IOP Conf. Series: Materials Science and Engineering **394** (2018) 032041 doi:10.1088/1757-899X/394/3/032041

Size and Temperature Effect of Compressive Strength and Deformation Modulus of Fly Ash Concrete Prism

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Abstract. In this paper, the prism specimens of fly ash concrete were tested under the axial compressive load, and the prism specimens were cast with different curing temperature in winter. The aim of this project is to find how section size, curing temperature and fly ash content influence the compressive performance of the long curing age prism specimens. The side length of prisms cross section have a total of 6 dimensions from 100mm to 500mm. Concrete mixtures were prepared by substituting 0, 25% and 50% fly ash respectively. The average curing age of specimens is 570 days. The results show that when the size of the specimens increases, the axial compressive strength of the prism specimen, modulus of elasticity, and the peak value of secant modulus increase as well. Replacing part of cement with fly ash and increasing specimen size are beneficial to the strength and elastic modulus growth of concrete under construction and low temperature curing conditions in winter.

1. Introduction

Size effect is the specific characteristic of the brittle and quasi-brittle material. People urgently want to know the mechanical factor of the material through the testing laboratory, thus it is necessary to know the size effect. In the meantime, we can also deduce the brittleness of concrete through the macroscale mechanical factor of the size effect, and that is a main reason why size effect is an issue of universal concern of concrete.

It is usually shown that the bigger the size of the specimens, the lower the compressive strength of the concrete specimens is, this phenomenon is largely due to the interpretation of the mechanics. The most famous theory of size effect has three kinds, one is that Weibull' s theory [1] (1939) based on the internal defects of the probability distribution, the two is Bazant's interpretation [2] (1984) based on the fracture mechanics explanation of the energy release, and three is Carpinteri's law [3] (1995) based on the size effect of the crack fractal.

The mechanical interpretation of the size effect of the concrete is relative to the internal defects and the macro-deficiencies of the concrete. For ordinary Portland cement concrete (OPC), there is a weak interface transition zone (ITZ) around the coarse aggregate [4]. There are also lots of orientation crystals of calcium hydroxide, microcracks and capillary pores with big volumes in the ITZ, and those are considered as the weakest links of the microstructure of the concrete and the source of the brittle failure. Mineral admixtures and superplasticizer have become essential components of high performance concrete (HPC). The porosity of the microstructure around the coarse aggregate decreases due to the drop of the water usage and the filling-effect and the secondary hydration of the fine mineral admixture [5], and the interface transition zone is improved at the same time. It is a theoretical and practical issue worthy of attention that how improvement of transition zone and microstructure of concrete interface affects the size effect law based on defect and fracture theory.

Compared with the original size effect, more and more research studies have got the unsimilar, or even the opposite results [6-12]. The ratio of the coarse aggregate size to the length of the specimens and the variability difference between the large-size and small-size specimens may influence the test result of the small-size specimens [13, 14]; for large-size specimens, it may be related to the curing temperature of specimens. Even the concrete without fly ash will get some inconsistent conclusions, as mineral mixed cement has been widely used in concrete, and the appearance of these abnormal conclusions can also be associated with the influence of mineral admixtures.

The temperature influence of concrete curing period mainly comes from two aspects, one is environmental temperature, and the other is hydration heat release. Environmental temperature is also reflected in the temperature of concrete. Neville pointed out that the mass of the concrete depends on its own temperature rather than the ambient temperature. The size of the specimen will affect the temperature caused by the hydration of the cement, that is, the release of the hydration heat is related to the size [15]. The temperature of the environment is also influenced by the hydration heat. For example, during the winter construction, the heat loss of hydration heat will decrease with the increase of specimen size, and that will maintain proper curing temperature for concrete [7]. The hydration heat of cement can prevent the freezing of the capillary pore water of the newly poured concrete [17], which helps to provide the suitable curing temperature [16], promotes the hardening of the concrete [17], and is beneficial to the development of the concrete strength of the concrete poured in winter.

The delay of ash reaction of fly ash can reduce the hydration heat of cement concrete and release slowly [17-19], and the hydration heat of cement can also improve the activity of fly ash. Therefore, some scholars have pointed out that the performance of mass fly ash concrete may be different from that of small specimens at room temperature.

The objective of this study is to investigate the mutual influence between the size effect and the temperature. The mineral admixture of this experiment is fly ash which is commonly used in the practical engineering. The specimens of the concrete prisms were made in the cold winter with low temperature. Through changing the volume of the specimens and the replacement of the fly ash, we will find how the cast and curing temperature influence the mechanical property of the fly ash concrete (FAC) under the 570d curing-age

2. Experimental program

Ordinary Portland cement (P.O.42.5R) is used as the primary binder in all mixtures. ClassIIfly ash (GB/T 50146-2014) is used as a cement replacement. The particle size of the natural coarse aggregate was continuously distributed within the range of 5-25mm, and the fine aggregate is medium sands. The concrete mix proportions are listed in Table 1, where C, FA, B, W, G and S respectively indicate the consumption of cement, fly ash, cementitious material, water and coarse and fine aggregate. The water/binder ratio of all the mix proportions is 0.33. The substitution levels of fly ash are 0, 25% and 50%, respectively.

The shape of the specimens is prism, and the cross-section of the specimens is square. The lengths of the cross-section a are 100mm, 150mm, 200mm, 300mm, 400mm and 500mm, respectively, the hight is 2a. The mould consists of bottom mood mould and lateral steel mould.

The samples were cast in vertical direction. The concrete specimens of each mix ratio are cast at one time, and the three are matched with three times pouring. Due to the mould turnover, the time interval of each batch was approximately 8 days.

Table 1. Mix ratio of concrete design.

Number	FA/B	Mix ratio (kg/m^3)				
		C	FA	W	G	S
I-0 O-0	0	530	0	175	1050	640
I-0.25 O-0.25	0.25	398	133	175	1050	640
I-0.5 O-0.5	0.5	265	265	175	1050	640

The tested samples were cast at the end of 2014, and the curing process ended at the middle of 2016. Thus, the average curing age of the specimens is up to 570 days. All of the specimens are made by a local concrete component plant. After pouring the concrete into the moulds, the quilt and plastic film were covered around the molds in the production factory. The specimens were demolded after 5 days and transported to the different curing places. For indoor curing specimens, they were curd in the laboratory and covered by the quilt and plastic film, until the 90 days, removed the quilt and film. The indoor temperature of the laboratory in winter was generally (20±3) ℃. The curing age, construction temperature at the time of casting the concrete, curing condition and the average curing temperature at 28d and 56d are listed in Table 2. The grouping number is composed of curing method and replacement rate of fly ash and the first upper-case letter O or I represent outdoor curing method or indoor curing method, respectively.

Table 2. Production and maintenance of test parts.

Place-FA/B	Curing age /d	Making temperature /°C	Average exposure temperature /°C	Maintenance state
I-0	577	-10	20±3°C	Cover plastic film and remove 90 days later
I-0.25	568	-6	20±3°C	
I-0.5	556	-5	20±3°C	
O-0	572	-10	-18/-17	Cover the film with the quilt and remove 90 days later
O-0.25	572	-6	-18/-17	
O-0.5	570	-5	-14/-17	

The specimens were tested under the servo-hydraulic testing machine with 5000kN load capability and the servo-hydraulic testing machine with 20000kN load capability, and the load rate was 0.3Mpa/s. In the center of the column, the strain gauges are pasted vertically along the middle side, and the stress state is controlled by the strain values on both sides during the test. The prisms were placed inside the testing frame and both ends of prismatic specimens were capped with a layer of 15mm depth fine sand to eliminate the hoop effect, so the uniaxial compression condition of the specimens could be guaranteed. As presented in Fig.1, from the failure pattern of the specimens, the cracking development of the concrete was basically parallel to the direction of the load, this phenomenon showed that the anti-friction measures achieved by the fine sand was successful.

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Figure 1. The destruction form of prism.

3. Organization of the Text

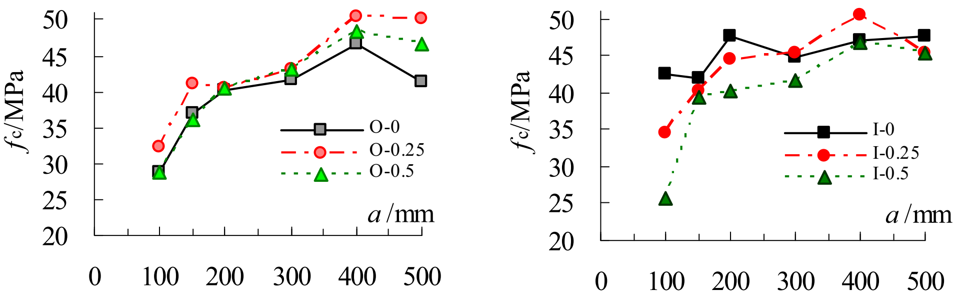
The raw data was calculated by triple mean square error method to remove the singular value.

3.1. Compressive strength

The main experimental data can be seen in Table 1 and Figure 2, respectively. In group I-0, the variation of the compressive strength is not relatively dependent on the size of the specimens, while the compressive strength increases when ranges from 100mm to 400mm in other five group (I-0.25, I-0.5, O-0, O-0.25, O-0.5). For all the experimental groups ranging from 400mm to 500mm, the trend of the compressive strength may not increase. For indoor curing groups (Fig.2), the compressive strength of the reference concrete group I-0 is the highest, while the group I-0.5 is lowest. For indoor curing groups, the compressive strength of each size fly ash concrete (FA/B≠0) is higher than that of the reference concrete (FA/B=0), of which the strength of FA/B is 0.25 (Figure 2 (b), O-0.25) is the highest.

Table 3. Main test results of prismatic uniaxial compression.

Indoor maintenance			Outdoor maintenance		
Number	f_c /MPa	$f_c/f_{c,150}$	Number	f_c /MPa	$f_c/f_{c,150}$
I-0-100	42.5	1.02	O-0-100	28.9	0.78
I-0-150	41.8	1.00	O-0-150	36.9	1.00
I-0-200	47.7	1.14	O-0-200	40.2	1.09
I-0-300	44.8	1.07	O-0-300	41.7	1.13
I-0-400	47.0	1.12	O-0-400	46.8	1.27
I-0-500	47.6	1.14	O-0-500	41.3	1.12
I-0.25-100	34.5	0.85	O-0.25-100	32.3	0.79
I-0.25-150	40.3	1.00	O-0.25-150	41.2	1.00
I-0.25-200	44.5	1.10	O-0.25-200	40.6	0.99
I-0.25-300	45.2	1.12	O-0.25-300	43.2	1.05
I-0.25-400	50.6	1.25	O-0.25-400	50.3	1.22
I-0.25-500	45.2	1.12	O-0.25-500	50.1	1.22
I-0.5-100	25.7	0.65	O-0.5-100	28.8	0.80
I-0.5-150	39.3	1.00	O-0.5-150	36.0	1.00
I-0.5-200	40.3	1.02	O-0.5-200	40.4	1.12
I-0.5-300	41.6	1.06	O-0.5-300	43.2	1.20
I-0.5-400	46.7	1.19	O-0.5-400	48.3	1.34
I-0.5-500	45.2	1.15	O-0.5-500	46.7	1.30



(a) Indoor maintenance (b) Outdoor maintenance

Figure 2. Test results of prismatic axial compression strength.

Fig. 3 shows the relationship between the f_c^O/f_c^I and the size of the specimens. For reference concrete group, the ratio of f_c^O/f_c^I is smaller than 1. For FA/B=0.5 fly ash concrete, except for 150mm side length specimens, f_c^O/f_c^I is greater than 1. The strength difference of fly ash concrete affected by curing temperature is less than that of ordinary concrete.

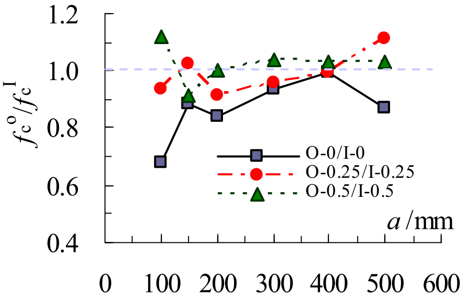
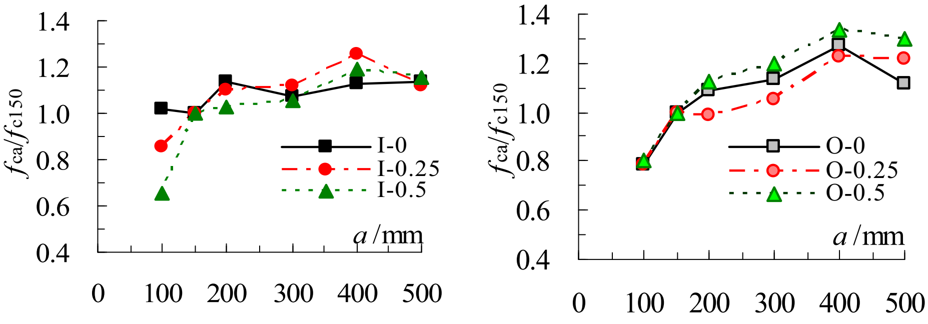


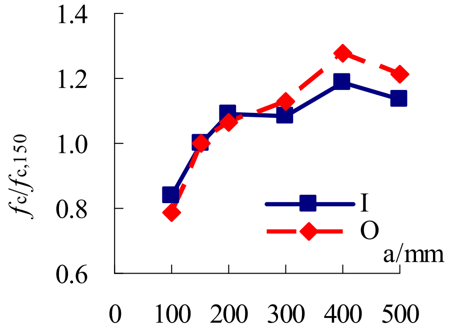
Figure 3. Axial compressive strength ratio of prism in outdoor and indoor maintenance.

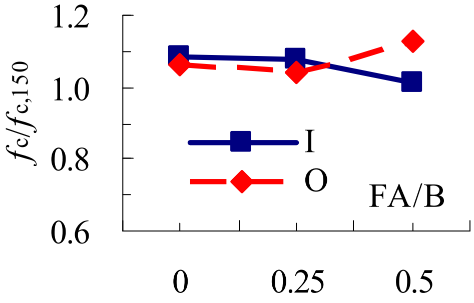
The ratio of the compressive strength f_c of each prism to the compressive strength of the 150mm column is $f_{c,150}$, that is, the dimension effect coefficient $f_c/f_{c,150}$ of the axial compression strength is shown in Table 3 and Figure 4, and the average value is shown in Figure 5. It can be seen that the size effect coefficient increases with the increase of a, and the size effect coefficient of small size specimen is low, and the $f_c/f_{c,150}$ of the test parts above the length of 200mm is more than 1. The average size effect of outdoor low temperature curing is higher than that of indoor temperature maintenance (Fig. 5a), and when FA/B is equal to 0.5, the average value of $f_c/f_{c,150}$ is the largest.



(a) Indoor maintenance (b) Outdoor maintenance

Figure 4. Size effect coefficient of axial compression strength $f_c/f_{c,150}$.





(a) Averaging by AF/B (b) Averaging by size

Figure 5. The mean value of the size effect coefficient of the axial compression strength.

3.2. Compressive deformation modulus

Table 4. Test results of compressive deformation modulus.

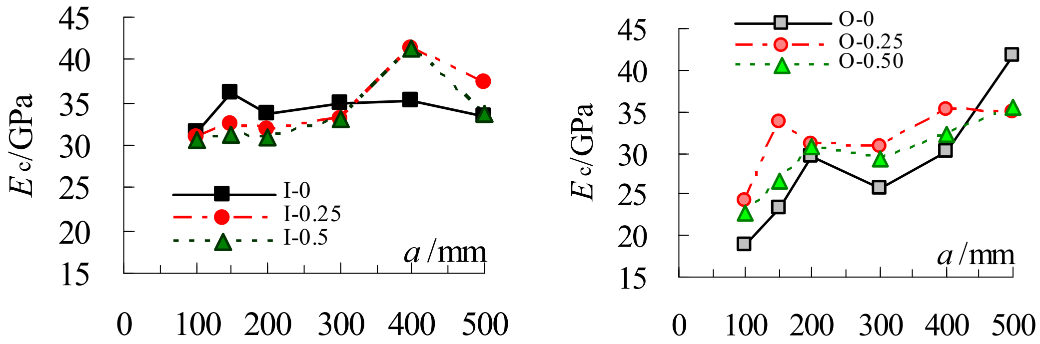
Indoor maintenance			Outdoor maintenance		
Number	E_c/GPa	E_0/GPa	Number	E_c/GPa	E_0/GPa
I-0-100	31.4	21.9	O-0-100	18.9	10.4
I-0-150	36.0	20.8	O-0-150	23.2	14.4
I-0-200	33.7	22.1	O-0-200	29.5	19.9
I-0-300	34.8	27.6	O-0-300	25.8	20.2
I-0-400	35.2	29.4	O-0-400	30.1	24.6
I-0-500	33.4	26.8	O-0-500	41.8	26.1
I-0.25-100	30.9	14.6	O-0.25-100	24.2	14.7
I-0.25-150	32.5	19.9	O-0.25-150	33.7	21.0
I-0.25-200	31.8	23.0	O-0.25-200	31.1	21.6
I-0.25-300	33.0	24.7	O-0.25-300	30.7	22.9
I-0.25-400	41.3	32.8	O-0.25-400	35.2	25.0
I-0.25-500	37.5	31.8	O-0.25-500	34.9	27.3
I-0.5-100	30.6	22.0	O-0.5-100	22.6	13.6
I-0.5-150	31.1	19.4	O-0.5-150	26.7	20.3
I-0.5-200	30.8	22.1	O-0.5-200	30.6	21.0
I-0.5-300	33.0	21.4	O-0.5-300	29.2	23.2
I-0.5-400	41.2	35.1	O-0.5-400	32.2	26.8
I-0.5-500	33.7	27.2	O-0.5-500	35.5	26.3

The experimental results of the compressive deformation modulus of the prism are shown in Table 4. In Table 4, E_c is the elastic modulus of the prism. And its value is the string modulus from the stress-strain curve with a first point at the strain of 50×10^{-6} and the second point at 33% of the peak stress. E_0 is the peak secant modulus, and its value is the ratio of FC to peak pressure strain.

1) Elastic modulus

Fig. 6 is a comparison of elastic modulus E_c under indoor and outdoor curing conditions. With the increase of a, E_c shows a general trend of increase, while E_c converges when a exceeds 400mm. In indoor maintenance, E_c changes little, while outdoor maintenance, E_c changes greatly. Fig. 7 is the change curve of the ratio of the elastic modulus of the outdoor curing prism to the indoor curing prism. The majority of E_c^O/E_c^I is less than 1, indicating that the outdoor low temperature environment is unfavorable to the growth of modulus of elasticity, and the smaller the size of the specimen, the more the outdoor modulus is lower than that in the room.

Fig. 8 is a variation curve of the size effect coefficient of elastic modulus with the length of column section *a*. $E_c/E_{c,150}$ increases with the increase of size. When *a* is greater than 400mm, there is convergence trend except O-0. The $E_c/E_{c,150}$ of small size fly ash concrete is low.



(a) Indoor maintenance (b) Outdoor maintenance

Figure 6. The change of elastic modulus E_c with the length of column cross section.

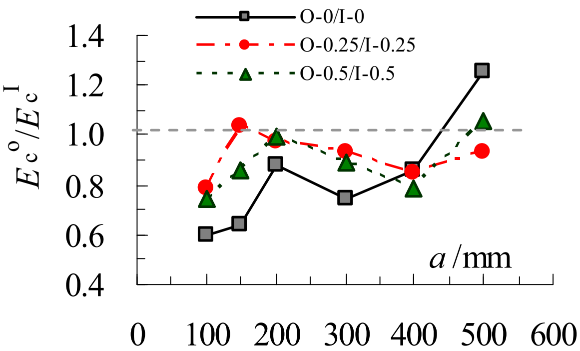


Figure 7. The ratio of elastic modulus between outdoor and indoor maintenance columns.

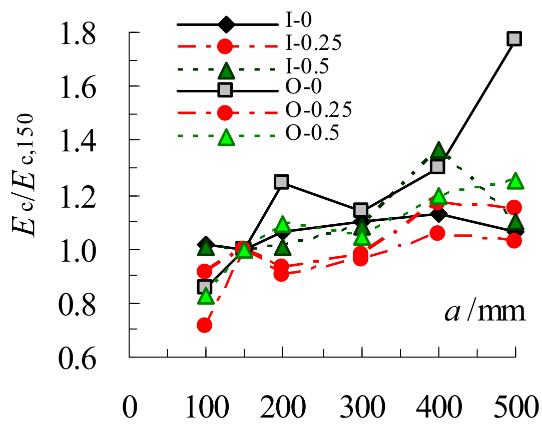
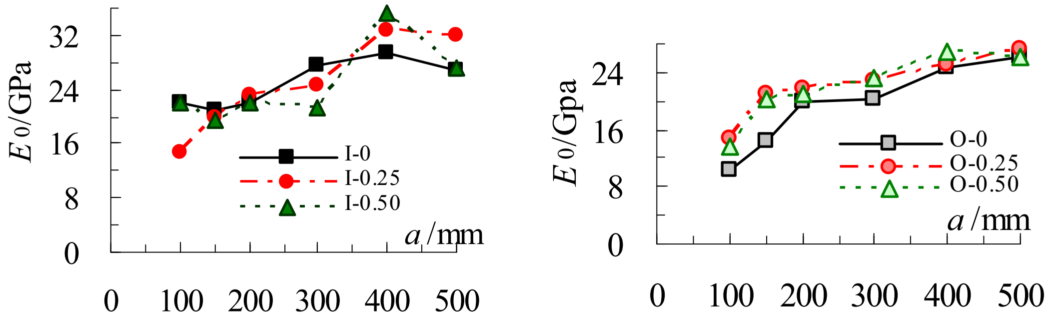


Figure 8. The size effect coefficient of the compressive elastic modulus $E_c/E_{c,150}$.

2) Peak secant modulus

The results of the peak secant modulus E_0 are shown in Figure 9. Similar to f_c and E_c, when the length of column section *a* increases from 100mm to 400mm, E_0 increases as *a* increases. When *a* is greater than 400mm, the curve of indoor curing group converges.



(a) Indoor maintenance (b) Outdoor maintenance

Figure 9. The variation of E_0 with the length of column cross section.

Fig. 10 is the ratio of the prism peak secant modulus E_0^O to the outdoor maintenance prism peak secant modulus E_0^I and the change of E_0^O/E_0^I along the length of the column section a. The E_0^O/E_0^I of the reference concrete is less than 1, and the smaller the A is, the smaller the E_0^O/E_0^I is. For fly ash concrete, E_0^O/E_0^I is greater than that of reference concrete.

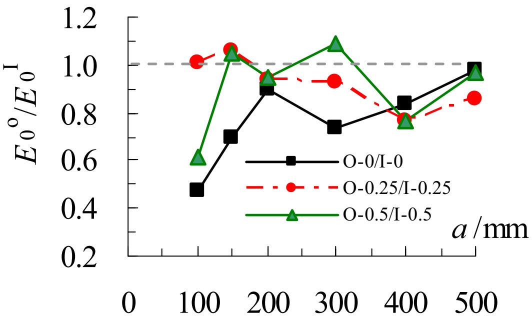


Figure 10. E_0^O/E_0^I.

Fig. 11 is the change curve of the ratio of the prism peak secant modulus E_0^O/E_0^I to the outdoor maintenance E_0^O and the indoor maintenance E_0^I with the increase of the column side length *a*. Compared with Figures 8 and 10, we can see that $E_0/E_{0,150}$ is larger than $E_c/E_{c,150}$ in general, that is, the size effect of E_0 is stronger than E_c. Compared with Figures 8, 10 and 4, it is found that the size effect of E_0 and E_c is stronger than that of f_c.

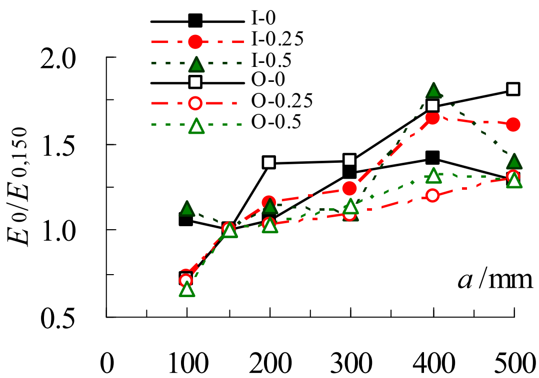


Figure 11. The size effect coefficient of the peak secant modulus $E_0/E_{0,150}$.

3) The relationship between E_c and E_0

Figure 12 is the relationship between the E_c and E_0 test values. It can be seen that E_0 increases with the increase of E_c. The linear regression equation is E_0=0.721 E_c, and its R^2 is 0.69, indicating that its linear relationship is highly fitted.

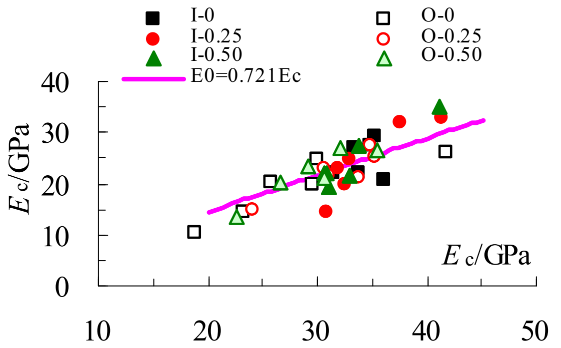


Figure 12. The relationship between E_c and E_0 E_c/E_0.

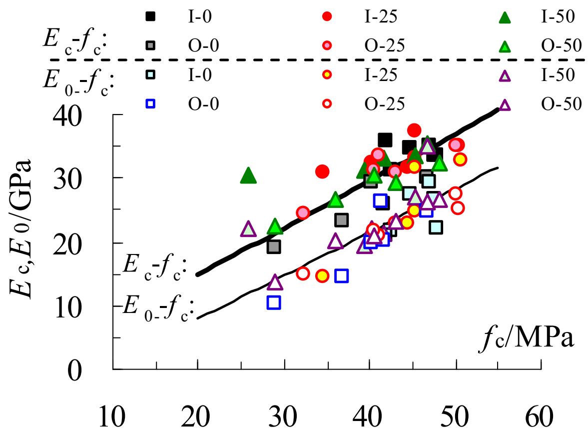


Figure 13. E_c, E_0 and f_c.

Fig. 13 is the change curve of elastic modulus and peak secant modulus with increasing axial compressive strength respectively. It can be seen that E_c and E_0 show a good linear increasing trend with the increase of f_c of the size column.

The relationship between peak elastic coefficient (υ_0) and the size of the specimens is plotted in Fig.14, where the peak elastic coefficient (υ_0) is defined as the ratio of E_0 to E_c. From Fig. 13, υ_0 increases as a ranges from 100mm to 400mm. When a is greater than 400mm, υ_0 may not increase any longer. The power-function regression equation is υ_0=0.266 $a^{0.178}$, the curve of this equation can fit this trend best (shown in the thick solid line in Fig.13). When a ranges from 100mm to 500mm, the average values of ν_0 regardless of fly ash replacement and curing method are 0.61, 0.64, 0.69, 0.75, 0.81 and 0.77, respectively, and the average of these 6 values mentioned above is 0.71. In the same way, the value of E_c/E_0 varies between 1.68 and 1.24, and the average value of E_c/E_0 is 1.43. The reason that can explain ν_0 increases as a increases is that the size effect on peak secant modulus is more important than that on elastic modulus.

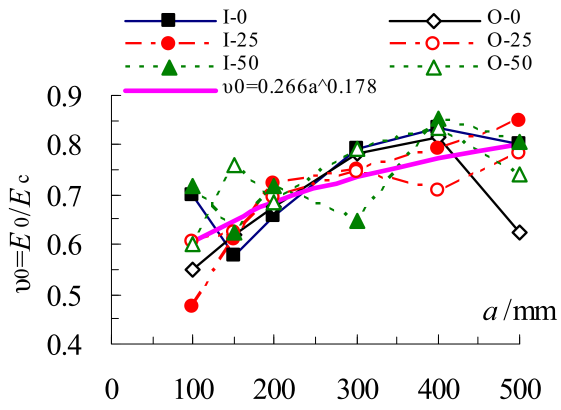


Figure 14. The relationship between E_0/E_c and the length of column cross section.

4. Conclusion

(1) The compressive strength (f_c), the deformation modulus (E_c) and (E_0) and the peak elasticity coefficient of the prismatic axis ($\upsilon_0=E_0/E_c$) are increased with the increase of the edge length of the prism section, and the peak pressure strain decreases with the increase of the side length of the section. When the section length is greater than 400mm, the increasing trend is changed.

(2) The strength of the base concrete is the highest when the room temperature is maintained. The strength and elastic modulus of fly ash concrete are lower than that of benchmark concrete.

(3) In both indoor and outdoor maintenance, the strength of the fly ash replacement rate for FA/B=0.25 is higher than that of the same size FA/B= 0.5.

(4) The intensity difference of indoor and outdoor maintenance group decreased with the increase of size, and the intensity difference was the smallest when the length was 400mm. The difference of indoor and external maintenance strength and deformation modulus of fly ash concrete is less than that of benchmark concrete.

(5) When the curing is outdoors in low temperature, the size effect of FAC is larger than that of OPC.

(6) The size effect of compression modulus of prism is greater than that of compressive strength.

5. Summary analysis

The conclusion of this experiment is obtained during winter casting and winter curing temperature, and the compressive strength test of the column adopts the measures to reduce friction. The above results show that: a. during the cold winter construction, the low temperature curing has adverse effects on the long-term strength development of concrete, and the smaller the size, the worse; b. Adding fly ash is beneficial to the compressive strength of low-temperature curing concrete during winter construction; c. The size effect of concrete is related to the function of curing temperature and fly ash; d. E_c/E_0 decreased with increasing specimen size, namely the limit of large size specimen deformation may be less than the relevant parameters of small size specimen, this is serious, the phenomenon is likely to make reinforced concrete compression member in the role of compressive reinforcement was overvalued.

Acknowledgments

The authors thank the staff of the structural laboratory in Beijing University of Civil Engineering and Architecture.

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