Influence of Coarse Aggregate Grade on Air Void Structure of Air-entrained Concrete

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Abstract. *Air void structure has always been a key factor affecting the frost resistance of concrete. The refinement of air void structure mainly comes from the extrusion of slurry and the cutting of aggregates. However, there is no systematic theory on the influence of aggregate on air void structure. In this paper, the effects of different coarse aggregate grades on the concrete air void structure were studied. The fractal dimension D value was used to represent the coarse aggregate gradation. In the range of coarse aggregate particle size between 4.75-26.5 mm, D=2.1, D=2.3, D=2.5, D=2.7 were selected as the experimental group, and single-graded coarse aggregate of 4.75 and 26.5 mm were selected as the control group, with a total of six test groups. By means of an air content tester, Rapid Air, freeze-thaw durability test and other measurements, the air content, air void structure, freeze-thaw durability and other performance parameters were measured. The differences in air void structure parameters of specimens, such as air content, spacing factor and the number of bubbles were compared to obtain the relationship between the coarse aggregate grading and air void structure. Further analysis of its influence on frost resistance can provide a reference for scientific research and engineering application of concrete air void structure.*

Keywords: *Fractal Dimension, Coarse Aggregate Grading, Air Content, Air Void Structure, Air-entrained Concrete.*

1. Introduction

Air-entrained concrete has the advantages of improving the durability of concrete, rheological properties of newly mixed concrete, regulating the setting and hardening properties and air content of concrete, and providing special properties for concrete[1-4]. Therefore, air-entrained concrete is the most widely used type of concrete in northern cold areas[5, 6]. As a kind of porous building material, the characteristics of the porous structure of air-enlivened concrete affect the physical properties of the material such as compactness, frost resistance, impermeability and chemical corrosion resistance as well as the mechanical properties such as compressive strength and flexibility[7, 8], among which the particularly important pore structure is one of the main characteristics affecting the frost resistance of concrete. Pigeon M is divided into four types according to its size, namely gel pores at 1-3 nm, capillary pores at 5 nm-1000 nm, pilot pores at 5-1250 μm, and inset holes above 1000 μm[9]. Academician Wu Zhongwei[10]defined the pore smaller than 20 nm as harmless, while the pore larger than 20 nm was defined as harmful, and the larger the pore size, the greater the harm. In air-entrained concrete, if the air content of concrete is too low, it cannot meet the requirements of frost resistance, and if the strength is too high, it will decrease obviously. Generally, the air-entrained concrete content is between 4.5% and 5.5%.

In fact, the pore structure of concrete has many parameters, including slurry air ratio, air content, porosity, bubble spacing coefficient, bubble chord length, and so on. Researchers[11] use these parameters to express the superiority of concrete porosity to concrete frost resistance, among which bubble spacing coefficient is an evaluation method for scholars[12, 13]to use porosity structure to protect concrete against frost. In short, it is hoped to increase the number of small bubbles as much as possible while controlling the air content unchanged. The smaller the spacing coefficient of bubbles, the better. When the spacing coefficient of bubbles is less than 200 μm, the concrete will have a better anti-freezing effect[13, 14]. However, there are many factors affecting the porosity structure of concrete, including water-cement ratio, admixture, fiber, aggregate, mixer type, external environment, etc.[15-20]

As the most important component of concrete, aggregate is the part of concrete skeleton, which affects the strength, permeability, durability and other properties of concrete[21-23]. In the past, the research of aggregate on concrete performance was mainly focused on the influence of aggregate on concrete performance, and the corresponding research on how it affects the internal pore structure was rarely made. Du[24]et al. showed that the shape and texture of aggregate particles, particle size distribution and the maximum particle size of coarse aggregate may reduce the amount of aeration. For the constant cement and AEA content, the increase of fine aggregate can increase the aeration volume. The sand particle with diameter between 160 μm and 630 μm is conducive to increase the aeration volume, while the increase of sand particle with diameter less than 160 μm will significantly reduce the aeration volume. Some aggregates contaminated with oil or organic matter may significantly affect the entraining effect.

Fractal theory is a mathematical theory that studies the properties of self-similar objects and is now used in a variety of fields. Many researchers have applied fractal theory to the gradation direction of concrete aggregate. The study of Zhou Yu et al.[25]showed that the gradation, size and type of coarse aggregate had a great influence on the freezing resistance of concrete, and found that the better aggregate gradation, the better the freezing resistance of concrete.

The research results of Guo Jiao et al.[26] showed that the best mechanical properties and frost resistance of mass concrete were achieved when the fractal dimension of the aggregate gradation was between 2.3 and 2.5. In fact, the frost resistance durability of concrete is the macroscopic reflection of the micro-pore structure and porosity of cement slurry. It can be seen that the micro-pore structure and porosity of concrete will change with the change of aggregate gradation, which leads to the difference in the frost resistance of concrete. At present, there is no study to directly show the influence of porosity in concrete with coarse aggregate grade and the relationship between porosity structure and frost resistance of concrete with coarse aggregate grade.

In order to study the influence of coarse aggregate grade on concrete porosity structure, and further study the relationship between concrete porosity structure and frost resistance when coarse aggregate changes, so as to improve the accuracy of judging concrete porosity structure and frost resistance by aggregate grading under given aggregate conditions. In this study, based on the fractal gradation theory of aggregate, concrete specimens were prepared by coarse aggregate gradation with different fractal dimensions. By testing the newly mixed air entrained, hardened porosity structure and frost resistance of concrete specimens, the variation rule of porosity structure and frost resistance of concrete under the fractal dimension of different coarse aggregate grading was analyzed, and the mechanism of the influence of coarse aggregate grading on porosity structure and frost resistance of concrete was revealed by simulating the results between bubbles and aggregate layer obtained by aggregate test. The relationship model of concrete coarse aggregate gradation-pore structure-frost resistance was established. Based on this model, a method is proposed to make concrete reach the required frost resistance standard by adding appropriate air entrained agents under different aggregate gradation conditions, which provides a reference for scientific research and engineering application of modern porous structures in concrete.

2. Material and Experiment

2.1 Material

The concrete is made of ordinary Portland cement with a strength grade of 42.5 Mpa produced by Guangxi Nanning China Resources Cement Co., LTD. Machine-made sand is from Longmeng Mountain stone farm in Guangxi, and stones are from Hengshan Stone Farm in Guangxi.,and tap water is used in the casting process. The entraining agent is made of sodium dodecyl sulfate anionic surfactant (SDS) produced by Shanghai Maclin Biochemical Technology Co., LTD., and the water reducing agent is made of naphthalene series water reducing agent produced by Shandong Wanshan Chemical Co., LTD.

2.2 Mix Ratio and Sample Preparation

Li Guoqiang et al.[27]used fractal theory to analyze and derive fractal gradation formula in aggregate gradation:

$$P(X)=\frac{X^{3-D}-Xmin^{3-D}}{Xmax^{3-D}-Xmin^{3-D}}\times 100\% \quad (1)$$

Where X is the particle size of aggregate; D is the fractal dimension; % (mass fraction); P(X) is the passing rate of aggregate sieve; X min is the minimum particle size of aggregate; X max is the maximum particle size of aggregate; In general, X min in continuous aggregate is very small and can be ignored considering the existence of fine aggregate. The above equation can be simplified to the coarse aggregate gradation formula

$$P(X)=\frac{X^{3-D}}{Xmax^{3-D}} \quad (2)$$

The characteristics of the aggregate itself determined that the fractal dimension value D of common aggregate gradation was generally between 2-3. The experiment designed four component dimension values and two groups of single particle size control groups. The four fractal dimensions were D=2.1, D=2.3, D=2.5, and D=2.7, respectively. The control group used all large stones (19-26.5 mm), and the control group used all small stones (4.75-9.5 mm). D value is used instead of aggregate gradation to explore the influence rule of concrete porosity structure. In this experiment, the maximum particle size of coarse aggregate was 26.5 mm. According to Formula (2), coarse aggregate zone screening residues under several gradations can be obtained (see Table 1). The mixing ratio of m(cement):m(water):m(sand):m(coarse aggregate):m(air entraining agent) was 487:195:515:1200:0.24, and The water-cement ratio is 0.4, the sand rate is 30%, and the mixing ratio of each grade is shown in Table 1.

The prepared continuously graded stones (4.75-31.5 mm) are screened with 6 square sand and stone screens, and the screen sizes are 4.75 mm, 9.5 mm, 16 mm, 19 mm, 26.5 mm and 31.5

mm, respectively. Finally, the stones in the interval of 4.75-9.5 mm, 9.5-16 mm, 16-19 mm and 19-26.5 mm are selected. The sand and stone are evenly mixed in the forced single horizontal shaft concrete mixer for 15s, and then the cement is poured into the mixer for 15s, and then the prepared quantitative air entraining agent solution is mixed in water and added to the mixer. The water reducing agent solution is slowly added through the dropper during the mixing process, so that the slump of the concrete can reach about 120 mm. The whole mixing process needs 180s to complete the preparation of fresh concrete. Part of the fresh concrete needs to be used for air content testing, while the other part needs to be poured into a test block sample.

Table 1. The coarse aggregate ratio under different fractal dimension.

Mix proportion	Fractal dimension	4.95-9.5(mm)	9.5-16(mm)	16-19(mm)	19-26.5(mm)
a	D=1.8	0	0	0	1
b	D=2.1	0.14	0.33	0.16	0.37
c	D=2.3	0.27	0.30	0.14	0.29
d	D=2.5	0.43	0.24	0.11	0.22
e	D=2.7	0.63	0.17	0.07	0.13
f	D=3.0	1	0	0	0

Firstly, the newly mixed concrete was poured into the 100 mm cube mold, and 3 specimens were poured into each group of mix ratio. Secondly, the specimens with molds were vibrated for 30 s on the shaking table, and then the molds were removed after standing for 24h. Finally, the specimens were transferred to the curing room (temperature 20±2℃, relative humidity > 95%) and cured the specimen for 28 days.

2.3 Experimental Method

2.3.1 Air content test of fresh concrete

The air content of concrete was tested in strict accordance with the Standard of Test Method for Performance of Ordinary Concrete Mixtures (GB/T50080-2016).

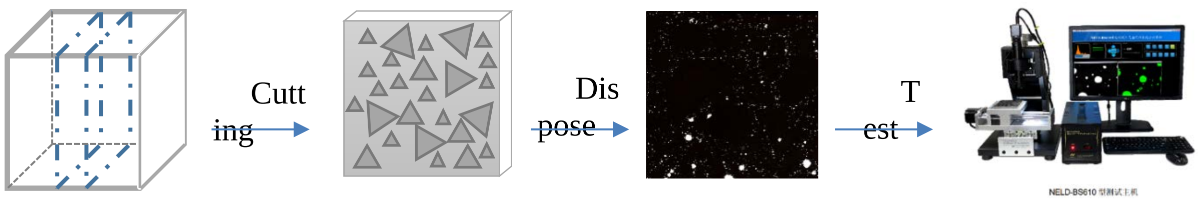

Fig.1. Formation diagram of pore structure specimen.

2.3.2 Air hole test of hardened concrete

The simulation diagram of the hardened concrete pore structure test is shown in Figure 1.

2.3.3 Air hole test of hardened concrete

We investigated the rise of bubbles in the air-entraining agent solution using simulated experiments. We needed to simulate the previous aggregate grading test and designed a device to examine the interaction between air bubbles and aggregate particles by observing the results. The device for the experiment consisted of an acrylic plate water tank with a syringe and needle attached to the bottom of the tank (Figure 2). The tank was 15 cm long, 25 cm high and 5 cm wide. A layer of randomly stacked plastic cubes with 4.75-26.5 mm sides was floated on top of the aqueous solution of the air-entraining agent. The air injected into the system from below produced bubble sizes of 1-3 ml. To study the effect of solid particles on the number of bubbles in the air-entraining system, we need to capture the bubble movement process in detail using a high-definition camera.

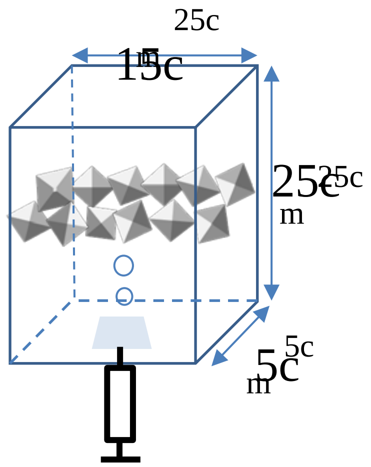

Fig.2. Formation diagram of pore structure specimen.

3 Result and Analysis

3.1 Study on Structural Characteristics of Concrete Pore under Different Aggregate Gradation Fractal Dimension

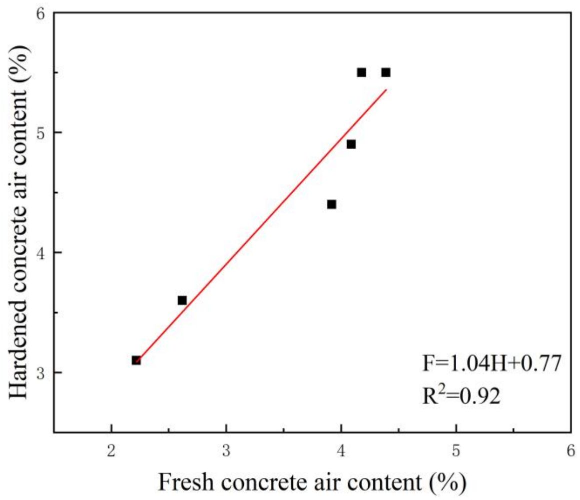

Fig.3. Fitting of fresh and hardened air content.

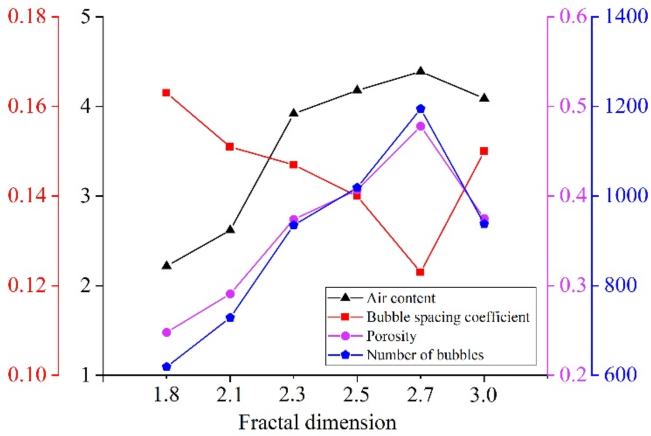

Fig.4. Relationships between stomatal hardening parameters in different D.

Based on the available fresh air content, the relationship between fresh air content and hardened air content can be obtained, as shown in Figure 3, which shows a positive correlation between fresh air content and hardened air content, and a good correlation result is obtained by fitting the two,R^2=0.92.Figure 4 represents the relationship between several parameters of the hardened pore structure of concrete with different fractal dimensions. The bubble spacing coefficients of the six groups of specimens were 0.163mm, 0.151mm, 0.150mm, 0.147mm, 0.140mm and 0.123mm in descending order, with the number of bubbles ranging from 600 to 1200 and the air content ranging from 2% to 5%.It can be seen that the air content, porosity and number of bubbles of the six groups of specimens have the same trend of increasing and then decreasing, while the trend of the bubble spacing coefficient is completely opposite, decreasing and then increasing, with the extreme value at D=2.7. The higher the air content, the smaller the bubble spacing coefficient, indicating that the variation of coarse aggregate gradation forces the difference between air content and bubble spacing coefficient in hardened concrete with the same test slump and air-entraining agent content. according to Han [28], the fractal dimension is a parameter that can be used to mark the complexity of a fractal set, and each fractal set corresponds to a fractal dimension defined in some way.

From the above graphs, it can be found that the air content, porosity, number of bubbles, of single-grain concrete in both groups are lower than the other groups, while the bubble spacing coefficient is relatively high, showing poor pore structure characteristics. For the test group, the pore structure of concrete also showed a large difference with the change of concrete coarse aggregate grading, the fractal dimension was between 2.5 and 3.0, and all parameters of concrete pore structure tended to exist an extreme value, which made the concrete pore structure show relatively better results.

3.2 Interaction of Air Bubbles with Aggregates

The test is shown in Fig. 5(a), which represents a small stone grading model, all replaced by a 7 mm cube. A 1 ml gas was punched in from the bottom and the bubbles started to touch the bottom of the aggregate particles after a certain distance and the frequency of the bubbles getting stuck, splitting around the particles or moving around the particles without splitting was tracked by repeating the experiment. The test results show that when 1 ml of gas enters the aggregate layer from the bottom, the gas bubbles, because they very easily collide with the edges of small aggregates, essentially split when touching the edges of small aggregates, splitting into two bubbles of about the same size as in Fig. 5(a), or possibly splitting into bubbles with a large size difference, or possibly splitting multiple bubbles. Fig. 5(b) is a model of the simulated full boulder gradation, with All of them are replaced by 23 mm aggregate cubes, and the splitting of bubbles under the action of 1 ml of bubbles is different from that of small aggregates, instead, the bubbles of large aggregates are more likely to pass inside the pores of the aggregate pile, and there is also splitting but less.

(a) (b) (c)

Fig.5. Air bubble-aggregate interactions in three case a) 7mm aggregate and enlarged, b) 23mm aggregate, and c) four aggregate models, 7mm, 13mm, 18mm, 23mm.

From Fig. 5(a) (b)shows that for the same size aggregate, the larger the bubbles collide into the aggregate the easier it is to break, which also explains the increasing fractal dimension in the process of increasing the air content of the concrete and the content of small pores. Fig. 5(c) shows a test using four aggregate models to simulate continuously graded concrete, and it is obvious that the compactness of the continuously graded aggregate layer is better than that of a single graded aggregate, with the large aggregate group having the worst compactness. When receiving 1 ml of bubble collision, the bubbles not only easily collide and split into various bubbles, but also due to their better compactness, the bubbles do not easily escape inside the aggregate layer, which also explains that for the fractal dimension at 2.7 the air content of concrete reaches the maximum, and at close to 3.0, i.e., when all small aggregates, the air content of concrete decreases instead, which is probably because of the concrete gradation This is probably due to the poor grading of the concrete, which is not dense enough.

4 Conclusion

The fresh air content and hardened pore structure of concrete under different coarse aggregate gradations were investigated experimentally. The results show that the fresh air content and hardened pore structure parameters of concrete with different coarse aggregate gradations under the same conditions are different, and there is a best gradation between fractal dimension 2.5-

3.0 which makes the concrete pore structure optimal. The following conclusions are drawn: the porosity, hardened air content, and number of bubbles of concrete show a trend of increasing and then decreasing as the D value increases, while the bubble spacing coefficient and slurry gas ratio show the opposite trend. For single-size graded concrete, it shows smaller air content and larger bubble spacing coefficient, while for continuous graded concrete, it shows smaller bubble spacing coefficient and larger air content, and its bubbles are finer and more uniform. The larger the ratio of bubble to aggregate size, the greater the probability of breaking when the bubbles collide. The higher the content of small aggregates, the more likely to produce small bubbles. However, the denseness of concrete with continuous grading is better than that of single-graded concrete, which is more tolerant of escaping air bubbles. For this experiment, the effect of the viscosity of the liquid on the test is not considered at this time because we believe that the rate at which air is drawn into the concrete is very small.

References

Gan, D.C. et al. *Effects of different types of air-entraining agents on the rheological and mechanical properties of filled slurry*. Mining Research and Development, 2022. 42(01): pp. 23-28.

Song X et al. *Effect of different types of air-entraining agents on air content and pore structure of concrete*. Sichuan Building Materials, 2020. 46(11): pp. 3-4+8.

Yang Qianrong et al. *Effect of air-entraining agents on characteristic parameters of concrete air bubbles*. Journal of Tongji University (Natural Science Edition), 2008(03): pp. 374-378.

Qianrong Yang and Shiyuan Huang, *Characterization of air-entrained concrete.* Concrete, 2008(05): pp. 3-7.

Song Yupu et al, *Study of biaxial damage criterion of air-entrained concrete after freeze-thaw cycles*. Engineering Mechanics, 2007. 24(6): pp. 134-141.

Deng Xianghui et al, *Experimental study on the frost durability of concrete in high altitude cold regions.* Engineering Mechanics, 2022: pp. 1-11.

Nambiar, E.K.K. and K. Ramamurthy, *Air‐void characterisation of foam concrete*. Cement and Concrete Research, 2007. 37(2): p. 221-230.

Jin, S., J. Zhang and B. Huang, *Fractal analysis of effect of air void on freeze‐thaw resistance of concrete*. Construction and Building Materials, 2013. 47: p. 126-130.

Ren Bin, *Mechanical properties and porous structure of mixed fiber fly ash concrete under freeze-thaw cycles*, 2021, Anhui University of Technology. Page 87.

Interpretation of the "Central mass hypothesis of cementitious composites" by C.W. Wu _ Lian Huizhen.

Zhang, X., et al., *Effect of bubble feature parameters on rheological properties of fresh concrete*. Construction and Building Materials, 2019. 196: p. 245-255.

Liu Qi, Ph.D. Thesis: *Study on the formation mechanism and influencing factors of air-entrained concrete pore structure* 20210918.

Lyu, K., et al., *Relationship between fine aggregate size and the air void system of six mortars: I. Air void content and diameter distribution.* Cement and Concrete Composites, 2022. 131: p. 104599.

He, J. F., *Research on microstructure and properties of road cement concrete,* 2009, Chang'an University. Pp. 143.

Li Xuefeng, Fu Zhi & Luo Shua, *Study on the effect of low pressure enviro nment on air content and pore structure of concrete*. Highway Transportation Technology, 2015. 32(02): pp. 49-54.

Gao F, Zhang X & Zhang YJ, *Effect of chemical admixtures on the pore structure and hydration of concrete*. Functional Materials, 2013. 44(23): pp. 3416-3420.

Jiang J, Lu ZY & Niu YF, *Study on the effect of water reducing agent on the pore structure and performance of physical method super light foam concrete.* Journal of Wuhan University of Technology, 2014. 36(11): pp. 25-31.

Zhou P, Xie S-L & Li Q. *Analysis of the effect of water-cement ratio on the properties and pore structure of concrete*. Silicate Bulletin, 2018. 37(03): pp. 974-978.

Yang Wenzui, *Study on the effect of inorganic salts on the pore structure and frost resistance of concrete*, 2009, Harbin Institute of Technology. Harbin Institute of Technology. p. 137.

Xu Jiangtao et al, *Pore structure of mortars containing dolomite and limestone micropowder at different curing temperatures*. Journal of Silicates, 2017. 45(02): pp. 268-273.

*Effect of coarse aggregate particle shape index and grading on the workability of self-compacting concrete*_Yan, Lin.

*Influence of coarse aggregate shape on mechanical properties of concrete*_Xing Xinkui.

*Influence of aggregate admixture and shape on compressive properties of foam concrete*_Li Zhaorui.

Du, L. and K.J. Folliard, *Mechanisms of air entrai nment in concrete*. Cement and Concrete Research, 2005. 35(8): p. 1463-1471.

Yu Zhou, *Study on the effect of aggregates on the frost resistance of hydraulic concrete and the mechanism of action*, 2019, Changjiang Academy of Sciences. Pp. 73..

Guo Jiao, *Fractal study of frost resistance of concrete aggregate grading*, 2011, Inner Mongolia Agricultural University.

Fractal effect of graded aggregates_ Li G.

Zheng, D., et al., *Research on mechanical characteristics, fractal dimension and internal structure of fiber reinforced concrete under uniaxial compression.* Construction and Building Materials, 2020. 258: p. 120351.

Belien, I.B., K.V. Cashman and A.W. Rempel, *Air accumulation in particle-rich suspensions and implications for bubble populations in crystal-rich magma*. Earth and Planetary Science Letters, 2010. 297(1-2): p. 133-140.