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Study of stress-strain dependence of polystyrene-modified concrete under axial compression

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Concrete modified with polystyrene particles is a new type of energy-conserving construction material that can be used as wall material characterized by light weight, heat preservation and insulation, and energy saving. Taking polystyrene-modified concrete as the research object, five prismatic specimens and cube specimens with different densities were prepared. The experiments were conducted to study the effect of specific gravity on the failure mode, mechanical properties and stress-strain curve of polystyrene-modified concrete. The experimental results show that the specific weight of polystyrene-modified concrete affects significantly on the mechanical properties of prismatic specimens. When the specific gravity of concrete increases from 495 kg/m^3 to 1269 kg/m^3, the peak stress, elastic modulus and brittleness index increase by 473.4 %, 199.35 % and 58.93 % respectively, while the ultimate strain and toughness index decrease by 23.72 % and 30.21 % respectively. In addition, the higher the content of polystyrene particles in concrete, the more slowly the stress-strain curve declines in the softening stage, and the larger the residual stress and residual strain. The stress-strain full curve equation was established by using the Guo model equation and the power function for polystyrene-modified concrete with medium and high specific gravity. The equation is in good agreement with the experiment results, which can provide a theoretical basis for engineering applications.

Keywords: polystyrene-modified concrete, uniaxial compression, stress-strain curve, specific weight, constitutive equation.

Дослідження залежності напруги-деформації полістирол-модифікованого бетону при осьовому стисканні. *Чжоупін Юй, Цзяхан Цай, Вейцзюнь Ян*

Вивчені механічні властивості та напруга-деформація полістирол-модифікованого бетону. Результати експерименту показують, що питома вага полістирол-модифікованого бетону надає істотний вплив на механічні властивості призматичного зразка. При збільшенні питомо+ ваги бетону з 495 кг/м^3 до 1269 кг/м^3 пікова напруга, модуль пружності і показник хрусткості збільшуються на 473,4 %, 199,35 % і 58,93 % відповідно, а гранична деформація і показник в'язкості знижуються на 23,72 % і 30,21 % відповідно. Крім того, чим вище вміст частинок полістиролу в бетоні, тим повільніше спадає крива напруга-деформація на стадії розуміцнення і тим більше остаточна напруга і остаточні деформації. Рівняння повної кривої напруги-деформації було отримано з використанням урівноважених моделей і ступеневої функції для полістирол-модифікованого бетону з середньою і високою питомою вагою. Рівняння добре погоджується з результатами експерименту, що може служити теоретичною основою для інженерних додатків.

1. Introduction

Polystyrene foam plastic particles composed of 98 % air and 2 % polystyrene belong to an ultra light closed cell material. It is widely used in packaging materials, decoration materials, insulation materials, road engineering, etc. [1]. Polystyrene particles cannot be degraded on their own due to their inherent stable chemical properties, causing increasingly serious environmental pollution. Therefore, polystyrene particles are used as raw materials to develop polystyrene-modified concrete [2]. As a new type of energy-saving material, polystyrene-modified concrete is popular and appreciated in the construction industry for its stable mechanical properties, good thermal insulation performance, deformation capacity, and shockproof and shock absorption effect [3]. Therefore, the development and research of the application of polystyrene-modified concrete has considerable economic benefits, engineering benefits and environmental implications.

Polystyrene particles have the characteristics of hydrophobicity, poor bonding performance, low strength and high compressibility, which leads to a large difference between the performance of polystyrene-modified concrete and ordinary concrete [2]. The influence of the size of polystyrene particles [4, 5] and the substitution rate on compressive strength [6, 7], splitting tensile strength [8] and flexural strength [9, 10] has been studied. Dong et al. used polymer modifiers to improve the adhesion of polystyrene particles and tested the mechanical properties of the modified concrete [1]. Herki et al. studied the mechanical properties and durability of concrete with polystyrene particles, and supposed that polystyrene particles will reduce the compressive strength, volume expansion resistance and dry shrinkage of concrete [9]. Babu et al. [11] tested the stress-strain behavior of fly ash concrete in which polystyrene particles partially replace natural crushed stone, and found that the elastic modulus decreases with an increase in the volume percentage of polystyrene particles: the elastic modulus of concrete decreases by 40% for every 10 % increase in the volume of polystyrene particles. Liu [12] studied the stress-strain curve of concrete partially replaced with crushed stone by polystyrene particles, and established the constitutive equation of modified polystyrene particle concrete under uniaxial compression. Cui et al. [13] established the stress-strain curve equation of non-modified polystyrene particle concrete with dry density of 800 kg/m^3, 1000 kg/m^3 and 1200 kg/m^3. Cheng [14] studied the effect of the particle size and content of EPS on the stress-strain curve. Yuan [15] tested the compressive strength, flexural strength and stress-strain curve of concrete prepared after surface coating treatment of polystyrene particles, and proposed a stress-strain curve model for the polystyrene-modified concrete after the coating treatment.

There are many researches on compressive strength, splitting tensile strength and flexural strength of concrete partially replaced by natural crushed stone with polystyrene particles. However, there are fewer studies of stress-strain curves of concrete with polystyrene particles replacing natural crushed stone. In this paper, the failure mode of the polystyrene-modified concrete prism is analyzed by uniaxial compression test; the stress-strain curve of the polystyrene-modified concrete is tested; the mechanism of the influence of the concrete specific gravity on the peak stress, strain, elastic modulus, toughness and brittleness of polystyrene-modified concrete is explored, and the constitutive equation of the stress-strain curve is established, which provides a reference for the research, application and promotion of polystyrene-modified concrete.

2. Raw materials and test methods

2.1 Testing of raw materials

Cement: P O 42.5 Ordinary Portland cement. Sand: river sand, fineness modulus 2.34, apparent density 2430 kg/m^3. Modified polystyrene particles: polystyrene particles modified with Italian EIA additives. The particle size is 3–5 mm, and the bulk density is 8.4 kg/m^3. Water-reducing agent: polycarboxylic acid superplasticizer. Water: tap water.

2.2 Mix ratio

Through changing the amount of sand and the volume of modified EPS particles, five kinds of concrete with particles of modified polystyrene were developed with different specific gravity of 500 kg/m^3, 700 kg/m^3, 900 kg/m^3, 1100 kg/m^3 and 1300 kg/m^3 were designed. See Table 1 for the mix proportion.

2.3 Preparation of polystyrene-modified concrete

The preparation process of polystyrene-modified concrete is as follows: the modified polystyrene particles, cement and me-

Table 1. Mix proportion of polystyrene-modified concrete

Test piece number	Cement, kg	Sand, kg	EPS, L	Water, L	W/C	Water reducing agent, kg	Bulk density, kg/m^3		Bulk density type
							Design	Measured	
E1	350	190	850	140	0.40	3.5	500	495	Low bulk density
E2	350	285	800	140	0.40	3.5	700	679	Medium bulk density
E3	350	500	680	175	0.50	3.5	900	847	Medium bulk density
E4	350	650	600	175	0.50	4.0	1100	1092	High capacity weight
E5	350	850	450	175	0.50	4.5	1300	1269	High capacity weight

dium sand are places into a 60 L forced mixer to mix for 2 minutes at medium to low speed. After adding water and water reducing agent, the material is mixed at low speed for about 5 minutes until the EPS and paste are uniform. The uniformly mixed concrete with modified polystyrene particles is placed into the mold in turn. The periphery of the test mold is then gently tapped with a wooden rod to fill the pores of the slurry and manually compact and smooth it.

The polystyrene-modified concrete in this test is self-compacting concrete. According to Chinese standard JGJ/T283-2012, the slump of each group of the polystyrene-modified concrete is 580 mm ~ 650 mm, which meets the requirements of self-compacting concrete. After curing for 24 hours, a sample of polystyrene-modified concrete in a test mold is removed from the mold and placed in a standard curing box for 28 days at a temperature of 20±2°C and a relative humidity of 95 %. The test piece is removed from the prism, placed in the oven, and dried at 85°C for 96 hours, then dry density is tested, and the dry density value is taken as the specific gravity of polystyrene-modified concrete.

2.4 Curing and testing of test pieces

The cubic specimen of polystyrene-modified concrete for compressive strength testing had the size 100 mm×100 mm×100 mm. For the prism axial compression test, the size of the test piece was 100 mm×100 mm×300 mm. The test was conducted according to the GB/T50081-2016 Chinese Standard. Before the sample cracks, the stress value is calculated according to formula (1) by applying a load on a universal testing machine and reading the strain using a strain gauge. After the crack strain gauge of the test piece fails, the displacement measured by the displacement gauge is calculated according to formula (2):

$$\sigma = \frac{N}{A}, \tag{1}$$

$$\varepsilon = \frac{\Delta l}{l}, \tag{2}$$

N is the axial pressure of prism specimen, kN; A — full cross-sectional area of the prism test piece, mm^2;

Δl is the compressive displacement of prism specimen, mm; l is the gauge distance measured by the prism test piece, mm.

3 Analysis of test results

3.1 Failure mode

At the initial stage of loading in the uniaxial compression test, cracks first appear at the top or bottom of the polystyrene-modified concrete specimen. With continuous increasing the load, the cracks at both ends extend to the middle of the specimen until they penetrate the entire section. It can be seen from Fig. 1 that the polystyrene concrete with modified particles with low specific gravity shows greater compressibility during loading. It can be seen from Fig. 1a that the concrete on the top of the test piece is crushed, and no cracks are found on the surface of other parts. The content of polystyrene particles in concrete with low bulk density is high, while the content of sand is low, and the strength of

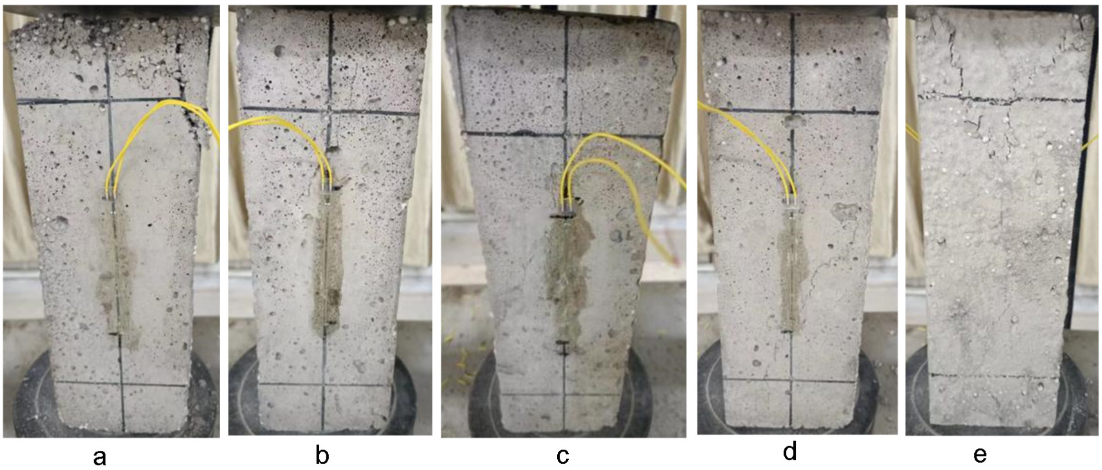

Fig. 1. Failure mode of polystyrene-modified concrete prism in axial compression test. (a) E1, (b) E2, (3) E3, (d) E4, (e) E5.

the cement matrix is low. When the load continues to increase, the polystyrene particles undergo more compression and rupture, and the concrete with the modified polystyrene particles shows a local rupture phenomenon. It can be seen from Fig. 1b, c that polystyrene concrete with modified particles with the medium specific gravity shows certain compressibility during loading, but with an increase in the specific gravity, the compressibility decreases, and one or more vertical cracks appear on the test piece. It can be seen from Fig. 1d, e that there is no crushing at the top of the test piece, but there are long oblique cracks or vertical cracks at the side. This is mainly due to the high strength and brittleness of the concrete with high bulk density. It can be seen from Fig. 1e that the concrete at the end of the test piece is relatively complete, and there are splayed cracks extending in the top two corners on the surface of the test piece, with more obvious brittleness characteristics.

3.2 Cube compressive strength

It can be seen from Fig. 2 that the compressive strength of polystyrene concrete increases with an increase of its specific gravity. The compressive strength increases with an increase in the curing age of the concrete. The specific gravity of the concrete reduces from 1269 kg/m^3 to 495 kg/m^3; the compressive strength of the concrete decreased from 6.25 MPa to 1.06 MPa after 28 days. The compressive strength decreased by 81.42 % after 7 days; and after 28 days, the compressive strength decreased by 83.04 %.

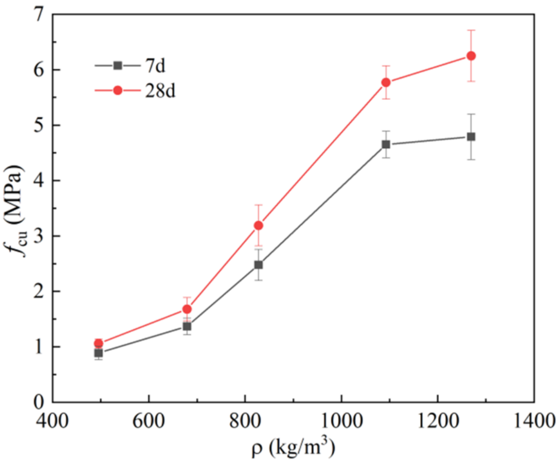

Fig. 2. Effect of specific gravity on compressive strength of polystyrene-modified concrete.

3.3 Mechanical properties of prisms

The mechanical properties of the polystyrene-modified concrete prism under axial compression test are characterized by six values: peak stress, peak strain, elastic modulus, limit strain, toughness index and brittleness index.

3.3.1 Peak stress

It can be seen from Fig. 3a that the peak stress of the concrete prism specimen increases with increasing specific gravity. The maximum specific gravity is 1269 kg/m^3. The compressive strength of the concrete prism increased by 473.40 %, 264.19 % and 89.79 %, respectively for 495 kg/m^3, 679 kg/m^3, 847 kg/m^3 specific gravity. The test results show that the f_c/f_{cu} value of the polystyrene-modified concrete is between

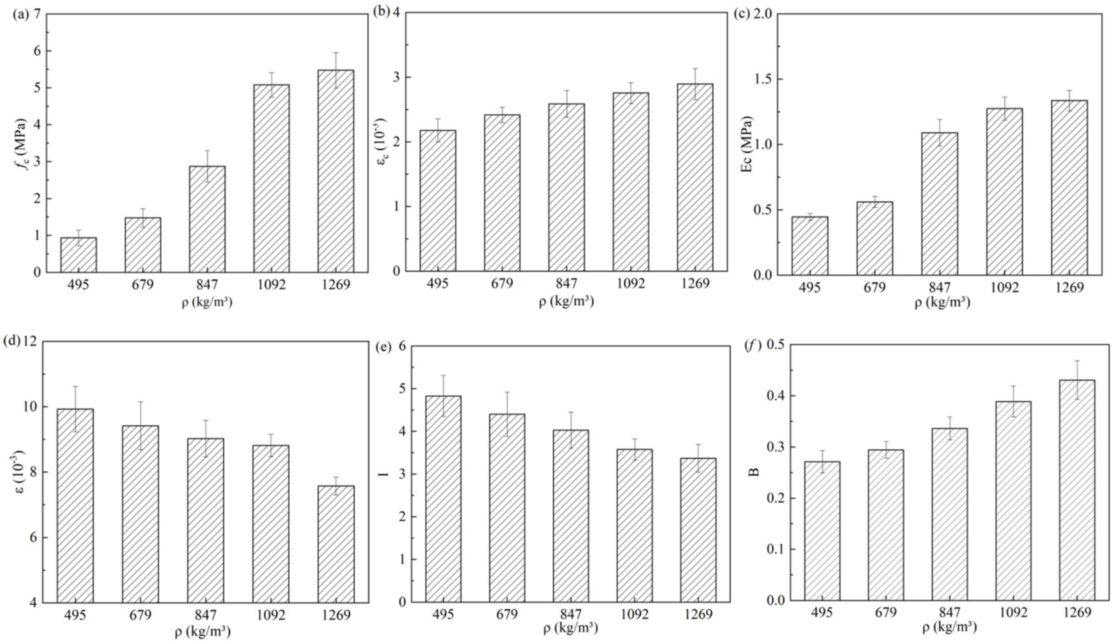

Fig. 3. Effect of specific gravity on mechanical properties of a polystyrene-modified concrete prism (a) peak stress, (b) peak strain, (c) elastic modulus,(d) ultimate strain,(e) toughness index, (f) brittleness index.

0.84 and 0.91, which is higher than 0.76 [16] of the f_c/f_{cu} value for ordinary concrete. This is mainly because the reduction of the end to the middle of the modified polystyrene particle concrete prism specimen is weaker than that of the ordinary concrete.

3.3.2 Peak strain

It can be seen from Fig. 3b that peak strain of polystyrene concrete increases slightly with an increase in its specific gravity [13, 17]. As the specific gravity decreased from 1269 kg/m^3 to 495 kg/m^3, the peak strain increased by 24.66 %; while as the specific gravity was 1079 kg/m^3, the peak strain decreased by 5.35 %. This is mainly due to the high content of polystyrene particles and low strength in the polystyrene-modified concrete with low bulk density, as well as low strain when reaching the peak strength. When the specific gravity of polystyrene concrete is 1269 kg/m^3, the content of polystyrene particles is low, the bulk density is high, the elastic modulus is large, and the compressibility is relatively low.

3.3.3 Elastic modulus

Elastic modulus is a measure of the ability of concrete to resist elastic deformation. The relationship between the elastic modulus of polystyrene concrete and the specific gravity is shown in Fig. 3c. The elastic modulus of polystyrene concrete increases with an increase in the specific gravity. When the specific gravity of polystyrene concrete increased from 495 kg/m^3 to 849 kg/m^3, the elastic modulus increased by 102.44 %. When the specific gravity of polystyrene concrete increased from 849 kg/m^3 to 1269 kg/m^3, the elastic modulus increased by 47.87 %. This is mainly because the polystyrene particles with light weight and large deformation greatly reduce the elastic modulus of concrete. The elastic modulus of polystyrene concrete with medium bulk density increases greatly. However, due to the high content of sand and low content of polystyrene particles, the elastic modulus of the polystyrene concrete with a high specific gravity increases with increasing specific gravity, but this increase is significantly reduced.

3.3.4 Ultimate strain

Ultimate strain is the amount of deformation during concrete damage, which can reflect the ultimate deformation capacity of modified polystyrene concrete. It can be seen from Fig. 3d that the ultimate strain of polystyrene concrete decreases with an increase in the specific gravity. However, the reduction is not significant. At low specific gravity 495 kg/m^3, the limit strain of polystyrene concrete is $9.929{\cdot}10^{-3}$, while at the medium specific gravity of 849 kg/m^3

and high specific gravity of 1269 kg/m^3, the ultimate strain of polystyrene concrete is, respectively, 9.11 % and 23.72 % lower than that of low bulk density concrete. It can be seen that the ultimate deformation capacity of the polystyrene concrete with high specific gravity is obviously weakened.

3.3.5 Toughness index

The toughness of concrete is reflected in the ability to absorb energy during plastic deformation and failure, which is usually expressed by the toughness index (I). The ratio of the toughness index to the area around the peak strain is 3 times greater than for the area around the peak strain on the stress-strain curve. It can be seen from Fig. 3e that the toughness index of polystyrene concrete decreases with an increase in the specific gravity of the concrete. When the specific gravity of polystyrene concrete is 495 kg/m^3, it has the best toughness. While the medium specific gravity is 849 kg/m^3 and high specific gravity is 1269 kg/m^3 the elastic modulus of the polystyrene concrete is, respectively, 16.54 % and 30.21 % lower than that of the low bulk density concrete. This shows that increasing the content of polystyrene particles can enhance the toughness of concrete. In practical engineering, especially in structures or components that experience vibrations or deformations, provided that the requirements for mechanical characteristics are met, polystyrene particles can be added to improve its deformation ability.

3.3.6 Brittleness index

Concrete is neither an elastic material nor an ideal elastic-plastic material, and there must be some brittleness. The brittleness of polystyrene-modified concrete is expressed by the brittleness index (B), which is the ratio of the area limited by the peak strain on the stress-strain curve to the area limited by 1–3 times the peak strain. It can be seen from Fig. 3f that the brittleness index of polystyrene concrete increases with an increase in the specific gravity. When the specific gravity of polystyrene concrete is 495 kg/m^3, its brittleness index is the lowest at 0.271. As the specific gravity of polystyrene concrete increased from 849 kg/m^3 to 1269 kg/m^3 and to 495 kg/m^3, respectively, the brittleness index increased by 23.99 % and 58.93 %.

3.4 Relationship between mechanical indexes and specific gravity

3.4.1 Peak stress and cube compressive strength

The dependence of the peak stress on the specific gravity of the prismatic sample of polystyrene concrete ρ, as well as the peak stress f_c and the compressive strength f_{cu} of the cubic sample show a linear trend of change [13, 17]. Regression analysis of the relationship between peak stress and the specific gravity and cubic compressive strength of 15 groups of test results shows the following function equation:

$$f_c = 0.288 - 6.7 \cdot 10^{-4}\rho + 0.97f_{cu} \quad (3)$$
$$(R^2 = 0.9978).$$

3.4.2 Peak strain and limit strain

The peak strain increases with an increase in the specific gravity of the polystyrene concrete, while the limit strain decreases with an increase in the specific gravity. Based on the regression analysis of the change relationship between the two strains and specific gravity, the change relationship function between peak strain, specific gravity and limit strain is established as follows:

$$\varepsilon_c = 1.54 + 9.56 \cdot 10^{-4}\rho + 0.021\varepsilon_{cu} \quad (4)$$
$$(R^2 = 0.9823).$$

3.4.3 Modulus of elasticity and cube compressive strength

The elastic modulus of polystyrene concrete is related to the internal structure of concrete. Polystyrene particles are a kind of porous lightweight organic aggregate, and their elastic modulus can be ignored. Therefore, the incorporation of polystyrene particles reduces the specific gravity, compressive strength and elastic modulus of concrete. Based on the test results of 15 test pieces, the regression analysis of the relationship equation between elastic modulus, specific gravity and compressive strength is as follows:

$$E_c = 0.255 + 8.56 \cdot 10^{-5}\rho + 0.16f_{cu}, \quad (5)$$
$$(R^2 = 0.9909).$$

3.4.4 Toughness index and brittleness index

According to the definition of the toughness index and brittleness index, a relationship of $I = 1 + 1/B$ can be determined. It can be seen from Fig. 4e, f that the content of polystyrene particles and the specific gravity of concrete have a significant impact on the toughness index and brittleness index. Due to comprehensive analysis of specific gravity, toughness index and brit-

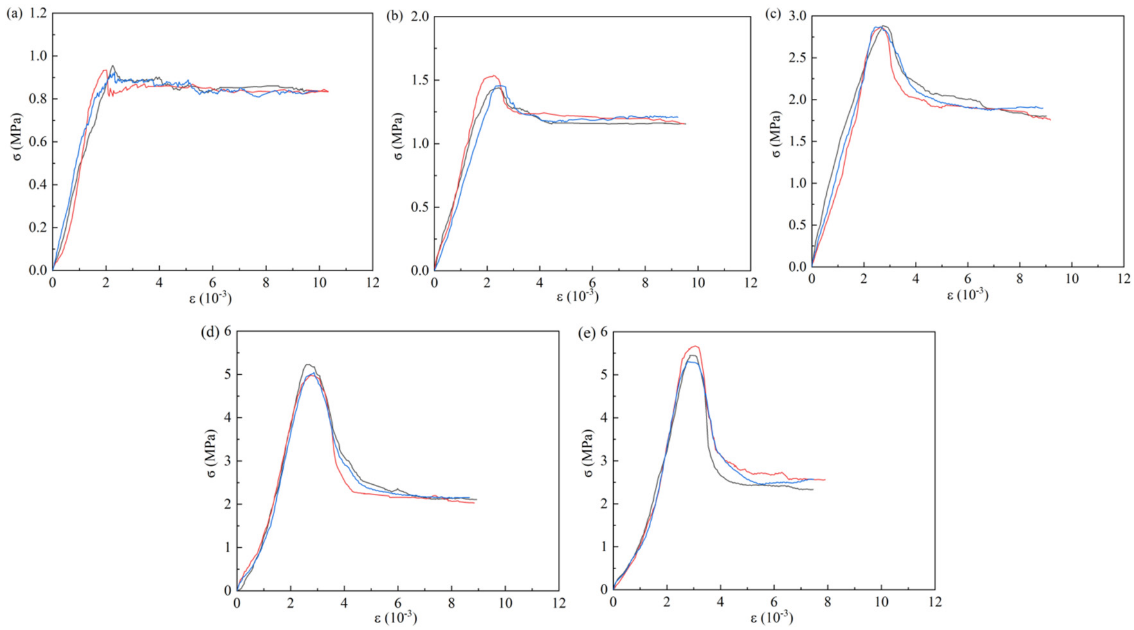

Fig. 4. Stress-strain curves of polystyrene-modified concrete (a) E1, (b) E2, (c) E3, (d) E4, (e) E5.

tleness index, the following functional relationship is established:

$$B = -0.18 + 3.25 \cdot 10^{-4}\rho + 0.061I \quad (6)$$
$$(R^2 = 0.9955)$$

3.5 Stress-strain curve of modified polystyrene particle concrete

It can be seen from Fig. 4 that the stress-strain curve of polystyrene concrete mainly goes through four stages: elastic stage, strengthening stage, softening stage and residual stage. At the initial stage of loading, the polystyrene concrete has not yet cracked, it experiences elastic deformation, and the stress-strain curve shows a linear relationship. In the process of crack appearance and development, the polystyrene concrete experiences plastic deformation, and the stress-strain curve is nonlinear. When the load continues to increase after the peak stress, the stress decreases rapidly and the strain continues to increase to the softening stage. When the stress decreases to a certain value, it tends to be stable. The stress is basically kept constant while the strain gradually increases, resulting in a large amount of residual deformation.

The stress-strain curves of polystyrene concrete are shown in Fig. 4. There are three numbered samples, and each sample corresponds to a stress-strain curve in Fig. 4. The stress-strain curves of polystyrene concrete with different specific gravity are significantly different. It can be seen from Fig. 4 a that when the low bulk density polystyrene concrete reaches the peak stress, the stress decreases slightly with increasing strain, and then enters into the vibration stage of repeated increase and then decrease, and finally tends to be stable. This is mainly due to the high content of polystyrene particles in the low bulk density polystyrene concrete, while the porous polystyrene particles continue to flow, collapse and redistribute stress after densification during compression, resulting in the stress increase [18]. From Fig. 4b~e, it can be seen that the stress-strain curves of polystyrene concrete with medium and high specific gravity are similar in the rising section. When the polystyrene concrete reaches the peak stress, the stress decreases to varying degrees with increasing strain, and the decreasing range increases with an increase in the specific gravity. With the increase in the specific gravity of the polystyrene concrete, the peak stress gradually increases and the residual deformation gradually decreases.

3.6 Complete stress-strain curve equation of concrete with modified polystyrene particles

3.6.1 Constitutive relationship model of concrete

The stress-strain relationship of concrete is the constitutive relationship, which is one of the basic characteristics of materials. At present, the mathematical models of concrete constitutive relations mainly include polynomial, trigonometric function, rational fraction, exponential function, power function and other forms. The mathematical model of concrete constitutive relation may be a single function [19] or a piecewise equation of two functions [16, 20]. According to the literature, the piecewise function can more accurately express the change of stress-strain curve. The models given by Yang [19], Guo [20] and Code for Design of Concrete Structures [16] are widely used.

(1) Yang et al. [19] established the constitutive equation of power function:

$$y = \frac{\beta + 1)x}{\beta + x^{\beta+1}}, \tag{7}$$

$$\beta = \begin{cases} 0.20\exp[0.73(\frac{10}{f_c})^{0.67}(\frac{\rho}{2300})^{1.17}], & \varepsilon < \varepsilon_c \\ 0.41\exp[0.77(\frac{10}{f_c})^{0.67}(\frac{\rho}{2300})^{1.17}], & \varepsilon > \varepsilon_c \end{cases}. \tag{8}$$

(2) Guo [20] established the constitutive equation by decomposing the stress-strain curve of low strength concrete into ascending and descending segments according to the dependence of the change in the stress-strain curve.

$$y = \alpha x + (3 - 2a)x^2 + (\alpha - 2)x^3 \quad x \le 1, \tag{9}$$

$$y = \frac{x}{\beta(x + 1)^2 + x}, \quad x > 1. \tag{10}$$

α is the ratio of initial elastic modulus to peak secant modulus, $1.5 \le \alpha \le 3$.

β is the coefficient related to concrete strength grade and constraint equation, requirements $\beta \ge 0$.

According to literature [21] $\alpha = 2.2$, $\beta = 0.4$.

(3) The constitutive equations given in the Chinese Standard GB50010-2010 [16] are formulas (11) and (12). The specific gravity of polystyrene concrete is relatively low, and the value is 0.74 according to Chinese specifications.

$$y = \begin{cases} \frac{nx}{n - 1 + x^n}, x \le 1, \\ \frac{x}{\alpha_c(x - 1)^2 + x}, x > 1, \end{cases} \tag{11}$$

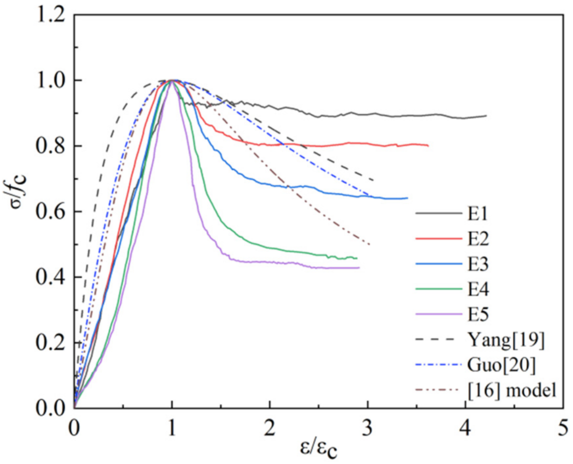

Fig.5. Normalized stress strain curve of polystyrene-modified concrete.

$$n = \frac{E_c\varepsilon_c}{E_c\varepsilon_c - f_c}, \tag{12}$$

3.6.2 Normalized stress-strain curve

After normalizing the stress based on peak stress and peak strain of polystyrene concrete, the average value of three test pieces is taken to draw the normalized stress-strain curve, as shown in Fig. 5. The normalized stress-strain curve of polystyrene concrete has the following characteristics:

(1) The stress and strain at the origin of the stress-strain curve are 0.

(2) The stress increases with increasing strain before reaching the peak stress, but the slope of the stress-strain curve decreases monotonically.

(3) The stress dropped sharply after reaching the peak stress due to rapid development of internal cracks. There is an inflection point in the stress-strain curve at this stage, $d^2(\sigma/f_c)\hat{}/\hat{}d(\varepsilon/\varepsilon_c)^2 = 0$.

(4) When $\varepsilon/\varepsilon_c$ continues to increase, σ/f_c tends to be stable. Polystyrene concrete has residual stress and residual strain at this stage.

It can be seen from Fig. 5 that the change trend of the stress-strain curve of polystyrene concrete is similar to that of the Yang model, the Guo model and the model in the Chinese Standard GB50010-2010 for conventional concrete, but the change trend of the downward section is very different. Therefore, the strain-strain curve of the polystyrene concrete can't be

Table 2. Parameters of the stress-strain curve equation

Specimen number	Bulk density, kg/m^3	Ascending segment				Descent section			
		a	b	c	correlation coefficient R^2	d	e	f	correlation coefficient R^2
E1	495	0.944	1.266	–1.3	13	0.9958	–17.6	85	–29.3
E2	679	0.750	1.368	–1.1	10	0.9993	0.082	0.055	–0.92
E3	847	0.679	0.911	–0.6	11	0.9976	0.067	0.062	–0.94
E4	1092	0.608	0.872	–0.3	41	0.9925	0.042	0.071	–0.95
E5	1269	0.565	0.544	–0.0	25	0.9972	0.033	0.091	–0.97

fully expressed by the original model equation.

3.6.3 Constitutive equation of the complete stress-strain curve This paper describes the stress-strain curve of concrete with modified polystyrene granules more accurately by using the subsection method. After comprehensive analysis of the Yang model, the Guo model and the Chinese standard GB50010-2010 model, combined with the characteristics of the normalized stress-strain curve of the polystyrene concrete, the polynomial equation of the Guo model was used in the rising section, as shown in equation (13). The curve change characteristics are consistent with the model, but there are differences. All parameters need to be further modified. Based on the regression analysis and the characteristics of residual deformation, this paper proposes the power function equation for the descending section of the polystyrene concrete, as shown in formula (14).

$$y = ax + bx^2 + cx^3, \tag{13}$$

$$y = \frac{d}{x^e + f}. \tag{14}$$

The first inflection point in the stress-strain curve occurs when the stress reaches the peak stress. $a = d(y)/d(x)|subx{=}0 = E_0/E_c$, E_0 and E_c are the moduli of elasticity at the origin of the stress-strain curve and at the secant of the peak stress point, respectively. Other parameters are determined by corresponding curve regression analysis, see Table 2 for details. It can be seen from Table 2 that the stress reduction of the polystyrene concrete with the low specific gravity after failure is very small, and the residual stress and residual deformation are very large. In this paper, it is suggested that the stress-strain curve dependence of the polystyrene concrete with the low specific gravity is given by the following equations:

$$x \le 1, \quad y = ax + bx^2 + cx^3, \tag{15}$$

$$x > 1, \quad y = 1. \tag{16}$$

It can be seen from Table 2 that the parameters a, b and d of the constitutive equation of the polystyrene concrete with the medium and high specific gravity decrease with increasing the specific gravity of the polystyrene concrete, while the parameters c, e and f increase with an increase in its specific gravity. Therefore, the relationship between the parameters and the specific gravity of the polystyrene concrete is established by the constitutive equation using the dimensionless regression analysis, as follows:

$$a = 1.142 - 7.241 \cdot 10^{-4}\rho + 2.127 \cdot 10^{-7}\rho^2 \tag{17}$$

$$b = 2.406 - 0.002\rho + 2.441 \cdot 10^{-7}\rho^2, \tag{18}$$

$$c = -3.41 + 0.004\rho - 1.346 \cdot 10^{-6}\rho^2, \tag{19}$$

$$d = 0.182 - 1.79 \cdot 10^{-4}\rho + 4.785 \cdot 10^{-8}\rho^2, \tag{20}$$

$$e = 0.093 - 1.133 \cdot 10^{-4}\rho + 8.733 \cdot 10^{-8}\rho^2, \tag{21}$$

$$f = -0.849 - 1.288 \cdot 10^{-4}\rho + 2.526 \cdot 10^{-8}\rho^2. \tag{22}$$

3.6.4 Verification of the constitutive equation of the stress-strain curve

The stress-strain curve measured in the uniaxial compression test of the polystyrene concrete prism is compared with the theoretical model curve obtained from the parameter formula to verify the applicability of the constitutive equation established in this paper. In Fig. 6a, there is no stress softening stage in the theoretical equation, which is directly the residual deformation

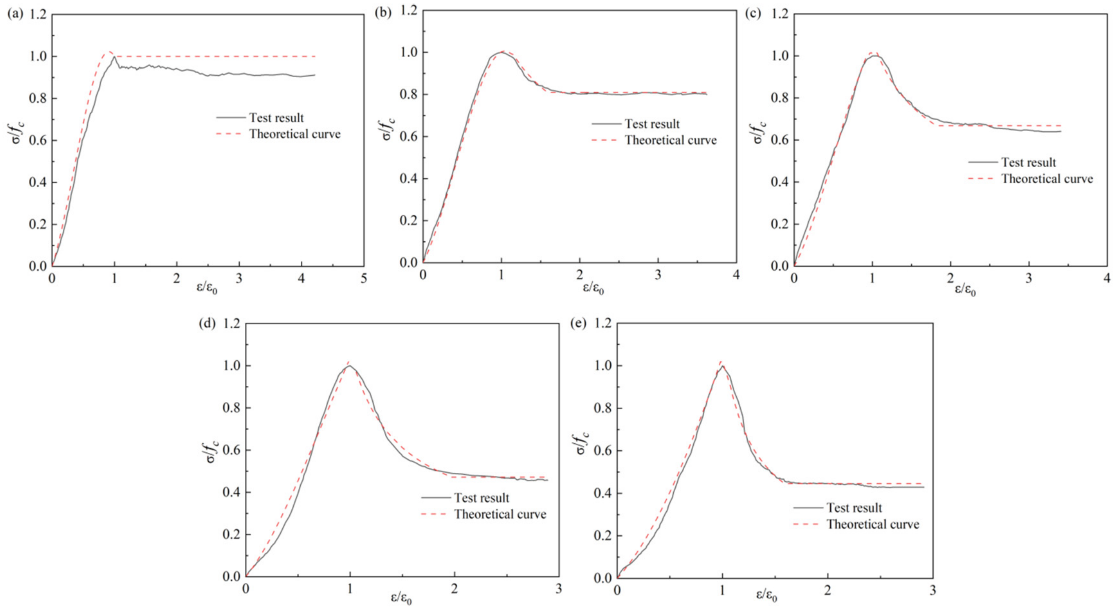

Fig. 6. Comparison between test results of EPS concrete stress-strain curve and theoretical curve (a) E, (b) E2, (c) E3, (d) E4, (e) E5.

stage. The polystyrene concrete with the low specific gravity has high compressibility, large residual stress and a small amount of stress softening, which leads to the difference between the theoretical constitutive equation and the measured value. It can be seen from Fig. 6b~e that the stress-strain constitutive equations established for the polystyrene concrete with the medium and high specific gravity are basically consistent with the measured values, which can better reflect the whole process of the stress-strain curve development of the polystyrene concrete specimen under uniaxial compression, and can better characterize the stress-strain behavior of the polystyrene concrete under uniaxial compression.

4. Conclusion

(1) The f_c/f_{cu} of the concrete with modified polystyrene particles is larger than that of ordinary concrete in the range of 0.84 ~ 0.91. The relationship equation between the peak stress and the specific gravity and the cube compressive strength of the polystyrene concrete prism specimen is $f_c = 0.288 - 6.7\cdot10^{-4} + 0.97f_{cu}$.

(2) The full stress-strain curve of polystyrene concrete showed an elastic stage, a hardening stage, a softening stage and a residual stage. The stress-strain curve of the polystyrene concrete is quite different in the softening stage. The higher the content of polystyrene particles, the lower the specific gravity of the concrete, the slower the decline of the stress-strain curve in the softening stage, and the greater the change of residual stress and residual strains.

(3) The specific gravity of the polystyrene concrete significantly affects the peak stress, the elastic modulus, the limit strain, the toughness and brittleness. When the specific gravity of the polystyrene concrete increases from 495 kg/m^3 to 1269 kg/m^3, the peak stress, the elastic modulus and the brittleness index increase by 473.4 %, 199.35 % and 58.93 % respectively, while the limit strain and the toughness index decrease by 23.72 % and 30.21 % respectively,

(4) In this paper, the stress — strain model equation of concrete with modified polystyrene particles having the medium and high specific gravity is proposed, in which the rising section is described by the Guo model equation, and the falling section is described by the power function. It is verified that the theoretical model is in good agreement with the test results, which can serve as a guide for engineering applications.

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