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Dynamic properties impact toughness and abrasiveness of polymer-modified pastes by using nondestructive tests

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Abstract

This paper reports on the results of a study of the dynamic properties impact toughness and abrasiveness of polymer-modified pastes (PMPs) using a styrene–acrylic ester copolymer emulation. The dynamic elastic modulus E_d and the specific damping capacity Y of PMP were studied using a free vibration method. The propagation velocity of stress wave V and the scattered damping of stress wave in PMP were studied using an ultrasonic testing method. The impact toughness and abrasiveness were also studied. The dynamic modulus and the velocity of stress wave decreased with an increase in polymer–cement ratio (P/C) by mass. The specific damping capacity, impact toughness, and abrasiveness increased with an increase in P/C, thereby improving the ability of PMP to resist dynamic loads. When P/C is 15–20%, PMP demonstrates the best dynamic behaviour within the adopted range of testing.

Keywords: Cement paste; Vibration; Elastic moduli

1. Introduction

Polymer-modified paste (PMP) is a composite material made from rigid and ductile materials. So long as the content of polymer added is suitable, the polymer and the hydrates of cement in PMP will form a space network weaving with into each other and turning into a double cross net system [1,2]. As compared with ordinary cement paste with equal water–cement ratio (w/c), even though PMP has lower compressive strength at an early age, its flexural strength–compressive strength ratio (f_{sz}/f_p) is higher and is less brittle [3]. This means that PMP has better resistance against dynamic loads. Thus, PMP and polymer-modified concrete (PMC) are generally used for constructing structures or elements for resisting dynamic action, such road and airport pavements, bridge floors, and the like [4]. This creates a need to study the dynamic behavior of PMC. Dynamic properties of composite materials, such as fiber-reinforced concrete (FRC) [5–8] and polymer concrete (PC), where the binder is a polymer only, without cement [9] have been studied. However, there is no work reported on PMP or PMC, as well as polymer-modified mortar (PMM). The dynamic behavior of PMP has been systematically investigated, and the results are reported in this paper. In order to simplify the influencing factors, only PMP was investigated since it is the base element for PMC.

When the stress wave reaches the interface between two kinds of media, part of the energy is scattered. The scattered damping factor α depends on the interface area, interface shape, and the difference of specific acoustic impedance between the two media at the side of the interface. Therefore, it can be presumed that α explains the distribution state of every phase within PMP, in an approximate fashion.

The factor α of an ultrasonic wave traveling in a homogeneous medium can be given by the expression [10]:

$$A = A_0 \exp^{(-\alpha x)} \tag{1}$$

where A is the intensity of sound after traveling a distance x; A_0 is the intensity of sound; α is the scatter damping factor; and x is the distance.

When a material is vibrated, the vibration energy is assumed to arise from the internal friction sources, which are the interface of phases and defects in the materials. This property of a material is known as internal friction Y. The higher the value of Y, the more is the consumption of vibration energy in the material.

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Table 1
Compressive and flexure strengths of cements

Compressive strength (MPa)				Flexure strength (MPa)			
OPC		HAC		OPC		HAC	
3 days	28 days	1 day	3 days	3 days	28 days	1 day	3 days
25.4	56.8	49.2	54.3	4.8	7.5	5.4	6.2

The most direct method for defining internal friction is by the specific damping capacity. The specific damping capacity Y is defined by the following expression [11]:

$$Y = \Delta W / W \tag{2}$$

where Y is the specific damping capacity; ΔW is the energy dissipated in one cycle; and W is the total energy of the cycle.

2. Materials

2.1. Cement

Ordinary Portland cement (OPC) equivalent to GB175-92 and high-aluminum cement (HAC) equivalent to GB201-81 were used. Their strengths are shown in Table 1.

2.2. Polymeric admixture

Styrene–acrylic ester (SAE) copolymer emulsion that has 48% solid content by mass was used.

2.3. Chemical admixtures

In order to remove the foams in mixture and adjust the fluidity of the mixture, suitable amounts of antifoamer and superplasticizer were used.

3. Testing procedures

3.1. Preparation of specimens

3.1.1. Mixture proportion

The water–cement ratio (w/c) for all the tested samples was 0.3. The mass of water included the mass of water in the emulsion added. Polymer–cement ratios (P/C) used were 0%, 5%, 10,% 15%, 20%, and 25%.

3.1.2. Size of specimens

- $40 \times 40 \times 40$ mm cube specimens were used for testing propagation velocity and scatter damping factor of stress wave.
- $10 \times 40 \times 160$ mm prism specimens were used for testing the dynamic elastic modulus and the specific damping capacity.
- $\Phi 25 \times 25$ mm cylinder specimens were used for testing the impact toughness and the abrasiveness.

3.1.3. Curing system

The dynamic behaviours of PMC are apparently influenced by the curing system and are closely related with the property of the polymer. The following system is used in experiments, based upon the results of preliminary tests. The specimens are cast in mist room under normal temperature (20 ± 2 °C) and are cured in the same place in the mould for 17 h. They are then cured in a climate box at 70 °C and 96% relative humility for 6 h. The specimens are further cured at a temperature of 20 ± 2 °C, under a relative humility of 90%, until the start of the test.

3.2. Tests on dynamic properties

3.2.1. Brief description of measurement process

3.2.1.1. Vibration parameters. The specimen is hung flexibly and is excited by a small hammer to vibrate. The frequency response curve, natural frequency f_0, and the frequencies at semipower points (f_1 and f_2) are measured.

On the basis of these measurements [11], the dynamic elastic modulus E_d and the specific damping capacity Y are calculated as follows [11]:

$$E_d = 9.66 \times 10^{-6} W L^3 T f_0^2 / b h^3 \tag{3}$$

where E_d is the dynamic elastic modulus; L is the length of specimen; W is the weight of specimen; f_0 is the natural frequency; b and h are the width and height of a cross-section of a specimen, respectively; and T is the correction factor:

$$Y = f_0/(f_2 - f_1) \tag{4}$$

where Y is the specific damping capacity; f_0 is the natural frequency; f_2 is the frequency higher than natural frequency, which has an amplitude of 0.707 of the natural frequency;

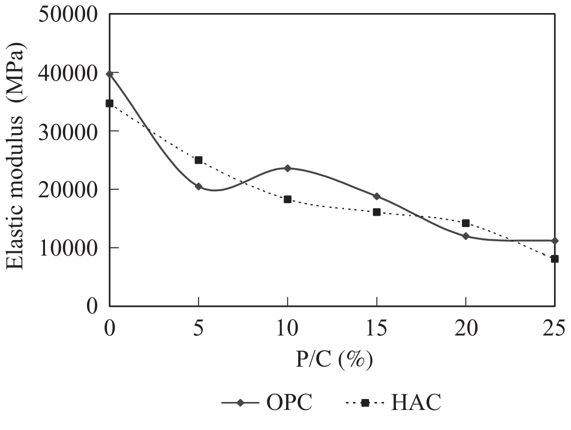

Fig. 1. Relationship of elastic modulus and P/C.

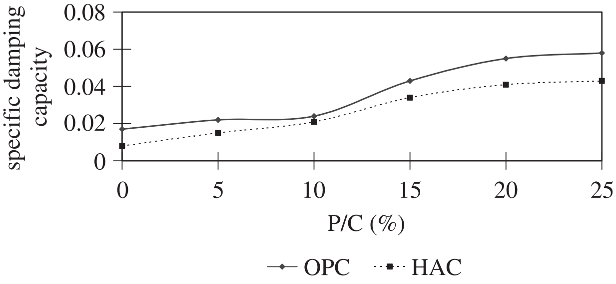

Fig. 2. The relationship of specific damping capacity and P/C.

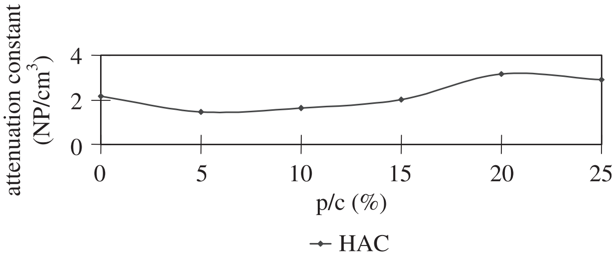

Fig. 4. The relationship of attenuation constant and P/C.

and f_1 is the frequency lower than natural frequency, which has an amplitude of 0.707 of the natural frequency.

3.2.1.2. Propagation character of stress wave. Transducers were used to excite and receive the stress wave at the frequency of 250 kHz. Propagation times of stress wave through the specimen and damped waveform were measured. From Eq. (1), α can be expressed as follows:

$$\alpha = \frac{1}{X} \ln \frac{A_0}{A}.$$

If we measured the transit time interval (Δt) between A_0 and A_0/e, the propagation velocity V can be determined by:

$$V = L/t \tag{5}$$

where V is the propagation velocity; L is the transit distance; and T is the transit time.

Thus, α can be calculated by:

$$\alpha = 1/(V\Delta t). \tag{6}$$

3.2.1.3. Impact toughness and abrasiveness. The testing processes of impact toughness and abrasiveness of the stone were adopted. The experimental results are calculated as follows:

$$N_{\mathrm{im}} = P(1 + 2 + 3 + \cdots + n)/V_{\mathrm{s}} \tag{7}$$

where N_{im} is the impact toughness; P is the weight of hammer; V_{s} is the volume of specimen; and n is the elevation for the hammer to fall so as to damage the specimen:

$$K_{\mathrm{h}} = 20 - (m_0 - m_1)/3 \tag{8}$$

where K_{h} is the abrasiveness; m_0 is the original weight of specimen; and m_1 is the weight of the specimen after abrasion.

4. Test results and discussion

4.1. Dynamic elastic modulus E_d

Fig. 1 shows that the dynamic elastic modulus E_{d} decreases rapidly with an increase in P/C. When P/C is greater than 20%, the variability of E_{d} tends to be more gentle.

4.2. Specific damping capacity Y

Fig. 2 shows that the specific damping capacity Y increases with P/C. When P/C is less than 20%, the relationship between Y and P/C is linearly correlated. When P/C is greater than 20%, the variability of Y with P/C tends to be less pronounced.

4.3. The propagation character of stress wave in PMC

4.3.1. The velocity of stress wave V

The propagation velocity of PMC decreases with an increase in the P/C because of the apparent analeptic hysteresis phenomena of the polymer. V and P/C are linearly

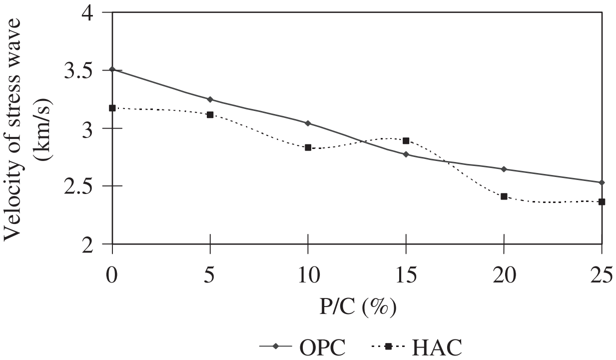

Fig. 3. Relationship velocity of stress wave and P/C.

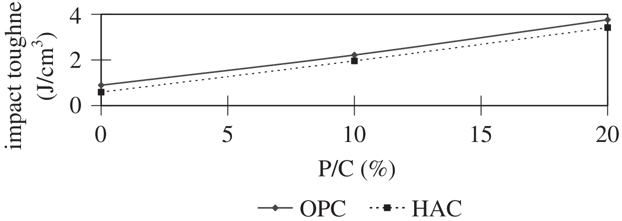

Fig. 5. The relationship of impact toughness and P/C.

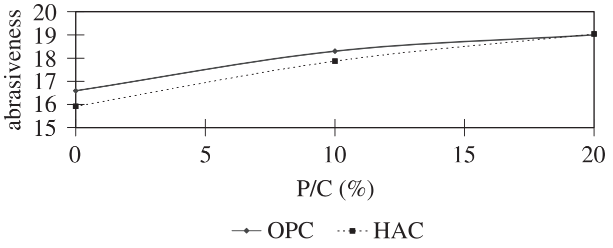

Fig. 6. The relationship of abrasiveness and P/C.

correlated within the adopted range of tests, as shown in Fig. 3.

4.3.2. The scattered damping of stress wave in PMC

It is shown in Fig. 4 that the scatter damping factor α indicates the following three distribution states of polymers in mixtures with the increase of P/C:

(a) Stage I, when P/C is 0–5%, the polymer crams a part of pores and converts part of the solid–air interface into solid–gel interface. Thus, the difference of specific acoustic impedance between two media at the side of the interface decreases. The factor α decreases with an increase in the P/C.
(b) Stage II, when P/C is 5–20%, due to the increase of the polymer content, the area of solid–gel interfaces becomes larger; thus, α increases with an increase in the P/C.
(c) Stage III, when P/C is more than 20%, with an increase of polymer content, the polymer becomes a continual phase and a "wave bridge" is formed, so the scatter damping is decreased.

The factor α may be used as a way to analyze the distribution state of the polymer in PMC. According to the simplified model of formation of polymer–cement comatrix by Ohama [1], the composite mechanism of PMC [12], and the relationship between α and P/C, we can assume that there would be a model for PMC with three kinds of internal structure at different P/C values. When P/C is small, the polymer content is just enough to disperse in the cement phase. When P/C is adequate, the polymer and the cement hydrates in PMC form net space frames, which weave into each other and form a double cross net system. When P/C is high, the cement–gel–unhydrated cement disperses in the polymer phase. For SAE copolymer emulsion-modified cement, the two critical P/C values are 5% and 20%. The PMC under this state would have the best ability to resist dynamic loads.

4.4. Impact toughness and abrasiveness

The experiment results are illustrated in Figs. 5 and 6. The impact toughness and abrasiveness are improved apparently. When the P/C moves from 0% to 20%, the impact toughness of PMC is increased by a factor of 5.83, while the abrasiveness is increased by 20%. As a result, PMC is a better material for pavement construction.

5. Conclusions

When a suitable polymer is added to the cement, the dynamic elastic modulus and the velocity of stress wave decrease with an increase in P/C. The specific damping capacity, impact toughness, and abrasiveness all increase with an increase in P/C. Thus, PMC improves the ability to resist dynamic loads. From the test results, it is found that the PMC would have the best dynamic behaviour when the added polymer content is in the range of 15–20%.

Due to its dynamic behaviour, PMC is highly recommended for use in the construction of structures or elements that need to resist dynamic loads.

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