Research Journal of Applied Sciences, Engineering and Technology 6(11): 2012-2018, 2013
DOI:10.19026/rjaset.6.3817
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: November 24, 2012 Accepted: January 03, 2013 Published: July 25, 2013

Research Article

Mechanical Properties and Energy-saving Effect of Polypropylene Fiber Foam Concrete

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Abstract: Compared with ordinary concrete, foam concrete possesses advantages such as lightweight, heat insulation, etc., but the internal bubbles have of great influence on its strength. This study examined the impact of polypropylene fibers on mechanical properties of foam concrete using flexural deformation control method and obtained complete load-deformation curve. The results show that, polypropylene fibers significantly affect the compressive property of the foam concrete and improve the carrying capacity after the peak compression load, but have little effect on the compressive strength; polypropylene fibers improve the flexural performance significantly.

Keywords: Foam concrete, mechanical property, polypropylene fiber

INTRODUCTION

Foam concrete is a kind of porous concrete (Kearsley and Wainwrigh, 2001). Because of containing a large number of closed pores, it shows excellent physical and mechanical properties of light weight, high strength, energy conservation, thermal insulation, etc., having a wide application range. The foam concrete almost has compatibility with all kinds of building materials, with strength adjustable (Kearsley and Wainwrigh, 2002a).

Despite the above advantages, foam concrete has demonstrated some shortcomings of the performance in use, which still calls for further improvement and enhancement. The strength of foam concrete will reduce with the increase of the porosity; the compressive strength of foam concrete with porosity of 800 kg/m^3-850 kg/m^3 is generally lower than 2.0 Mpa (Savoly and Elko, 2003). The number of bubbles in the foam concrete is related to the porosity after hardening. More bubbles mean smaller density and better thermal and heat insulation; meanwhile, the strength declines significantly. Therefore, the unique characteristics of foam concrete are taking the reduction in strength as the price. Due to the presence of a large number of bubbles, the brittle characteristics of the concrete are more significant (Paul *et al*., 2004). The size, shape and volume of the bubbles have a significant effect on mechanical and insulation properties of the foam concrete. To improve the mechanical properties, domestic and foreign scholars have done a lot of work in foam concrete with polypropylene fibers. It is a commonly used method to add fibers into ordinary concrete to improve the mechanical properties of the cement-based materials. Number of Researches (Jones and McCarthy, 2006; Kearsley and Wainwrigh, 2002b) on performance improvement through adding fiber into foam concrete is still limited and the degrees of performance improvement as well as the mechanism are still under discuss. Especially, the qualitative and quantitative research on improvement due to polypropylene fibers is very insufficient.

In this study , compressive and flexural performance testing of foam concrete with polypropylene fibers are performed and analysis on mechanical properties as well as energy-saving effect are implemented, which lays foundation for the design of performance-based composite materials.

SIMULATION METHOD

It has an important significance to improve the design level of the engineering industry and increase the economic benefits using ANSYS numerical simulation. Analysis on ultimate load of concrete in ANSYS is related to material constitutive, failure criteria, network density, convergence tolerance and load mode (Santhakumar and Chandrasekaran, 2004). In this study, we examined the mechanical properties and the energy-saving effect of polypropylene fiber foam concrete using the software of ANSYS.

Constitutive of concrete: In recent years, research on concrete constitutive has greatly developed, but it shows the characteristics of relatively concentrated. We will review the development of the concrete constitutive in two points. The impact of newly emerging interdisciplinary research on the development of concrete constitutive

Constitutive relation based on fracture mechanics:

- **Linear constitutive model:** In recent years, some researchers proposed crack propagation resistance curve based on cohesion, revealing the relation between cohesion and crack propagation resistance in the crack propagation process of quasi-brittle materials and indicating the softening linear constitutive of concrete is closely related to the analytical solution of the resistance curve.

- **Non-linear constitutive model:** In order to express the whole process of the non-linear relationship of load-deformation, we can export the formula of the crack angle according to the principle of minimum strain energy. The strain of concrete with crackes can be decomposed into the strain of fracture plane and the strain of the intact part. Take the stiffness of the descent stage of the stress-strain curve as the normal stiffness of the fracture plane, take the elastoplastic constitutive model for the intact part, we can export the three-dimensional non-orthogonal smeared crack model:

$$\Delta\sigma = \left\{\left(D^{co}\right)^{-1} + \sum_{i=1}^{k} N_i \left(D_i^{cr}\right)^{-1} N_i^T\right\}^{-1} \Delta\varepsilon$$

Where, D^{co} and D^{cr}_i is the constitutive matrix of the intact concrete and cracked concrete respectively.

After processing the full curve of various types of fracture, we obtained the stress-strain constitutive through fitting the unified mathematical expression of the softening curve:

$$\begin{cases} \sigma_e = E\varepsilon_1 & \varepsilon_1 \le \varepsilon_0 \\ \sigma_e = \sigma_{ec}\left[1 - \left(\left(\varepsilon_1 - \sigma_e / E\right) / \varepsilon_{max}\right)^{\alpha} \right. & \\ \qquad \left. e^{\beta\varepsilon / \left(\varepsilon_1 - \sigma_e / E\right)_{max}}\right] & \varepsilon_1 > \varepsilon_0 \end{cases}$$

where,
ε_1 = The main strain
ε_0 = The limit elastic strain

From the viewpoint of energy, the stress-strain constitutive can be converted into energy-strain constitutive, which is conductive to track the expansion process of three-dimensional cracks.

The existing elastoplastic nonlinear analysis is mainly based on incremental theory. Although the classic plasticity theory is relatively stricter in mathematics, it is developed on the basis of metal crystal slip. The failure mechanism of concrete is mainly micro-cracking, which is far different from the case of metal; therefore, the results of classical plasticity theory will present some deviations from actual situation.

The concrete constitutive model has a significant impact on the results of nonlinear finite element analysis. Based on the existing framework of continuum mechanics, a suitable concrete constitutive model can be obtained. The existing theoretical models include elastic theory, nonlinear elasticity theory, elastic-plastic theory, viscoelasticity theory, fracture mechanics and damage mechanics. According to the practice of many scholars, nonlinear elastic constitutive relation shows good consistency with tests when stress is below 70% of the limit stress. The three conditions must be defined before the application of the nonlinear elastic constitutive model:

- **Failure criterion:** There are a great number of concrete failure criterions proposed by scholars from various countries, which can be selected according to practice, such as the Kupfer formula for two-dimensional stress, the Ottosen formula for three-dimensional stress.
- **Nonlinear index:** The nonlinear index indicates the relative levels of the stress state, whereby you can determine the nonlinearity degree of concrete's deformation.
- **The equivalent one-dimensional stress-strain relationship:** Sargin expression is adopted in programming. The immediate secant modulus and the relationship with the nonlinear index can be determined by the Sargin expression.

$$E_s = \frac{1}{2}E_0 - \beta\left(\frac{1}{2}E_0 - E_c\right)$$

$$\pm\sqrt{\left[\frac{1}{2}E_0 - \beta\left(\frac{1}{2}E_0 - E_c\right)\right]^2 + \beta E_c^2\left[D\left(1-\beta\right) - 1\right]}$$

Where,
E_0 = The initial elastic modulus
Ec = The elastic modulus under peak stress
D = The coefficient for controlling the falling section

Treatment of concrete cracks: In the nonlinear finite element analysis of concrete, the commen used crack model includes distributed crack model, discrete crack model and fracture mechanics model. In this study, the distributed crack model is adopted. The advantages are:

- The cracks can be automatically generated, without changing the layout of the elements.
- The cracks can be generated in any direction, without being specified in advance.

Once the cracks appear, the concrete turns into anisotropic material and the improved constitutive relation matrix in the local coordinate system is:

$$\begin{bmatrix} d_{\sigma_x} \\ d_{\sigma_y} \\ d_{\sigma_\tau} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & E & 0 \\ 0 & 0 & \beta G \end{bmatrix} \begin{bmatrix} d_{\varepsilon_x} \\ d_{\varepsilon_y} \\ d_{\varepsilon_\tau} \end{bmatrix}$$

where, β is the shear residual coefficient, reflecting the friction effect of the fracture surface and $0 \le \beta \le 1$. For the specific value of β, yet it is still under argued,

Table 1: Mixing ratios of polypropylene fiber foam concretes

number	1	2	3
Density(kg/m^3)	1000	700	500
concrete(g/L)	610.7	610.7	427
Fly ash(g/L)	152.7	152.7	106.8
water(g/L)	267.2	267.2	187
Sand(g/L)	114.5	114.5	80.2
Polypropylene fiber(g/L)	0.0	5.3	3.7

because it has a significant effect on the convergence of the finite element program solution. Generally, the value of β is within the range of 0.3-0.5.

ANSYS provides a three-dimensional solid element Solid 65 for the simulation of concrete under tension or pressure. Solid 65 is able to describe the stress-strain relationship under uniaxial tension or pressure using linear elastic or elastoplastic constitutive. If not specify a constitutive relation for Solid 65, ANSYS will adopt the default linear elastic constitutive, that is, the stress-strain relationship keeps to be linear before cracking or crushing. For lastoplastic constitutive, the Muhilinear Isotmpic Hardening model is adopted, with Mises yield criterion. In addition to describe the uniaxial stress performance, the uniaxial stress-strain curve can also indirectly describe the stress-strain relation of concrete under complex stress state.

The establishment of the computational model: The maximum volume content of the fibers is typically between 0.5%-0.8% and it has different suggestions in literature (Yoo-Jae and Hu, 2010). In the calculation of the volume content, the ratio of fiber volume and the total volume is usually adopted as measurement parameter; however, there is always a large number of closed pores in the foam concrete, which occupies half (even more) of the total volume. And the smaller the density, the more pores per unit volume and the slurry is only a small part of the total volume. According to the distribution characteristics of tiny pores and fibers, combined with the experimental results, we can infer that no fiber passes through the sealed pores. We take three kinds of polypropylene fiber foam concretes with density of 1000, 700 and 500 kg/m^3, respectively with following mixing ratios (Table 1):

In this study, a concrete block of 150 mm×150 mm×150 mm is adopted as the test object and the compressive strength is measured. For concretes with density of 1000, 700 and 500 kg/m^3, the Young's modulus is 1GPa, 0.6 GPa and 0.2 GPa respectively.

Calculation methods: For the above concrete blocks, we will analyze the ultimate load in the uniaxial compression test from the influencing factors. In this study, we simulated with linear elastic constitutive based on the compressive strength and flexural strength measured in the test (Ramamurthy, 2009).

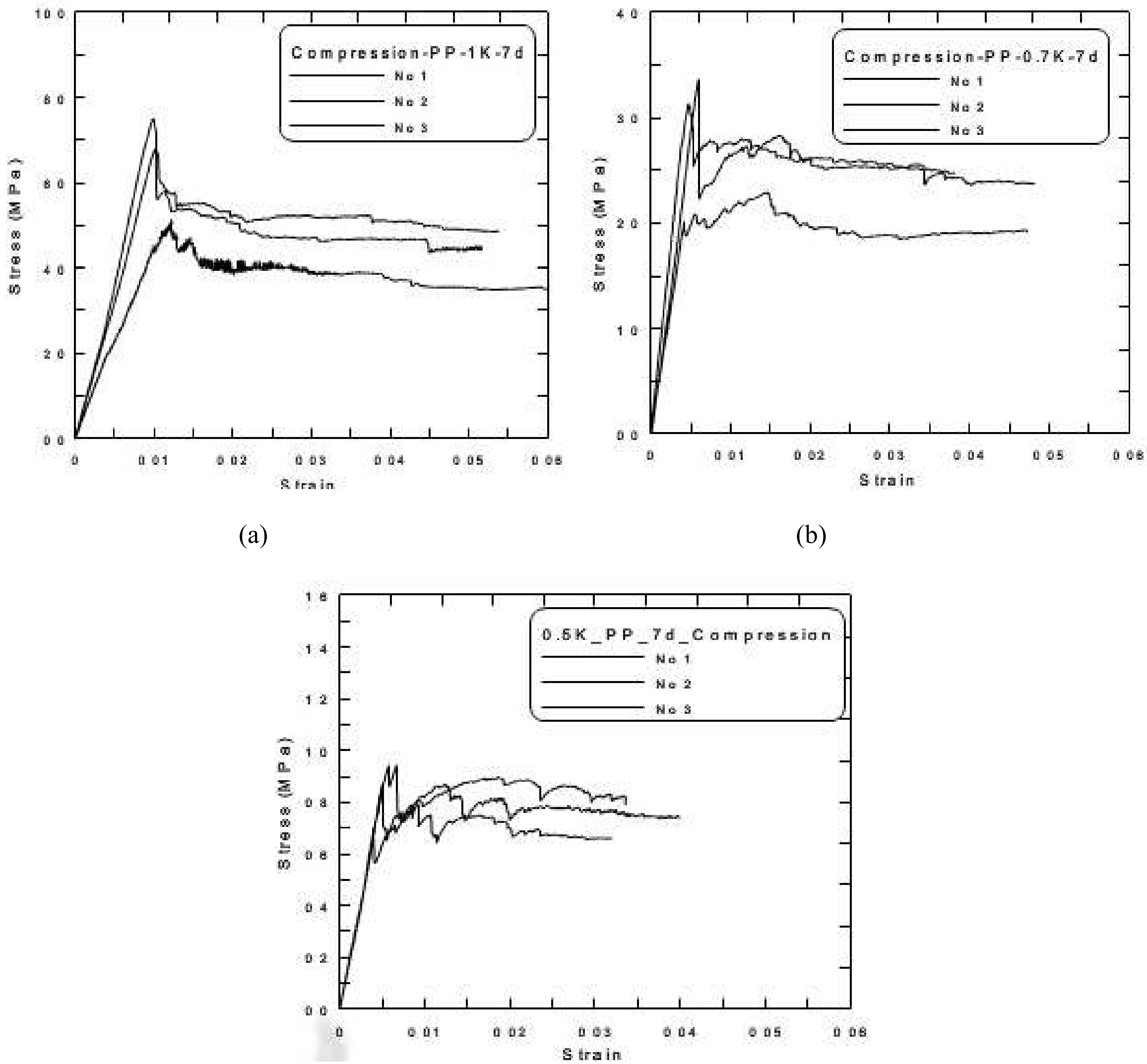
- **Failure criterion:** The William. Wamke 5 parameters failure criteria is adopted in this study, in which the uniaxial compressive strength can be either positive or negative.
- **Mesh density:** As a numerical method, the calculation accuracy of the finite element method is impacted by the density of the elements divided. Currently, there is no definitive theory or indicators to define the results accuracy of the finite element calculation. According to finite element theory, the numerical solution will approximate the analytical solution when the elements are small enough. The above practice is subjected to the limitation of computer hardware and for general concrete structure, there is no analytic solution comparable. So the appropriate mesh density only can be obtained by trying out various mesh density. In this study, we take the largest element mesh that is closest to the experimental results as the ANSYS computational grid of the concrete model.
- **Iterative method:** To solve concrete nonlinear problem using ANSYS, the Newton. Raphson method or arc-length method can be adopted. For structure model with descent load-displacement curve, when the load reach the peak of the carrying capacity, the stiffness matrix of the model becomes a pathological matrix, leading to the divergence of the Newton. Raphson method; while, the arc-length method has a strong solving ability for negative stiffness problems.

ANALYSIS OF RESULTS

Compression results: Figure 1 shows the comparative simulation of the three concrete cubes without fiber; Fig. 2 shows the stress-strain curve of the three concrete cubes with fiber. As can be seen, the compressive strength of the concrete cubes with or without fiber are almost equal, indicating that the influence of the fiber added in this study is limited for compressive strength. Besides, the compressive strength improvement of the fiber is mainly reflected in the post-peak stage, in which, the post-peak carrying capacity of all the three concrete cubes has been improved.

Bending results and the energy-saving effect: During bending simulation, a 10 mm deep incision is reserved in the middle of the bottom of the model, to control the position where the crack emerges. The flexural properties of the polypropylene fiber foam concrete are characterized by the relationship of the bending load and the width of the crack. Figure 3 shows the comparative simulation of the three concrete cubes without fiber; Fig. 4 shows the stress-strain curve of the three concrete cubes with fiber; Fig. 5 shows the curve of the relation of bending strength and the density with or without fiber.

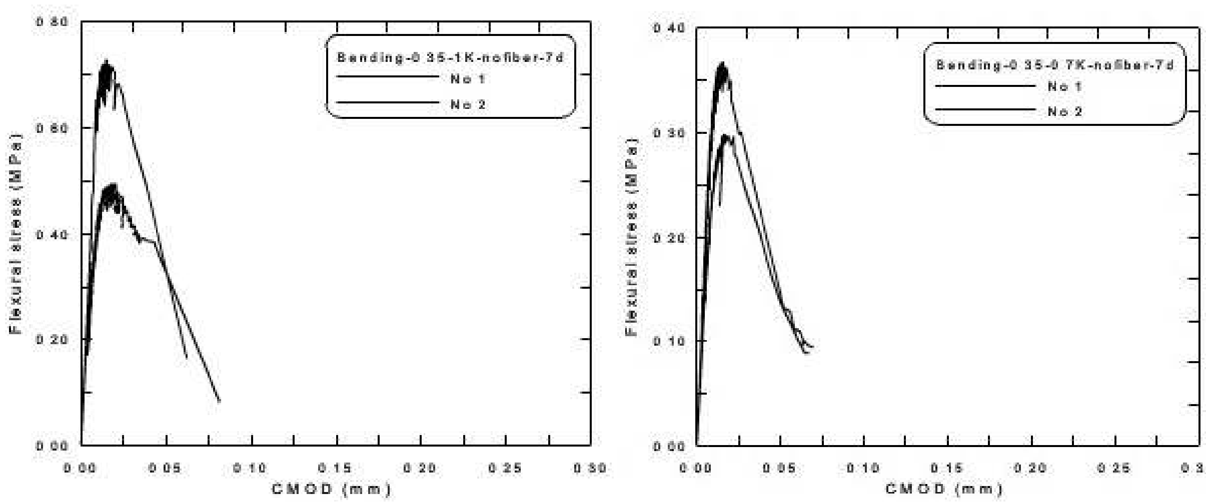
The results show that the fiber added can significantly improve the bending performance of



(a) (b)

(c)

Fig. 1: Stress-strain curve of the three concrete cubes without fiber



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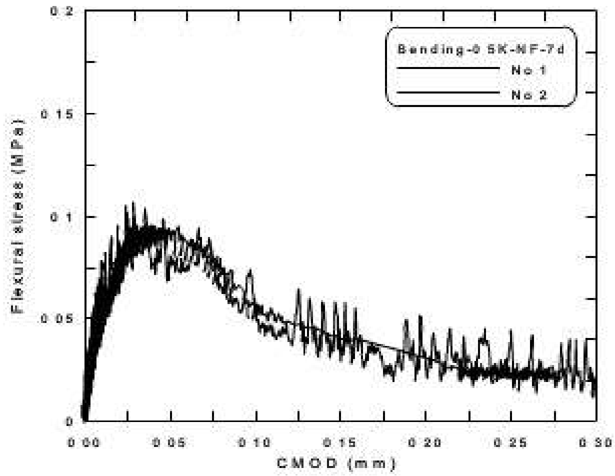

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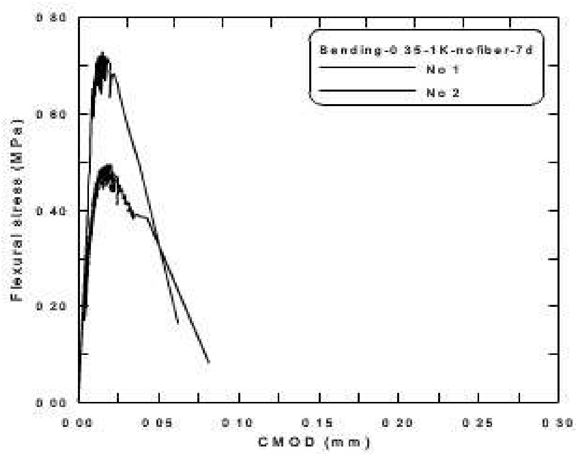
Fig. 2: Stress-strain curve of the three concrete cubes with fiber



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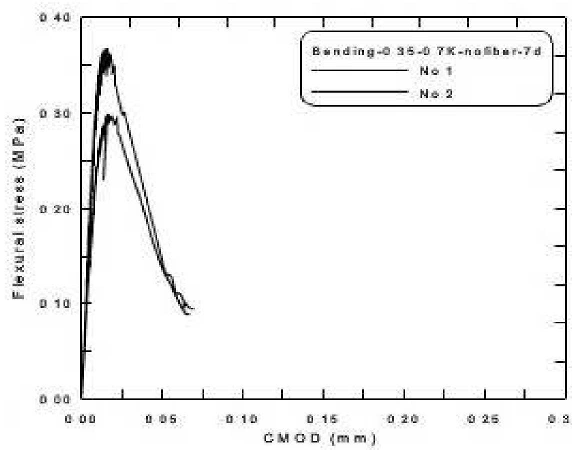

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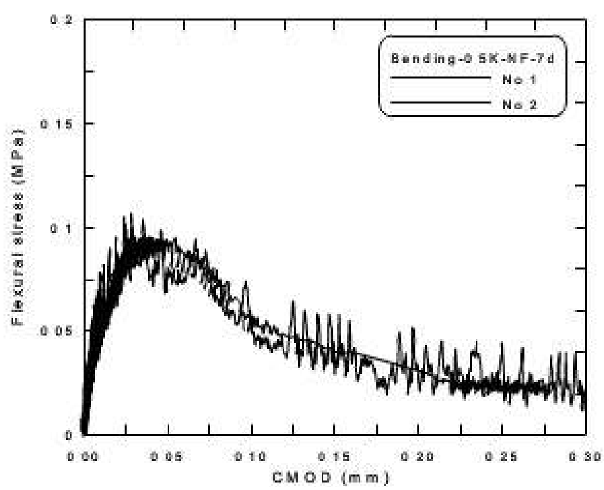

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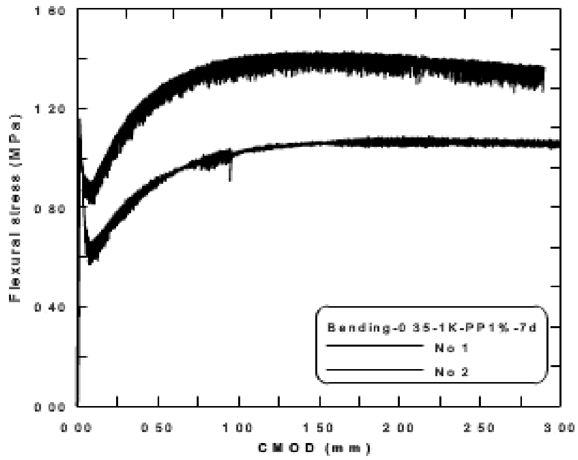
Fig. 3: Stress-strain curve of the three concrete cubes without fiber



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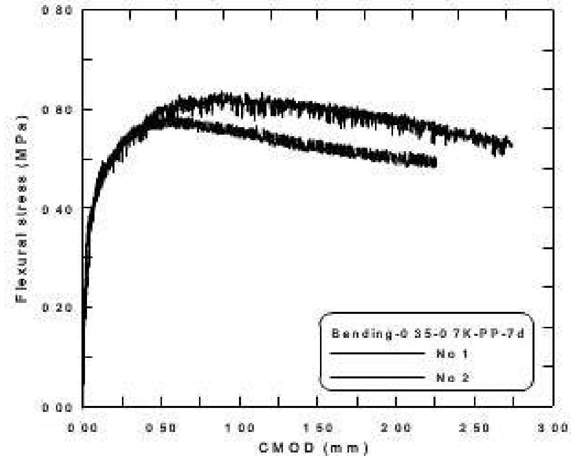

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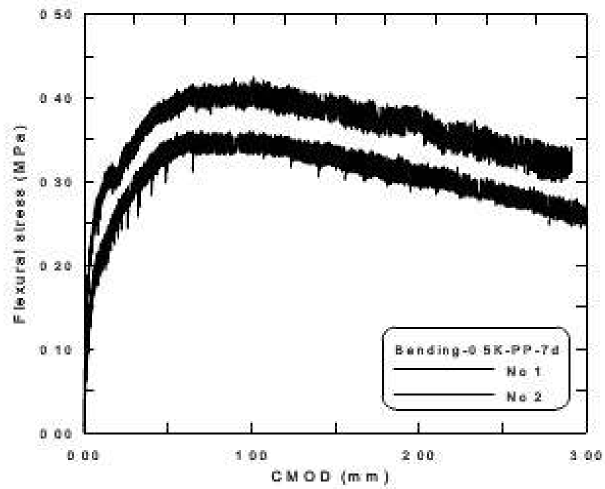

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Fig. 4: Stress-strain curve of the three concrete cubes without fiber

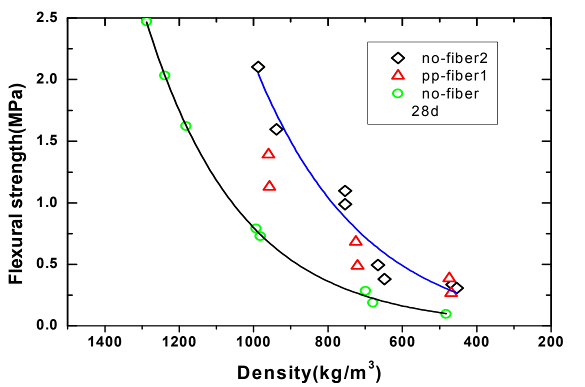

Fig. 5: The relation of bending strength and the density with or without fiber

lightweight foam concrete. The main improvement effect is reflected in bending peak load and after-peak carrying capacity, as well as the improvement of material behavior. Without fiber, the bending strength of the foam concretes with density of 1000, 700 and 500 kg/m^3 is 0.8, 0.3 and 0.1 Mpa respectively; after adding fiber, the incensement of the bending strength is 0.7, 0.4 and 0.3 Mpa respectively. In addition, it can be seen from Fig. 5, the flexural capacity after peak load has also been significantly improved, indicating the energy-saving effect of the fiber added. For ordinary foam concrete, the flexural capacity is close to zero when the CMOD value reaches 0.1 mm, namely, the material is basically out of work; while for foam concrete with polypropylene fibers, the bearing capacity of the specimen is still able to maintain a maximum of 80% of the carrying capacity when CMOD reaches 3.0 mm, which means that the ductility is also greatly improved while enhancing the ultimate bearing capacity.

The elastic modulus of the polypropylene fiber is only about 1/10 of the concrete and the polypropylene fiber presents thickening effect and poor interface effect, which are unfavorable factors for the strength of concrete; but because the volume of polypropylene fibers is very small compared with the concrete, the polypropylene fiber will not significantly affect the quasi-static strength of the concrete. The influence degree of fibers on the strength of concrete is related to the volume ratio. Due to price and process, fiber content in the concrete is very low (volume ratio is generally less than 2%) and fibers are in a state of three-dimensional chaotic distribution, leading to a low enhancing efficiency. Therefore, under normal circumstances, fibers in the concrete will not make significantly improvement on the tensile strength. The fiber will bear the load when concrete matrix crackes. When the fiber content reaches a certain level, the fibers can bear a load level higher than that before cracking, namely, the ultimate tensile strength is improved. In conducting flexural strength test, due to a certain degree of tensile strength maintained by the fibers after cracking, the neutral axis of the beam under test rises, thus the flexural strength of the concrete shows a substantial growth. The mechanism of action of the polypropylene fiber is realized through eliminating or decreasing the number and dimension of the native fracture, so that the continuity of the material is improved; besides, the impac energy absorption capacity of the organic materials enhances the impact resistance and fatigue resistance. In America, some highway and airport pavements are being rebuilded with the ultrathin white topping making from polypropylene fibers, which is the use of the excellent impact resistance and fatigue resistance of polypropylene fibers. The small elastic modulus of the polypropylene fiber makes a limited practical significance because of excessive deformation, even high fiber content can keep a certain tensile strength after craking. Therefore, the method with high fiber content to improve the tensile/bending strength is not taken in practice. The good effect of fiber reinforced concrete confirmed by a large number of engineering practice is the result that fibers in concrete enhaces the impact and fatigue resistance.

CONCLUSION

In this study, the mechanical properties of the polypropylene fiber foam concrete are examined using the software of ANSYS. The compressive and flexural performances of polypropylene fiber foam concretes with different density are studied through compressive and bending test. We obtained the following main conclusions:

- The incorporation of fiber into foam concrete has a significant impact on the compressive properties, namely the fiber can improve the compressive after-peak load carrying capacity, but has little effect on the compressive strength.
- The incorporation of fiber into foam concrete improves the flexural performance significantly. The flexural strength is enhanced and a considerable load bearing capacity is remained after the peak load, besides, the fiber added has certain energy-saving effect.

ACKNOWLEDGMENT

The study was supported by project of the Suzhou college fund for master(ProjectID:2010yss09).

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