Mathematical analysis of the geometric structure of pores in autoclaved aerated concrete

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This paper presents a study on the geometric pore structure and the distribution of pores in AAC, based on an idealistic mathematical model. The aim is to provide information that is practically relevant for the optimization of AAC products.

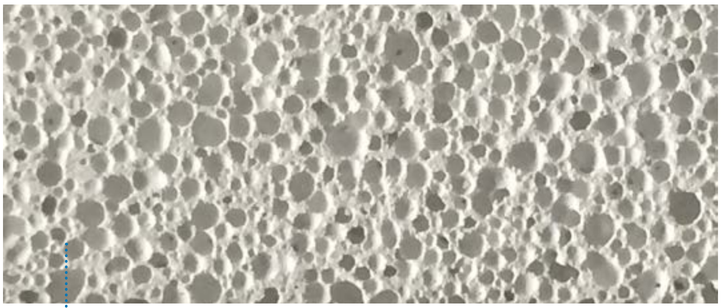


Fig. 1: Example of pore structure of AAC (Yitong, Changxin)

Autoclaved aerated concrete is a porous concrete formed by chemical gas generation of aluminum powder. The geometric shape of the hole is a spherical pore or a near-spherical pore, and the pores are closed independently (Fig. 1).

Ideal model of pore structure distribution in AAC

The wall thickness of the matrix, i.e. the minimum distance between the edges of two neighbouring pores, as well as the pore size distribution have important effects on the performance of AAC. When matrix performance and wall thickness are fixed, then an increase in the curvature of the pore surface, i.e. a decrease in the equivalent diameter of the pore, results in an increase in the relative pore compressive strength (Fig. 2). When the equivalent diameter of the pore is fixed, then an increase in the wall thickness of the matrix results in an increase in the matrix compressive strength (Fig. 3).

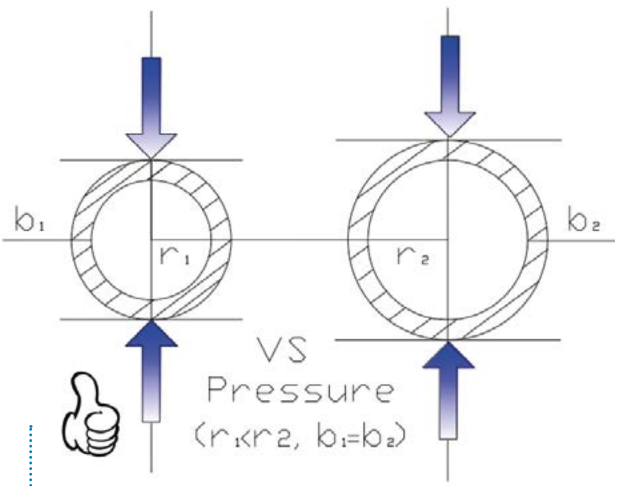


Fig. 2: When the matrix performance and wall thickness are fixed, the larger the curvature of the pore surface (the smaller the equivalent diameter of pore), the larger the relative pore compressive strength.

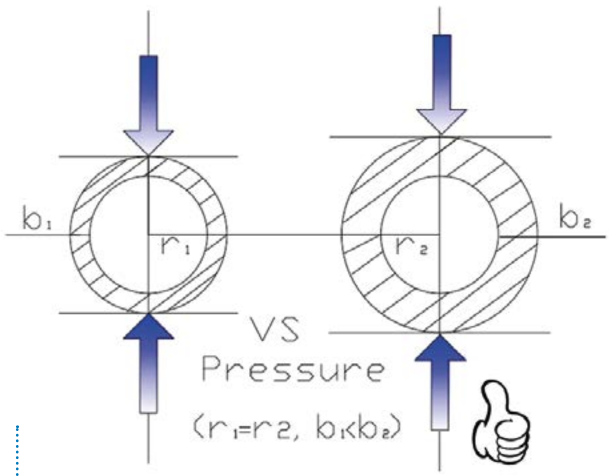


Fig. 3: When the equivalent diameter of the pore is fixed, then a larger wall thickness of the matrix results in higher matrix compressive strength.

Compared to the case of small quantity of pores with large diameter, when there are large quantity pores with small diameter, the total surface area is lager and the compressive strength of the pore structure is high. However, when the wall thickness is smaller, the compressive strength is lower. Therefore, we need to further discuss the most suitable pore size distribution and the corresponding wall thickness. In this paper, the pore size distribution and the wall thickness of the matrix are analyzed based on the assumption that the pore distribution follows a hexahedron structure (Fig. 4).

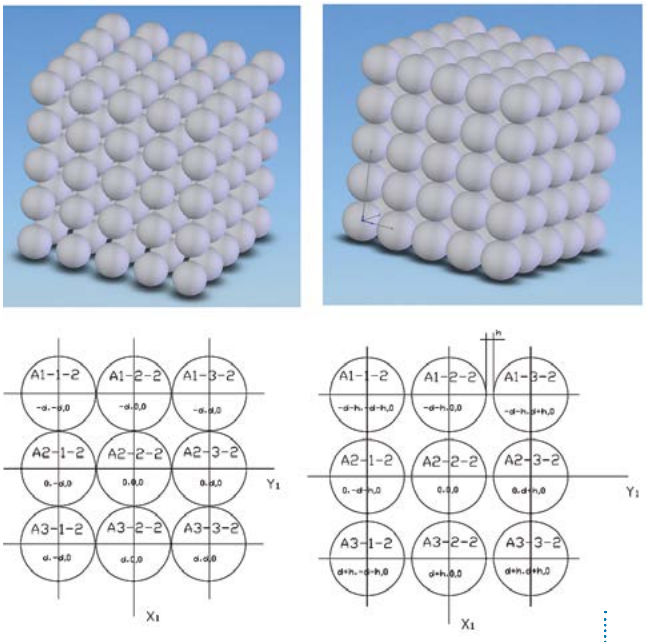


Fig. 4: The assumed model of the pore structure

The assumed model is a cube, which is closely packed and arranged, and can expand to three dimensions infinitely. It is composed of n^3 equal pores with diameter of d, and the minimum distance between the pores is h. Therefore:

Cube side length = n×(d+h)
Cube volume = $[n\times(d+h)]^3$
Pore volume V = $1/6\ \pi d^3 = 0.5236\ d^3$ [mm^3],
with d = pore diameter [mm]

Table 1 summarizes the current situation in most production plants. Companies can make appropriate adjustments according to their actual production conditions and discuss the distribution of pores suitable for their own conditions.

Analysis of the pore structure distribution

Single pore diameter

Wall thickness diameter ratio of single pore distribution: $h_{1AA}/ d_{1A} = \sqrt[3]{0.5236/v} - 1$

Number of pores of single pore distribution X1A:
X_{1A} $=19.0985V/d1_A^3$ (100 million PCs. / m^3)
X_{1A} $=1909.85V/d1_A^3$ (PCs./ cm^3)

When two pores of the single pore distribution are tangential, that is, $h_{1AA} = 0$, the volume of matrix with single pore distribution is the smallest, and the corresponding volume of gas generation per unit aluminum powder is the largest. It can be calculated that the upper limit value of gas generation volume per unit aluminum powder for single pore distribution is 0.524 m^3/m^3. As shown in Table 1, the gas generation

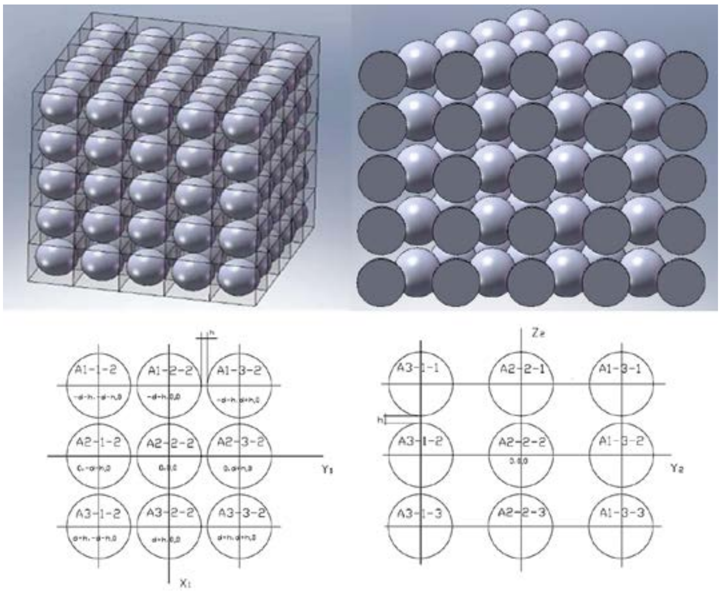


Fig. 5: The supposed distribution structure of pores with a single diameter

Table 1: Gas generation volume of aluminum powder in AAC with different dry densities

Dry density, kg/m³	700	650	600	550	500	450	400	350	300
Pore volume percentage, %	71.4	73.5	75.5	77.5	79.5	81.5	83.6	85.6	87.6
Gas generation volume of aluminum powder m³/m³	0.387	0.427	0.469	0.511	0.554	0.596	0.634	0.675	0.713

Table 2:
The wall thickness with different dry densities and different diameters of pores, assuming single pore distribution (h, mm)

Dry density, kg/m³	**Pore diameter (mm)**								
	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.50	3.00
700	0.053	0.080	0.106	0.133	0.160	0.186	0.213	0.266	0.319
650	0.035	0.053	0.070	0.088	0.105	0.123	0.140	0.175	0.210
600	0.019	0.028	0.038	0.047	0.057	0.066	0.075	0.094	0.113
550	0.004	0.006	0.008	0.010	0.012	0.014	0.017	0.021	0.025

of aluminum powder required for AAC with a dry density less than 500 kg/m³ is greater than 0.524 m³/m³, that is, the conditions for AAC with a dry density of less than 535 kg/m³ to form a single diameter circular pore are not available.

As shown in Table 2, for single pore distribution, for AAC with a dry density less than 600 kg/m³, the wall thickness is too small. For AAC with a dry density more than 650 kg/m³, a certain wall thickness shall be ensured, and the pore diameter of the pore shall be more than 1 mm.

Fig. 6: The supposed distribution structure of pores with two diameters

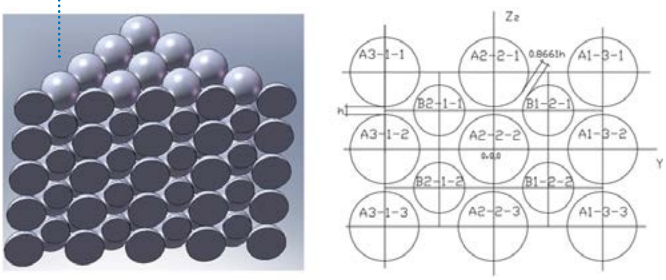
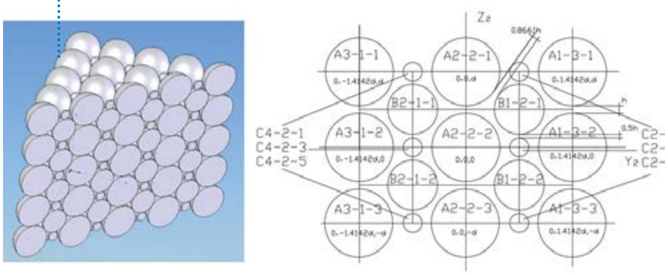


Fig. 7: The supposed distribution structure of pores with three different diameters



Two different pore diameters

In Fig. 6, the large pore in the right illustration is called A pore, and in the 3-dimensional system the pore situated between 8 pcs of A pores is called B pore. It can be calculated that for an infinitely expanded cube, the quantity of A pores is equal to the quantity of B pores. In case of two pore sizes, the upper limit of gas generation volume per unit aluminum powder is 0.729 m³/m³. The set volume of gas generation in AAC (dry density of 300 kg/m³) is 0.713 m³/m³.

i_{2dBA} = 0.732
h_{2BA}/h_{2AA}= 0.866
A pore percentage V_{2A}% = 71.82%
B pore percentageV_{2B}% = 28.18%

Based on the calculations (the details can be obtained from the authors): compared with a single pore distribution, the structure with two pores allows the volume of gas generation to be increased by 39% times, so that the upper limit value of the maximum volume of gas generation can be increased from 0.524 m³/m³ to 0.729 m³/m³ to make low-density AAC products.

Three different pore diameters

Ratio of quantity of the three kinds of pores distribution, $X_{3A}:X_{3B}:X_{3C}$ = 1:1:3
Ratio of pore diameter of three kinds of pores distribution, $d_{3A}:d_{3B}:d_{3C}$ = 1:0.732:0.268
Ratio of pore volume of three kinds of pores distribution: i3VCA = 0.019, i3VCB = 0.0490
Volume percentage: V3A% = 68.97%, V3B% = 27.06%, V3B% = 3.97%

Based on the calculations (the details can be obtained from the authors): Compared with two kinds of pores distribution: due to the small diameter of d_C pore, the volume of C pore is only about 5% of

Table 3:
Dry density: 600 kg/m³, A pore diameter = 0.75 mm, diameter, wall thickness and pore volume of three kind of pores distribution

Pore distribution	d_A (mm)	d_B (mm)	d_c (mm)	h_{AA} (mm)	h_{BA} (mm)	h_{CB} (mm)	V_A%	V_B%	V_C%
Single pore	0.75			0.03			100		
Two pores	0.75	0.55		0.12	0.10		71.82	28.18	
Three pores	0.75	0.55	0.20	0.13	0.11	0.07	68.97	27.06	3.97

that of A pore, and consequently, the gas generation volume will not increase significantly. The upper limit of the maximum volume of gas generation will only increase from 0.73 m³/m³ to 0.76 m³/m³.

Table 3 shows that the wall thickness under the distribution structure of three kinds of pores does not increase as obvious as is the case with increasing from one to two pore diameters. Although h_{3AA} and h3BA are slightly bigger than h_{2AA} and h_{2BA}, h_{3CB} is small. In any case, the wall thickness of low-density AAC is originally small, so that the distribution structure of three kinds of pores still plays a role in increasing the wall thickness.

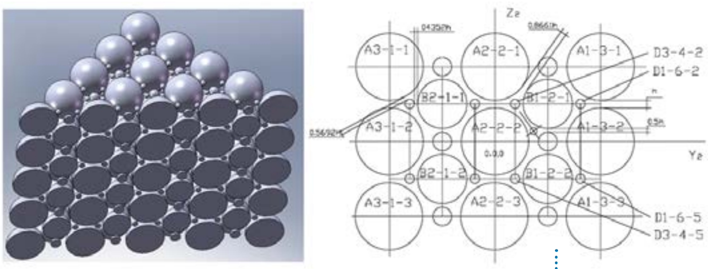


Fig. 8: The supposed distribution structure of pores with four different diameters

Four different pore diameters

Ratio of number of pores of four pores distribution, X4A:X4B:X4C:X4D = 1:1:3:12
Ratio of pore diameter of four pores distribution, d4A:d4B:d4C:d4D = 1:0.732:0.268:0.138
Wall thickness ratio of four kinds of pores distribution: i4VDA = 0.0026, i4VDB = 0.0067, i4VBA = 0.3924, i4VCA = 0.0192, i4VCB = 0.0490
Volume percentage: V4A% = 67.49%, V4B% = 26.48%, V4C% = 3.89%, V4D% = 2.14%
Wall thickness ratio of four kinds of pores distribution: $h_{4BA} / h_{4AA} = 0.866$, $h_{4DA} / h_{4AA} = 0.569$, $h_{4CB} / h_{4AA} = 0.500$, $h_{4DB} / h_{4AA} = 0.435$

Table 4 shows the upper limits of gas generation for the various pore size distributions.

Based on the calculations (the details can be obtained from the authors): for four kinds of pore diameters, the volume total gas generation for pore D is only about 2.14%. Consequently, it does not play a significant role in increasing the wall thickness for producing high-density AAC, but it will be helpful for producing AAC with low dry density. The wall thickness of the four kinds of pores distribution is larger than that of the three pores distribution when the dry density of the AAC is 300 kg/m³ and the pore diameter is equal.
It is very difficult to form pores of very small diameter, even if the total gas generation volume will not increase too much. It is meaningless to study five kinds of pores distribution.

Table 4: Upper limit of gas generation for different pore distributions structure m³/m³

Pore distribution	Single kind of pores	Two kinds of pores	Three kinds of pores	Four kinds of pores
The upper limit of gas generation	0.524	0.729	0.759	0.776

Prof. Lu Jie is the Vice-MD of Keda Suremaker. He has edited five national standards for China's AAC industry, including: Code for design of AAC plant, the production standard of AAC panel, etc. He has also published many technical articles, eg. "analysis of heat consumption and energy-saving way of AAC products" and "hydration mechanism of CaO-SiO_2-H_2O and CaO-SiO_2-Al_2O_3-H_2O two systems in AAC and its influence on AAC performance". Through decades of effort, he has made outstanding contributions to the development of China's AAC industry.

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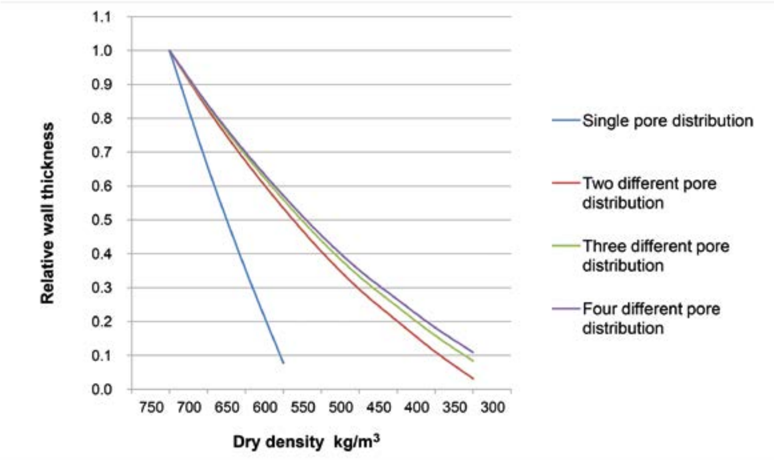

Fig. 9: Relative wall thickness in relation to dry density, based on the wall thickness of AAC with a dry density of 700 kg/m³ being set as 1

Suggestions of the pore structure distribution for producing AAC with different dry densities

When the wall thickness of AAC with a dry density of 700 kg/m³ is set as 1, the corresponding relative wall thickness curve of the other dry densities is shown in Fig. 9. The figure shows that as the dry density of AAC decreases, its wall thickness decreases accordingly, and its descending rate slows down in sequence according to the distribution of a single kind of pore, two kinds of pores, three kinds of pores and four kinds of pores. The curves of distribution structures of single kind of pore and two kinds of pores are obviously different.

For AAC with dry density of more than 600 kg/m³, there is no obivious difference in the distribution structures of two kinds of pores, three kinds of pores and four kinds of pores, so it is suggested to only adopt the distribution structure of two kinds of pores; for AAC with a dry density of 450 kg/m³ to 550 kg/m³, it is suggested to adopt three kinds of pores distribution structure. For AAC with a dry density of less than 400 kg/m³, the wall thickness is very small, and it is recommended to adopt four kinds of pores distribution structure. The detailed underlying calculations can be obtained from the authors.

In practical production, it is suggested to adopt the three kind of pores distribution if it turns out to be difficult to produce AAC with four kinds of pores distribution structure.

Closing remarks

The above proposals are only based on the ideal model calculation. The pore structure formation of the actual product is not only related to the matching between the equivalent particle size and gradation of aluminum powder particles and the required pore distribution, but also related to the consistency of the slurry, the fineness of the material particles, the height of a certain point in the mould, the ambient temperature of gas generation, the randomness of gas generation process, etc.

Therefore, the pores in the practical production will not be only a few kinds of pores arranged in a certain order. The proposed pore size distribution only provides the basis for controlling the pore size (including aluminum powder selection), which needs to be determined by the plant according to the practical production situation. Generally, for the two kinds of pores distribution, one kind of matching aluminum powder is required, while for the three or four kinds of pores distribution structure, two or even three kinds of aluminum powder should be combined according to the volume proportion of the pores. For high-density AAC, in order to reduce the production cost and production difficulty, two kinds of pores distribution can be adopted. For low- density AAC, three kinds of pores or four kinds of pores distribution structure can be adopted.

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