



## Microstructures and mechanical properties of polymer modified mortars under distinct mechanisms



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### HIGHLIGHTS

- Microstructures of polymer modified pastes are illustrated by a computer model.
- Effects of different polymer latexes on mechanical properties of mortar are revealed.
- Gel/space ratio is modified for polymer modified cement composites.

### ARTICLE INFO

#### Article history:

Received 25 January 2013  
Received in revised form 17 April 2013  
Accepted 4 May 2013  
Available online 8 June 2013

#### Keywords:

Polymer modified mortar  
PA  
PU/PA  
Interaction mechanism  
Mechanical properties

### ABSTRACT

In this study, two types of acrylic latexes, PA (polyacrylate) and PU/PA (polyurethane modified PA), are investigated in their influences on mechanical properties of mortar under different interaction mechanisms. In light of a previous study, the polymer–cement hydrates interaction mechanisms in PA and PU/PA modified mortars are illustrated respectively, and the microstructures are simulated using a computer model. Through mechanical experiments, it is revealed that the incorporation of polymer tends to reduce the compressive strength and elastic modulus except PA at low P/C ratio, while improve the flexural strength and toughness. As compared with PA, PU/PA is more effective in these influences. All of the influences of PA and PU/PA on mechanical properties can be explained successfully based on the interaction mechanisms and microstructures. In addition, it's also found that the compressive strength of polymer modified mortar can be roughly estimated based on a modified gel/space ratio, and the incorporation of polymers does not change the relationship between elastic modulus and compressive strength. A high-temperature curing procedure is concluded to be suitable for preparation of high-performance cement composites in short period.

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### 1. Introduction

In the last half century, polymer modified mortar and concrete have been widely utilized in construction practice, as polymer modification can improve the workability, adhesive strength, waterproofness and many other properties of cement based materials [1–4]. Although polymer modified mortar and concrete are mainly used as finishing or repair materials in their history [3], following the development of polymerization and composition techniques, they have been sometimes used massively as the major construction material in some projects, e.g. pavement [5]. In such applications, polymer modification may be expected to increase the tensile or flexural strength and toughness of the cement-based materials, without inducing severe decrease in compressive strength.

In polymers that are commonly used for modification of cement-based materials, in forms of latex, emulsion or re-dispersible powder, SBR (styrene butadiene rubber), EVA (ethylene–vinyl acetate copolymer) and acrylics have been deeply studied and broadly utilized in practice [2,3,6–8]. In hardened state, the phenomena of noticeable increase in flexural strength and no improvement or even reduction of compressive strength of polymer modified cement-based composites, as compared with unmodified ones, have been commonly reported [3,4,9]. Of course, there are a lot of different and even contrary reports, e.g. Pei et al. [10] found that the incorporation of polymer latex negatively influence both compressive and flexural strength; Mohammed et al. [11] reported that waste latex paint modification with low P/C (polymer to cement mass ratio) might be positive in improving compressive strength of concrete. Actually, results from the literature cannot be compared with each other directly, if one does not recognize that polymers are generally added into cement composites in two different ways, say, keeping constant W/C (water to cement ratio) to obtain similar hydration of cement and keeping constant

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consistency by adjusting the W/C or the inclusion of plasticizer [12,13]. The former is a typical laboratory procedure, while the latter is a trial-and-error procedure with its results directly applicable in practice. Generally, significant improvements of flexural strength were reported in studies using the later method. Barluenga and Hernández-Olivares [12] noted that with SBR latex modification, keeping constant W/C, resulted in constant flexural strength and noticeably decreased compressive strength, while keeping constant consistency led to constant compressive strength and significantly increased flexural strength.

In a recent study, the advantages and disadvantages of different types of polymers, as modifiers of cement composites, were introduced [14], through which it can be seen that acrylics have perfect mechanical properties and durability. They are indeed frequently employed in flooring compounds and mortars where the highest level of physical performance (adhesion, abrasion resistance, flexural strength, and impermeability) is required [2,6]. Compared with SBR, acrylics as modifier can improve flexural strength more significantly at the same P/C, and may not reduce the compressive strength at low P/C [15]. The purpose of the present study is right to modify cement mortar using acrylic latexes, and improve the flexural strength and toughness without reducing compressive strength obviously.

Mechanisms of the interaction between organic and inorganic phases in acrylics modified mortars have been discussed in the previous study [14]. Two types of acrylic latexes were used as modifiers. One was polymerized by emulsion polymerization with monomers of MMA (methyl methacrylate), AA (acrylic acid), HEMA (2-hydroxyethyl methacrylate) and cross-linking agent. It was labeled as PA (polyacrylate). The other one was PU/PA (polyurethane modified PA). In the present study, the interaction mechanisms are introduced firstly. Then, the microstructure evolution of polymer modified cement pastes are simulated using a status-oriented computer model based on the interaction mechanisms. Keeping constant W/C, influences of PA and PU/PA latexes on mechanical properties of mortars are investigated experimentally, and explained based on the interaction mechanisms and simulated microstructures.

## 2. Materials and experiments

PA and PU/PA latexes were used as polymer modifiers. The details of the syntheses and physical properties of them can be found in the previous work [14]. Cement that satisfies the requirements of BS EN197-1:2000 for CEM I Portland cement of strength class 52.5N (roughly equivalent to the requirements of ASTM C150 for Type I Portland cement) was used as binder. The chemical compositions and physical properties of the cement are listed in Tables 1 and 2, respectively. Siliceous sand was used for preparing mortars with and without polymer. The fineness modulus of the sand is 1.73, while the average and maximum grain sizes of the sand are 0.33 mm and 2.36 mm respectively. Deionized water was used for mixing various mixtures. Besides, in the mixing process of polymer modified mixtures, a type of organosilicon defoamer in proper amount was added to suppress the foaming effect of surfactants in the latexes.

In the preparation of all mortars, with and without polymer, the W/C ratio was kept 0.5, while the sand to cement weight ratio (S/C) was kept 2. Various P/C ratios were selected to investigate its influence on mechanical properties. The mix proportions of these mixtures are listed in Table 3. After mixing, the mixtures were cast in steel moulds with different sizes for different test purpose. The size of specimen is 50 mm × 50 mm × 50 mm for compression test, 40 mm × 40 mm × 160 mm for flexural test, and 25 mm × 25 mm × 160 mm for fracture energy test. After casting, the mixtures were covered with plastic sheets to avoid evaporation. After 24 h, all specimens were demoulded and cured according to three different procedures. Procedure 1 was a simple wet curing in a moisture room where the temperature and

relative humidity were approximately 23 °C and 95% respectively. Procedure 2 consisted of a 2-day wet curing and a following dry curing in ambient environment (22 ± 2 °C and 40–70% RH). In procedure 3, a 2-day steam curing at 60 °C was followed by a 4-day oven-drying at 60 °C and subsequently a dry curing in ambient environment. Procedure 1 is the most beneficial to cement hydration, and thus to the evolution of mechanical properties of unmodified mortars. Procedure 2 is a commonly adopted method for polymer modified mortars as the dry curing is believed to be necessary for polymer film formation [3]. Procedure 3 is similar to the one that was used to prepare a high flexural strength cement paste, in which the steam curing and oven drying were used to promote cement hydration and film formation respectively in short stages [16].

Mechanical tests were conducted at ages of 3, 7, 28 and 60 days. Compressive strengths of mortars were measured according to ASTM C109, on a MTS 815 ROCK Mechanics machine. Flexural strengths were tested using three-point bending on a MTS 858 Mini machine, and calculated as

$$f_f = \frac{3P_p L}{2bt^2} \quad (1)$$

where  $f_f$  represents flexural strength,  $P_p$  the peak load,  $L$  (140 mm) the span of specimen,  $b$  (40 mm) and  $t$  (40 mm) the width and height of the cross-section of the specimen respectively. Elastic moduli of mortars were estimated from the load–displacement curves of three-point bending according to the following equation,

$$E = \frac{L^3}{4bt^3} \cdot \frac{dP}{d\delta} \quad (2)$$

where  $dP/d\delta$  is the gradient of the load–displacement curve corrected for the small amount of distortion in the three-point loading system. As this was not a standard method, the results could not be compared with the data in the literature. Thus, only the relative values of elastic moduli  $E_r$ , i.e. the values after being normalized by the elastic modulus of the reference mortar MPC at 60 days, would be shown in the present paper. The fracture energy  $G_f$  of mortars were roughly determined using a simplified method. This method imitated the draft recommendation proposed by RILEM Committee on Fracture Mechanics of Concrete–Test Methods [17] based on the fictitious crack model. Small-size specimens that could not fulfill the recommendation were used, and the notch length was equal to half depth of the beam. It must be noted that  $G_f$  measured in this way may not be the true values, thus they can only be used to compare with each other, rather than with other data in the literature.

## 3. Latex-hydrates interaction mechanisms and microstructure evolution

### 3.1. Interaction mechanisms of different types of polymer latexes and cement hydrates

The interaction mechanisms of the two different types of latexes (PA and PU/PA) and cement hydrates have been studied in a previous work [14]. It has been found that after being incorporated into cement paste, PA latex is destabilized and demulsified. PA molecules react with cement hydrates chemically to form a compound rather than form high purity film. On the other hand, PU/PA latex is just slightly demulsified, and still forms film with high purity. Behaviors and properties of PU/PA latex modified paste or mortar can be explained by Ohama's multi-step model [3] to a large extent, as PU/PA latex is sterically stabilized and PU/PA molecules are relatively passive. Behaviors of PA latex modified cement composites have to be explained by the newly developed 4-step model [14]. In step 1, immediately after mixing, a large amount of polymer particles adsorb on the surface of cement particles or coalesce because of the demulsification. The rest are still dispersed in the aqueous phase. Adsorption happens in mixing process and the first several minutes after mixing. In step 2, the hydration of cement is successively governed by dissolving and migration of ions. Some chemical reactions take place between latex and cement hydrates. Polymer particles adsorbed on the surface of cement particles are partially or totally embedded in hydrates. This stage lasts for tens of minutes until flocculation occurs. In step 3, cement hydration further progresses. With the reaction between calcium hydroxide and surfactant, the dispersion is severely destabilized. Polymer particles with cement hydrates settle down together, and flocculation happens. Due to the porous nature of the flocs, the growth or sedimentation of hydrates and the chemical reactions can continue in it, so that a complex

**Table 1**  
Chemical composition (%) of cement.

SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	MgO	SO <sub>3</sub>	Loss on ignition
21.1	5.6	3.4	65.3	1.6	2.1	0.85

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