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Flexural Behavior of Polymer Mortar Permanent Forms Using Methyl Methacrylate Solution of Waste Expanded Polystyrene

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Abstract: This experimental study examines the applicability of polymer mortar permanent forms using a methyl methacrylate (MMA) solution of waste expanded polystyrene (EPS) to develop effective recycling processes for the EPS, referring to the flexural behavior of a polymer-impregnated mortar permanent form with almost the same performance as commercial products. An MMA solution of EPS is prepared by dissolving EPS in MMA, and unreinforced and steel fiber-reinforced polymer mortars are mixed using the EPS-MMA-based solution as a liquid resin or binder. Polymer mortar permanent forms (PMPFs) using the EPS-MMA-based polymer mortars without and with steel fiber and crimped wire cloth reinforcements and steel fiber-reinforced polymer-impregnated mortar permanent form (PIMPF) are prepared on trial, and tested for flexural behavior under four-point (third-point) loading. The EPS-MMA-based PMPFs are more ductile than the PIMPF, and have a high load-bearing capacity. Consequently, they can replace PIMPF in practical applications.

Keywords: Waste expanded polystyrene, methyl mehtacrylate, polymer mortar, permanent form, reinforcement.

1. Introduction

Expanded polystyrene is nowadays used as a popular packaging or insulating material in various industrial fields in the world because of its good properties such as lightweight, low thermal conductivity and high impact resistance. However, most of the expanded polystyrene is disposed as a bulky waste immediately after only one-time use, and the disposal of a large quantity of waste expanded polystyrene has become serious environmental issues in the world. The development of the effective recycling processes is strongly requested for the waste expended polystyrene. In recent years, the authors have prepared the vinyl monomer solutions of the waste expanded polystyrene by dissolving the waste expanded polystyrene in styrene or methyl methacrylate, and developed new polymer mortar systems by using the vinyl monomer solutions as liquids resins or binders for the systems.[1-3] Such new polymer mortar systems are considered to be effective recycling processes for the waste expanded polystyrene. In Japan, polymer-impregnated mortar permanent forms have been employed only in the limited applications giving a good cost-performance balance for them for the past 30 years. Only Materras Oume Concrete Industry Co., Ltd. currently produces the polymer-impregnated mortar permanent forms as commercial products to order.[4,5] The purpose of this experimental study is to examine the applicability of polymer mortars using a methyl methacrylate solution of waste expanded polystyrene to permanent forms for the development of effective recycling processes for it, referring to the flexural behavior of a polymer-impregnated mortar permanent form with almost the same performance as commercial products.

In the present paper, a methyl methacrylate solution of waste expanded polystyrene is prepared by dissolving waste expanded polystyrene in methyl methacrylate, unreinforced and steel fiber-reinforced polymer mortars using the methyl methacrylate solution as a liquid resin or binder are mixed, and tested for strength properties. Permanent forms using the polymer mortars without and with reinforcements and steel fiber-reinforced polymer-impregnated mortar permanent form are prepared on trial, and tested for flexural behavior. The flexural behavior of the polymer mortar permanent forms is compared to that of the polymer-impregnated permanent form.

2. Materials

2.1 Materials for polymer mortars

2.1.1 Chemicals for binder system

Expanded polystyrene (EPS), specified in JIS (Japanese Industrial Standards) A 9511 (preformed cellular plastics thermal insulation materials), was used as a model of waste EPS. Table 1 gives the physical properties of the EPS. Methyl methacrylate (MMA) for industrial use was employed not only as a solvent to dissolve EPS but also as an ingredient of the liquid resin for polymer mortars. Table 2 lists the properties of the MMA monomer. Fifty percent dicyclohexyl phthalate powdered dispersion of benzoyl peroxide (BPO) was used as an initiator, and N, N-dimethyl-p-toluidine

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Table 1 Physical properties of EPS.

Molecular weight	Density (kg/m^3)	Thermal conductivity (W/m·K)	Flexural strength (N/cm^2)	Compressive strength (N/cm^2)
ca. 300000	17	0.040	24	10

Table 2 Properties of MMA monomer.

Monomer	Molecular weight	Density (g/m^3, 20°C)	Viscosity (mPa·s, 20°C)	Purity (%)
MMA	100.1	0.94	0.85	99.9

(DMT) was done as a promoter. The water content of the EPS was controlled to be less than 0.1% by heat drying at 60°C for 48 hrs.

2.1.2 Filler and fine aggregates

Fly ash Type II as specified in JIS A (fly ash for use in concrete) was employed as a filler. Two types of crushed sands were used as fine aggregates. Table 3 gives the properties of the fine aggregates. The water contents of the filler and fine aggregates were controlled to be less than 0.1% by heat drying at 105°C for 48 hrs.

2.1.3 Reinforcements

Commercially available steel fibers (size, 0.3 × 0.4 × 15 mm; tensile strength, 585 MPa; elastic modulus, 200 GPa; elongation, 50%) and the crimped wire cloth (tensile strength, 412 MPa; elastic modulus, 59 GPa; elongation, 24.5%) as specified in JIS G 3553 (Crimped wire cloth) were used as reinforcements.

2.1.4 Materials for polymer-impregnated mortar

Ordinary portland cement as specified in JIS R 5210 (Portland cement) and the same crushed sands and steel fibers for polymer mortars as mentioned above were also employed for base mortar. For the preparation of an impregnant, the same MMA monomer for polymer mortars as stated above was used, together with azobisisobutyronitrile (AIBN) as an initiator.

2.2 Testing procedures

2.2.1 Preparation of EPS-MMA-based solution for liquid resin

An EPS-MMA-based solution with an EPS concentration of 30.0% for the liquid resin for polymer mortars was prepared by dissolving expanded polystyrene (EPS) in methyl methacrylate (MMA) at 20°C.

2.2.2 Preparation of polymer mortar specimens and polymer mortar permanent form specimens

According to JIS A 1181 (Test methods for polymer concrete), polymer mortars using an EPS-MMA-based binder with the formulations of EPS-MMA-based solution: BPO : DMT = 100 : 2.0 : 1.0 (by mass) were mixed with the mix proportions shown in Table 6. Beam specimens 40 × 40 × 160 mm for flexural and compressive strength tests and cylindrical specimens Φ50 × 100 mm for splitting tensile strength test were molded using the polymer mortars, and subjected to a 24h-20°C-60% (RH)-dry plus 15h-70°C-heat curing and a 24h-20°C-60% (RH)-dry plus 3h-100°C-heat curing. Polymer mortar permanent form specimens 450 × 900 × 30 mm without or with embedded crimped wire cloth reinforcement were also molded using the polymer mortars, and subjected to a 24h-20°C-60% (RH)-dry plus 15h-70°C-heat curing. Fig. 1 represents the molding process for the polymer mortar permanent form specimens.

2.2.3 Preparation of polymer-impregnated mortar permanent form specimens

According to JIS R 5201 (physical testing methods for cement), steel fiber-reinforced mortar was mixed with the following mix proportions (kg/m^3): water 175, cement 500, crushed sand (fine) 958, crushed sand (coarse) 715, steel fibers 95 and superplasticizer 3.5; steel fiber content = 1.2% (volume fraction) and water-cement ratio = 35.0%. Base mortar specimens 450 × 900 × 30 mm for polymer-impregnated mortar permanent form specimens were molded using

Table 3 Properties of fine aggregates.

Type of fine aggregate	Size (mm)	Fineness modulus	Bulk density (kg/*l*)	Density (g/cm^3)	Water absorption (%)
Crushed sand (fine)	0.15~2.5	3.29	1.48	2.62	0.94
Crushed sand (coarse)	2.5~5	4.83	1.64	2.63	0.58

Table 4 Mix proportions of polymer mortars.

Steel fiber content (%) (volume fraction)	Mix proportions (by mass)				
	Binder	Filler	Crushed sand (F) (0.15~2.5 mm)	Crushed sand (C) (2.5~5 mm)	Steel fibers
0	12.0	12.0	46.0	30.0	0
1.2	12.0	12.0	42.0	30.0	4.0

Table 5 Strength properties of EPS-MMA-based polymer mortars.

Curing condition	Fiber content (%) (volume fraction)	Compressive strength (MPa)	Tensile strength (MPa)	Flexural strength (MPa)
15h-70°C- heat curing	0	112.2	14.0	27.6
	1.2	123.0	15.4	30.1
3h-100°C-heat curing	0	105.6	13.1	26.2
	1.2	126.4	14.8	30.2

Table 6 Flexural behavior of EPS-MMA-based polymer mortar and polymer-impregnated mortar permanent forms (PMPFs and PIMPF).

Type of permanent form	Flexural behavior				
	Max. extreme tension fiber strain ($\times 10^{-6}$)	Max. deflection (mm)	Flexural toughness (kN·mm)	Flexural strength (MPa)	Flexural modulus of elasticity (GPa)
PMPF without reinforcement	1,153	4.92	36.8	29.7	22.0
PMPF with steel fiber reinforcement	1,203	4.91	38.5	31.1	24.5
PMPF with crimped wire cloth reinforcement	1,120	5.13	39.6	29.3	19.5
PIMPF with steel fiberreinforcement	564	2.55	20.4	30.8	50.5

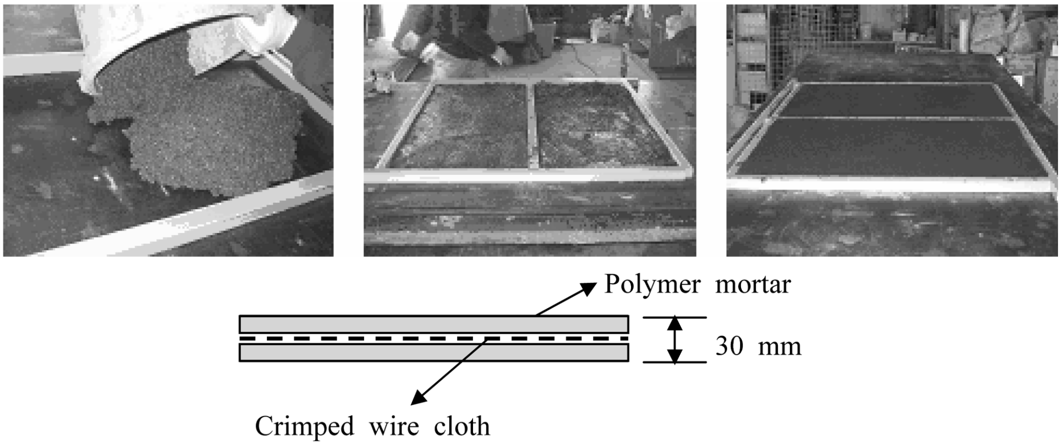

Fig. 1 Molding process for polymer mortar permanent form specimens.

the steel fiber-reinforced mortar in accordance with the same molding process as seen in Fig. 1, and subjected to a 2h-ambient temperature-precuring plus 3h-60°C-steam plus 7d-20°C-60% (RH)-dry curing. The cured base mortar specimens were dried at 120°C for 15hrs in an oven. The dried base mortar specimens were cooled to ambient temperature, evacuated at 400 to 667 Pa for 2hrs, and then soaked in an impregnant with the formulations of MMA : AIBN = 100 : 1 (by mass) under atmosphere pressure for 2hrs. After monomer impregnation, the specimens were placed in a hot water at 70°C for 4hrs for thermal polymerization to make polymer-impregnated mortar permanent form specimens. Their polymer loading was 5.0%.

2.2.4 Strength test for polymer mortar specimens

Beams specimens were tested for flexural and compressive strengths in accordance with JIS A 1181, and cylindrical specimens were done for splitting tensile strength according to JIS A 1181.

2.2.5 Flexural test for polymer mortar and polymer-impregnated mortar permanent form specimens

Polymer mortar and polymer-impregnated mortar permanent form specimens were tested for flexural behavior under four-point (or third-point) loading with a span of 750 mm and a loading rate of 50 N/s by using the Amsler-type universal testing machine. Fig. 2 illustrates the setup of flexural test for the permanent form specimen. At the same time, the central (or midspan) deflection of the specimens was measured by a sensitive LVDT (linear variable differential transformer), and their extreme tension fiber strain was measured by the three 30-mm-long paperback electrical strain gages installed on the extreme tension fiber at the midspan. Their flexural toughness was calculated as an area under a flexural load-deflection curve up to a deflection at the maximum flexural load (at failure load). Their flexural strength was calculated using the following Eq. (1):

$$\sigma_f = \frac{Pl}{bh^2} \tag{1}$$

where σ_f is flexural strength (MPa), P is maximum flexural load (N), l is span (mm), b is width (mm) of specimen, and h is thickness (mm) of specimen. Their flexural modulus of elasticity was calculated by the following Eq. (2):

$$E_f = \frac{23Pl^3}{54bh^3\delta} \tag{2}$$

where E_f is flexural modulus of elasticity (10^{-3}GPa), P is flexural load (N), σ is central (midspan) deflection (mm), l is span (mm), b is width (mm) of specimen, and h is thickness (mm) of specimen.

3. Test results and discussion

3.1 Effects of steel fiber reinforcement and curing conditions on strength properties of EPS-MMA-based polymer mortars

Table 8 shows the strength properties of unreinforced and steel fiber-reinforced EPS-MMA-based polymer mortars, made by applying two types of heat curings. The effects of heat curing conditions on the compressive, tensile and flexural strengths of the unreinforced and steel fiber-reinforced EPS-MMA-based polymer mortars are not significantly evident, however, the strength properties of 15h-70°C-heat-cured polymer mortars are somewhat higher

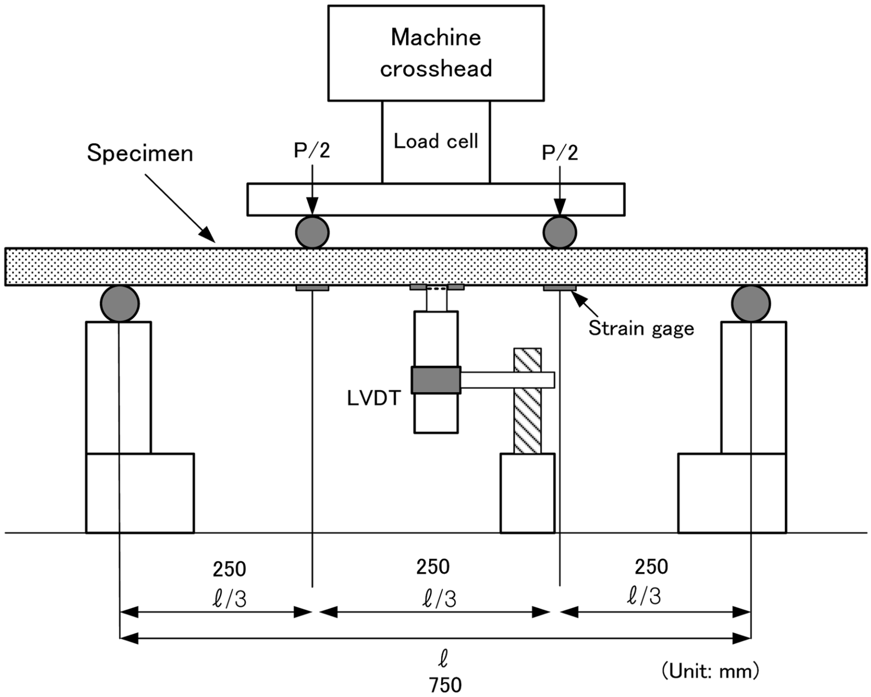

Fig. 2 Setup of flexural test for permanent form specimen.

than those of 3h-100°C-heat-cured polymer mortars. This is attributed to the acceleration of the polymerization reaction of MMA monomer in the matrixes by a longer heat curing. The steel fiber reinforcement of the EPS-MMA-based polymer mortars improves their compressive, tensile and flexural strengths regardless of the heat curing conditions.

3.2 Flexural behavior of EPS-MMA-based polymer mortar permanent forms and polymer-impregnated mortar permanent form as reference form

Figs. 3 to 6 represent the flexural stress-extreme tension fiber strain curves for EPS-MMA-based polymer mortar permanent forms (PMPFs) without reinforcement and with steel fiber and crimped wire cloth reinforcements and for a polymer-impregnated mortar permanent form (PIMPF) with steel fiber reinforcement as a reference form. The flexural stress-extreme tension fiber strain relationships of the EPS-MMA-based PMPFs without reinforcement and with steel fiber and crimped wire cloth reinforcements are almost the same, and the effects of the steel fiber and crimped wire cloth reinforcements on the relationships are hardly recognized. The maximum flexural stress of the EPS-MMA-based PMPFs without reinforcement and with steel fiber and crimped wire cloth reinforcements is comparable to that of the PIMPF with steel fiber reinforcement, but the maximum extreme tension fiber strain of the PMPFs is about twice larger than that of the PIMPF.

Fig. 7 and Table 6 show the flexural behavior of EPS-MMA-based PMPFs without reinforcement and with steel fiber and crimped wire cloth reinforcements and of a PIMPF with steel fiber reinforcement as a reference form. The deflection of the EPS-MMA-based PMPFs without reinforcement and with steel fiber and crimped wire cloth reinforcements increases almost linearly with increasing flexural load until the maximum flexural load giving a brittle failure irrespective to the type of reinforcement. The flexural load-deflection relation of the PIMPF with steel fiber reinforcement also is almost linear like the EPS-MMA-based PMPFs. The maximum deflections, flexural toughnesses, flexural strengths and flexural moduli of elasticity of the EPS-MMA-based PMPFs without reinforcement and with steel fiber and crimped wire cloth reinforcements are almost the same, and the effects of steel fiber and crimped

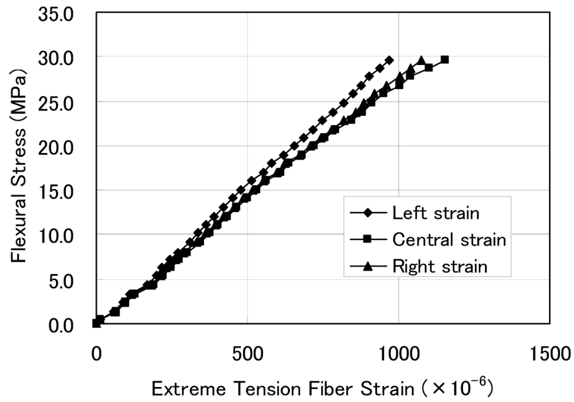

Fig. 3 Flexural stress-extreme tension fiber strain curves for EPS-MMA-based PMPF without reinforcement.

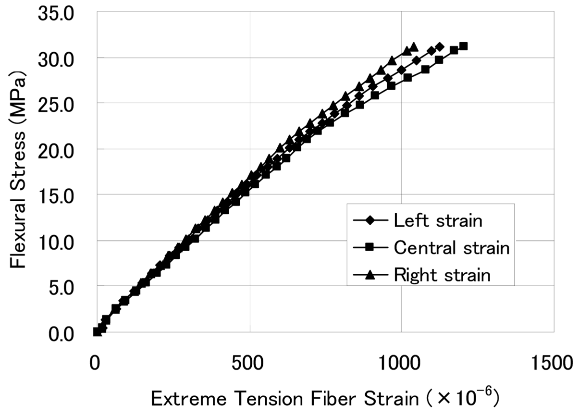

Fig. 4 Flexural stress-extreme tension fiber strain curves for EPS-MMA-based PMPF with steel fiber reinforcement.

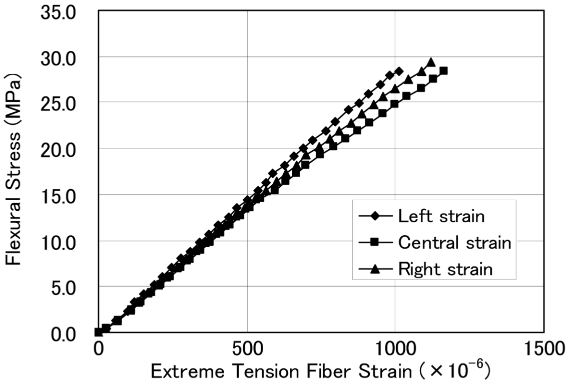

Fig. 5 Flexural stress-extreme tension fiber strain curves for EPS-MMA-based PMPF with crimped wire cloth reinforcement.

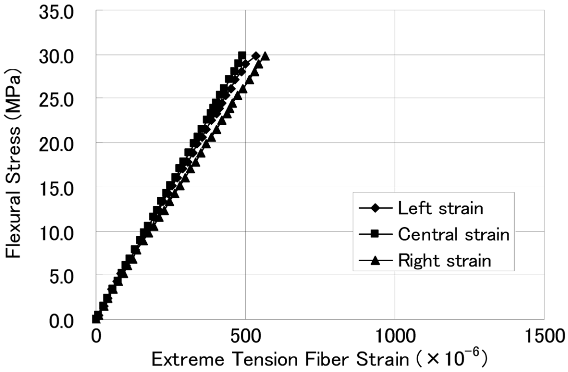

Fig. 6 Flexural stress-extreme tension fiber strain curves for PIMPF with steel fiber reinforcement.

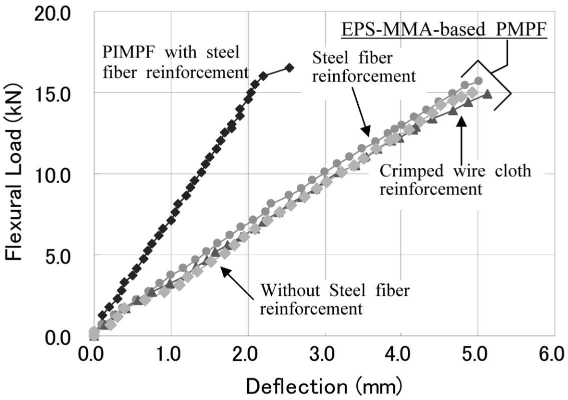

Fig. 7 Flexural load-deflection curves for EPS-MMA-based PMPFs and PIMPF.

wire cloth reinforcements on their flexural behavior are hardly recognized. The flexural strength of the EPS-MMA-based PMPFs is almost the same as that of the PIMPF. However, the maximum deflection and flexural toughness of the EPS-MMA-based PMPFs are about twice larger than those of the PIMPF, and the flexural modulus of elasticity of the PMPFs is almost a half of that of the PIMPF. From the above flexural behavior trend, it is obvious that the EPS-MMA-based PMPFs are more ductile than the PIMPF. This means that the EPS-MMA-based PMPFs have a high load-bearing capacity compared to the brittle PIMPF.

4. Conclusions

The conclusions obtained from the test results are summarized as follows:

1) The effects of curing conditions on strengths of EPS-MMA-based polymer mortars are not significantly evident. The steel fiber reinforcement of the EPS-MMA-based polymer mortars improves their strength properties regardless of the curing conditions.

2) The maximum flexural stress of EPS-MMA-based PMPFs without reinforcement and with steel fiber and crimped wire cloth reinforcements is comparable to that of PIMPF with steel fiber reinforcement, but the maximum extreme tension fiber strain of the PMPFs is about twice larger than that of the PIMPF.

3) The effects of reinforcements on the flexural behavior of EPS-MMA-based PMPFs are hardly recognized. Nevertheless, any reinforcements for the EPS-MMA-based PMPFs are needed to prevent the brittle failure by sudden impact loading under their installation and use. The flexural strength of the EPS-MMA-based PMPFs without reinforcement and with steel fiber and crimped wire cloth reinforcements is almost the same as that of PIMPF with steel fiber reinforcement. However, the maximum deflection and flexural toughness of the EPS-MMA-based PMPFs are about twice larger than those of the PIMPF, and the flexural modulus of elasticity of the PMPFs is almost a half of that of the PIMPF.

4) From the above flexural behavior trend, it is obvious that EPS-MMA-based PMPFs are more ductile than PIMPF and have a high load-bearing capacity compared to brittle PIMPF. Consequently, it is concluded that the production of the EPS-MMA-based PMPFs as precast products is possible and they can be used in place of PIMPF in the practical applications.

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