Feasibility Study on the Utilization as Repair Grouting of High Flowable Polymer-Modified Cement Mortar, Adding High Volume Polyacrylic Ester (PAE)

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Abstract
To investigate the modification of PAE-modified cement mortar with high flowability and fracture mode of adhesive strength properties in tension, experimental parameters were set as PAE solid-cement ratio (P/C) and cement: fine aggregate (C:F) and experiments regarding unit weight, flow, consistency change, crack resistance and segregation were conducted. Adhesion in tension was measured to comprehend the properties and fracture mode in tensile load. It was found to be superior to that of resin based materials such as polyurethane and epoxy which showed entire loss of consistency in an elapsed time of 90 min. after mixing. Adhesive strength in tension increased with continuity during curing period and showed the maximum in the case of C:F=1:1 and P/C=20%.

Keywords: grouting; repair; PAE; cement mortar; consistency change; high volume; high flowability

1. Introduction
A number of studies on a material and/or a method of construction to improve the performance of cement mortar as well as to obtain economic efficiency by enhancing its properties, particularly flowability and workability, have been carried out. In the case of application of cementitious mortar, the reduction of physical performance through segregation and bleeding is inevitable. However, consistency and workability indicated as flow values tend to increase with an increase in the water-cement ratio. Although there have been various material methodologies to settle the problem of abrasion resistance, water resistance, chemical resistance, etc., organic polymeric materials that have the characteristics of hydrophilic colloid have been widely used as a modification of cementitious mortar. It is already known that polymeric materials of polymer dispersion and redispersible powders have both the rheological properties and adhesive strength of cementitious mortar improved through surface active reaction and specific high viscosity of the polymer solid itself in comparison with non-modified mortar.

Ohama, et al. [1-3] performed an experiment on the adhesion of polymer-modified mortars to ordinary cement mortar as a substrate, measured by four types of test methods such as adhesion in tension, flexure, direct shear and slant shear. In that study, it was concluded that the development of adhesion was attributed to the high adhesion of polymers and that the adhesion was usually affected by the polymer-cement ratio, the properties of substrates used and stresses. Moreover, the data on adhesion often showed considerable scatter, and varied depending on the testing methods, service conditions or porosity of substrates.

The use of polymer in building materials can compensate for the above weakness but can also result in a substantial increase of the material cost. Therefore, polymers have to be used only in areas where the higher material cost can be compensated for (e.g. low labor cost), to make the total cost reasonable.

For the purpose of improving the durability related to chemical resistance and permeability as well as the above deficiencies, mortar mainly composed of resin such as epoxy and polyurethane (Resin Mortar; RM), not including the cementitious materials as binder, or modified mortar by adding the polymer emulsion such as the dispersion of SBR, PAE, EVA, and PVAC etc and redispersible powder such as SBR, EVA, and VA/VeoVa, etc. has been applied in situ. Adhesion in tension between the mortar and the substrate of old concrete is the required property for grouting repair materials used to protect old concrete. When applying resin mortar, various defects can occur at the interface between the grouting repair material and the substrate because the former is heterogeneous with the substrate in nature. Considering that it is also possible that a similar phenomenon can occur when a polymer-modified mortar is used in repair work, adhesion in

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tension between them is likely the most important requirement, as most of the defects such as spalling/delamination and scaling originated from the decrease in adhesion.

Thus, general properties such as unit weight and consistency change of high flowability specimens made with polyacrylic ester (PAE) were measured in order to investigate both adhesion and fracture mode that are dependent on the curing age, PAE solid-cement ratio (P/C), and cement-fine aggregate ratio (C:F) [9-12]. To analyze the feasibility of the utilization as grouting repair materials this study investigates the general properties of cement mortar with high flowability modified by high volume-added PAE emulsion, while additionally analyzing the interface between the specimens and concrete substrate through SEM examination.

### 2. Experimental Program

#### 2.1 Material properties

**2.1.1 Cement and fine aggregate**

In this study, the ordinary Portland cement specified in KS 5201 was used for all the mortar mixes. Fine aggregate whose grade size is not more than 1.2mm as shown in Fig.1. was used.

**2.1.2 Polymer dispersions for cement modifier**

The commercial cement modifier used was polyacrylic ester (PAE) emulsion. The properties of the cement modifier used are given in Table 1.

**2.1.3 Antifoaming agent**

In most polymer-modified mortars, a large quantity of air is entrained compared to that in ordinary cement mortar because of the action of the surfactants contained as emulsifiers and stabilizers in polymer dispersion [3]. An excessive amount of entrained air causes a reduction in strength and is controlled by using 0.7 wt% of proper silicone-emulsion type antifoamer to the total solid weight of polymer dispersion.

**2.1.4 Resin-based materials**

Polyurethane and epoxy, having the characteristics of thermosetting liquid resin, were used in order to analyze the mechanical performance of fresh and hardened materials, and its properties were compared with those of polymer-modified cement mortar with high flowability for grouting repair materials by wide application of repair materials in the same condition.

Commercial cementitious grouts (named as SL-1, SL-2, respectively) were used for the purpose of comparing the basic properties such as adhesion in tension and consistency change etc., with the specimen in this study.
2.1.5 Chemical admixtures for adjusting the flowability

In this study, a viscosity-enhancing agent of water-soluble cellulose ether type (hydroxy ethyl cellulose, HEC) was used when excessive water existed. The naphthalene type was employed in the case of the opposite.

2.2 Preparation of specimen and experiments

2.2.1 Manufacture of substrate

The substrate for the test was designed for concrete with the target compressive strength of $f_{ck} = 24$ MPa and a required slump value of not less than 15 cm. Mix design proportions with any material content as presented in Table 2 were determined after trial mixing. The size of the substrates for the test was $300\text{mm} \times 300\text{mm} \times 60\text{mm}$. The surfaces of these were cleaned using No. 150 abrasive papers as specified in the KS L 6003 (Abrasive papers), to eliminate the effects of dust such as laitance, etc.

2.2.2 Mix design for specimen preparation

In accordance with JIS A 1171 (Method of Making Test Sample of Polymer-Modified Mortar in the Laboratory), polymer-modified cement mortars were prepared with cement-sand ratios of 1:1 and 1:3 (by weight) respectively and polymer-cement ratios (calculated on the basis of the total solids of each emulsion) of 50% and 75%. The mortars were prepared with the mix proportions given in Table 3 and their flow was adjusted to be constant at $200 \pm 5$ mm.

2.2.3 Experimental items

The unit weight was measured as specified in KS F 2475 (Method of Test for Unit Weight and Air Content of Fresh Polymer-Modified Mortar). The flows of the specimens were measured by using a cylindrical mold of the size $5\phi \times 5$ mm, as specified in JASS-16B-103, and consistency change, as specified in KS F 4716 (Cement Filling Compound for Surface Preparation). Testing was carried out immediately after mixing (F1) and then 90 minutes after mixing (F2) to determine the consistency change. Flows of the specimens in all mixtures and conventional grouting repair materials were observed and the consistency change was calculated as follows.

Consistency change ($\%) = \frac{F_i - F_f}{F_f} \times 100$

In accordance with KS F 4716 (Cement Filling Compound for Surface Preparation), 40$\times$40$\times$2 mm specimens were molded, and then subjected to a 20°C-65% R.H.-dry cure. It was carried out conforming to the procedure as follows.

a. Procedure of adhesion test

The surface of each specimen placed horizontally was coated with an adequate adhesive. Then the upper jig for tensile loading was gently set and bonded on the epoxy-coated surface, and the adhesive forced out around the jig was carefully removed. After storing the specimen with the upper jig for tensile loading in the room for 24 hours, as shown in Fig. 2, the load was vertically applied to the specimen by use of the lower jig for tensile loading. The maximum load indicated by the testing machine until the failure of the specimen was estimated \(^9\), \(^10\).

After the adhesion test, the fracture modes of the specimen were recorded. The adhesion of the specimen was calculated from the following equation, and rounded off to one decimal place.

$$\sigma_a = \frac{L}{16}$$

where; $\sigma_a$ is the adhesion (MPa), and $L$ is the maximum load (Newton).

3. Results and Discussion

3.1 Unit weight

Fig. 3. represents the relation between PAE solid-cement ratio and the density of the specimen designed as 1:1 and 1:3 of cement:fine aggregate in the case of being coordinated with a flow value of $200 \pm 5$ mm. The unit weight of specimens decrease with increase in PAE-cement ratio independent of the relative ratio between cement and fine aggregate. Unit weights were measured to be approximately 2.0 to 1.5 kg/liter because the specific gravity of the fine aggregates used in this study is about 2.0, and that of PAE solid is about 1.0 or lower. With the increase of PAE-cement ratio, the volume occupied by the PAE solid over the unit volume is also increased but the volume occupied by the fine aggregate decreases.

The unit weight of the specimens in which the ratio of fine aggregate to cement (by weight) is equal to 1:3 is higher than that of the specimens of C:F = 1:1 in the range of 1.5% ~ 2.5% in the difference of occupied volume of each materials with respectively different specific gravity. Fig. 4. shows the unit weights of commercial grouting repair materials being applied to the concrete structures. The resin-based grouting repair materials composed of Polyurethane and Epoxy resin, respectively, have a unit weight of 1.5 or below, while SL-1 and SL-2 are almost similar or higher unit weights than the specimens used in this study.

3.2 Flow and consistency change

Figs. 5. and 6. illustrate the flow and the consistency change of the PAE modified cement mortar with the change of the P/C ratio as well as the C:F ratio and the
commercially grouting repair materials, respectively. It can be noted through this study, that the consistency change decreases with the increase in P/C ratio. Also the consistency change for specimens with a cement-sand ratio of 1:3 is higher than that with a ratio of 1:1 because of the difference in the water absorption caused by the fine aggregates. This is the reason why the grain shape of silica sand seems to be angular and the quantity of water adsorbed in the surface of the fine aggregates increases with the increasing amount of fine aggregates. When the ratio of the fine aggregates to cement (by weight) is equal to 1:3, segregations occurred in both 10% and 20% of the PAE-cement ratio. This is because of the insufficiency of the PAE solid which is capable of preventing segregation of the mixture by enhancing the viscosity regardless of the inevitable high W/C caused by the flow coordination of the mixtures. The consistencies of polyurethane and epoxy resins decreased after an elapsed time of 90 minutes because of fast initial chemical reaction as seen in Fig.6. SL-1 and SL-2, which are commercial cementitious grouting repair materials showing a good consistency property with a change of lower than 3% with time.

3.3 Crack resistance of confined specimen and segregation

In general, the volume of the cement paste is dependent on the moisture content of the paste. Drying induces volume reduction (drying shrinkage) and it is inevitable that the initial drying (i.e. drying out phenomenon) of paste derives maximum dry shrinkage from paste. Applying the above drying process to cement mortar results in the development of cracks. This is due to the tensile stress according to the restraint provided by the bonding of the substrate at the ends and underneath. Moreover cracks can occur when the tensile strength of the specimen is lower than the tensile stress developed by both surface tension...
and restraint. Based on the consideration above, all the specimens prepared with PAE emulsion in this study did not crack in the standard condition of 20°C and 65% relative humidity. However, segregation and bleeding occurred in the specimens with a C:F ratio of 1:3 and P/C of 10% and 20%.

3.4 Adhesion in tension

Fig. 7 represents the relation between the P/C ratio and the adhesion in tension of specimens with various curing ages for the relatively long term of 50 days. Considering only the adhesive strength out of the several required properties of the specimen, the specimen with a P/C ratio and C:F ratio of 20% and 1:1, respectively, shows the highest adhesive strength value. The adhesion in tension of the PAE-modified cement mortar with high flowability decreases with increasing P/C ratio, where in this mix a P/C ratio of 20% and a C:F ratio of 1:1 were used. This decrease is due to the fact that an increase in the P/C ratio gives rise to the increase of unit water (water content per 1 cubic meter) in the mix. This phenomenon is the reason why solid and water are fixed in the PAE emulsion. When the P/C ratio is 75%, the water-cement ratio of the mixture, with direct relation to strength and durability, amounts to as much as 80%. Adhesion in tension also decreases with an increase in the C:F ratio because the quantity of the binder (cement + PAE total solid) that can be made to promote adhesion relatively decreases with increasing fine aggregates in all mixtures. Adhesive strength in tension is almost linearly increased with the curing age for specimens with a C:F ratio of 1:1 because of the effect of strength development by cement hydration and water retention and the sealing phenomenon by the PAE emulsion.

Fig. 8 shows the comparison of the adhesion in tension between the PAE-modified cement mortar with high flowability and the resin-based materials, i.e., polyurethane and epoxy resin. The specimen in this study appears to be somewhat inferior to that of the grouting repair materials using polyurethane resin. Most of the specimens have adhesions over 2.0 MPa at a curing age of 28 days. Adhesion in tension over 3.0 MPa is recorded only for cases where the curing age is 50 days.

Figs. 9 and 10 present the fitting curve of the data on the adhesion in tension based on the change of the unit polymer solid content and unit aggregate, respectively, together with the related formula. This fitted curve is capable of being used in the material design considering the required adhesion strength of the grouting repair materials.

It was found that the correlation between the adhesion in tension and the unit weight of each
ingredient of specimens proved to be expressed as a 2 degree function. Thus, the peak of adhesion in tension is attained and after that, adhesion in tension tends to decrease together with the increase of both unit polymer content and unit fine aggregate. From the above result, it was proven that the adhesion in tension of the specimen and the concrete substrate when the C:F ratio is 1:1.

Fracture of the specimens occurred when the P/C ratio was not more than 30% and when the C:F ratio was 1:3. Also, the cement mortars with high flowability modified by PAE emulsion has the properties of showing the fracture at the interface between the specimen and concrete substrate because the C:F of 1:1 has a greater quantity of binder than that of 1:3 when the PAE-cement ratio is over 30%. The tensile strength of the specimen with a P/C of 20% and a C:F ratio of 1:1 can be estimated to be about 3.5 MPa or slightly below, from the schematic diagram of Fig.11, because the adhesion in tension of the specimen shows about 3.5 MPa.

3.5 Fracture mode of specimens

Fig.11 illustrates the schematic diagram and analysis of the fracture mode of the specimen in the adhesive test. Table 4 presents the fracture mode of specimens caused by a tensile load according to cement-fine aggregate and PAE-cement ratio ranging from 10 to 75% with change in curing age.

Adhesion in tension at the interface between the specimen and the concrete substrate increases with curing age because the adhesion in tension of the specimen increases with curing age and the fracture mode is fixed. It is observed that specimens with a P/C ratio below 20% fail at the specimen of the PAE-modified cement mortar, while those with a PAE-cement ratio over 30% fail at the interface between the specimen and the concrete substrate when the C:F ratio is 1:1.

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Table 4. Fracture Mode of Cement Mortar with High Flowability Modified by PAE Emulsion

<table>
<thead>
<tr>
<th>C:F</th>
<th>P/C (%)</th>
<th>3 days</th>
<th>7 days</th>
<th>28 days</th>
<th>50 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:1</td>
<td>10</td>
<td>S frac</td>
<td>S frac</td>
<td>S frac</td>
<td>S frac</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>S frac</td>
<td>I frac</td>
<td>I frac</td>
<td>I frac</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>S frac</td>
<td>I frac</td>
<td>I frac</td>
<td>I frac</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>S frac</td>
<td>I frac</td>
<td>I frac</td>
<td>I frac</td>
</tr>
<tr>
<td>1:3</td>
<td>75</td>
<td>I frac</td>
<td>I frac</td>
<td>C frac</td>
<td>I frac</td>
</tr>
<tr>
<td>10</td>
<td>S frac</td>
<td>S frac</td>
<td>S frac</td>
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</tr>
<tr>
<td>20</td>
<td>S frac</td>
<td>1 frac</td>
<td>C frac</td>
<td>C frac</td>
<td>C frac</td>
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<tr>
<td>30</td>
<td>S frac</td>
<td>S frac</td>
<td>S frac</td>
<td>S frac</td>
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<tr>
<td>50</td>
<td>I frac</td>
<td>I frac</td>
<td>C frac</td>
<td>C frac</td>
<td>C frac</td>
</tr>
<tr>
<td>75</td>
<td>I frac</td>
<td>I frac</td>
<td>C frac</td>
<td>C frac</td>
<td>C frac</td>
</tr>
</tbody>
</table>

a. C:F and P/C indicate cement:fine aggregate and polymer-cement ratio, respectively.

3.6 Adhesion process and observation of interfacial layer by SEM

Fig.12. illustrates the adhesion process of the PAE-modified mortar with high flowability which is similar to the formulation of a co-matrix which consists of cement gel and polymer films. Normally, the process of polymer film formation on the cement follows the principle of polymer modification in which, after the mixtures of cement gel and unhydrated cement particles are enveloped with a closely-packed layer of polymer particles, with water withdrawal by cement hydration, the closely-packed polymer particles on the cement hydrates coalesce into continuous films or membranes. Similarly, the adhesion process of polymer-modified cement mortar with high flowability to the substrate can be represented by the procedure that, after being placed on the concrete substrate,
the polymer particles are partially deposited on the concrete substrate and the layer of the closely-packed polymer particles is subsequently formed and the closely-packed polymer particles then coalesce into continuous films.

The adhesive strength of highly flowable polymer-modified cement mortar is thought to be principally dependent on the continuous films formed on the concrete substrates when fracture of the specimen in the adhesive test occurs in the interface between the specimen and the concrete substrate (16-17). The layer of the polymer film formed between the specimen and the concrete substrate is primarily responsible for the adhesive strength.
concrete substrate can be observed in Fig.13., which is an electron micrograph figure of the interfacial layer.

4. Conclusions
This study has shown which properties of the cement mortar with high flowability modified by the PAE emulsion were developed. Based on the test results, the following conclusions can be drawn.

1) The unit weights of the specimens decrease with an increase in the PAE-cement ratio (P/C) and range between approximately 1.5 to 2.0 kg/liter.

2) Consistency change decreased with the increase in the P/C ratio, and consistency change of the specimens with a cement-fine aggregate (C:F) ratio of 1:3 was higher than that with a ratio of 1:1. While on the contrary, polyurethane and epoxy resin of commercial grouting repair materials had considerable difficulty regarding consistency change.

3) Adhesion in tension of the PAE-modified cement mortars was highest when the P/C ratio was 20% and the C:F ratio was 1:1. The adhesion in tension of the specimen with P/C and C:F ratios of 20% and 1:1, respectively, was higher at a curing age of 50 days than that of polyurethane resin, SL-1 and SL-2, although it was lower than that of epoxy resin.

4) Crack resistance of the confined cement mortar with high flowability modified by the PAE emulsion was very good because all specimens were not cracked, and segregation occurred at a P/C ratio of 10% and 20% when the C:F ratio was 1:3.

5) Adhesive characteristics in the tension of the specimens are comparable to those with conventional resin-base grouting repair materials of polyurethane and epoxy. From the SEM investigation, its interfacial layer with the concrete substrate is found to be composed of the polymer film forming the coalescence of the polymer particle. The adhesive strength of the highly flowable polymer-modified cement mortar is thought to be principally dependent on the continuous films formed on the concrete substrates when the fracture of the specimen in the adhesive tests occurs at the interface between the specimen and the concrete substrate.

6) It is found that the high flowable polymer-modified cement mortar with high volume PAE is very effective in terms of good adhesive properties as well as superior workability identified by flow and consistency tests.

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