40	65.30	1.50	0.10	0.40	-	-	2.70	0.90

Table 2 : Physical properties of FA, PC, and SF

Materials	FA	PC	SF
Specific gravity	2.68	3.15	2.29
Median Particle Size, d_{50} (µm)	15.4	14.5	0.22
Blaine fineness (cm^2/g)	4,310	3,650	210,000

2.2. Preparation of geopolymer power (GPP) and AACP paste

The GPP preparation followed the work of Phiangphimai et al. [14]. Table 3 summarizes the mix proportions and 7-day strength of the geopolymer paste. According to the work of Phiangphimai et al. [14], the median particle size of the GPP was controlled at approximately 15 µm by using a ceramic ball mill machine.

For the AACP paste preparation, a mixture of 50%GPP, 40%PC, and 10%SF was used under different types of GPP, as illustrated in Table 4. According to Table 4, AACP paste was prepared using the water-to-binder (w/b) ratio of 0.35 and 2M SH solution at 10% by weight of binder for all mixes. Note that the SH solution of 2M was used to activate the chemical reactions in the mixture [14].

Table 3 : Mix proportions of geopolymer pastes

Mix	Symbol	L/B ratio	SS/SH ratio	Pre-curing		FA (g)	PC (g)	SS (g)	SH (g)	7-day Strength (MPa)
				Temperature (ºC)	Time (h)					
GPP1	100FA	0.5	1.0	25	24	100	-	20	20	35.4
GPP2	90FA10PC					90	10	20	20	43.3
GPP3	80FA20PC					80	20	20	20	48.9
GPP4	70FA30PC					70	30	20	20	52.0
GPP5	100FA	0.5	2.0	25	24	100	-	27	13	47.7
GPP6	90FA10PC					90	10	27	13	60.2
GPP7	80FA20PC					80	20	27	13	70.1
GPP8	70FA30PC					70	30	27	13	72.5

Table 4 : Mix proportions of one-part AACP and control pastes

Symbol	Types of GPP	GPP (g)	FA (g)	PC (g)	SF (g)	SH (g)	Tab water (g)
50GPP-40PC-10SF	GPP1-GPP8	50	-	40	10	10	35

2.2. Setting time and compressive strength test

The setting time of the AACP paste was tested as described in ASTM C191-13 [16] using a Vicat apparatus. For the compressive strength test, all samples were tested in accordance with ASTM C109 [17]. After mixing, fresh AACP paste was put into 50x50x50 mm3 cube molds and then they were immediately wrapped by using plastic sheet in order to prevent moisture loss for 24 h in a 25±2 controlled room. After 24 h, the samples were then demolded and again covered using vinyl sheet and stored in a controlled room for 1, 7, 28, and 90 days prior to the day of testing. Note that five samples were tested and averaged for measurement of its strength devolvement.

2.3. Pull-out test

Pull-off test was based on the ASTM C234 [18] and RILEM standards [19]. The experimental set-up for pull-out test as displayed in Fig. 1. For normal concrete, the mix design was based on ACI211-91 [20] with a target 28-day compressive strength of 28 MPa and slump at 100 ± 25 mm. Prior to the samples casting, the reinforcing steel bar coated by AACP paste was prepared under ambient temperature for 24 h [14]. To determine the bond strength between concrete and reinforcing steel bar, a 200x200x200 mm3 cube sample with a 12 mm diameter deformed steel bar and a bond length of 4d were prepared. Note that the sample preparation and testing were based on the previous study [14]. The pull-off samples were tested at the age of 28 days with the reported values represent the average of three samples. The equation (1) is a calculation of the ultimate bond strength between concrete and reinforcing steel bar.

$$\tau = \frac{F}{\pi l d} \tag{1}$$

Where τ is the ultimate bond stress (MPa), F is the ultimate pullout force (N), l is the bond length (mm), and d is the diameter of reinforcing bar (mm).

Fig. 1: Experimental set-up for pull-out test

3. Results and Discussion

3.1 Setting time and compressive strength of AACP paste

Fig. 2 compares the setting time of AACP paste to that of control mixes (100PC and PC with FA+SF). The SS-to-SH ratio and PC content were found to have a marginal effect on the setting time of AACP paste. According to Fig. 2, the setting time of AACP paste was obviously faster than that of the control mixes. As reported by the work of Phoo-ngernkham et al. [5, 21, 22], a combination of FA and PC activated with high SS-to-SH ratio in the production of alkali-activated binder exhibited rapid setting. They also reported that the incorporation of alkali-activated high-calcium FA with calcium oxide accelerated the dissolution rate within the matrix. After modifying the alkali-activated binder, differences in its setting time were observed, especially for one-part alkali-activated binder and dry mix geopolymer [23], which tended to increase its setting time. The reaction of AACP and PC was similar to the pozzolanic reaction as reported by Phiangphimai et al. [14].

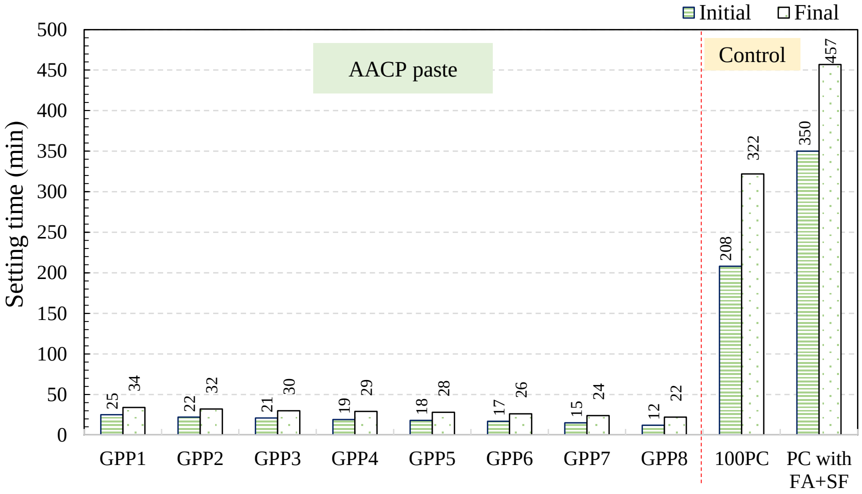

Fig. 2 Setting times of AACP paste

Table 5 displays the results for compressive strength of AACP paste under different types of GPP. As with the control mixtures (100PC and PC with FA+SF), the strength development of AACP paste tended to increase as the curing time increased. This is in line with the work of Liew et al. [24] that the strength development of one-part-mixing geopolymers increased as the curing time increased. Moreover, the trend of their strengths was comparable to that of the PC with FA+SF representing the use of pozzolanic materials in the PC system. With regard to the effect of SS-to-SH ratio and PC content, there were no significant effects on their strength development.

Table 5 : Strength development of AACP paste

Symbol	Compressive strength (MPa)			
	1-d	7-d	28-d	90-d
GPP1	3.92	8.01	10.47	11.89
GPP2	3.95	8.15	10.75	12.51
GPP3	4.00	8.24	11.38	13.04
GPP4	4.13	8.34	11.69	13.61
GPP5	4.07	8.49	10.74	12.80
GPP6	4.08	8.62	11.34	13.49
GPP7	4.11	8.69	11.96	14.07
GPP8	4.15	8.99	13.00	14.86
100PC	20.49	37.01	41.93	46.51
PC with FA + SF	4.86	19.00	24.25	29.96

3.2 Bond strength of reinforced concrete using AACP paste-coated steel bars

Fig. 3 shows the test results for the bond strength of reinforcing steel bars in concrete when coated with AACP paste as a corrosion-prevention coating. According to Fig. 3, the surface-treated reinforcing steel bar is effective at increasing the bond strength of concrete. The bond strength of reinforcing steel bars treated with AACP pastes were higher than those of control pastes (100PC and PC with FA+SF mixtures). A number of researchers [25, 26] reported that the $Ca(OH)_2$ on the concrete surfaces could react with SiO_2 and/or Al_2O_3 from GPP powder, resulting in an increase in reaction products at the contact zone. As reported by Damrongwiriyanupap et al. [27, 28], the coexistence of C-(A)-S-H and N-A-S-H gels could enhance the interaction between concrete and alkali-activated binder. This is why the bond strength of reinforcing steel bars coated with AACP paste is greater than those of both 100PC and PC with FA+SF mixtures.

The load-slip curves of reinforced concrete under different paste-treated reinforcing steel bars are depicted in Fig. 4. It is revealed that the initial load capacity of all mixtures was relatively high, and the slope of the curve progressively increased until its peak point. The bond tension subsequently diminished as the reinforced steel bar began to separate from the surrounding concrete surfaces. This is in line with the work of previous studies [27, 29-31]. According to Figure 8, the load capacity of reinforced concrete using AACP paste-treated steel bars tended to be greater than those of the 100PC and the PC with FA+SF mixtures. As explained previously, the additional formation of C-(A)-S-H gels enhanced the bond strength of steel bars coated with AACP paste at the transition zone. However, Yeih et al. [32] demonstrated that the bond strength of epoxy/FA-coated rebar decreased by 13.7% compared to that of uncoated rebar. They also reported that When the epoxy was combined with FA, there was a lower chance that the FA would react with $Ca(OH)_2$ in the surrounding concrete. In contrast to the findings of Yeih et al. [32], the bond strength of steel bars coated with AACP paste followed a different trend. This is because pozzolanic and geopolymerization reactions are responsible for a significant portion of the enhancement in bond strength, as reported by Yeih et al. [32]. In addition, the bond-slip tendency of steel bars coated with AACP pastes appeared to be greater than those of 100PC, PC with FA+SF, and uncoated bar. Note that the significant increase in the bond-slip at the peak point is extremely advantageous in terms of deformation resistance prior to fracture and the increased strain capacity of concrete.

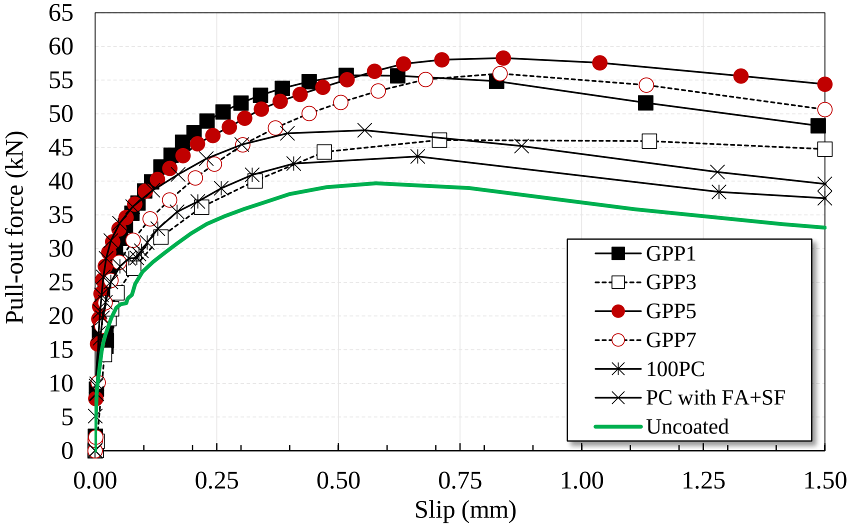

Fig. 3 Load-slip curves of reinforced concrete under different paste-treated reinforcing steel bars

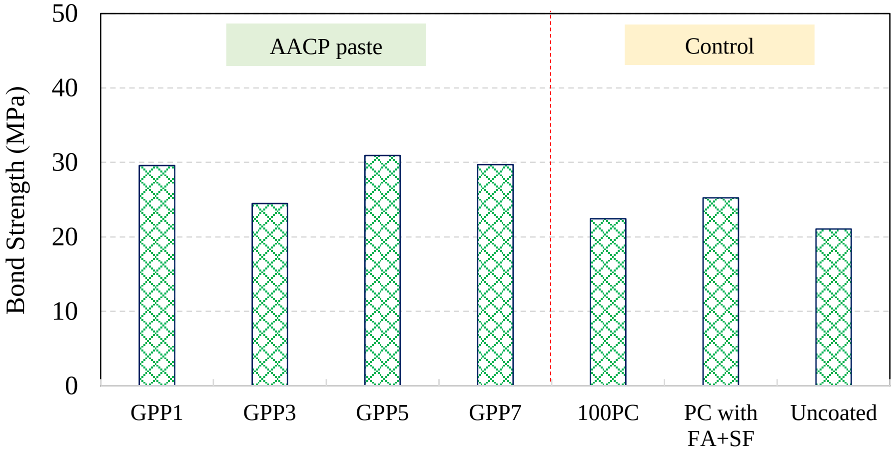

Fig. 4 Bond strength of concrete under different paste-treated reinforcing steel bars

4. Conclusion

From the results for strength development and bond strength of alkali activated/cement powder for alternative coating applications, the following conclusions can be drawn:

1) The GPP produced by the incorporation of FA and PC activated with higher SS-to-SH ratio resulted in a decrease in setting time of fresh AACP pastes and increased their strengths of hardened pastes. Their performance was comparable to those of the PC containing FA+SF like the use of pozzolanic materials in the PC system. In addition, the SS-to-SH ratio and PC content marginally affected their strength development.

2) The AACP paste-coated reinforcing steel bar effectively improved the bond strength of concrete and increased the bond-slip at the peak point. The addition of reaction products at the contact zone facilitated in the strengthening of their bonds.

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