Comparison of Physical Properties of PAE Polymer-Modified Mortars From Recycled Waste Artificial Marble and Waste Concrete Fine Aggregates

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Abstract: In this study, we compared the properties of PAE (polyacrylic ester) polymer-modified mortars prepared from recycled waste artificial marbles and waste concrete fine aggregates. We used PAE emulsion as a polymer modifier; 30 types of specimens of polymer-modified mortars were prepared by varying the portions of the polymer modifier and the recycled fine aggregates. To evaluate the properties of the polymer-modified mortars, we determined the air contents, water-cement ratios, unit weights, water absorptions, compressive strength, flexural strength, hot water resistance, and pore volumes. The compressive and flexural strengths of the specimens decreased upon increasing the replacement ratios of the recycled fine aggregates, while they increased upon increasing the additive amount of the polymer modifiers. For the specimens that were prepared from waste artificial marble, the compressive and flexural strengths of the specimens, determined after hot water resistance testing, were decreased significantly. The pore volumes, determined after hot water resistance testing had decreased.

Keywords: PAE polymer modifier, polyer-modified mortar, recycling, polymer-cement ratio, replacement ratio

Introduction

As the construction industry grows rapidly together with economic growth, the demand for aggregates is rapidly increasing. River sand, river gravel, and even ocean sand are currently being exhausted and the natural environment of the land is being destroyed as a result of aggregates collecting works to obtain crushed aggregates. Because the demand for aggregates steadily increases, while the supply is absolutely limited, the use of recycled aggregates obtained by crushing waste concrete is inevitable when attempting to balance demand and supply [1,2]. Because the amount of waste concrete generated in Korea is estimated to be ca. 24 million tons a year [3], while the capacities of the landfills of construction wastes has almost reached the limit and new landfills are difficult to site, recycling of waste concrete is being considered as a very urgent assignment [4] with respect to the smooth supply of aggregates and environmental protection. Because recycled aggregates from waste concretes have low strength and high water absorption, due to their high cement paste content, concretes made of recycled aggregates are known to have poorer properties [5,6], particularly lower strength, relative to original concretes. These problems can be overcome by using an organic polymer or polymer modifier [7-14] in conjunction with Portland cement. The polymer modifier is well known to offer the improvement of higher strength, durability, good resistance to chemicals, and strong resistance to damage from freeze-thaw cycles [15-21]. Besides, due to the recent preference for high-class housing construction materials, much acrylic artificial marble is being used as a housing construction material and, consequently, huge amounts of waste artificial marble are generated during the production of acrylic artificial marbles. Because waste artificial marbles are treated as industrial wastes, they are burned or disposed, which leads to environmental pollution, waste of primary materials, and increased disposal costs and, consequently, it
results in weakening of industrial competitive power. Therefore, recycling technologies [22-26] of fine aggregates derived from waste concretes and waste artificial marbles are urgently needed.

In this study, we prepared many types of specimens of PAE polymer-modified mortars [27], which had originally excellent properties themselves, by varying the replacement ratios of recycled fine aggregates and the polymer-cement ratios; we performed various tests to determine their properties, including water absorption, compressive and flexural strengths, hot water resistance, and pore volume tests.

### Experimental

**Test Materials**

In this study, we used ordinary Portland cement (Type I) and standard sand. Waste concrete and waste artificial marble fine aggregates were obtained by crushing waste concrete and waste artificial marble and collecting the materials in the range of 0.1 ~ 1.2 mm diameter. PAE emulsion was used as a polymer modifier; its physical properties are listed in Table 1.

**Mix Proportions**

**Preparation of Specimens**

Tables 2 and 3 illustrate the Mix Proportions of the PAE polymer-modified mortars prepared from recycled waste concrete and waste artificial marble fine aggregates, respectively. We used PAE emulsion as a polymer modifier and prepared specimens by combing materials with polymer-cement at ratios of 0, 10, and 20 wt% and replacement ratios of recycled fine aggregates at 0, 25, 50, 75, and 100 wt%. Water-cement ratios were adjusted for the flow values of all combinations to be 170 ± 5 mm, in accordance with KS F 2476. We prepared specimens with 40 × 40 × 160 mm mold and carried out the following curing compliant with the curing conditions using a constant temperature and humidity conditioner: humidity curing (20 °C, 80 % R.H.) for 2 days; water curing (20 °C) for 5 days; air curing (20 °C, 50 % R.H) for 21 days [28,29].

### Results and Discussion

**Properties of Fresh Polymer-Modified Mortars**

**Variation of Water-Cement Ratio**

As we can see from Figure 1, the water-cement ratio increases with an increase of the replacement ratios of the recycled fine aggregates, but the water-cement ratio decreased remarkably with an increase of the polymer modifier. As for the mortars made of recycled waste concrete fine aggregates, the water-cement ratio of the fresh mortar with the added polymer modifier was lower than that of the fresh mortar without the polymer modifier by 17 with 10 % addition of PAE and by 30 with 20 % PAE. On the other hand, for the mortars made of recycled waste artificial marble fine aggregates, the water-cement ratio of the fresh mortar with the added polymer modifier was lower than that of the fresh mortar without the poly-

### Table 1. Physical Properties of Polymer Cement Modifier

<table>
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<tr>
<th>Type</th>
<th>sp. gr. (20 °C)</th>
<th>Viscosity (20 °C, cP)</th>
<th>pH (20 °C)</th>
<th>Total solids (wt%)</th>
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### Table 2. Mix Proportions of PAE Polymer-Modified Mortars Containing Concrete Waste Fine Aggregates

<table>
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<tr>
<th>Cement : (Sand + WCFA) (by weight)</th>
<th>WCFA/WCFA + Sand (wt%)</th>
<th>P/C Ratio (wt%)</th>
<th>W/C ratio (%)</th>
<th>Unit weight (g/mL)</th>
<th>Air Content (%)</th>
<th>Flow value</th>
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</table>

※ WCFA: Waste Concrete Fine Aggregate
### Table 3. Mix Proportions of PAE Polymer-Modified Mortars Containing Artificial Marble Waste Fine Aggregates

<table>
<thead>
<tr>
<th>Cement : (Sand + AMW*) (by weight)</th>
<th>AMW/(AMW + Sand) (wt%)</th>
<th>P/C ratio (wt%)</th>
<th>W/C ratio (%)</th>
<th>Unit weight (g/ml)</th>
<th>Air content (%)</th>
<th>Flow value</th>
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* WCFA: waste concrete fine aggregate
**WAM: waste artificial marble

**Variation of Air Content**

Figure 2 shows that the air content of fresh polymer-modified mortars decreased with an increase of the replacement ratio of waste concrete fine aggregates, but increased with an increase of the replacement ratio of waste artificial marble fine aggregates. As for the air contents entrained at 50 % of the substitute content of the fresh mortar without the polymer modifier was 16.4 %, but the entraining air content of the fresh mortar with 10 and 20 % PAE emulsion modifier added increased significantly by 40.4 and 41.2 %, respectively. Generally, adding ca. 1 % of an antifoaming agent is a common way to reduce the excessively entrained air content and improve the properties of the mortar [28]. In this study, we determined that we needed to add an appropriate amount of an antifoaming agent into the polymer modifier in accordance with the properties of the purposed product.

**Variation of Unit Weight**

Figure 3 shows that as the replacement ratio of the waste concrete fine aggregates increased, the unit weight of the fresh mortar without the polymer modifier decreased gradually, but that of the fresh mortar with the polymer modifier added increased gradually. Generally, the unit weight of fresh mortars is in inverse proportion to the water/cement ratio. Therefore, the fresh mortars with polymer modifier had lower water/cement ratios and hence lower unit weights than those without.
Properties of Hardened Polymer-Modified Mortars

Water Absorption of Polymer-Modified Mortars

Figure 4 shows the results of water absorption tests of polymer-modified mortars cured for 28 days. The water-tightness of the specimen with 10% of polymer modifier added did not improve as much as that of the specimen without the polymer modifier, probably because the air entraining effect of adding the polymer modifier is much larger than the water-tightness effect by bonding of polymers. With 20% of polymer modifier, the water absorption rate decreased significantly, probably because the polymer modifiers were firmly bonded to the surfaces between hydrated cement and hydrated cement, between hydrated cement and aggregate, or between aggregate and aggregate, which consequently improves the water-tightness [11, 28].

Strength Properties of Polymer-Modified Mortars

In Figure 5, the compressive strength of the polymer-modified mortar is significantly lower than that of the cement mortar without the polymer modifier, probably because of the strong air entraining property of PAE polymer modifier. In addition, as the replacement ratio of the waste artificial marble and the waste concrete fine aggregates increases, the compressive strength decreases gradually. In particular, the compressive strength of the mortar made of waste artificial marble decreases more than that of the mortar made of waste concrete fine aggregates. This situation probably arose because the entraining air content decreases with an increase of the substitute content of waste concrete fine aggregates, but the entraining air content increases remarkably with an increase of the replacement ratio of waste artificial marble fine aggregates.

As we can see in Figure 6, for the flexural strength, there is no strength decrease such as that which appeared on the compressive strength and, as the additive amount of PAE emulsion modifier increases, the flexural strength increases significantly instead. The compressive and flexural strengths are both higher in the specimens made of the waste concrete fine aggregates.
The effect of the increase of the amount of polymer modifier added is higher on the flexural strength than on the compressive strength. This situation probably arose because the compressive strength is mostly influenced by the bonding forces generated by the hydration reaction of cements, whereas the flexural strength is mostly influenced by the bonding forces of the polymer modifier adhering to the surfaces of the aggregates [11,28,30].

**Hot Water Resistance Test**

Figures 7 and 8 show the compressive and flexural strengths determined before and after hot water resistance testing, which was carried out in 90 °C hot water for 28 days. As we can see in Figure 7, the compressive strength of the specimens made from waste concrete fine aggregates increased after the hot water resistance test, probably because the effect of the completed hydration reaction of the cement paste in hot water on the increase of the strength is much greater than the effect of the deterioration of the polymer modifier on the decrease of the strength. However, the compressive strength of the specimens made of waste artificial marble fine aggregates decreased significantly after the hot water resistance test, and the degree of decrease was greater upon increasing the replacement ratio of waste artificial marble fine aggregates. Thus, the reason why the compressive strength of the specimens made of waste artificial marble fine aggregates decreased after the hot water resistance test seems to be because the methylmethacrylate resin contained in the waste artificial marble fine aggregates deteriorated or decomposed during the hot water resistance test [31].

As we can see in Figure 8, the results of the determination of the flexural strengths of the specimens made of waste concrete fine aggregates are contrary to the results of the compressive strength in Figure 7. The reason why the flexural strength decreased after the hot water resistance test seems to be because the effects of the deterioration of the polymer modifier on the decrease of the strength are much greater than the effect of the completed hydration reaction of the cement paste in hot water on the increase of the strength. Likewise, with the compressive strength, the flexural strength gradually decreased upon increasing the replacement ratio of the waste concrete fine aggregates.

Meanwhile, the decreased rate of the flexural strength of the specimens made of waste artificial marble fine aggregates is greater by 21.1 and 16.2 % with 10 and 20 % addition of PAE polymer modifier, respectively, as compared with that of the specimen made of waste concrete fine aggregates. This situation probably arose because the polymer binder resin, which is contained in the waste artificial marble fine aggregates, deteriorated or decomposed upon being exposed in hot water, which consequently, led to a significant decrease of the strength.
Properties of Pore Volume and Density Change

Figure 9 shows that the total pore volume gradually increases upon increasing the replacement ratio of waste concrete fine aggregates. The reason why the total pore volume increases with an increase of the replacement ratio of waste concrete fine aggregates seems to be because the cement paste having a high pore volume adheres to the surfaces of waste concrete fine aggregates. The pore volume determined after the hot water resistance test was 5% lower than that determined before the test, probably because the hydration reaction of cement paste is accelerated in hot water, which leads to the formation of a firmer complex [28,30,32]. As the replacement ratio of the waste concrete fine aggregates increases, the density decreases significantly because a profusion of waste concrete fine aggregate, which has lower density than standard sand, was used for replacement. In addition, we believe that the water-cement ratio increment was also affected by increasing the replacement ratio of waste concrete fine aggregate. The reason why the density decrement rate of the polymer-modified mortars using waste artificial marble fine aggregate was much higher than that of the polymer-modified mortars using waste concrete fine aggregate is that the waste artificial marble fine aggregate has a lower density relative to standard sand. Furthermore, we believe that it was affected by the increment of entraining air content and water-cement ratio upon increasing the replacement ratio of waste artificial marble fine aggregates.

Figure 10. Variation of bulk density vs. replacement ratios of recycled fine aggregates (— : before hot water immersion; ----- : after hot water immersion).

As we can see in Figure 10, the density determined after the hot water resistance test was ca. 1% higher than that determined before the test, probably because the hydration reaction of cement paste is accelerated in hot water, which leads to the formation of a firmer complex [28,30,32]. As the replacement ratio of the waste concrete fine aggregates increases, the density decreases significantly because a profusion of waste concrete fine aggregate, which has lower density than standard sand, was used for replacement. In addition, we believe that the water-cement ratio increment was also affected by increasing the replacement ratio of waste concrete fine aggregate. The reason why the density decrement rate of the polymer-modified mortars using waste artificial marble fine aggregate was much higher than that of the polymer-modified mortars using waste concrete fine aggregate is that the waste artificial marble fine aggregate has a lower density relative to standard sand. Furthermore, we believe that it was affected by the increment of entraining air content and water-cement ratio upon increasing the replacement ratio of waste artificial marble fine aggregates.

Conclusions

To recycle waste concrete and waste artificial marble fine aggregate for polymer-modified mortar production, we prepared and tested specimens by varying the replacement ratio of recycled fine aggregates and polymer-cement ratio. As a result, we reached the following conclusions:

1) The water-cement ratio of the polymer-modified mortar increased upon increasing the replacement ratios of the recycled fine aggregates, but it decreased upon increasing the amount of polymer modifier added.

2) The air content of the fresh polymer-modified mortar, which used the waste concrete fine aggregate, decreased upon increasing the replacement ratios of the recycled fine aggregates. However, the air content of the polymer-modified mortar, which used the waste artificial marble fine aggregate, increased upon increasing the replacement ratios of the recycled fine aggregates. The entraining air content remarkably increased upon adding the polymer modifier.

3) The water absorption of polymer-modified mortar was increased upon increasing the replacement ratios of the recycled fine aggregates, but it decreased upon increasing the amount of polymer modifier additive.

4) The compressive and flexural strengths of the polymer-modified mortar decreased upon increasing the replacement ratios of the recycled fine aggregates. The flexural strength was enhanced considerably upon adding the polymer modifier.
5) After performing the hot water resistance test, the compressive strength of the specimen, which used the waste concrete fine aggregate, increased, but the flexural strength decreased. The compressive and flexural strengths of the specimen, which used the waste artificial marble fine aggregate, both decreased.

6) The pore volume of the polymer-modified mortar increased upon increasing the replacement ratios of the recycled fine aggregates. The pore volume after performing the hot water resistance test decreased when compared with the pore volume before testing.

Acknowledgment

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References

12. Y. Ohama and K. Shiroishi, SP-89, American Concrete Institute, pp.313-322 (1985).