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# Static and dynamic mechanical behaviour of ECO-RPC

Lai Jianzhong Sun Wei Lin Wei Jin Zuquan

(Department of Materials Science and Engineering, Southeast University, Nanjing 210096, China)

**Abstract:** Ecological reactive powder concrete (ECO-RPC) with small sized and different volume fraction steel fibers was prepared by substitution of ultra-fine industrial waste powder for 50% to 60% cement by weight and replacement of ground fine quartz sand with natural fine aggregate. The effect of steel fiber volume fraction and curing ages on the static mechanical behaviour of ECO-RPC was studied. Using the split Hopkinson pressure bar technique, the dynamic mechanical behaviour of ECO-RPC was investigated under different strain rates. The results show that the static mechanical behaviour of ECO-RPC increases with the increase of steel fiber volume fraction and curing ages. The type of ECO-RPC with the substitution of 25% ultra-fine slag, 25% ultra-fine fly ash and 10% silica fume is better than the others with compressive strength, flexural strength, and fracture energy more than 200 MPa, 60 MPa and 30 kJ/m$^2$, respectively. ECO-RPC has excellent strain rate stiffening effects under dynamic load. Its peak stress, peak strain and the area under strain-stress curve increase with the increase of strain rate. Its fracture pattern changes from brittleness to toughness under high strain rates.

**Key words:** ecological reactive powder concrete (ECO-RPC); industrial waste powder; interfacial bond strength; fracture energy; static and dynamic mechanical behaviour; high strain rate

Reactive powder concrete (RPC) is a new kind of cementitious composite with ultra-high performance. However, the high cost of RPC restricts its application[1-6]. In this paper, 50% to 60% of cement was replaced by ultra-fine industrial waste powder. The ground fine quartz sand with the maximal diameter of 600 μm was totally replaced by natural fine aggregates with the maximal diameter of 3 mm. By the means of binary and trinary composition of ultra-fine industrial waste powder, the advantages of granular packing and component complementing were achieved. Three types of ecological reactive powder concrete (ECO-RPC) were prepared, which had the advantages of high property to price ratio, resource and energy saving and ecological and environmental protection[7-10].

The static and dynamic mechanical behaviour of ECO-RPC was researched. By utilising the reinforcement of fine steel fibers, excellent mechanical performance of ECO-RPC was achieved. Results show that the mechanical performance of ECO-RPC increa-ses with the increase of curing age and steel fiber fraction. By the split Hopkinson pressure bar (SHPB) technique, the effect of strain rate on ECO-RPC mechanical behaviour is investigated under the impact loading.

## 1 Experiments

### 1.1 Materials

Four cementitious materials are used in the research, including portland cement, silica fume, ultra-fine fly ash and ultra-fine slag. Their chemical compositions and properties are tabulated in Tab. 1. The strength grade of cement is P · Ⅱ 42.5 in accordance with the relevant Chinese standard. The maximum particle size of natural sand is 3 mm with a fineness modulus of 1.34. The superplasticizer is produced by the Sika Company in Guangzhou, China with a water-reducing ratio of no less than 35%. The equivalent diameter, length and tensile strength of the fine steel fiber are 0.175 mm, 13 mm and 1 800 MPa, respectively.

**Tab. 1** Chemical compositions and properties of cementitious materials

| Items | Chemical composition/% | | | | | | Specific surface/ | Density/ |
|---|---|---|---|---|---|---|---|---|
| | $w(SO_3)$ | $w(SiO_2)$ | $w(Fe_2O_3)$ | $w(MgO)$ | $w(Al_2O_3)$ | $w(CaO)$ | $(m^2 \cdot kg^{-1})$ | $(g \cdot cm^{-3})$ |
| Cement | 2.24 | 20.60 | 4.38 | 0.55 | 5.03 | 65.06 | 346 | 3.02 |
| Silica fume | 0.80 | 94.50 | 0.83 | 0.97 | 0.27 | 0.54 | 20 000 | 2.20 |
| Ultra-fine fly ash | 1.45 | 54.98 | 5.93 | 1.27 | 31.34 | 3.90 | 720 | 2.33 |
| Ultra-fine slag | 1.00 | 34.20 | 0.43 | 6.70 | 14.20 | 41.70 | 800 | 2.82 |

### 1.2 Composition of ECO-RPC

Three types of ECO-RPC matrix ($M_1$, $M_2$ and $M_3$) were designed. Their compositions are listed in Tab. 2. 50% to 60% of cement was replaced by ultra-

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**Biographies:** Lai Jianzhong(1978—), male, graduate; Sun Wei(corresponding author), female, professor, sunwei@seu.edu.cn.

fine industrial waste powder. Ground fine quartz sand was totally replaced by natural fine aggregates. The water-binder and sand-binder ratio were 0.15 and 1.2, respectively. The volume fraction $V_f$ of steel fiber was 0 to 4%.

**Tab. 2** Composition of ECO-RPC matrix %

| Matrix | Cement | Silica fume | Ultra-fine fly ash | Ultra-fine slag | Super-plasticizer |
|---|---|---|---|---|---|
| $M_1$ | 50 | | 25 | 25 | 1.7 |
| $M_2$ | 50 | 10 | | 40 | 1.7 |
| $M_3$ | 40 | 10 | 25 | 25 | 1.7 |

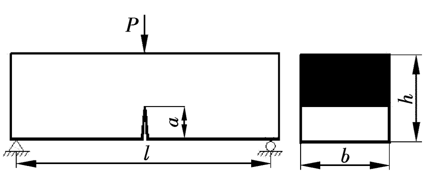
### 1.3 Test of ECO-RPC

The cementitious materials and sand were put in a forced mortar mixer at the same time and mixed for 3 min. Then the water and superplasticizer were mixed together and the liquid was put into the mixer to mix for another 6 min. Finally, fibers were dropped into the mixture and it was mixed for 3 min so that fibers were well distributed throughout the mortar. After mixing, the mixture of ECO-RPC was cast into steel moulds and compacted using a standard vibrating table. The specimens were stored in standard conditions ((20 ± 2) ℃, RH > 90%) and demoulded after 24 h. Then the specimens were cured in standard conditions for 28, 90 and 180 d before testing.

"8" shaped specimens were used to test the interfacial bond strength according to the Chinese standard test methods for steel fiber reinforced concrete. Specimens for the test of flexural strength, compressive strength and fracture energy were 40 mm × 40 mm × 160 mm prisms. Flexural strength and compressive strength were tested according to standard GB/T 17671—1999. Through three point bendings the fracture energy was tested (see Fig. 1). The testing span $l$was 150 mm and the rate of deformation was 0.02 mm/min. The fracture energy $G$ is given by

$$G = \frac{\int_0^{\delta_{max}} P\mathrm{d}\delta + \frac{1}{2}mg\delta_{max}}{(h-a)b}$$

where $\int_0^{\delta_{max}} P\mathrm{d}\delta$ is the work of load $P$, $\frac{1}{2}mg\delta_{max}$ is the work of specimen weight, $m$ is the mass of a specimen, $\delta$ is the deformation, $b$ and $h$ are the width and height of a specimen and $a$ is the depth of the kerf. In this test, $b = h = 40$ mm, $a = 15$ mm.




(a)


(b)

**Fig. 1** Test of fracture energy. (a) Set up of three point bending test; (b) Load-deformation curve of bending

The cylinder dimension for the SHPB test is 70 mm in diameter and 35 mm in length. A typical SHPB set-up is outlined in Fig. 2. It is composed of an elastic input and output bars with a short specimen placed between them. The impact of the projectile at the free end of the input bar develops a compressive longitudinal incident wave $\varepsilon_I(t)$. Once this wave reaches the bar specimen interface, a part of its $\varepsilon_R(t)$, is reflected, whereas another part goes through the specimen and transmits to the output bar $\varepsilon_T(t)$. Those three basic waves are recorded by the gauges pasted on the input and output bars. According to the wave propagation theory, the average stress, strain and strain rate of specimens can be calculated by the following equations:

$$\sigma = E\,\varepsilon_R(t)\frac{A}{A_0}$$

$$\dot{\varepsilon} = -\frac{2c_0}{l_0}[\varepsilon_T(t) - \varepsilon_I(t)]$$

$$\varepsilon = \int_0^t \dot{\varepsilon}(\tau)\mathrm{d}\tau$$

where $E$ is the Young's modulus; $A$ and $A_0$ are the cross section area of the bar and the specimen, respectively; $l_0$ and $c_0$ are the length of the specimen and the elatic wave speed, respectively.

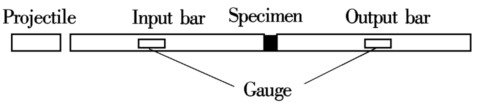



**Fig. 2** SHPB test setup

## 2 Results and Analysis

### 2.1 Interfacial bond strength between ECO-RPC matrix and steel fiber

The bond strength between matrix and fiber is one of parameters used to evaluate the interfacial properties used of ECO-RPC. The experimental results are shown in Fig. 3. The interfacial bond strength increases with the increase of curing age. At the same age the interfacial bond strength of $M_3$ is the largest and that of $M_2$ is the second largest. There is a large quantity of industrial waste powder in the ECO-RPC.

As curing age increases, its pozzolanic activity develops completely and the interfacial zone is improved continuously.

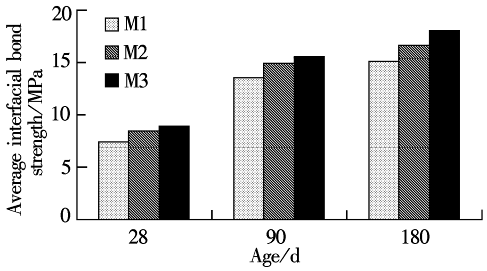



**Fig. 3** Influence of curing age on the average interfacial bond strength

## 2.2 Flexural strength and compressive strength

Fig. 4 shows the influence of fiber content and curing age on the flexural strength of ECO-RPC. The flexural strength increases with the increase of fiber content and curing age. The matrix of ECO-RPC is very brittle. When steel fiber is added, its toughness and ductility are improved greatly. As curing age increases, the pozzolanlic reaction of ultra-fine industrial waste powder increases too, so the microstucture of ECO-RPC is improved and the bond between fiber and matrix is enhanced. Therefore, the flexural strength of ECO-RPC increases with curing age.

Fig. 5 shows the influence of fiber content and curing age on the compressive strength of ECO-RPC. As well as flexural strength, the compressive strength of ECO-RPC increases with the increase of fiber content and curing age. From Fig. 4 and Fig. 5 we can also see that the influence of matrix composition on flexural and compressive strength is the same: $M_3 > M_2 > M_1$, when fiber content and curing age are the same. For $M_3$ in particular, flexural and compressive strength are over 60 MPa and 200 MPa after curing for 180 d under standard conditions. This fact shows that the properties of ECO-RPC are improved through trinary composition of ultra-fine industrial waste powder, which reacts with $Ca(OH)_2$ to form more CSH.

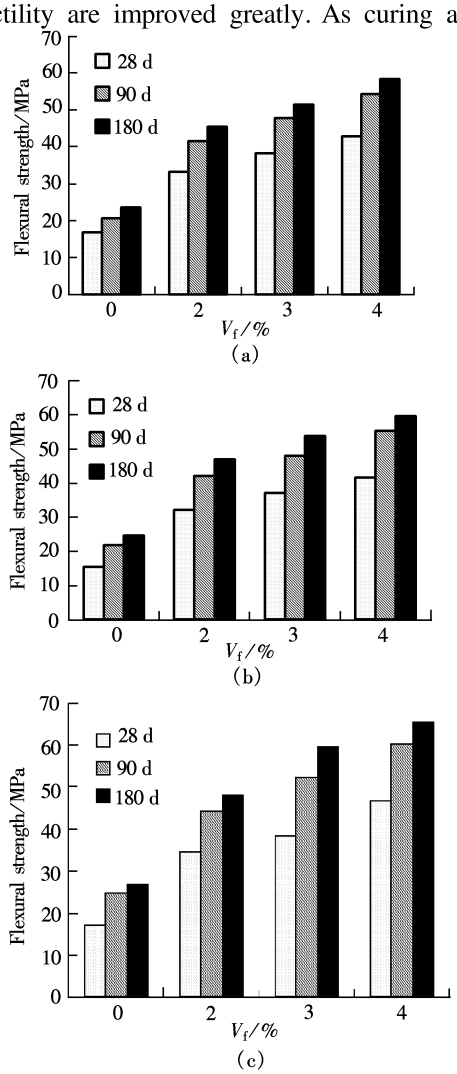



**Fig. 4** Influence of steel fiber volume fraction on the flexural strength of ECO-RPC. (a) $M_1$; (b) $M_2$; (c) $M_3$

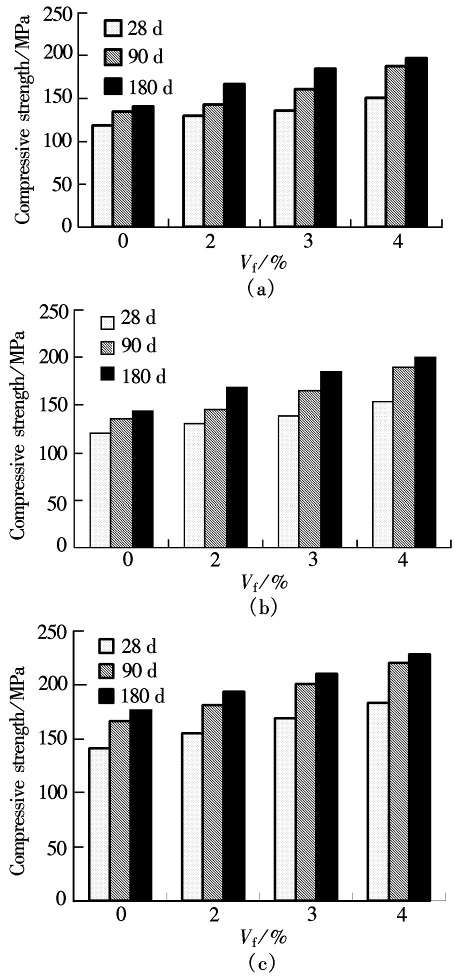



**Fig. 5** Influence of steel fiber volume fraction on the compressive strength of ECO-RPC. (a) $M_1$; (b) $M_2$; (c) $M_3$

## 2.3 Fracture energy

Fig. 6 shows that the fracture energy of ECO-

RPC increases with the increase of fiber content. The fracture energy of ECO-RPC matrix is very low. The energy of ECO-RPC with 2% fiber is over 100 times larger than that of matrix. With the increase of fiber content, the average distance between fibers decreases and the reinforcement of fibers improves. The development of cracking is prevented by fibers, so the fracture energy of ECO-RPC increases with the increase of fiber content. From Fig. 4, we can see that fracture energy at 28 d reaches 20 kJ/m$^2$ and it is more than 30 kJ/m$^2$ at 90 d, so curing age has an important effect on the fracture energy of ECO-RPC with a large quantity of industrial waste powder whose pozzolanic activity increases with curing age.

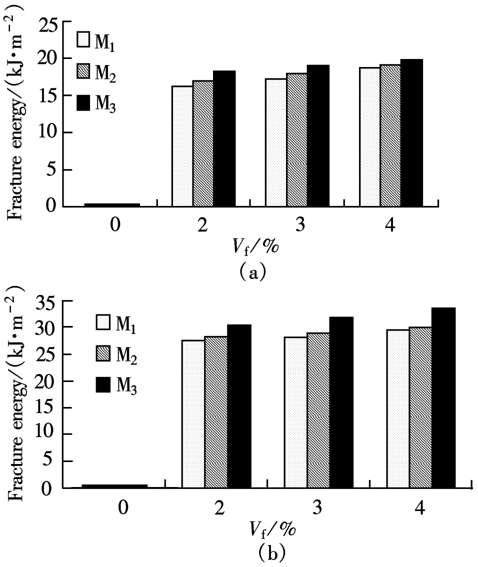



**Fig. 6** Influence of fiber volume fraction on the fracture energy of ECO-RPC. (a) 28 d; (b) 90 d

## 2.4 High-speed impact strength

Fig. 7 shows the influence of strain rate on the stress-strain curve of ECO-RPC under high speed compressive impact (The matrix is $M_3$). Tab. 3 shows peak stress and strain at peak stress under different strain rates (30 to 100 s$^{-1}$). Results show that: ① In general, the peak stress increases obviously with the increase of strain rate. The areas under the stress-strain curve evidently increase with the increase of strain rate. The fact shows that ECO-RPC has an excellent effect of strain rate stiffening. The strain under peak stress also increases with the strain rate. ② Steel fibers have an excellent effect on the toughness of ECO-RPC. The peak stress of fiber reinforced ECO-RPC is larger than that of ECO-RPC matrix. Furthermore, the damage of ECO-RPC matrix is more serious than that of fiber reinforced ones under near rate of strain . As shown in Fig. 8, under high speed

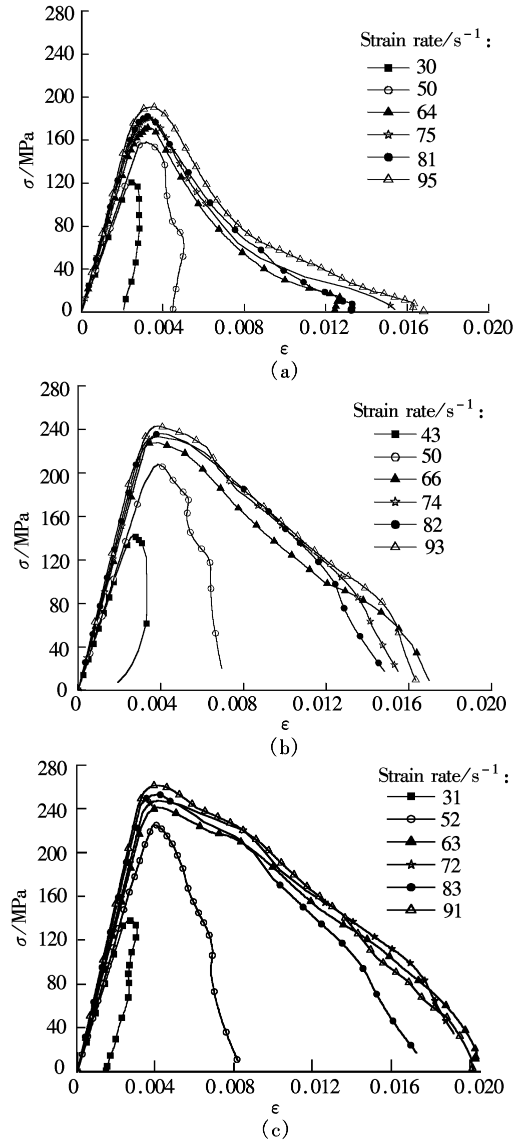



**Fig. 7** Influence of strain rate on stress-strain curves of ECO-RPC. (a) $V_f = 0\%$; (b) $V_f = 3\%$; (c) $V_f = 4\%$

**Tab. 3** Data of impact compression of ECO-RPC

| $V_f$/% | Strain rate/s$^{-1}$ | Peak stress/MPa | Strain at peak stress/10$^{-3}$ | Area under the strain-stress curve |
|---|---|---|---|---|
| 0 | 30 | 120.7 | 2.515 | 0.178 |
| | 50 | 158.1 | 3.210 | 0.480 |
| | 64 | 171.4 | 3.300 | 0.973 |
| | 75 | 180.9 | 3.310 | 1.119 |
| | 81 | 182.5 | 3.315 | 1.105 |
| | 95 | 190.6 | 3.588 | 1.327 |
| 3 | 43 | 142.1 | 2.645 | 0.252 |
| | 50 | 208.0 | 3.879 | 0.892 |
| | 66 | 227.8 | 3.889 | 2.195 |
| | 74 | 233.3 | 3.901 | 2.261 |
| | 82 | 236.3 | 3.911 | 2.290 |
| | 93 | 243.0 | 3.920 | 2.421 |
| 4 | 31 | 138.2 | 2.684 | 0.164 |
| | 52 | 225.3 | 3.903 | 1.048 |
| | 63 | 241.6 | 4.091 | 2.995 |
| | 72 | 247.6 | 4.138 | 3.079 |
| | 83 | 253.5 | 4.159 | 3.085 |
| | 91 | 261.4 | 4.166 | 3.133 |

impact the matrix of ECO-RPC is damaged into small parts while those reinforced with steel fibers only have some cracks on the sides. The experimental results also show that the content of steel fibers has little effect on the ultimate stress of fiber reinforced ECO-RPC.

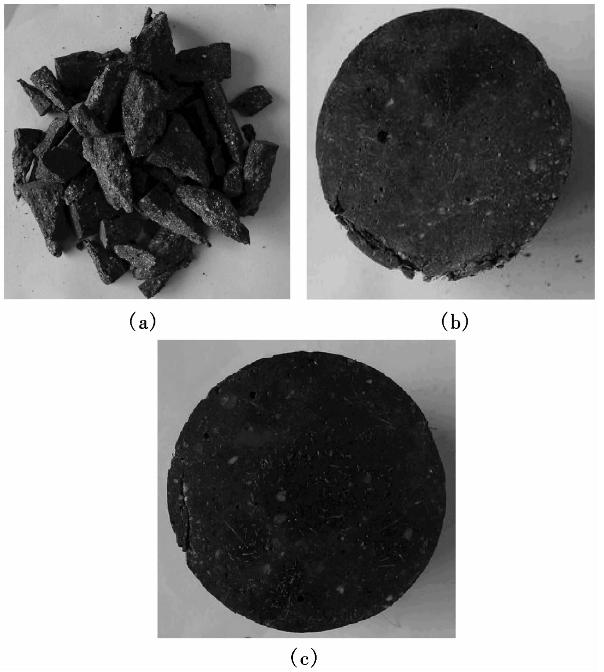


**Fig. 8** Fracture pattern of ECO-RPC $M_3$ under high speed impact. (a) $V_f = 0\%$; (b) $V_f = 3\%$; (c) $V_f = 4\%$

## 3 Conclusions

By means of binary and trinary composition of ultra-fine industrial waste powder, ecological reactive powder concrete is prepared which has excellent static and dynamic mechanical performance. In this paper the effects of curing age, steel fiber content and the rate of strain on the mechanical performance of ECO-RPC are studied.

1) Under standard curing conditions, the strength of ECO-RPC increases with the increase of curing age because of the development of pozzolanic action of ultra-fine industrial waste powder. The performance of trinary composition matrix is better than binary ones. After curing for 180 d, its compressive strength, flexural strength and fracture energy are more than 200 MPa, 60 MPa and 30 $kJ/m^2$ respectively.

2) ECO-RPC matrix is a brittle material. Through the reinforcement of small size steel fibers its toughness and ductility are improved significantly. With the increase of fiber content, its mechanical properties increase simultaneously.

3) Strain rate has an important effect on the dynamic performance of ECO-RPC. With the increase of strain rate, its peak stress and relevant strain increase. With the reinforcement of steel fibers, the damage degree of material under impact decreases largely.

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# 生态型 RPC 材料在静态和动态荷载下的力学行为研究

赖建中　孙　伟　林　玮　金祖权

(东南大学材料科学与工程系, 南京 210096)

**摘要**: 以 50% ~60% 的超细工业废渣取代水泥, 用天然黄砂取代磨细石英砂, 采用超细工业废渣多元复合技术, 制备出生态型活性粉末混凝土(ECO-RPC). 研究了不同纤维掺量和不同养护龄期对 ECO-RPC 静态力学性能的影响. 采用霍普金森杆方法研究了高速冲击下应变速率对 ECO-RPC 动态力学性能的影响. 结果表明, 随着纤维掺量和养护龄期的增加, ECO-RPC 各项静态力学性能不断提高. 通过超细粉煤灰(25%)、超细矿粉(25%)和硅灰(10%)三掺制备的 ECO-RPC 性能最佳, 其抗压强度、抗折强度和断裂能分别达到 200 MPa, 60 MPa 和 30 kJ/m$^2$ 以上. ECO-RPC 具有明显的应变率强化效应, 随着应变率的提高, 峰值应力及峰值应变显著增长, 应力-应变曲线所包围的面积不断增大, 破坏特征从脆性转变为韧性.

**关键词**: 生态 RPC; 工业废渣; 界面粘结强度; 断裂能; 静态和动态力学行为; 高应变率

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