Evaluation on feasibility of fly ash cement mortar as adhesive of post-installed rebar

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Abstract. This study evaluates the feasibility of using fly ash cement mortar as the substitute of commercial anchorage adhesives by means of experimental tests. Temperature effect is also investigated. Different amounts of fly ash are added in the cement mortar and the mortars are mixed according to the proportion design methods illustrated in the literature. In addition, silica sand is used instead of river sand in some mortar. By summarizing the results of flow test, compression test, and fire resistance test of the mortar specimens, three better mixture proportions are determined. The pull-out specimens were prepared by implanting #3 (D10) steel bars into concrete cylinders to a depth of 9 cm. The specimens for temperature effect tests are heated and kept in furnace under 400℃ or 600℃ for 60 minutes and cooled naturally before conducting experimental tests. The feasibility assessment is carried out by comparing the pull-out test results of this study with those of rebars installed with commercial adhesives from earlier study. The results have shown that rebars installed with the proposed cement mortar may achieve acceptable bonding effect, although the bonding strength at room temperature is lower than those of commercial adhesives-installed rebars.

1. Introduction
Repair, reinforcement or expansion of reinforced concrete structures often requires the implantation of deformed steel bars. Since most of the epoxy resin-based adhesives have high strength, material stability, durability, and good bonding effect, the performance of post-installed rebar is usually even better than the cast-in reinforcement [1]. However, study has shown that the adhesive can only withstand 120℃ within a short period of time, otherwise softening and bond failure would occur [2]. For safety reason, efforts have been made to study bonding material substitutions such as cement-based mortar [3, 4]. Since adding fly ash in concrete can help control temperature rise and produce mortar with better workability, mechanical properties and durability, the main purpose of this paper is to develop proper mixture proportions of fly ash cement mortar and to investigate the rebar implanting effect by using fly ash cement mortar.

2. Experimental programs
The experimental tests are performed in two stages. The first stage is to determine the mixture proportion of fly ash cement mortar, while the second stage is to determine the bond strength of post-installed rebar system by the selected mortar either under ambient temperature or after exposure to some levels of elevated temperatures.
There are three series of tests in the mixture proportion stage. The major task of series I is to determine the proper amount of fly ash to be added in the mortar. Series II and Series III are the design of mixture proportions. River sand and silica sand, as the fine aggregates, are used in Series II and Series III, respectively. Three mixtures of mortar providing better workability and strength obtained from the first stage are to be used as the anchorage mortars to install the deformed steel bars into concrete cylinders to prepare the pull-out test specimens. The bonding performance is to be investigated by the failure mode and the bond strength.

2.1. Materials
The composition of fly ash cement mortar includes cement, fly ash, fine aggregate, and superplasticizer. Portland I cement and F-type low-calcium fly ash are used as the cementitious materials. River sand or silica sand is the fine aggregate. The carboxylic acid-based water-reducing agent is selected to be the superplasticizer because it can improve the workability, lower dry shrinkage of the mortar, and is friendly to the environment. The base material of pull-out test specimens is lab-mixed concrete with a slump of 10 cm and a 28 days compressive strength $f'_c$ of 34.3 MPa. The installed rebar uses #3 steel deformed bars ($10\phi$, nominal diameter $d = 10$ mm) with measured yielding load and ultimate tensile load of 26.8 kN and 38.0 kN, respectively. To protect the rebar outside the concrete while the pull-out test is heated in the high temperature furnace, one spray-applied fire resistive coating whose major components including cement, vermiculite and inorganic fire resistive material is utilized. All the materials mentioned above used are obtained from the same batches to minimize variations between samples.

2.2. Specimen preparation
Due to the limitation of our lab equipment, we are unable to perform any tests in fire. Therefore, the temperature effect is investigated by testing at normal ambient temperature on the specimens heated beforehand in the furnace up to the target temperature and hold constantly for another 60 minutes. This procedure is called fire damage process in this paper. All specimens to go through the fire damage process, either mortar cubes or pull-out samples, are kept in the 110°C oven for 24 hours to remove excess humidity for avoiding the possible explosion at elevated temperature.

2.2.1. Cement mortar. Series I include four different proportions of mixture prepared basically according to ASTM standard [5] with slight adjustment of the water-cement ratio in order to fulfil the aimed flow 110±5%. 0, 10%, 15% and 20% by weight of cement is replaced by fly ash for each mixture. Series II includes two mixture proportions designed by means of the proportioning method suggested in the literature [6]. Polycarboxylic acid high-performance water-reducing agent (superplasticizer) is added in the fly ash cement mortar to further improve the workability and strength. There are other two proportions of mortar mixtures in Series III, both use silica sand instead of river sand as aggregate. 5cm×5m×5cm cubic specimens are made of all the mortar mixtures to be tested in compression. There are three identical specimens in each series of tests.

2.2.2. Concrete cylinder and steel bar. The concrete substrate for installing reinforcement is made of standard cylindrical compressive test specimens (15cm×30cm). Steel bars before being installed into concrete are cut with a 45-degree inclination in order to be inserted more easily into the concrete hole filled with fresh mortar.

2.2.3. Pull-out test specimen. First drill a 9-cm deep hole at the centre of the concrete cylinder by a drill bit of 16-mm diameter. Clean the hole completely before filling fly ash cement mortar. Then screw the steel bar into the hole and hold steady until the mortar is set. The pull-out test can be carried out when the age of mortar reaches 7 days. If the specimen is to undergo the fire damage process, it is coated with 1-2 cm thick fireproof covering (figure 1) 3 days before sending into furnace. Open the
door of furnace and let the specimen air-cooled after the fire damage process is finished. Then perform the test after gently removing the fireproof covering.

2.2.4. Fire damage process. The surface cracks are visible when concrete exposed to the temperature reached 600℃ and the cracks become very pronounced at 800℃. In addition, the compressive strength of concrete decreases drastically when the temperature reached above 400℃, and the strength loss is about 80% at 800℃ [7]. Therefore, the ultimate temperature is chosen as 600℃ and the standard time-temperature curve is not followed to perform the fire test. The temperature settings in this study are as shown in figure 2. The temperature inside the drilled hole in the concrete cylinder is also measured and shown in the figure. Obviously, the fire-resistant coating outside the rebar and the surrounding concrete help to delay the temperature rising in the hole.

![Figure 1](image1.png)

**Figure 1.** Pull-out specimen before and after spraying on with fire-resistant material.

![Figure 2](image2.png)

**Figure 2.** Temperature measured during fire damage process.

3. Results and discussions

3.1. Material and mixture proportion test results

The flow test results of all cement mortar mixes are shown in table 1. After several trials and adjustments of the water-to-cementitious material ratio (w/c-m), four mixes in Series I have met the aimed limitation of 110% flow according to the test standards [8]. The mixes with fly ash used less amount of water yet have the same flow. This phenomenon indicates that the addition of fly ash helps to improve the workability of the mortar.

| Series | Mix | w/c-m | water | cement | fly ash | sand | super-plasticizer | flow (%) |
|--------|-----|-------|-------|--------|---------|------|-------------------|---------|
| I      | 68-00-0-r | 0.68  | 0.68  | 1.00   | 0.00    | 2.75 | 0.00             | 110     |
|       | 65-10-0-r | 0.65  | 0.65  | 0.90   | 0.10    | 2.75 | 0.00             | 110     |
|       | 62-15-0-r | 0.62  | 0.62  | 0.85   | 0.15    | 2.75 | 0.00             | 110     |
|       | 59-20-0-r | 0.59  | 0.59  | 0.80   | 0.20    | 2.75 | 0.00             | 110     |
| II     | 38-15-1-r | 0.38  | 0.38  | 0.85   | 0.15    | 0.80 | 0.01             | >300    |
|       | 36-15-1-r | 0.36  | 0.36  | 0.85   | 0.15    | 0.52 | 0.01             | >300    |
|       | 36-15-1-s | 0.36  | 0.36  | 0.85   | 0.15    | 0.52 | 0.01             | >300    |
|       | 29-15-1-s | 0.29  | 0.29  | 0.85   | 0.15    | 0.52 | 0.01             | ≈250   |

*a Mixture numbering (αα-ββ-γ-λ) description: αα represents the water-to-cementitious material ratio (%); ββ is the fly ash proportion in the cementitious material (%); γ is the dosage of superplasticizer in the mortar (%); λ denotes the sand type, r for river sand and s for silica sand. The cementitious material includes Portland cement and fly ash.
There is no limitation of flow for mortar mixes in Series II. The flow test results have shown that the flow ratios of these mortars are over 300 and cannot be accurately determined. The water proportions of mixes in Series II and III are much less than those in Series I. But the flows of these mortars are larger due to the effect of the superplasticizer. The second mix in series III has a relatively low water-to-cementitious material ratio so that the mixture is a little more viscous than the other mixes in Series II and III.

The results of the compression tests of Series I mortar mixtures are shown in table 2 and figure 3. It can be seen from figure 3 that the compressive strength of each mortar increases with age. Among all mixes, the mortar mix without fly ash (68-00-0-r) has the highest strength until 7 days. However, the fly ash mortar mixtures display higher strength after 28 days. We are aiming to have a compressive strength of cement mortar no less than 45 MPa [3]. Unfortunately, none of the mixes in Series I meets the requirement. Because the mix with 15% fly ash (62-15-0-r) has the highest strength on 56 days, 15% of cement is replaced by fly ash for the rest mortar mixtures in Series II and Series III.

| Mix            | Average Compressive strength (MPa) |
|----------------|-----------------------------------|
|                | 3 day    | 7 day    | 28 day   | 56 day   |
| 68-00-0-r      | 26.5     | 32.0     | 38.1     | 41.1     |
| 65-10-0-r      | 23.8     | 29.2     | 38.9     | 42.5     |
| 62-15-0-r      | 22.2     | 24.6     | 36.2     | 42.7     |
| 59-20-0-r      | 23.3     | 28.1     | 40.0     | 39.9     |

Table 3 and figure 4 show the compression test results of different proportions of 15% fly ash cement mortar designed in this study. The 7-day and 28-day compressive strengths of all the four mixtures in Series II and III are higher than the aimed strength 45 MPa. Obviously, the lower the water-to-cementitious material ratio is, the higher the strength would be. Mix 36-15-1-s and Mix 36-15-1-r have the same proportions of all materials except the type of sand. However, the average compressive strength of Mix 36-15-1-s is about 30% higher than that of Mix 36-15-1-r. It indicates that using silica sand as aggregate could promote the compressive strength of cement mortar by a significant degree.

| Series | Mix          | Average compressive strength (MPa) |
|--------|--------------|-----------------------------------|
|        |              | 3 day    | 7 day    | 28 day   |
| II     | 38-15-1-r    | 36.3     | 46.6     | 51.7     |
|        | 36-15-1-r    | 39.2     | 46.8     | 63.0     |
| III    | 36-15-1-s    | 51.1     | 63.4     | 76.1     |
|        | 29-15-1-s    | 61.3     | 65.7     | 95.2     |
We further compare the compressive strength after fire damage process at 400℃ and 600℃ of cement mortar specimens of Mixes 36-15-1-r, 36-15-1-s, and 29-12-1-s. The test results are listed in table 4 and the comparison among different mixes at different ages are as shown in figure 5. Obviously, the specimens after 400℃ fire damage process have much higher compressive strengths than the specimens at ambient temperature and after 600℃ fire damage process. The 3-day and 7-day strengths increased dramatically, especially in Mix 29-15-1-s, the 7-day compressive strength raises to 57.4%. Strengths of most specimens after 600℃ fire damage process decrease. The degree of decline ranges from 2.78% to 23.7%. Nevertheless, even the specimens were heated to 600℃ in the furnace for 60 minutes, the compressive strengths of these mortar mixture are still higher than the aimed strength 45 MPa.

**Table 4.** Average compressive strength of fly ash cement mortar at room temperature and after fire damage process.

| Mix       | Temperature (°C) | 3 day Strength (MPa) | Variation 1 (%) | 7 day Strength (MPa) | Variation 2 (%) | 28 day Strength (MPa) | Variation 1 (%) | Variation 2 (%) |
|-----------|------------------|----------------------|-----------------|----------------------|-----------------|-----------------------|-----------------|-----------------|
| 36-15-1-r | 25               | 39.2                 | -               | 46.8                 | -               | +19.4                 | 63.0            | -               | +60.7           |
|           | 400              | 47.9                 | +22.2           | 58.1                 | +24.1           | 21.3                  | 71.1            | +12.9           | +48.4           |
|           | 600              | 45.5                 | +16.1           | 45.5                 | -2.78           | 0.0                   | 52.8            | -16.2           | +16.0           |
| 36-15-1-s | 25               | 51.1                 | -               | 63.4                 |                | 24.1                  | 76.1            | -               | +48.9           |
|           | 400              | 59.4                 | +16.2           | 73.8                 | +16.4           | 24.2                  | 82.6            | +8.54           | +39.1           |
|           | 600              | 48.5                 | -5.09           | 48.4                 | -23.7           | -0.206                | 72.6            | -4.60           | +49.7           |
| 29-15-1-s | 25               | 61.3                 | 0               | 65.7                 |                | +7.17                 | 95.2            | -               | +55.3           |
|           | 400              | 94.1                 | +53.5           | 103.4                | +57.4           | 9.88                  | 106.7           | +12.1           | +13.4           |
|           | 600              | 54.6                 | -10.9           | 50.8                 | -22.7           | -6.96                 | 73.9            | -22.4           | +35.3           |

* Variation 1 (%) = \( \frac{\text{strength}_{\text{high temp}} - \text{strength}_{25\,\text{°C}}}{\text{strength}_{25\,\text{°C}}} \) × 100

* Variation 2 (%) = \( \frac{\text{strength}_{\text{other age}} - \text{strength}_{3\,\text{day}}}{\text{strength}_{3\,\text{day}}} \) × 100

**Figure 5.** Compressive strength of fly ash cement mortars after fire damage process.

### 3.2. Pull-out test results

The specimens of pull-out tests use three fly ash cement mortar mixtures, Mixes 36-15-1-r, 36-15-1-s, and 29-15-1-s, as anchorage materials. All the pull-out tests were carried out 7 days after the rebar post-installed in the concrete cylinders. The test results are shown in table 5. The failure loads of three
mixes at normal ambient temperature are 29.5 kN, 22.3 kN and 30.7 kN, respectively. Let’s look back again at the 7-day compressive strength of these three mixes as listed in table 3, we can see the strengths of Mix 36-15-1-s (63.4MPa) and Mix 29-15-1-s (65.7MPa) are 35.5% and 40.4% higher than the strength of Mix 36-15-1-r (46.8MPa). However, the average pull-out load of rebar installed with Mix 29-15-1-s is only 4.04% higher than that with 36-15-1-r, and the pull-out load of rebar installed with Mix 36-15-1-s is lower than that with 36-15-1-r by 24.4%. We had seen the specimens display lower loads into halves to examine the interface between rebar and concrete hole and found that some of the cement mortar did not adhere to concrete well enough to produce better bond effect. This is partly due to the uneven mix of the compositions.

Table 5. Failure loads and failure modes of pull-out tests.

| Mix      | Temperature (℃) | Failure Mode       | $P_u$ (kN) | Variation 1\(^a\) (%) | Variation 2\(^b\) (%) | Variation 3\(^c\) (%) |
|----------|-----------------|--------------------|------------|------------------------|------------------------|------------------------|
| 36-15-1-r| 25              | bond failure       | 29.5       | -                      | -                      | -14.5                  |
|          | 200             | bond failure       | 31.4       | +6.18                  | -                      | -8.99                  |
|          | 400             | bond failure       | 26.2       | -11.4                  | -                      | -24.1                  |
|          | 600             | bond failure       | 14.5       | -50.9                  | -                      | -58.0                  |
|          | 25              | bond failure       | 22.3       | -                      | -24.4                  | -35.4                  |
| 36-15-1-s| 400             | bond failure       | 29.4       | +31.8                  | +12.2                  | -14.8                  |
|          | 600             | bond failure       | 18.5       | -17.0                  | +27.6                  | -46.4                  |
|          | 25              | bond failure       | 30.7       | -                      | +4.07                  | -11.0                  |
| 29-15-1-s| 400             | Steel fracture     | 34.5       | +12.4                  | +31.7                  | 0.0                    |
|          | 600             | bond failure       | 30.1       | -1.95                  | +108                   | -12.8                  |

\(^a\) Variation 1 (%) = \(\frac{P_{u, \text{other Temp}} - P_{u, 25℃}}{P_{u, 25℃}}\) \times 100; \(^b\) Variation 2 (%) = \(\frac{P_{u, \text{other mix}} - P_{u, 36-15-1-r}}{P_{u, 36-15-1-r}}\) \times 100; \(^c\) Variation 3 (%) = \(\frac{P_{u, 34.5} - 34.5}{34.5}\) \times 100, 34.5kN = the average pull-out capacity of steel bar fracture

Among the three mixes of mortar, the anchorage performance of Mix 29-15-1-s is the best. Obviously, to use lower water-to-cementitious material ratio and silica sand are beneficial. All three specimens undergone 400 ℃ fire damage process have failed by the fracture of steel bars. The bond force must be higher than the steel fracture load of 34.5 kN listed in table 5. Besides, figure 6 shows that the pull-out specimens go through the fire damage process at 400℃ display the best bonding performance. Although the failure loads reduce when the temperature reaches 600 ℃, the failure loads for three Mixes still retain 42.0%, 53.6% and 87.2% of the ultimate tensile force of the rebar.

Figure 6. Failure loads of pull-out tests of fly ash cement mortars.
3.3. Comparison with previous research results
In order to understand the difference of anchorage performance between the fly ash cement mortar and other adhesives, and to preliminary evaluate the effect of the proposed mortar, the experimental results of this study are compared with those of two commercially available resin-based adhesives [9] and a concrete quick repair material [10]. The relationship between compressive strength and temperature of these anchorage materials is shown in Table 6.

Table 6. Compressive strength of different anchorage materials at room temperature or after fire damage process.

| Anchorage materials | Average compressive strength (MPa) |
|---------------------|----------------------------------|
|                     | 25°C    | 100°C   | 200°C   | 300°C   | 400°C   | 600°C   |
| Adhesive I [9]      | 105     | 111     | 128     | 0       | 0       | 0       |
| Adhesive II [9]     | 100     | 111     | 55.2    | 0       | 0       | 0       |
| Repair Material [10]| 53.4    | NA      | 15.0    | 11.1    | 13.1    | 12.2    |
| Mix 36-15-1-r (28 day) | 63.0  | NA      | 95.1    | NA      | 71.1    | 52.8    |
| Mix 36-15-1-s (28 day) | 76.1  | NA      | NA      | NA      | 82.6    | 72.6    |
| Mix 29-15-1-s (28 day) | 95.2  | NA      | NA      | NA      | 106.7   | 73.9    |

Commercial adhesives have excellent compressive strengths below 200°C, but they are seriously damaged after the temperature rises to 300°C. The concrete rapid repair material has similar strength to the fly ash cement mortar Mix 36-15-1-r at room temperature. However, when the temperature exceeds 200°C, the strength reduces to 28% of the normal temperature strength. The compressive strength of fly ash cement mortar at room temperature is about 60% to 92% of the strength of the commercial adhesives, but even if the temperature rises to 400°C or 600°C, the compressive strengths are still higher than the aimed strength of 45 MPa. Compared with the other anchorage materials, the fly ash cement mortar mixtures proposed in this study have the best fire resistance.

Table 7 shows the relationship among the bond strengths of rebars installed by different anchorage materials before or after being heated to elevated temperatures. Surprisingly, the commercial adhesives have the best bonding performance among all kinds of anchorage materials even if the pull-out specimens have undergone 600°C fire damage process before testing. Both specimens using Adhesive I and Adhesive II maintain about 80% of the bond strength after fire damage process up to 500°C. Moreover, adhesive I displays good bond strength even after 800°C fire damage process. Concrete Rapid Repair Material has excellent bond strength, similar to the commercial adhesives, at room temperature, but loses most bonding ability once the temperature starts to rise. The bond strengths of the proposed fly ash cement mortars are only 50% as high as the commercial adhesives and the Concrete Rapid Repair Material at room temperature. However, the strength decreases with temperature is more moderate. After 600°C fire damage process, Mix 29-15-1-s retains the same bonding strength as at room temperature and it is higher than the bond strength of Adhesive II.

Table 7. Bond strength of rebars post-installed by different anchorage materials at room temperature and after fire damage process.

| Anchorage materials | Average bonding strength (MPa) |
|---------------------|-------------------------------|
|                     | 25°C    | 100°C   | 200°C   | 300°C   | 400°C   | 500°C   | 600°C   | 800°C   |
| Adhesive I [9]      | 21.9    | 23.8    | 22.8    | 22.3    | 21.6    | 17.3    | 11.9    | 10.8    |
| Adhesive II [9]     | 22.1    | 23.4    | 22.0    | 21.3    | 16.1    | 19.0    | 6.38    | 1.96    |
| Repair Material [10]| 20.9    | NA      | 3.34    | 3.83    | 5.00    | NA      | 3.04    | NA      |
| Mix 36-15-1-r       | 11.0    | NA      | NA      | NA      | 9.71    | NA      | 5.38    | NA      |
| Mix 36-15-1-s       | 3.48    | NA      | NA      | 10.9    | NA      | 6.89    | NA      | NA      |
| Mix 29-15-1-s       | 11.08   | NA      | NA      | 12.75   | NA      | 11.08   | NA      | NA      |
4. Conclusions

Several conclusions are drawn from this study.

- The additions of fly ash and superplasticizer can improve the workability and strength of cement mortar. Besides, to use lower water-to-cementitious material ratio and to use silica sand as aggregate are beneficial to the strength of fly ash cement mortar.
- The proposed mortar mixtures, using 15% fly ash, 1% superplasticizer, and water-to-cementitious material ratio of 0.36 or 0.29 can provide acceptable compressive strength at room temperature and after fire damage process.
- Among the three different mixtures of mortar proposed in this study, the compressive strength and the bonding performance of Mix 29-15-1-s is the best.
- Compared with the other anchorage materials, the proposed fly ash cement mortar mixtures have the best fire resistance.
- Although the bond strengths of the proposed mortar mixtures are about 50% of the commercial adhesives at room temperature, the bond strengths of the mixtures after fire damage process are similar to those of commercial adhesives. After 600°C fire damage process, Mix 29-15-1-s retains the same bond strength as at room temperature and it is higher than the bond strength of commercial Adhesive II.
- The preliminary evaluation of the fly ash cement mortar is considered feasible, but more detailed research is required before the actual application.

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