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Optimization of mix design of micro-concrete for shaking table test

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Abstract. Considering their similar mass densities, an attempt was made to optimize the mix design of micro-concrete that used barite sand as an aggregate by substituting marble powder (5%, 10%, 20%, 30%, 40%, 50%, 70%), clay brick powder (30%, 50%, 70%), and fly ash (30%, 50%, 70%) for the concrete (by mass) to form specimens for shaking table tests. The test results showed that for these three groups of materials, the substitutions had little effect on the density. The barite sand played a decisive role in the density, and the overall density of the specimens reached approximately 2.9 g/cm^3. The compressive strength and elastic modulus decreased with an increase in the substitution rates for the three types of materials. Among them, the 28 day compressive strength values of the 40% and 50% marble powder groups were 11.73 MPa and 8.33 MPa, respectively, which were 58.7% and 70.7% lower than the control group, respectively. Their elastic modulus values were 1.33×10^4 MPa and 1.42×10^4 MPa, respectively, which were 39.1% and 35% lower than those of the control group, respectively. The 28 day compressive strength values of the 50% and 70% clay brick powder groups were 13.13 MPa and 5.8 MPa, respectively, which were 53.8% and 79.6% lower than the control group, respectively. Their elastic modulus values were 1.54×10^4 MPa and 1.19×10^4 MPa, respectively, which were 29.7% and 45.4% lower than those of the control group, respectively. The 28 day compressive strength values of the 50% and 70% fly ash groups were 13.5 MPa and 7.1 MPa, respectively, which were 52.5% and 75% lower than those of the control group, respectively. Their elastic modulus values were 1.36×10^4 MPa and 0.95×10^4 MPa, respectively, which were 37.9% and 56.6% lower than those of the control group, respectively. There was a linear relationship between the 28 day compressive strength and elastic modulus, with the correlation coefficient reaching a value higher than 0.88. The test results showed that the model materials met the high density, low compressive strength, and low elastic modulus requirements for shaking table tests, and the test data of the three groups of different alternative materials were compared and analyzed to provide references and assistance for relevant model testers.

Keywords: clay brick powder; fly ash; micro-concrete; marble powder; shaking table test; similitude-scaling relationship

1. Introduction

A shaking table model test of a structure is performed to simulate its dynamic characteristics under earthquake loads. This can visually show the actual earthquake phenomenon and reproduce the failure process of the structure. It is an important method to study the failure mode and evolution mechanism of a structure and has great significance in the study and evaluation of the seismic performance and seismic design of building structures (Lourenço *et al*. 2013, Wang *et al.* 2016, Xu *et al.* 2018, Tsai *et al.* 2018, Guan *et al.* 2019). Most model tests are conducted using a scale model because of the constraints of the existing test equipment conditions and test costs. The similarity relationship between the prototype and the model is deduced based on the similarity theory, and then appropriate model materials are selected to meet the similarity relationship as closely as possible to achieve the purpose of simulating the dynamic properties of the prototype structure. Therefore, the reasonable selection of model materials is related to the success of the test (Phansri *et al.* 2010).

Micro-concrete is made of cement, water, and aggregates with a particle size of less than 5 mm mixed in proportion, which gives it mechanical properties similar to the prototype concrete (Li and Guo 2016). By adjusting the micro-concrete mix design, the mechanical properties such as the compressive strength and elastic modulus can be changed to achieve similarity. At present, micro-concrete is often used when selecting the model materials for shaking table tests. For example, Chen *et al.* (2015) used micro-concrete and galvanized iron wire to simulate concrete and steel rebars to create a model of a three-arch subway station. The damage mechanism of the model in liquefiable soil with strong motions was investigated using a shaking table test to provide a basis for the seismic design of similar structures. Zhuang *et al*. (2016) used micro-concrete reinforced by zinc-coated steel wires to create a shaking table model of a large subway station and studied the seismic response of the structure under various liquefied soil conditions, which assisted in evaluating the seismic responses of large underground structures in liquefiable ground. Yan *et al*. (2016) used micro-concrete to simulate prototype concrete when creating two models of curved bridges with and without considering bearing friction sliding isolation. The dynamic characteristics and responses of the structures were determined by shaking table tests,

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which provided a basis for the seismic design of curved bridges. Qiao *et al*. (2020) conducted a shaking table test of a model of a 5-story reinforced concrete frame with a 1/5 scaling ratio made of micro-concrete and galvanized iron wire to study the dynamic characteristics of a structure subjected to the actions of the main shock and aftershocks. A review of a large number of papers showed that most designers have used an additional artificial counterweight to achieve a similar mass density relationship, which has caused serious problems. This artificial counterweight model has been suitable for simulating the spatial distribution of the mass on the structure with low accuracy. However, when there was a need to accurately simulate the distribution of mass density in space, this model had large error, and the local stress of the structure near the additional weight changed as a result of the additional artificial mass, which could change the original stress distribution of the structure and distort the inertial force of the model. Moreover, the special structures mentioned in some papers made it difficult to add an artificial weight in the non-structural effect area during construction because of their unique structural forms or because their own bearing capacity was too small, which could cause large errors (Yang 2005, Lourenço *et al*. 2016). Given the insufficient research on the similarity relationship of the mass density in current shaking table model design, it is necessary to consider this problem, starting from the properties of the materials themselves, to optimize the mix design of micro-concrete and develop model materials with a low elastic modulus, low compressive strength, and high density for shaking table model tests to meet the similarity relationship and reduce test errors (Lu *et al*. 2012).

Based on the research methods in the references (Palaskar and Vesmawala 2020, Kadik *et al*. 2020, Eisa *et al*. 2021), low-reactive materials were used to replace cement to reduce the compressive strength and elastic modulus, while barite sand was used as an aggregate to increase the density. After reviewing a large number of relevant papers and conducting a large number of tests on the mix ratio, it was finally determined that the test plan would replace some of the cement with an equivalent mass of marble powder, clay brick powder, or fly ash, with barite sand used as the aggregate. The mechanical properties of the test specimens, including the density, compressive strength, and elastic modulus, were tested to better satisfy the similarity relationship, and thus find the model materials for micro-concrete that most appropriately fit the requirements for a shaking table test.

2. Experiment design

2.1 Similarity design

The similarity design of shaking table tests should not only satisfy the geometric or physical similarity requirements of the materials or medium, but also consider their kinematical and dynamic similarity (Wu *et al*. 2020). Therefore, it is necessary to accurately simulate the similarity of three forces: the inertial force, restoring force, and gravity. Based on the Buckingham π theorem, L, E, and ρ were taken as the basic unknown dimensions, and the similarity relationship between the model and prototype was derived using dimensional analysis, as shown in Eq. (1)

$$S_a = \frac{S_E}{S_L S_\rho} \tag{1}$$

where S represents the similarity ratio between the prototype and the model, and a, E, L, and ρ represent the acceleration, elastic modulus, length, and density, respectively. However, in an actual shaking table test, the acceleration of gravity cannot generally be changed; therefore, $S_a = S_g = 1$, while the similarity relationship of the shaking table model should satisfy Eq. (2) as follows

$$\frac{S_E}{S_L S_\rho} = 1 \tag{2}$$

A similarity relationship between the three variables cannot be chosen at will; therefore, model materials with a smaller elastic modulus and larger density than the prototype should be selected, which greatly limits their selection.

Table 1 Screening test results for barite sand

Mesh size (mm)	4.75	2.36	1.18	0.6	0.3	0.15
Accumulativeness (%)	0	15.3	31.7	53.4	66.1	76.9

Table 2 Chemical compositions of marble powder, clay brick powder, and fly ash (by mass%)

Materials	CaO	SiO_2	Al_2O_3	MgO	P_2O_5	K_2O	SO_3	Na_2O	Fe_2O_3
Marble powder	60.3	3.61	0.17	35.5	0.09	0.01	0.02	0.03	0.18
Clay brick powder	1.63	63.2	18.4	2.76	0.23	3.02	0.21	1.98	7.28
Fly ash	2.7	50.9	37.6	0.46	0.35	0.86	1.42	0.34	3.52

2.2 Raw materials

The cement used in this study was ordinary 42.5 grade cement produced by the Zhenxing Cement Plant. The aggregate was barite sand produced by the Tianjin Yandong Stone Plant with a fineness modulus of 2.43. The screening test results for the barite sand are presented in Table 1. The clay brick powder was obtained from clay bricks discarded after the demolition of a building, which was produced by removing the surface impurities, crushing the bricks with a crusher, and grinding them with a ball mill for 15 min. Marble powder with a particle size of 400 mesh was obtained from the market. The fly ash was the second-grade fly ash available on the market. The chemical compositions of the clay brick powder, marble powder, and fly ash were analyzed using X-ray fluorescence analysis (XRF), and the results are listed in Table 2. The particle size distribution curve of the clay brick powder was determined using a laser diffraction particle size analyzer (Mastersizer 2000), as shown in Fig. 1.

2.3 Mix ratio design

After extensive mix ratio tests based on previous

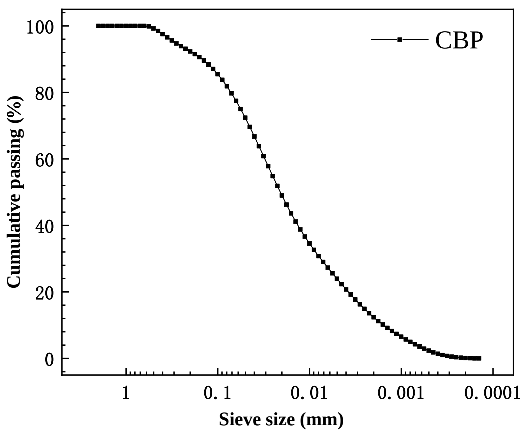

Fig. 1 Particle size distribution curve of clay brick powder

Table 3 Mix ratios of micro-concrete

No.*	Substitution rate	Cement	Marble powder	Clay brick powder	Fly ash	Barite sand	Water
	(%)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)
CO	0	326.53	0	0	0		
MP-5	5	310.2	16.33	0	0		
MP-10	10	293.88	32.65	0	0		
MP-20	20	261.22	65.31	0	0		
MP-30	30	228.57	97.96	0	0		
MP-40	40	195.92	130.61	0	0		
MP-50	50	163.27	163.27	0	0	2612.24	261.22
MP-70	70	97.96	228.57	0	0		
CBP-30	30	228.57	0	97.96	0		
CBP-50	50	163.27	0	163.27	0		
CBP-70	70	97.96	0	228.57	0		
FA-30	30	228.57	0	0	97.96		
FA-50	50	163.27	0	0	163.27		
FA-70	70	97.96	0	0	228.57		

*Note: 1. MP, CBP, and FA represent marble powder, clay brick powder, and fly ash, respectively, and the number represents the percentage of equivalent material substituted for the cement mass 2. The test blocks of the MP-70 group failed to form. Concrete segregation, bone and mortar separation, and serious bleeding occurred on the surface. Therefore, the MP-70 group is not included in the subsequent discussion

studies, the basic mix ratio used in the test was finally determined to be cement: barite sand: water=1:8:0.8. In addition to this basic ratio, marble powder, clay brick powder, and fly ash were used to replace a portion of the cement mass. To facilitate the collation of experimental data, each group of tests was named using the abbreviation of the material, with the basic mix ratio referred to as CO. The specific mix ratios are listed in Table 3.

2.4 Specimen preparation and testing

During the specimen preparation, the mass of the material was carefully weighed according to the mix ratio. The aggregate, cement, and other materials were added to the mixing pot and dry-mixed for 180 s; then, water was added and it was mixed for another 180 s. After the mixing was completed, the micro-concrete was loaded into the test mold and placed on the vibrating table until the surface was flat, pulpy, and no more bubbles emerged, after which the demolded specimens were placed in the standard curing room for maintenance. The maintenance temperature of the maintenance room was 20±1°C, and the relative humidity was greater than 95%. Six 70.7 mm×70.7 mm×70.7 mm cubic specimens and six 100 mm×100 mm×300 mm prismatic specimens were made for each group. The density, 7 day cube compressive strength, 28 day cube compressive strength, and elastic modulus of each specimen were tested according to the Chinese standard mechanical performance test method (Chinese code 2019).

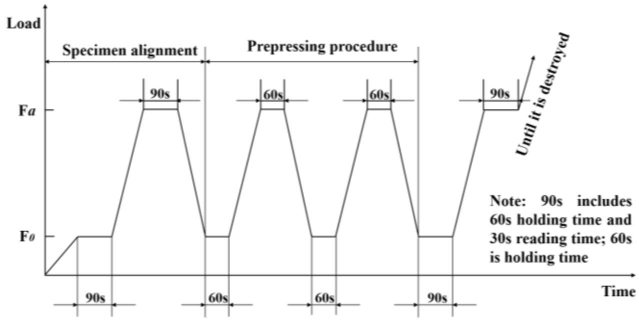

Fig. 2 Loading system for elastic modulus test

The mechanical properties of the specimens were tested using a computer-controlled electro-hydraulic servo universal testing machine, which was produced by the Shanghai Sansi Machinery Company. The maximum load of this hydraulic servo loading system was 1000 kN, and it could be loaded using force control, displacement control, and other control modes. Moreover, the cube compressive strength and elastic modulus tests were conducted according to the “compressive strength test” and “static compressive elastic modulus test” methods specified in the current national standard, GB/T 50081-2019. The 7 day and 28 day cube compressive strength tests were performed using the force-controlled mode at a loading rate of 2500 N/s, and the average value of the compressive strengths of three cube specimens was taken as the final result. The elastic modulus test adopted the displacement control mode and loaded at a speed of 0.2 mm/min. The strain gauges were attached at symmetric positions in the middle on both sides of the test specimen, and the strain data were collected by a DHDAS dynamic-static strain test system. The elastic modulus values were calculated based on the loading method shown in Fig. 2 and Eq. (3)

$$E_C = \frac{F_a - F_0}{A} \times \frac{1}{\varepsilon} \tag{3}$$

where E_C represents the static compressive elastic modulus of the concrete (MPa), F_a represents the load when the stress is 1/3 of the axial compressive strength (N), F_0 represents the initial load at a stress of 0.5 MPa (N), A represents the pressure-bearing area of the specimen, and ε represents the strain obtained from the last loading cycle (mm).

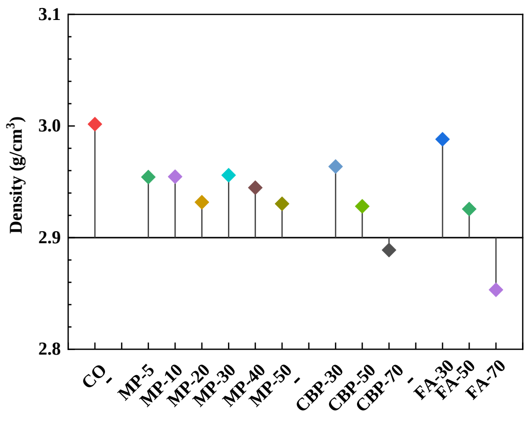

Fig. 3 Effects of different substitution groups on density

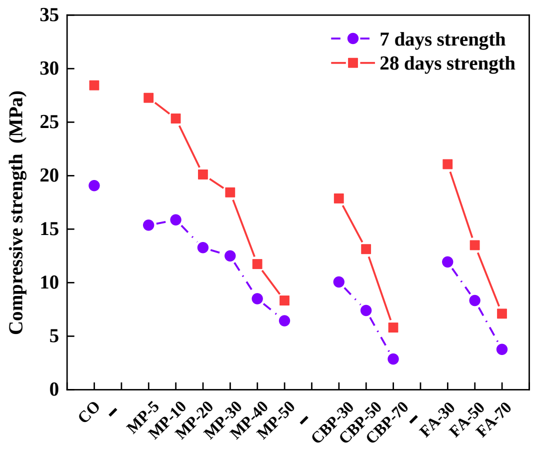

Fig. 4 Effects of different substitution groups on compressive strength

3. Results and discussion

3.1 Density

The 28 day density test results for each group of samples are shown in Fig. 3, with each point representing the average value of three specimens per group. It can be seen from the displayed results that the density range of all the samples was 2.85-3.0 g/cm^3. The highest density (3.0 g/cm^3) was found in the CO group, and the lowest density of 2.85 g/cm^3 was found in the specimen with 70% of the cement mass replaced by fly ash, but it was only 4.9% less than that of the CO group. The densities of the specimens of the three groups with different substitution amounts were slightly lower than that of the control group. The clay brick powder and fly ash substitution groups showed a tendency to decrease with an increase in the substitution amount, while the density of the marble powder substitution group showed no significant change with an increase in the substitution amount. However, from the test results, the density of the micro-concrete of the three material substitution groups was approximately 2.9 g/cm^3. This showed that substituting the three materials for equivalent masses of cement had little effect on the density, The density of the specimens could reach 2.9 g/cm^3 because of the high bulk density of the barite sand, which can reach 4.5 g/cm^3.

Table 4 Results for density, compressive strength, and elastic modulus, and their variation

No.	Density (g/cm^3)	Cube compressive strength (MPa) 7d	28d	28d Elastic Modulus (10^4 MPa)
CO	3.00(-)*	19.07(-)	28.43(-)	2.19(-)
MP-5	2.95(-1.6%)	15.37(-19.4%)	27.27(-4.1%)	2.14(-2.2%)
MP-10	2.95(-1.6%)	15.87(-16.8%)	25.33(-10.9%)	1.86(-14.9%)
MP-20	2.93(-2.3%)	13.27(-30.4%)	20.11(-29.3%)	1.69(-22.8%)
MP-30	2.96(-1.5%)	12.50(-34.4%)	18.43(-35.2%)	1.74(-20.4%)
MP-40	2.94(-1.9%)	8.50(-55.4%)	11.73(-58.7%)	1.33(-39.1%)
MP-50	2.93(-2.4%)	6.43(-66.3%)	8.33(-70.7%)	1.42(-35.0%)
CBP-30	2.96(-1.3%)	10.07(-47.2%)	17.87(-37.2%)	1.90(-12.9%)
CBP-50	2.93(-2.5%)	7.40(-61.2%)	13.13(-53.8%)	1.54(-29.7%)
CBP-70	2.89(-3.8%)	2.87(-85.0%)	5.80(-79.6%)	1.19(-45.4%)
FA-30	2.99(-0.4%)	11.93(-37.4%)	21.07(-25.9%)	1.91(-12.8%)
FA-50	2.93(-2.5%)	8.33(-56.3%)	13.50(-52.5%)	1.36(-37.9%)
FA-70	2.85(-4.9%)	3.77(-80.2%)	7.10(-75.0%)	0.95(-56.6%)

*Note: The values in parentheses are percentage changes compared to the control group, and a negative sign indicates a decrease

The bulk density of ordinary concrete is approximately 2.35-2.45 g/cm^3, To meet the lower compressive strength and elastic modulus requirements, the conventional model materials of the micro-concrete used in shaking table tests often use a large water–cement ratio. Thus, the bulk density of the model materials is generally lower than 2.35 g/cm^3. In contrast, the density in this study was approximately 2.9 g/cm^3, which was 1/4 times higher than the density of ordinary concrete, and the density of the model materials was much higher than that of previous ones.

3.2 Compressive strength

The slopes in Fig. 4 show the change in compressive strength with the replacement of the cement. It can be seen that the slopes of the changes in the 28 day cube compressive strengths of the three different substitution groups are significantly steeper than those for the 7 day cube compressive strengths of the same groups. This indicates that the three different substitutions had greater effects on the 28 day cube compressive strength values with increasing substitution amounts than on the 7 day cube compressive strength values of the same groups. It can be seen from Table 4 that the 28 day cube compressive strength values for the MP-40 group, MP-50 group, CBP-50 group, CBP-70 group, FA-50 group, and FA-70 group were 11.73 MPa, 8.33 MPa, 13.13 MPa, 5.8 MPa, 13.5 MPa, and 7.1 MPa, respectively, which were 58.7%, 70.7%, 53.8%, 79.6%, 52.5%, and 75% lower than that of the control group, respectively. Among them, the 28 day cube compressive strength values of the MP-50, CBP-70, and FA-70 groups decreased by more than 70%, and all of the were below 10 MPa.

The fluidity of the marble powder group increased with an increase in the substitution amount. The hydration reaction started after the cement particles came into contact with water, while the marble powder was inactive and only needed to be wetted and wrapped by water in the concrete system. Therefore, the required water consumption was far less than the water consumption of the cement. From the point of view of experimental design, the water consumption remained unchanged, and with an increase in the replacement ratio of marble powder, the water demand of the system decreased accordingly, causing a relative increase in the free water of the mixture. Therefore, the MP-70 group showed severe water secretion and bone and mortar separation, which led to a molding failure (Zhang *et al*. 2018).

Comparing the data for the three different substitution groups with 30% and 50% of the cement replaced, it can be seen that the marble powder group showed a significantly higher decrease in its 28 day compressive strength with an increase in the substitution amount than the other two groups. From a comparison of the experimental data of the clay brick powder and fly ash groups, it can be seen that the decreases in the 28 day compressive strengths were roughly the same, regardless of the replacement rate. This was partly because of the different potential pozzolanic activities of the three different materials (Kabeer and Vyas 2018). The SiO_2+Al_2O_3+Fe_2O_3 contents of the marble powder, clay brick powder, and fly ash accounted for 4.0%, 88.9%, and 92%, respectively. This indicates that the clay brick powder and fly ash had potential activity, while the marble powder did not participate in the hydration process of the cement, but only acted as a filler (Corinaldesi *et al*. 2010). With an increase in the amount of replaced cement, an increasing amount of marble powder with no pozzolanic activity gathered together. It is well known that an appropriate amount of marble powder can be used to better fill the pores between the cement and aggregate, thereby improving the internal pore structure. However, when an excessive amount of marble powder replaces the cement, the effective water-cement ratio increases. In addition, the marble powder has low activity. Thus, the compressive strength decreased after replacing a large amount of cement. Some papers also mention that excessive marble powder will repel each other with the fine powder in the sand, thus decreasing the compressive strength (Olofinnade *et al*. 2018). In contrast, the clay brick powder and fly ash groups had potential pozzolanic activity compared to the marble powder group. Thus, they were involved in the hydration process, and their strength values were slightly less affected than those of the marble powder group.

More satisfactory model materials for low-strength micro-concrete were obtained from the results of the three different material substitution tests. Among them, the MP-50, CBP-70, and FA-70 groups showed significant reductions in the 28 day compressive strength. Relevant testers could reasonably select substitution materials based on the actual situation when designing a similarity relationship for the compressive strength and select the optimal mix ratio based on the presented experimental data.

3.3 Elastic modulus

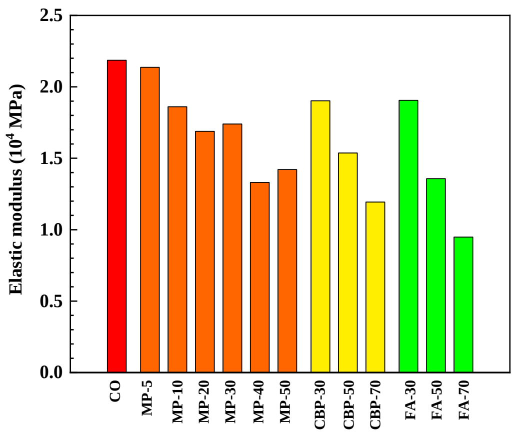

Fig. 5 Effects of different substitution groups on elastic modulus

The effects of the different substitution groups on the elastic modulus are shown in Fig. 5, where it can be seen that the elastic modulus values of the clay brick powder and fly ash groups decreased significantly with increases in the substitution amounts, and the marble powder group also showed a decreasing trend overall. The results show that the elastic modulus values for MP-40, MP-50, CBP-50, CBP-70, FA-50, and FA-70 were 1.33×10^4 MPa, 1.42×10^4 MPa, 1.54×10^4 MPa, 1.19×10^4 MPa, 1.36×10^4 MPa, and 0.95×10^4 MPa, respectively, which were 39.1%, 35%, 29.7%, 45.4%, 37.9%, and 56.6% lower than that of the control group, respectively. The decrease in the elastic modulus was mainly due to the slowing down of the hydration process by the use of materials with low activity to replace some of the cement, which changed the internal pore structure and loosened the internal structure. This made the structure more prone to damage when subjected to external forces.

A comparison of the data for the three different substitution groups with 30% and 50% replacement amounts, as seen in Table 4 and Fig. 5, shows that the of elastic modulus decreased in the descending order of the fly ash group, clay brick powder group, and marble powder group. A comparison of the experimental data for the clay brick powder and fly ash groups shows that the elastic modulus of the fly ash group decreased faster than that of the clay brick powder group, regardless of the substitution ratio. This was mainly due to the smoother shape of the fly ash particles and the large number of fly ash particles in the internal structure as a result of insufficient hydration in the early stage, which made it more likely to slip when subjected to external pressure, thus causing the elastic modulus to decrease sharply. It can be seen in Fig. 5 that the elastic modulus values of the MP-30 and MP-50 groups were higher than those of the previous group. This might have been because concrete is a composite material composed of a multiphase medium, and each component has the characteristic of a typical random distribution. When a large amount of marble powder is arranged randomly, the gaps between the aggregate and cement paste are better filled, thus increasing the elastic modulus (Alyousef *et al*. 2018).

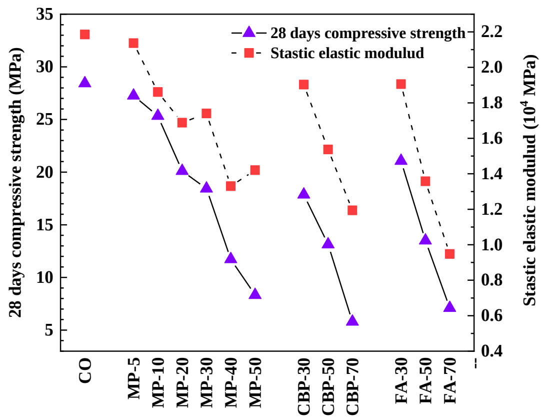

Fig. 6 Comparison of compressive strength and elastic modulus values of different substitution groups

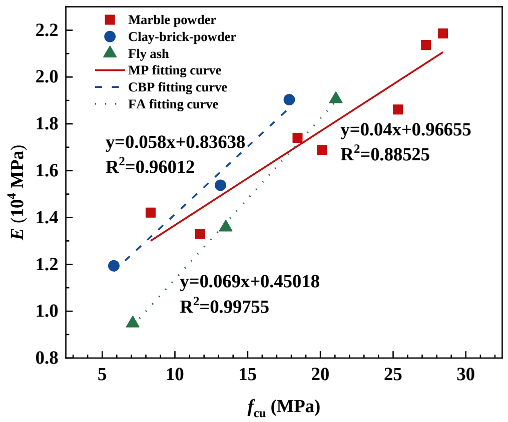

Fig. 7 Relationship between compressive strength and elastic modulus

The compressive strength and elastic modulus comparisons in Fig. 6 clearly show that the three different substitution groups had the same trends for the changes in the compressive strength and elastic modulus. The relationships between the 28 day compressive strength and elastic modulus values of the clay brick powder and fly ash replacement groups were approximately linear, with the marble powder group also showing a linear relationship between the 28 day compressive strength and elastic modulus overall, although there were fluctuations in the elastic modulus data of some of the substitution groups. The results of a linear regression analysis of the 28 day compressive strength and elastic modulus values of the three test groups are shown in Fig. 7, where the correlation coefficients (R^2) of the marble powder, clay brick powder, and fly ash groups are 0.88525, 0.96012, and 0.99755, respectively, indicating that the fitting accuracy is high. The compressive strength and elastic modulus values found in the tests of the three different substitution groups had a strong linear correlation. A similar relationship between the compressive strength and elastic modulus could also accurately be obtained using the fitting formula. Moreover, it would be possible to determine the optimal mix ratio of the micro-concrete to properly meet the model test requirements (Ge *et al*. 2012).

4. Conclusions

This paper provides reasonable solutions to the problem of inadequate information on the mass-density similarity relationship for the design of micro-concrete models for shaking table tests. Marble powder, clay brick powder, and fly ash were used as equivalent substitutes for a mass of cement, and barite sand was used to replace traditional aggregates in the test. Mechanical properties such as the density, compressive strength, and elastic modulus were tested to determine the optimum mix ratio of micro-concrete for the model test. The following specific conclusions were obtained

- The density of the specimens in the three substitution groups reached approximately 2.9 g/cm^3, and when equal substitution amounts were used for the three materials, the mass of the cement had little effect on the density, whereas the barite sand played a decisive role in the density.
- The 7 day and 28 day cube compressive strength values decreased with an increase in the replacement amount, but the degree of influence on the 28 day compressive strength was greater than that on the 7 day compressive strength. The 28 day cube compressive strength values of the MP-50, CBP-70, and FA-70 groups decreased by more than 70%, all of which were below 10 MPa. A comparison of the data for the three different substitution groups with the 30% and 50% cement replacements shows that the marble powder group had a significantly higher decrease in its 28 day compressive strength with an increase in the substitution amount than the other two groups. A comparison of the experimental data of the clay brick powder and fly ash groups shows that their 28 day compressive strength decreases were roughly the same, regardless of the replacement rate.
- The elastic modulus decreased with an increase in the replacement amount. The elastic modulus values for the MP-40, MP-50, CBP-50, CBP-70, FA-50, and FA-70 groups decreased by more than 29% compared to the control group. A comparison of the data for the three different substitution groups with the 30% and 50% cement substitutions shows that the decreases in the elastic modulus values had the following descending order: the fly ash group, clay brick powder group, and marble powder group. A comparison of the experimental data of the clay brick powder and fly ash groups shows that the elastic modulus of the fly ash group decreased faster than that of the clay brick powder group, regardless of the substitution ratio. The compressive strength and elastic modulus values of the three replacement groups showed a linear relationship, with correlation coefficients above 0.88, indicating that the correlation between the 28 day compressive strength and elastic modulus was significant.
- This paper describes three different material groups used in substitution tests to optimize existing micro-concrete materials for shaking table tests. The model materials were designed with a high density, low compressive strength, and low elastic modulus. A comparative analysis of the test data for the three

alternative materials was conducted. Relevant designers could reasonably select substitution materials and proportions based on the actual situation. This study provides a reference for designing a similarity model test.

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