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Advances in Cement Research

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ADHESION CHARACTERIZATION OF PORTLAND CEMENT CONCRETE AND ALKALI-ACTIVATED BINDERS UNDER DIFFERENT TYPES OF CALCIUM PROMOTERS

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Abstract - In this paper, alkali-activated binders (AAB) are investigated for their potential use as repair materials of Portland cement concrete (PCC). The adhesion characterization of PCC and repair materials using AAB made from fly ash (FA) and Portland cement (PC) activated with sodium hydroxide and sodium silicate solutions, AAB made from FA and calcium hydroxide (CH) activated with sodium hydroxide and sodium silicate solutions, and commercial repair material (RMs) have been investigated. Test results show that the AAB

with additives gives high bond strength which is similar to the use of RMs. Bond strength between PCC substrate and AAB with additives are improved, due to increased reaction products especially C-S-H gel. However, the CH replacement at 15% shows a large amount of calcite resulting in reduction in bond strength. The failure patterns and fracture interface images of the tested specimens also demonstrate the quality of the developed bond strength. It was shown that the interface zone of PCC substrate and AAB is homogeneous with no visible gap between the two bonding surfaces. It is suggested that the AAB with PC as additive can be used as a repair binding material which not only has high bond strength but also is cost-effective.

Keywords: Admixtures; Alkali-activated cements; Portland cements; Fly ash; Interfaces; Bond

Introduction

The good mechanical properties and low-cost advantages make ordinary Portland cement (OPC) as a popular choice for the use in construction industry although the OPC production produces a large amount of carbon dioxide (CO₂) emission to atmosphere; approximately one ton of CO₂ emissions for each ton of the OPC produced (Ferreira et al., 2014) and corresponding to approximately 7% of the greenhouse effect emissions worldwide (Metz et al., 2007). In general, OPC concrete could be used in many years but some of its performance could be degraded or damaged by many reasons as reported by many researchers (Zhang et al., 2012; Chindapasirt and Rattanasak, 2016; Duan et al., 2016a; Duan et al., 2016b; Aguirre-Guerrero et al., 2017). For example, a reduction in mechanical properties was probably due to improper design and/or management or poor durability of materials. Therefore, the repair and reinforcement of damaged concrete structures are essential not only

to extend their service-life but also to ensure the safety and serviceability of the associated components involved in the structures (Duan et al., 2016a).

For the repair and/or reinforcement of damaged concrete structures, a new concrete is normally required to replace part of the existing concrete. Wang and Zhang (2015) claimed that new concrete and repair materials to be used should have comparable performance such as high strength, good durability, and high bonding properties to the old concrete being repaired. Recently, polymer-modified cement mortar and epoxy-resin are widely used as repair mortar for repairing damaged concrete structures because they both have excellent mechanical properties. As reported by Ramli and Tabassi (2012), the durability of polymer-modified cement mortar was an important aspect to be considered in construction. Although the polymer-modified cement mortar and epoxy-resin have excellent performance they are rather expensive. Therefore, alternative repair materials in terms of costing as well as mechanical properties should be considered for repair and reinforcement works. In recent years various alternative repair materials have been suggested and developed. One of them is the alkali-activated binder, which has received great attention by many researchers because of its properties being similar to polymer-modified cement mortar and epoxy-resin in terms of rapid setting, high strength, high bond strength and good resistance to acid and sulfate attack (Pacheco-Torgal et al., 2008b; Songpiriyakij et al., 2011; Chindaprasirt et al., 2013; Phoo-ngernkham et al., 2015a; Phoo-ngernkham et al., 2015b; Duan et al., 2016a; Phoo-ngernkham et al., 2016b).

Alkali-activated binders could be classified into two systems. One is the mixture of blast furnace slag and mild alkaline solution that has calcium silicate hydrate (C-S-H) and/or calcium aluminosilicate hydrate (C-A-S-H) gels as main reaction products (Pacheco-Torgal et al., 2008a). The other is the mixture of metakaolin or low calcium fly ash and medium to high alkaline solution that has sodium aluminosilicate hydrate (N-A-S-H) gels as main reaction

products (Pacheco-Torgal et al., 2008a). The current research work focuses on a combination of these two systems because calcium aluminosilicate hydrate (C-(A)-S-H) co-existed with sodium aluminosilicate hydrate (N-A-S-H) gels can provide a binder with excellent mechanical properties when cured at ambient temperature (Puertas et al., 2000; Kumar et al., 2010; Rashad, 2013; Phoo-ngernkham et al., 2015a). The alkali-activated binders thus can be used as an ideal material for repair and reinforcement of damaged concrete structures. The importance of alkali activated materials used in the field of rehabilitation of deteriorated structures has been highlighted by Pacheco-Torgal et al. (2008b). The protective coating using alkali-activated materials for marine concrete and transportation infrastructures has been studied, which was found to have excellent performance for a sustainable protection of marine concrete structures (Zhang et al., 2010a; Zhang et al., 2010b; Zhang et al., 2012). Moreover, alkali-activated binders have also been used as pavement repair materials (Hawa et al., 2013; Alanazi et al., 2016; Duan et al., 2016a). For the use of alkali-activated binders as repair and reinforcement of damaged notched concrete beam, Phoo-ngernkham et al. (2016b) reported that the flexural strength of notched concrete beam filled with the alkali-activated binder made from low calcium fly ash plus granulated blast furnace slag activated with alkali solutions was similar to most commercial repair materials. The shear bond strength between old concrete and repair materials has been investigated in recent years. For instance, the shear bond strength between old concrete and low calcium fly ash-granulated blast furnace slag geopolymer or high calcium geopolymer mortars under different types of alkali solutions was studied by Phoo-ngernkham et al. (2016b). In addition, Pacheco-Torgal et al. (2008b) also examined the bond strength between concrete substrate and alkali-activated tungsten mine waste. The latter was found to have excellent bond strength like most commercial repair materials but the advantage of it is more cost-effective than that of most commercial repair materials.

Therefore, the aim of the present study is to investigate the suitability of alkali-activated binders as alternative repair materials for damaged concrete works and to understand the behavior of the shear bond strength between concrete substrate and different types of alkali-activated binder repair materials. The outcome of this study should lay a foundation for the future use of alkali-activated binders as fundamental of alternative repair materials.

Experimental procedure

Materials

Alkali-activated binders

Alkali-activated binders (AAB) is a mixture of fly ash (FA) from Mae Moh power plant in northern Thailand and calcium available additives, i.e., Portland cement (PC) and calcium hydroxide (CH) powders. 10M sodium hydroxide solution (SH) and sodium silicate solution (SS) with 11.67% Na₂O, 28.66% SiO₂, and 59.67% H₂O were used as liquid activators with constant liquid alkaline to binder ratio of 0.60 and SH/SS ratio of 2.0. 10M SH solution was used for this study because it provided high compressive strength as reported in previous studies (Rattanasak and Chindaprasirt, 2009; Somna et al., 2011). For the preparation of 10M SH, sodium hydroxide pellets of 400 gram was dissolved by distilled water of 1 liter and then allowed to cool down for 24 hours before use to avoid the uncontrolled acceleration of setting of alkali-activated binders (Nazari et al., 2012). The chemical compositions of FA and PC are shown in **Table 1**. The FA had sum of SiO₂+Al₂O₃+Fe₂O₃ at 60.96% and the CaO at 25.79%. Therefore, this FA was classified as class C FA as per ASTM C618 (2015). Moreover, FA had specific gravity of 2.65, median particle size of 15.6 μm, and Blaine fineness of 4400 cm²/g, respectively. While PC had specific gravity of 3.15, median particle size of 14.5 μm, and Blaine fineness of 3700 cm²/g, respectively. The CH powder is in white colour appearance and has a density of 2250 kg/m³ and a purity of 95%.

Seven different mixes of AAB were prepared for using as repair material. Mix proportions and properties of AAB are illustrated in [Table 2](#). The final setting time was 25-45 min for FA plus PC pastes, 15-35 min for FA plus CH pastes, and about 50 min for FA pastes, which were obtained by using a Vicat apparatus. The 28-day compressive strengths of the FA plus PC and the FA plus CH pastes were 32-38 MPa and 34-39 MPa, respectively; whereas the 28-day compressive strength of the FA pastes without additives was about 25 MPa. For the mixing of AAB paste, SH and SS solutions were mixed together prior to the start of mixing. The FA and additives were mixed together first. After the mixture was nearly uniformly distributed the liquid solution was added in and then they were mixed again for 3 minutes.

Portland cement concrete

Portland cement concrete (PCC) was prepared by mixing ordinary Portland cement, fine aggregate of natural river sand of size smaller than 5 mm, coarse aggregate of crushed limestone of size 5-25 mm and normal tap water. The mix proportions as the weight of the material required in a unit volume of PCC, e.g. in kg/m³, are 500 for cement, 510 for sand, 930 for crushed limestone, and 238 for water, respectively, which gives a water-to-cement ratio of 0.476. The 28-day compressive strength and Young's modulus of PCC were about 35.0 MPa and 27.5 GPa, respectively, which were obtained based on previous study (Phoo-ngernkham et al., 2016b). In the preparation of PCC samples for slant shear test, fresh PCC was cast in 50x50x125 mm prism moulds. After that, samples were cured in water for 28 days and then cured at ambient temperature (~25 °C) in laboratory for another 60 days. Then, the PCC prisms were cut in half in the middle section with an inclined angle of 45° to the cross-section (see Fig.1). All of samples were prepared in accordance with the previous studies (Phoo-ngernkham et al., 2014; Phoo-ngernkham et al., 2015a).

Commercial repair material products

Three available commercial repair materials (RMs) have been tested to compare with those of AABs. Types and properties of the RMs were reported in previous studies (Phoo-ngernkham et al., 2015b; Phoo-ngernkham et al., 2016a). RM-1 was a general purpose non-shrink grout mortar with the recommended water to binder ratio of 0.15 and the 28-day compressive strength of 62.0 MPa. RM-2 was a multi-purpose non-shrink grout with the recommended water to binder ratio of 0.14 and the 28-day compressive strength of 70.0 MPa. RM-3 was a polymer modified repair mortar with the recommended water to binder ratio of 0.17 and the 28-day compressive strength of 40.0 MPa.

Sample preparation and testing

Shear bond strength between PCC substrate and AAB or RMs

The shear bond strength between PCC and AAB or RMs was evaluated using the slant shear test adapted from FM3-C 882 (2015). The PCCs were cut at the middle section with an interface line at 45° to the cross-section for the calculation of the shear bond strength. The casting of shear bond strength samples was based on the previous studies (Phoo-ngernkham et al., 2014; Phoo-ngernkham et al., 2015a). For the casting of shear bond strength samples, the AAB was cast into a 50x50x125 mm³ prism mould with the existing PCC sample (i.e., half of the mould was with PCC and the other half was with AAB, see Fig.1). After that, samples were then covered by vinyl sheet to protect moisture loss and kept in the ambient temperature (~25 °C) in laboratory until testing. All samples were tested at the age of 28 days curing of the AAB. Five identical samples were tested for each mix and the average value was used as the test result. Test set up of shear bond specimens under a constant loading rate of 0.30 MPa/s is shown in Figure 1.

Interface zone between PCC substrate and AAB or RMs

For the observation of the interface zone between PCC substrate and repair materials, the samples with still intact surfaces were broken and analyzed by using Scanning Electron Microscopy (SEM) for material characterization of the interface zone of two surfaces.

Results and Discussions

Shear bond strength between PCC substrate and AAB or RMs

The average results of 45° shear bond strength between PCC substrate and AAB or RMs are plotted in Figure 2. The shear bond strength between old PCC and new PCC (base line) is 8.2 MPa. In contrast, the use of repair materials (AAB and RMs) could improve the bond strength. These results are consistent with what has been reported by other researchers (Júlio et al., 2004; Momayez et al., 2005; Júlio et al., 2006). According to Figure 2, the shear bond strengths of the 95FA5PC, 90FA10PC, and 85FA15PC mixes are 19.7, 22.7 and 25.5 MPa, respectively, whereas the shear bond strengths of the 95FA5CH, 90FA10CH, and 85FA15CH mixes are 21.0, 24.6 and 17.4 MPa, respectively. In contrast, the FA paste without additives is only 14.2 MPa, which is much lower than that of others. The noticeable increase in shear bond strength by using AAB with additives is probably due to the increase in reaction products at the interface zone between PCC and AAB. Similarly, it can be seen from Fig.2 that the use of RMs can also increase the shear bond strength. Dombrowski et al. (2007) and Gue et al. (2010a) reported that the readily available free calcium ions from PC and CH could react with silica and alumina in FA to form C-(A)-S-H gel co-existed with N-A-S-H gel, resulting in an enhancement of AAB properties. Pacheco-Torgal et al. (2008b) and Phoo-ngernkham et al. (2015a) reported that the reaction products between PPC and AAB at the interface zone enhanced the bonding strength between the two materials. However, 85FA15CH mix shows an obvious decrease in shear bond strength when compared to 90FA10CH mix. Some

researchers (Lee and van Deventer, 2002; Guo et al., 2010a) claimed that the hydration of $\text{Ca}(\text{OH})_2$ in alkali medium can generate a large amount of heat within the matrix. Although the high compressive strength of the 85FA15CH paste when cured at ambient temperature is very attractive (see [Table 2](#)), the CH replacement ratio at 15% has an adverse effect on the bond strength development. This is because a large amount of generated heat from CH and alkali solutions has influenced to composite materials surfaces similar to use of 100%GBFS with SH plus SS as reported in previous study (Phoo-ngernkham et al., 2015a). According to Figure 2, the shear bond strength between PCC substrate and RMs are 20.6 MPa for RM-1, 26.2 MPa for RM-2, and 12.8 MPa for RM-3. The AAB with PC at ranges between 10 to 15% and CH at ranges between 5 to 10% show high shear bond strength compared to those of RMs. This again indicates that AAB mixes with additives could be used as alternative repair material.

The shear bond strength behaviors can be explained by an observation of the reaction products growth within the matrix via the XRD pattern. The XRD patterns of AAB with additives cured at ambient temperature for 28 days are shown in Figures 3 and 4. The XRD pattern of AAB made from FA without additives is illustrated in Figure 3a, which consists of amorphous phase at the hump around approximately $20\text{-}40^\circ$ 2theta, crystalline phases of quartz (SiO_2) and Magnetite (Fe_3O_4); however, crystalline calcite (CaCO_3) and calcium silicate hydrate (C-S-H) phases are found in low values. This may explain why the obtained compressive and bond strengths were low (see [Table 2](#) and Figure 2). When a combination of FA and PC activates with alkali solutions, the main reaction products are amorphous and intermixed with crystalline phase inclusions especially C-S-H peaks. The reduction in quartz (SiO_2) with increasing C-S-H gel results in an enhancement of the strength. This corresponds well with the bond strength behaviors (see Figure 2) because silica and alumina from raw

materials could react with calcium hydroxide on the surface of PCC substrate. Therefore, the bond strength at the contact surface can be improved as reported by Pacheco-Torgal et al. (2008b) and Phoo-ngernkham et al. (2015b). It should be noted that the presence of the C-S-H phase within the matrix of AAB with calcium oxide content was also observed by many researchers (Guo et al., 2010a; Guo et al., 2010b; Kumar et al., 2010; Cwirzen et al., 2014).

With regard to the XRD patterns of FA plus CH activated with alkali solutions, the amorphous and crystalline phases are found similar to the combination of FA and PC activated with alkali solutions. However, the peaks of Hydrosodalite ($\text{Na}_4\text{Al}_3\text{Si}_3\text{O}_{12}(\text{OH})$) and calcite are easily observed in the XRD patterns (see Figures 4b-4d). The strong peak of calcite potentially results in the carbonation as reported by Cwirzen et al. (2014) and Hanjitsuwan et al. (2017). According to Figure 2, it is evident that the CH replacement ratio up to 10% is still positive to bond strength between PCC substrate and AAB. The difference of it from the 15%CH replacement is clearly noticeable as shown in Figures 2 and 4d. Lee and van Deventer (2002) claimed that the generated heat from hydration of $\text{Ca}(\text{OH})_2$ in alkali medium and carbonation formation caused the expansion of AAB sample. Thus, the bond strength of very-fast setting AAB is generally low, which is agreed with previous study (Phoo-ngernkham et al., 2015a).

Failure mode and interface zone between PCC substrate and AAB or RMs

The failure patterns of PCC substrate and AAB with additives from the shear bond tests (slant angle of 45°) are shown in Figure 5. In general, there are two failure patterns that can be observed, namely the monolithic failure mode and the shear bond failure mode. The shear bond failure pattern is observed in low bond strength between two materials, i.e. the 100FA and the 85FA15CH mixes (Figures 5a and 5g). The cracks were found mainly in the contact zone with

the PCC substrate remained relatively intact. In contrast, the monolithic failure pattern acted as a monolithic column and the cracks were formed in both sections passing through the slant plane. This failure mode is similar to that of the PCC prism (before cutting sample). As mentioned earlier, this causes a relatively high bond strength between the two surfaces. It can be seen from the figure that the mixes with additives show higher bond strength than those of the base line and the AAB paste without additives except for the 85FA15CH mix. For the samples using RMs, there are two types of failure modes observed, which are similar to the AAB mixes. The shear bond failure pattern is observed in the RM-3 (Figures 5j), while the monolithic failure pattern is found in the RM-1 (Figures 5h) and the RM-2 (Figures 5i). This implies that the AAB could be used as repair binding material similar to those of RMs in the market, which gives high resistance to cracking and high bond strength between the two materials at the contact surface.

The fracture interface between PCC substrate and repair materials from the shear bond tests obtained from SEM analysis can be used to explain the bond strength behavior at two surfaces similar to the failure pattern. Normally, an observation of bond strength in contact zone is essential to understand the reaction products in the zone. Figure 6 shows the SEM images of interface zone between PCC substrate and repair materials cured at ambient temperature for 28 days. The low bonding with clean separation of the two surfaces are found in the 100FA paste (without additives), the 85FA15CH paste and the RM-3, as illustrated in Figures 6a, 6g and 6j, respectively. This fracture interface is called a plane fracture surface between two materials. These results correspond well to the failure patterns shown in Figures 5a, 5g and 5j, respectively. The other fracture interface is called high bonding with a very homogeneous microstructure between two materials with no significant gap between the two bonding surfaces. A good bonding between the two surfaces is found in the mixes of

95FA5PC, 90FA10PC, 85FA15PC, 95FA5CH and 90FA10CH pastes. The bonding interfaces are still intact and cracks were passed through the PCC substrate and AAB. A very homogeneous surface corresponds with the increase in shear bond strength of AAB with additives. Normally, there is a lot of calcium hydroxide at the PCC substrate surfaces, which is one of the hydration products. This calcium hydroxide could react with silica and alumina from AAB system to form a coexistence of C-S-H and N-A-S-H gels as reported by Pacheco-Torgal et al. (2008b) and Phoo-ngernkham et al. (2015b), resulting in an enhancement of bond-strength development at the interface zone. Also, the increase in reaction products in contact zone is probably due to the calcium ions, which could be balanced with the negative charge of aluminum ions, leading to a dense surface gain (Pacheco-Torgal et al., 2008b; Phoo-ngernkham et al., 2015b). The SEM image of RM-2 as illustrated in Figure 6i indicated that a small gap with relatively good bonding is observed at the two surfaces. In contrast, the SEM image of RM-1 (Figure 6h) shows a noticeable gap existed at the interface, which is more visible than that of the RM-2. This leads to a slight reduction in bond strength in the RM-1 than in the RM-2. Note that both the RM-1 and RM-2 have the failure pattern with the monolithic failure mode (see Figures 5h and 5i). This implies that the use of AAB with additives as repair binding material is similar to those of commercially available in the market according to the slant shear bond test and the interface zone between two materials.

Bond strength quality by the interfacial bond strength test

One of the most important properties of the repair material is the bond strength between the concrete substrate and repair materials. In order to increase the bond strength, many researchers (Springkel and Ozyildirim, 2000; Alanazi et al., 2016; Rith et al., 2016) have developed individual bond strength criteria by using the tensile strength. For example, Phoo-ngernkham et al. (2016b) has applied the bond strength criterion to discuss the bond strength

quality of notched concrete beam filled with AAB made from low calcium fly ash-ground granulated blast furnace slag blends under different types of alkali solutions. Therefore, bond strength quality by the interfacial bond strength test was discussed in this study to understand the role of AAB and RMs as repair materials. Note that true bond strength occurred in the bond interface between two materials. While, failures at other locations have greater than the failure load whose high bond strength is essential for practical applications (Springkel and Ozyildirim, 2000; Alanazi et al., 2016). In this study, the bond strength quality was classified based on the five bond strength criteria used in literature (Springkel and Ozyildirim, 2000; Alanazi et al., 2016; Phoo-ngernkham et al., 2016b), whose conditions were obtained from compressive strength improvement from slant shear prism tests. First criterion is between 0 to 25%, called “Poor quality”. Second criterion is between 26 to 50%, called “Fair quality”. Third criterion is between 51 to 75%, called “Good quality”. Fourth criterion is between 76 to 90%, called “Very good quality”. Final criterion is better than 90%, called “Excellent quality”.

The shear bond strength quality used in this study is compared with that reported in the previous study, which is illustrated in **Table 3**. As mentioned earlier, the bond strength quality of old PCC substrate and new PCC (base line) is Poor. The use of AAB made from FA without additives gives the bond strength quality as Fair. Good to Excellent bond strength qualities are obtained by using the mixes of AAB with additives. While the bond strength qualities between PCC substrate and RMs are in the range of Fair to Excellent. These results correspond well with the failure modes and interface zone results as shown in Figures 5 and 6, respectively. Hence, it is recommended that the mixes of 90FA10PC, 95FA15PC and 90FA10CH are very attractive in terms of high-bond strength quality, which are similar to the use of RM-2. **Table 3** shows the comparison of them with previously tested results of using high calcium geopolymers under different sodium hydroxide concentrations (Phoo-ngernkham et al., 2015b) and low calcium fly ash-grounded blast furnace slag geopolymers under different types of

alkali solutions (Phoo-ngernkham et al., 2015a). It can be found from the table that the bond strength qualities of previous studies could be classified as Very good to Excellent. This implies that AAB could be practically used for the application as an alternative repair material.

Cost analysis

The cost-effectiveness of using AAB and RMs as the repair materials is evaluated in term of the cost to shear bond strength, which is estimated based on Thailand market prices in the year 2017. The cost of the materials used in the present study is summarized in [Table 4](#), which is done based on the total material used in [Table 2](#). According to [Table 4](#), the total costs of AAB and RMs are about £185-189 /m³ and £1048-2886 /m³, respectively; while the total cost of the base line is about £48 /m³. Figure 7 shows the comparison of the cost-effectiveness between AAB and RMs. It is found from the figure that the use of AAB with PC as additive is more cost-effective than the use of AAB with CH as additive or RMs. The excellent performance of the use of AAB with additives activated with SH plus SS solutions can be attributed to the high bonding between AAB and PCC substrate in the contact zone, which, similar to those of the RMs, exhibits Very good to Excellent bond strength quality. Based on the result of cost analysis, the high cost-effectiveness of the use of AAB with PC as additive confirms the suitability of this mix in term of excellent economic profitability. Therefore, the use of AAB with PC as additive cured at ambient temperature is very attractive due to its cheapest cost-effective solution when compared with the use of CH.

Conclusions

This paper has provided an experimental study on the shear bond strength between PCC substrate and various different repair materials including AAB made from FA and PC activated with sodium hydroxide and sodium silicate solutions, AAB made from FA and CH

activated with sodium hydroxide and sodium silicate solutions, and commercially available RMs. Based on the obtained experimental results, the following conclusions could be drawn:

1) The shear bond strength between PCC substrate and AAB with calcium promoters has an increase tendency when the calcium promoter replacement is increased, which is similar to those of RMs results. However, when CH replacement reaches to 15% a slight decrease in shear bond strength was found. This indicates that there is a peak point for the CH replacement.

2) The main reaction products of AAB with PC as additive are the amorphous phases and C-S-H peak; the latter can be linked to the high bond strength in the contact zone. While the products of AAB with CH as additive are the amorphous and crystalline phases, which are similar to the combination of FA and PC paste except for the case where the CH replacement is at 15%, for which case many calcite peaks were found in the XRD pattern.

3) The failure patterns of PCC substrate and AAB with additives from the shear bond tests (slant angle of 45°) were found almost in monolithic failure mode, where cracks were formed in both materials passing through the slant plane similar to those of RMs. However, the failure patterns found in the 100FA and 85FA15CH mixes were mainly in the contact zone, thus resulting in low bond strength.

4) Fracture interface between PCC substrate and AAB with additives showed a uniform microstructure with no significant gap between the two materials in the contact zone. The bond strength was developed due to increased reaction products in the interfacial transition zone. Similar to AAB, the fracture interface between PCC substrate and RMs also exhibited good bonding in the interfacial transition zone.

5) The AAB with PC as additive is recommended for the optimum mix design in this study. This mix provides cost-effective high bond strength and excellent bond quality when compared with those of AAB with CH as additive and RMs. The excellent performance of

AAB made from FA and PC activated with SH plus SS solutions is thus suitable for using as an alternative repair material.

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References

- Aguirre-Guerrero AM, Robayo-Salazar RA and De Gutiérrez RM (2017) A novel geopolymer application: Coatings to protect reinforced concrete against corrosion. *Applied Clay Science* **135**: 437-446.
- Alanazi H, Yang M, Zhang D and Gao Z (2016) Bond strength of pcc pavement repairs using metakaolin-based geopolymer mortar. *Cement and Concrete Composites* **65**: 75-82.
- ASTM (2005) C618-15: Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete. Annual Book of ASTM Standard, Vol.04.02.
- Chindaprasirt P and Rattanasak U (2016) Improvement of durability of cement pipe with high calcium fly ash geopolymer covering. *Construction and Building Materials* **112**: 956-961.
- Chindaprasirt P, Rattanasak U and Taebuanhuad S (2013) Resistance to acid and sulfate solutions of microwave-assisted high calcium fly ash geopolymer. *Materials and Structures* **46(3)**: 375-381.

- Cwirzen A, Engblom R, Punkki J and Habermehl-Cwirzen K (2014) Effects of curing: Comparison of optimised alkali-activated PC-FA-BFS and PC concretes. *Magazine of Concrete Research* **66(6)**: 315-323.
- Dombrowski K, Buchwald A and Weil M (2007) The influence of calcium content on the structure and thermal performance of fly ash based geopolymers. *Journal of Materials Science*, **42(9)**: 3033-3043.
- Duan P, Yan C and Luo W (2016a) A novel waterproof, fast setting and high early strength repair material derived from metakaolin geopolymer. *Construction and Building Materials*, **124**: 69-73.
- Duan P, Yan C, Luo W and Zhou W (2016b) A novel surface waterproof geopolymer derived from metakaolin by hydrophobic modification. *Materials Letters*, **164**: 172-175.
- Ferreira LFB, Costa HSS, Barata IIA, Santos Júlio ENB, Tiago PMN and Coelho JFJ (2014) Precast alkali-activated concrete towards sustainable construction. *Magazine of Concrete Research*, **66(12)**: 618-626.
- FM 3-C 882 (2015) Florida test method for performance of epoxy-resin systems with concrete by slant shear and compressive strength. in Florida Department of Transportation Standard Specifications for Road and Bridge Construction.
- Guo X, Shi H, Chen L and Dick WA (2010a) Alkali-activated complex binders from class c fly ash and ca-containing admixtures. *Journal of Hazardous Materials*, **173(1-3)**: 480-486.
- Guo X, Shi H and Dick WA (2010b) Compressive strength and microstructural characteristics of class c fly ash geopolymer. *Cement and Concrete Composites* **32(2)**: 142-147.

- Hanjitsuwan S, Phoo-Ngernkham T and Damrongwiriyapap N (2017) Comparative study using portland cement and calcium carbide residue as a promoter in bottom ash geopolymer mortar. *Construction and Building Materials* **133**: 128-134.
- Hawa A, Tonnayopas D, Prachasaree W and Taneerananon P (2013) Development and performance evaluation of very high early strength geopolymer for rapid road repair. *Advances in Materials Science and Engineering* DOI: **10.1155/2013/764180**.
- Júlio ENBS, Branco FAB, Silva VD and Lourenço JF (2006) Influence of added concrete compressive strength on adhesion to an existing concrete substrate. *Building and Environment*, **41(12)**: 1934-1939.
- Júlio ENBS, Branc, FAB. and Silva VTD (2004) Concrete-to-concrete bond strength. Influence of the roughness of the substrate surface. *Construction and Building Materials*, **18(9)**: 675-681.
- Kumar S, Kumar R and Mehrotra SP (2010) Influence of granulated blast furnace slag on the reaction, structure and properties of fly ash based geopolymer. *Journal of Materials Science* **45(3)**: 607-615.
- Lee, WKW and Van Deventer JSJ (2002) The effect of ionic contaminants on the early-age properties of alkali-activated fly ash-based cements. *Cement and Concrete Research*, **32(4)**: 577-584.
- Metz B, Davidson OR, Bosch PR, Dave R and Meyer LA, 2007. Climate change 2007. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, USA, 447-496.
- Momayez A, Ehsani MR, Ramezaniapour AA, Rajaie H (2005) Comparison of methods for evaluating bond strength between concrete substrate and repair materials. *Construction and Building Materials* **35**, 748-757.

- Nazari A, Khanmohammadi H, Amini M, Hajiallahyari H and Rahimi A (2012) Production geopolymers by portland cement: Designing the main parameters' effects on compressive strength by taguchi method. *Materials & Design* **41**, 43-49.
- Pacheco-Torgal F, Castro-Gomes J and Jalali S (2008a) Alkali-activated binders: A review. Part 1. Historical background, terminology, reaction mechanisms and hydration products. *Construction and Building Materials*, **22(7)**: 1305-1314.
- Pacheco-Torgal F, Castro-Gomes JP and Jalali S (2008b) Adhesion characterization of tungsten mine waste geopolymeric binder. Influence of opc concrete substrate surface treatment. *Construction and Building Materials* **22(3)**: 154-161.
- Phoo-Ngernkham T, Chindaprasirt P, Sata V, Hanjitsuwan S and Hatanaka S (2014) The effect of adding nano-sio₂ and nano-al₂o₃ on properties of high calcium fly ash geopolymer cured at ambient temperature. *Materials & Design* **55**: 58-65.
- Phoo-Ngernkham T, Hanjitsuwan S, Damrongwiriyanupap N and Chindaprasirt P (2016a) Effect of sodium hydroxide and sodium silicate solutions on strengths of alkali activated high calcium fly ash containing portland cement. *KSCE Journal of Civil Engineering* In Press: 1-9.
- Phoo-Ngernkham T, Hanjitsuwan S, Suksiripattanapong C, Thumrongvu J, Suebsuk J and Sookasem S (2016b) Flexural strength of notched concrete beam filled with alkali-activated binders under different types of alkali solutions. *Construction and Building Materials*, **127**: 673-678.
- Phoo-Ngernkham T, Maegawa A, Mishima N, Hatanaka S and Chindaprasirt P (2015a) Effects of sodium hydroxide and sodium silicate solutions on compressive and shear bond strengths of FA–GBFS geopolymer. *Construction and Building Materials* **91**, 1-8.

- Phoo-Ngernkham T, Sata V, Hanjitsuwan S, Ridthirud C, Hatanaka S and Chindaprasirt P (2015b) High calcium fly ash geopolymer mortar containing portland cement for use as repair material. *Construction and Building Materials* **98**, 482-488.
- Puertas F, MartíNez-Ramírez S, Alonso S and Vázquez T (2000) Alkali-activated fly ash/slag cements: Strength behaviour and hydration products. *Cement and Concrete Research* **30(10)**: 1625-1632.
- Ramli M and Tabassi AA (2012) Influences of polymer modification and exposure conditions on chloride permeability of cement mortars and composites. *Journal of Materials in Civil Engineering* **24(2)**: 216-222.
- Rashad AM (2013) Properties of alkali-activated fly ash concrete blended with slag. *Iranian Journal of Materials Science and Engineering* **10(1)**, 57-64.
- Rattanasak U and Chindaprasirt P (2009) Influence of naoh solution on the synthesis of fly ash geopolymer. *Minerals Engineering* **22(12)**: 1073-1078.
- Rith M, Kim, YK, Lee SW, Park JY and Han SH (2016) Analysis of in situ bond strength of bonded concrete overlay. *Construction and Building Materials* **111**: 111-118.
- Somna K, Jaturapitakkul C, Kajitvichyanukul P and Chindaprasirt P (2011) Naoh-activated ground fly ash geopolymer cured at ambient temperature. *Fuel* **90(6)**: 2118-2124.
- Songpiriyakij S, Pulngern T, Pungpremtrakul P and Jaturapitakkul C (2011) Anchorage of steel bars in concrete by geopolymer paste. *Materials & Design* **32(5)**: 3021-3028.
- Springkel MM and Ozyildirim C (2000) Evaluation of high performance concrete overlays placed on route 60 over lynnhaven inlet in virginia. Final report Virginia Transportation Research Council.
- Wang R and Zhang L (2015) Mechanism and durability of repair systems in polymer-modified cement mortars. *Advances in Materials Science and Engineering*, DOI: **10.1155/2015/594672**.

Zhang Z, Yao X and Wang H (2012) Potential application of geopolymers as protection coatings for marine concrete iii. Field experiment. *Applied Clay Science*, **67–68**: 57-60.

Zhang Z, Yao X and Zhu H (2010a) Potential application of geopolymers as protection coatings for marine concrete: I. Basic properties. *Applied Clay Science* **49(1–2)**: 1-6.

Zhang Z, Yao X and Zhu H (2010b) Potential application of geopolymers as protection coatings for marine concrete: II. Microstructure and anticorrosion mechanism. *Applied Clay Science* **49(1–2)**: 7-12.

Table 1. Chemical compositions of FA and PC (by weight)

Materials	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	Na ₂ O	SO ₃	LOI
FA	31.32	13.96	15.64	25.79	2.94	2.93	2.83	3.29	1.30
PC	20.80	4.70	3.40	65.30	1.50	0.40	0.10	2.70	0.92

Table 2. Mix proportions and properties of AAB (kg/m³)

No.	Mix symbols	FA (kg)	PC (kg)	CH (kg)	SH (kg)	SS (kg)	Properties of AAB	
							Final set. (min)	f _{c at 28d} (MPa)
1	100FA	754	-	-	151	302	50	25
2	95FA5PC	722	38	-	152	304	45	32
3	90FA10PC	689	77	-	153	306	40	35
4	85FA15PC	655	116	-	154	308	25	38
5	95FA5CH	730	-	38	154	308	35	34
6	90FA10CH	704	-	78	156	312	30	38
7	85FA15CH	677	-	119	159	318	15	39

Table 3. Bond strength quality in this study compared with previous studies.

Materials	Activators	Obtained results	Improvement of compressive strength from slant shear prisms test (%)	Quality
Base line	Water	This study	25	Poor
100FA	SH plus SS	This study	50	Fair
95FA5PC	SH plus SS	This study	71	Good
90FA10PC	SH plus SS	This study	81	Very good
85FA15PC	SH plus SS	This study	92	Excellent
95FA5CH	SH plus SS	This study	75	Good
90FA10CH	SH plus SS	This study	88	Very good
85FA15CH	SH plus SS	This study	63	Good
RM-1	Water	This study	74	Good
RM-2	Water	This study	94	Excellent
RM-3	Water	This study	46	Fair
14M10PC ¹	SH plus SS	(Phoo-ngernkham et al., 2015b)	87	Very good
LFA+GBFS ²	SH plus SS	(Phoo-ngernkham et al., 2015a)	111	Excellent
GBFS ³	SH plus SS	(Phoo-ngernkham et al., 2015a)	84	Very good

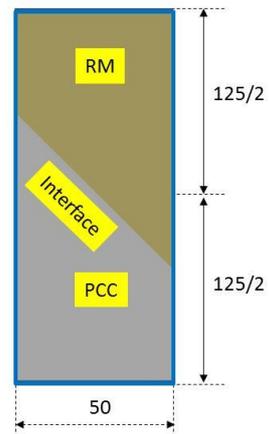
¹ 14M10PC was the mix of 90% high calcium fly ash and 10% Portland cement activated with 14M SH and SS.

² LFA+GBFS was the mix of 50% low calcium fly ash and 50% slag activated with 10M SH and SS.

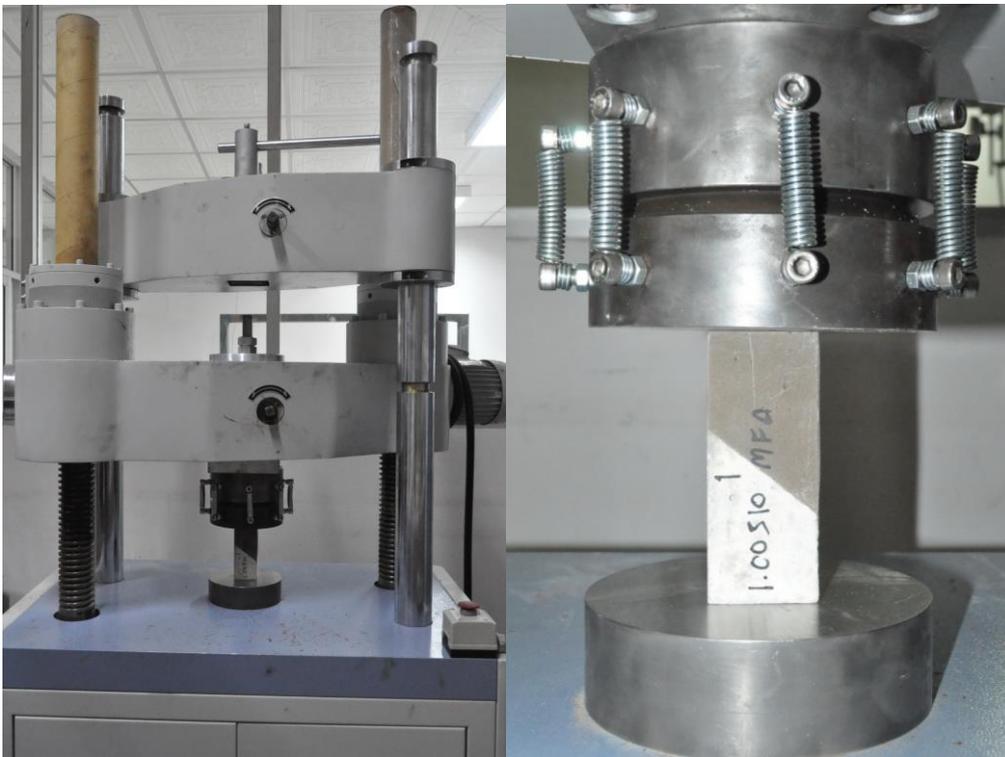
³ GBFS was the mix of 100% slag activated with 10M SH and SS.

Table 4. Cost of repair materials

Repair materials	Materials cost (£/m ³)						Total cost (£/m ³)
	FA (£/m ³)	PC (£/m ³)	CH (£/m ³)	SH (£/m ³)	SS (£/m ³)	RMs (£/m ³)	
100FA	34	-	-	57	94	-	185
95FA5PC	32	2	-	57	95	-	186
90FA10PC	31	4	-	58	95	-	188
85FA15PC	29	6	-	58	96	-	189
95FA5CH	32	-	861	58	96	-	1048
90FA10CH	31	-	1768	59	97	-	1955
85FA15CH	30	-	2697	60	99	-	2886
RM-1	-	-	-	-	-	3470	3470
RM-2	-	-	-	-	-	1447	1447
RM-3	-	-	-	-	-	2066	2066



(a)



(b)

Figure 1. Test set up of shear bond specimens. (a) Specimen (unit in mm) and (b) compression test apparatus.

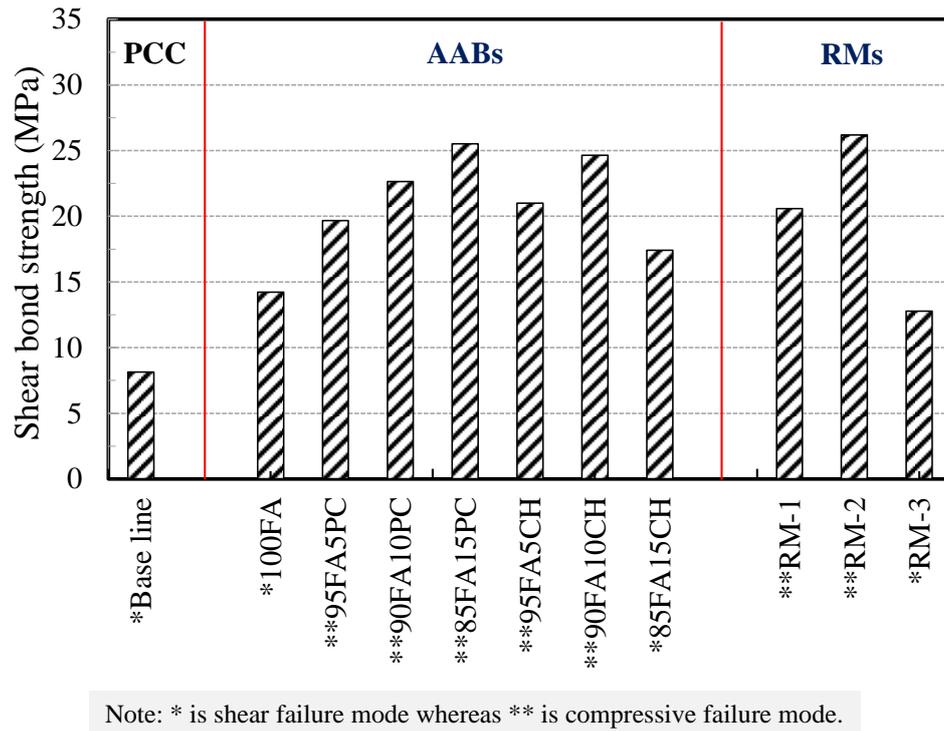


Figure 2. Shear bond strength between PCC and AAB or RMs

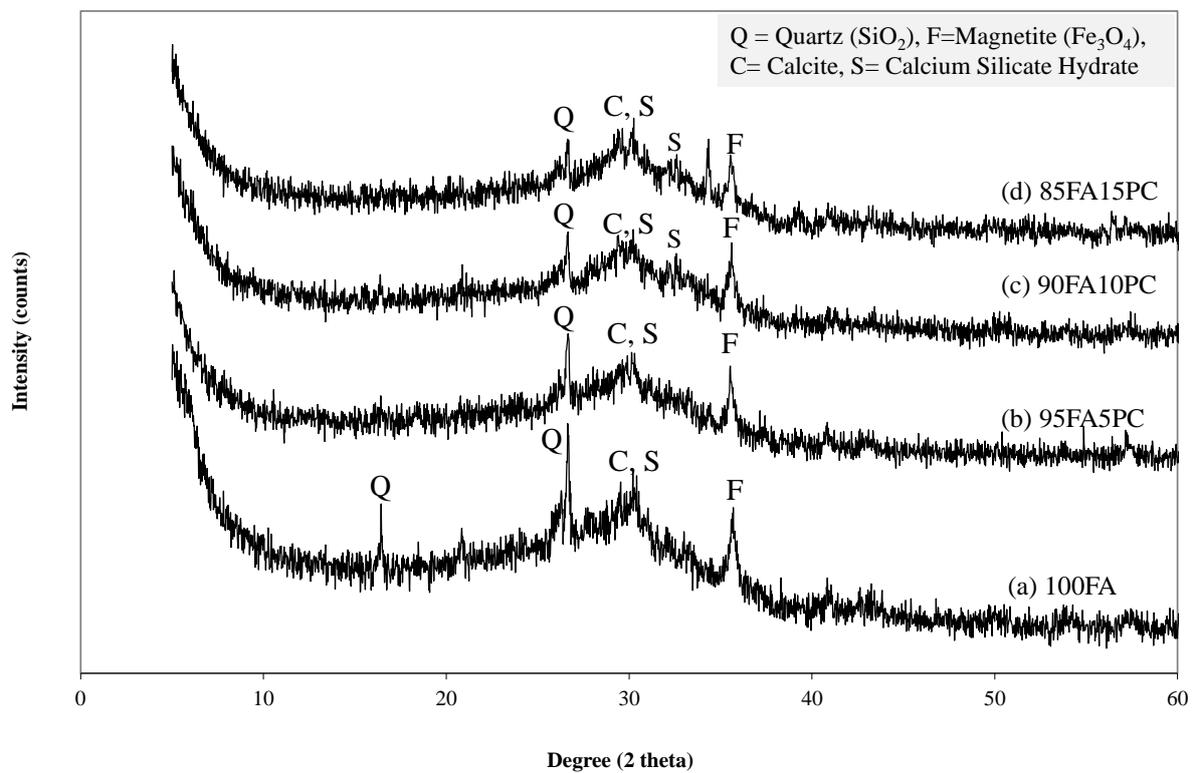


Figure 3. XRD patterns of AAB with PC as an additive

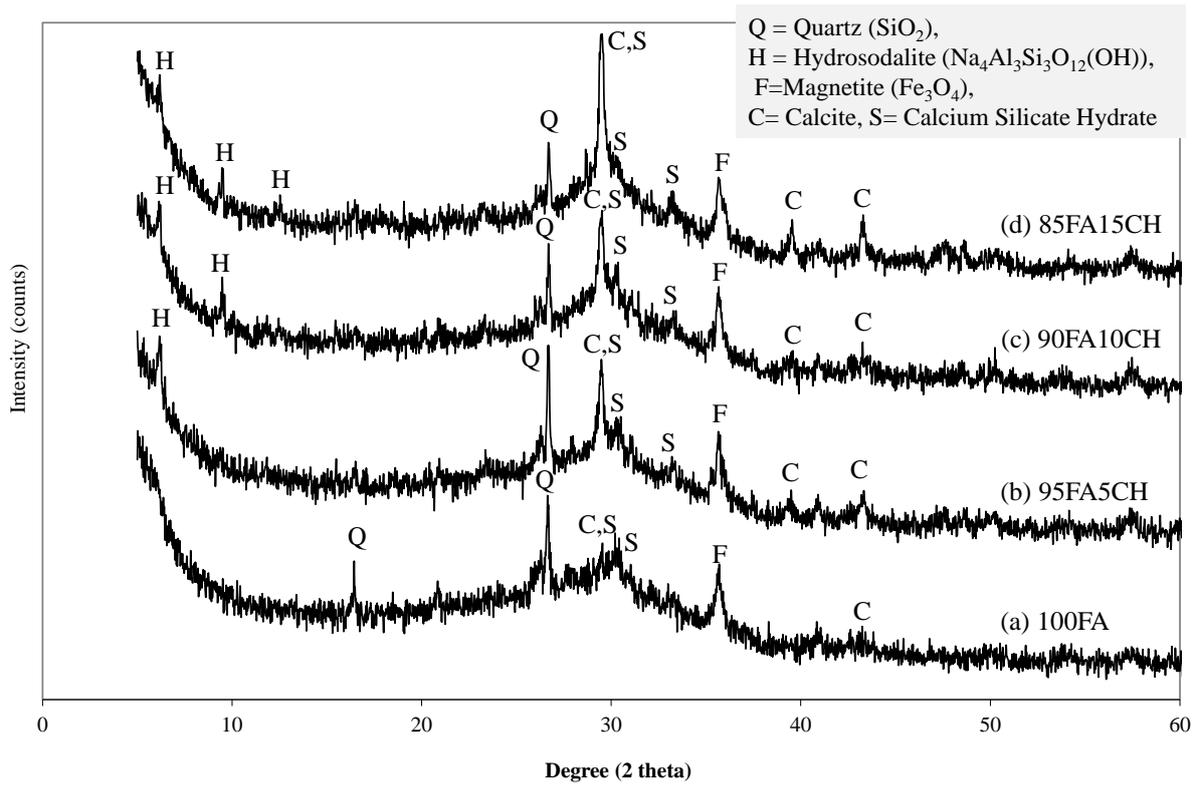


Figure 4. XRD patterns of AAB with CH as an additive

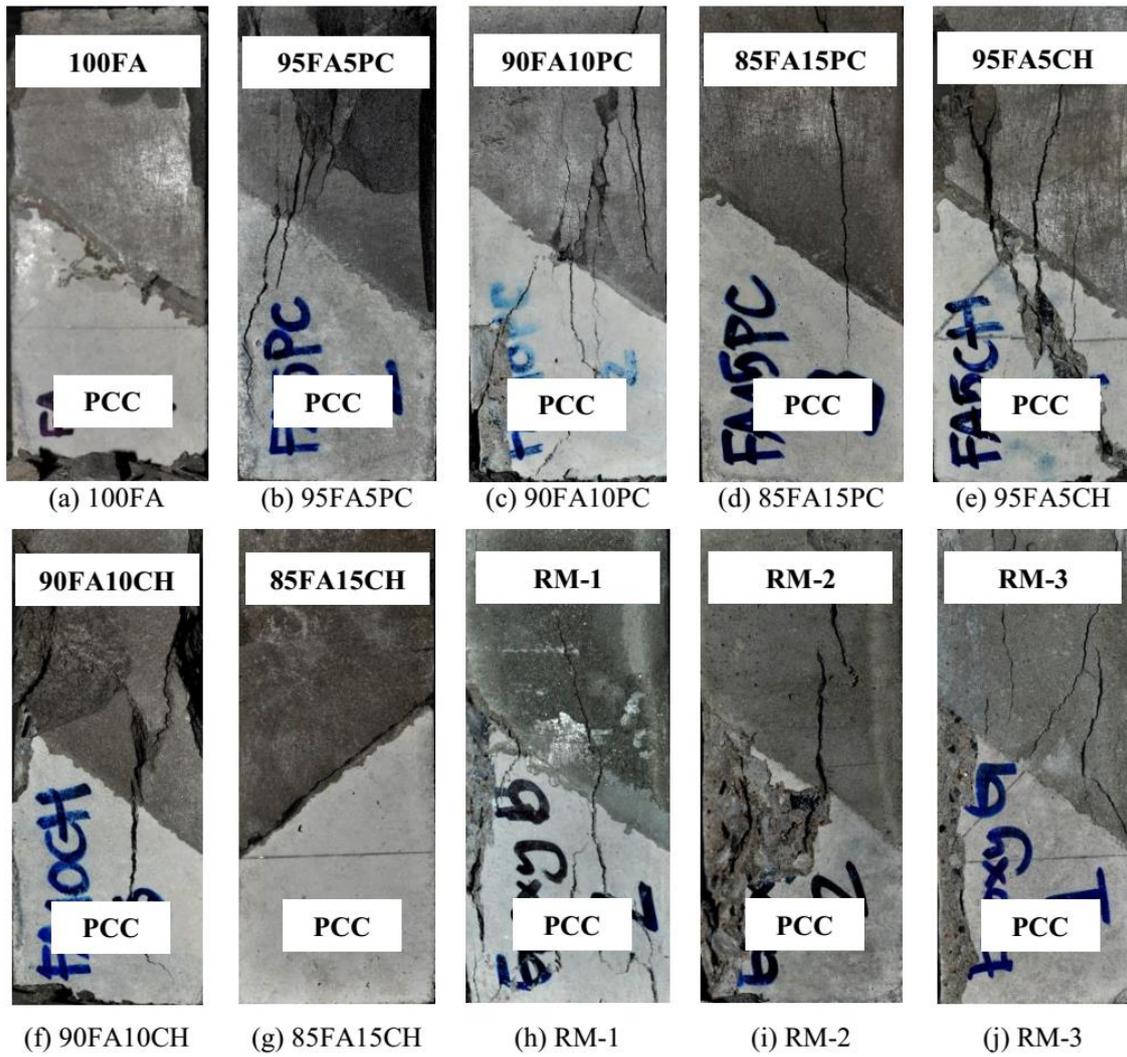


Figure 5. Fracture surface between PCC substrate and AAB and RMs

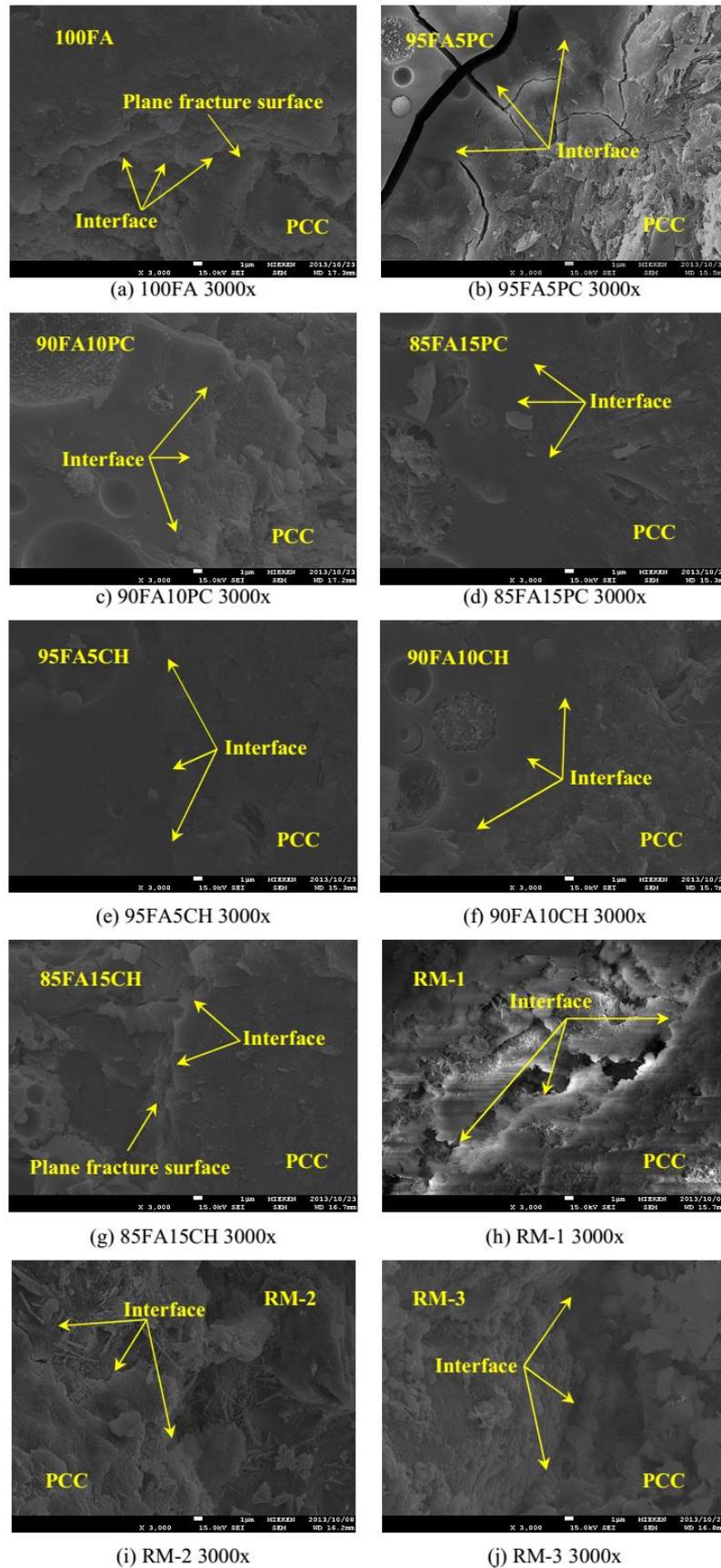


Figure 6. SEM of interface zone between PCC substrate and AAB or RM

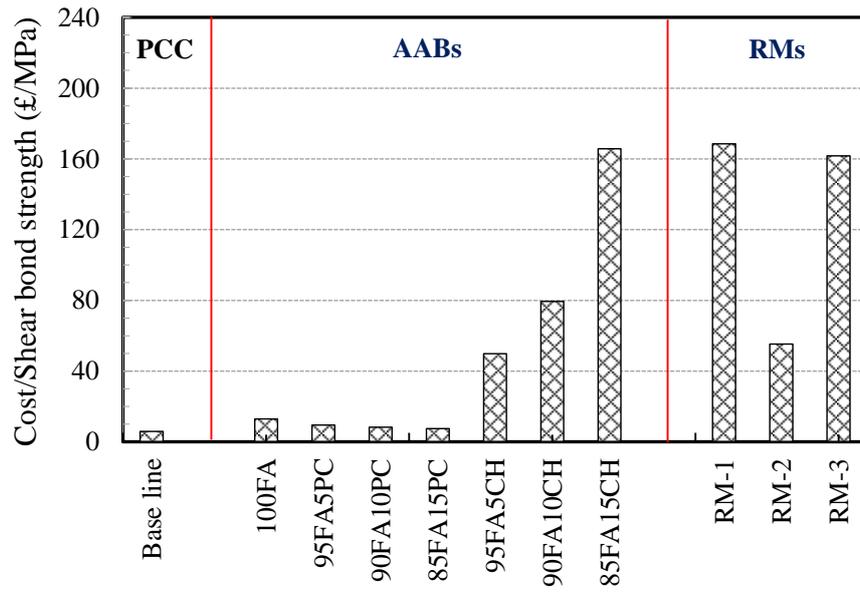


Figure 7. Comparison of cost-effective between AAB and RM