Study on Relationship between Pore Structure and Mechanical Properties of Concrete Using Municipal Solid Waste Incineration Bottom ash as Fine Aggregate

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Abstract. Municipal Solid waste incineration bottom ash (MSWI BA) is a silicon-calcium-aluminum oxide obtained by high-temperature calcining of municipal waste. Its appearance is similar to natural sand, and its chemical composition is similar to cement clinker. It can be used as concrete fine aggregate replace natural sand in a small amount. This paper tested the physical and chemical properties of MSWI BA, and obtained the compressive strength and microscopic pore structure parameters through experiments of 5 water-binder ratios, 3 sand replacement ratios, and 2 curing ages of municipal solid waste incineration MSWI BA concrete, and analyzed the relationship between pore structure and mechanical properties. The results show that the compressive strength of MSWI BA replacement sand concrete decreases with the increase of air content, bubble chord length and bubble spacing coefficient, and increases with the increase of bubble specific area. The fractal dimension of bubble distribution of MSWI BA replacement sand concrete is between 1.833~2.259, and that of ordinary concrete is between 2.138~2.495. The compressive strength increases with the increase of the fractal dimension of bubble distribution.

1. Introduction

With the continuous acceleration of China's urbanization process, the output of municipal Solid waste is also increasing year by year. According to the National Bureau of Statistics, PRC[1], In the five years from 2014 to 2018, the clearance volume of municipal Solid waste increased by an average annual rate of 6.3%, reaching 228 million tons in 2018. In order to deal with these wastes efficiently and safely, many areas in China have introduced waste incineration treatment technology. In the literature[2,3], the volume of domestic garbage literally reduces its volume by about 90% after incineration. Main solid products are municipal solid waste incineration fly ash (MSWIFA) and municipal solid waste incineration bottom ash (MSWI BA) . In the literature[4], MSWI BA containing heavy metals and other harmful substances, which have literally classified as HW18 in the National Hazardous Waste Directory. In the literature[5], the main treatment method of MSWI BA is landfill, which needs to occupy a certain amount of land and a small amount of heavy metal substances will leak out and cause harm to the environment. In the literature[6,7], The physical property of
MSWI BA is close to that of natural sand, and its chemical composition is similar to that of cement clinker. It can replace natural sand for concrete fine aggregate. According to the China Industry Information Network[8]. With the rapid development of China's construction industry, the demand for sand and gravel surges sharply. From 2009 to 2018, the demand for sand and gravel increases from 12 billion tons to 17.8 billion tons. In many regions, natural sand is in short supply and it is urgent to find alternatives. In view of the large accumulation of MSWI BA and the shortage of natural sand, this research group put forward the subject of using MSWI BA as fine aggregate for concrete. This paper analyzes the relationship between microstructure parameters of MSWI BA as sand and compressive strength through experiments, providing reference for the application of MSWI BA concrete.

2. Test overview

2.1. Materials
The MSWI BA was selected from a solid waste treatment factory in Hohhot, and the natural sand were come from Daheihe of Hohhot. Figure 1 (a) and Figure 1 (b) show the pictures of MSWI BA and natural sand under the laser confocal microscope. MSWI BA is gray, with irregular shape and multi-angular particles, and natural sand is usually gray yellow, round and full. Figure 1 (c) and Figure 1 (d) are the surface of MSWI BA and natural sand particles photographed by SEM. The MSWI BA surface is more prominent, with a large number of pore structures and loose texture, while the natural sand surface is relatively flat.

The chemical composition of MSWI BA are similar to Portland cement clinker, mainly composed of SiO$_2$, CaO, Al$_2$O$_3$, etc. The chemical composition of MSWI BA and cement are shown in Table 1. According to "Sand for Construction" (GB/T 14684-2011)[9], the aggregate characteristics of MSWI BA, natural sand and gravel were tested, and the test results were shown in Figure.2 and Table 2. As can be seen from the gradation curve in Figure.2, compared with the natural sand, the curve of MSWI BA is relatively gentle with no obvious abrupt change of slope and better gradation. According to the fineness, the MSWI BA and natural sand are II area of "Sand for Construction" (GB/T 14684-2011). According to the results of the crushing value, the natural sand is 21%, which is relatively strong, and the MSWI BA is 69%, with weak crushing resistance. In the literature[10], The MSWI BA moisture content and water absorption rate is both higher than the natural sand, which is determined by the porous nature of MSWI BA. The cement is PO 42.5 ordinary Portland cement, the coarse aggregate is first-grade macadam of Daqingshang in Hohhot, the silica fume is first-grade silica produced by a silicon material Limited liability company in Shijiazhuang; and the water-reducing agent is high-performance polycarboxylate water-reducing agent.
### Table 1. Chemical composition of MSWI BA and cement

| Materials       | Chemical composition (%) | SiO₂ | CaO | Al₂O₃ | Fe₂O₃ | Na₂O | MgO  | P₂O₅ | MnO |
|-----------------|--------------------------|------|-----|-------|-------|------|------|------|-----|
| MSWI BA         |                          | 48.26| 16.49| 8.89  | 4.60  | 3.94 | 2.71 | 2.17 | 0.085|
| Cement clinker  |                          | 23.44| 63.0 | 7.19  | 2.96  | —    | —    | —    | 1.00 |

### Figure 2. Grading curves of MSWI BA and sand

### Table 2. Test results of aggregate properties of materials

| Test project               | Materials | MSWI BA | Natural sand | Gravel |
|----------------------------|-----------|---------|--------------|--------|
| Apparent density (kg/m³)   |           | 2740    | 2450         | 2760   |
| Crush index value (%)      |           | 69      | 21           | 9.9    |
| Fineness modulus           |           | 2.36    | 2.64         | ---    |
| Water content (%)          |           | 11.0    | 2.0          | 0.3    |
| Water absorption (%)       |           | 10.4    | 1.5          | 0.6    |

### 2.2. Test Methods

60L uniaxial forced mixer was used to mix the concrete under laboratory conditions. The molded concrete specimens were placed for 24 hours and then demount, and then put into (20 ±2) °C water for curing to the specified age. After that, the compressive strength was tested in accordance with "Standard for Testing Methods for Mechanical Properties of Ordinary Concrete" (GB/T 50081-2016). Will be maintained to the stipulated age concrete specimens cut into 100 mm × 100 mm × 10 mm wafer, use silicon carbide of different meshes to grind and polish the surface. After cleaning the mark, thickly coat the melted petroleum jelly and zinc oxide on the surface of the black-coated and heated specimen and place it for 24 hours. After scrapping off the excess forest and zinc oxide. with the aid of Rapid Air 457 pore structure of hardened concrete surface tester using the color difference between hardened concrete pore structure and concrete, to cut the concrete pore structure on the surface of the automatic test and analysis, the characteristic parameters of stomatal structure of MSWI BA replacement sand concrete after hardening are obtained.
2.3. Mixture ratio

The test mainly studied the compressive strength of five ages: water-cement ratios (0.6, 0.5, 0.4, 0.3 and 0.2), three sand replacement ratios (0%, 50% and 100%), 28d and 90d curing age. The size of the specimen was 100 mm × 100 mm × 100 mms, and the specific mix ratio was shown in Table 3.

### Table 3. Mix ratio

| Water-binder ratio | Sand replacement rate | Water (kg/m³) | Water reducer (%) | Cement (kg/m³) | Silica fume (kg/m³) | Sand (kg/m³) | MSWI BA (kg/m³) | Gravel (kg/m³) |
|--------------------|-----------------------|---------------|-------------------|----------------|-------------------|-------------|----------------|---------------|
| 0.6                | 0%                    | 180.0         | 0.4               | 300.0          | 0                 | 742.7       | 0              | 1064.2        |
|                    | 50%                   | 180.0         | 0.8               | 300.0          | 0                 | 371.3       | 342.0          | 1064.2        |
|                    | 100%                  | 180.0         | 0.8               | 300.0          | 0                 | 0           | 684.0          | 1064.2        |
| 0.5                | 0%                    | 175.0         | 0.8               | 332.5          | 17.5              | 756.6       | 0              | 1040.7        |
|                    | 50%                   | 175.0         | 0.8               | 332.5          | 17.5              | 378.3       | 348.4          | 1040.7        |
|                    | 100%                  | 175.0         | 0.9               | 332.5          | 17.5              | 0           | 696.9          | 1040.7        |
| 0.4                | 0%                    | 170.0         | 0.8               | 382.5          | 42.5              | 777.2       | 0              | 985.6         |
|                    | 50%                   | 170.0         | 0.8               | 382.5          | 42.5              | 386.6       | 357.9          | 985.6         |
|                    | 100%                  | 170.0         | 1.3               | 382.5          | 42.5              | 0           | 715.8          | 985.6         |
| 0.3                | 0%                    | 170.0         | 1.0               | 481.7          | 85.0              | 776.9       | 0              | 873.3         |
|                    | 50%                   | 170.0         | 1.2               | 481.7          | 85.0              | 388.4       | 357.8          | 873.3         |
|                    | 100%                  | 170.0         | 1.7               | 481.7          | 85.0              | 0           | 715.5          | 873.3         |
| 0.2                | 0%                    | 165.0         | 1.6               | 701.3          | 123.8             | 699.8       | 0              | 726.1         |
|                    | 50%                   | 165.0         | 1.9               | 701.3          | 123.8             | 349.9       | 322.3          | 726.1         |
|                    | 100%                  | 165.0         | 1.0               | 701.3          | 123.8             | 0           | 644.5          | 726.1         |

3. Test results

3.1. Compressive strength

The test results of the compressive strength of the MSWI BA replacement sand concrete cube are shown in Table 4. The strength growth trend of MSWI BA replacement sand concrete is basically the same as that of ordinary concrete. Under the same curing, the compressive strength decreases with the increase of water-binder ratio, and decreases with the increase of sand replacement rate. Under the same water-binder ratio, the compressive strength decreases with the increase of sand replacement rate, and increases with the increase of age. On the whole, the strength value of 100% sand-replacement concrete is low under laboratory conditions, and does not have the conditions for large-scale direct use of concrete aggregates. In order to alleviate the large amount of useless accumulation of MSWI BA and the shortage of natural sand, it can replace sand as aggregate to a limited extent, or perform secondary treatment of MSWI BA, optimize MSWI BA treatment technology, etc.

### Table 4. Compressive strength of concrete cube

| Water-binder ratio | Sand replacement rate | Curing 28d (Mpa) | Curing 90d (Mpa) |
|--------------------|-----------------------|-------------------|------------------|
| 0.6                | 0%                    | 30.86             | 46.01            |
|                    | 50%                   | 24.17             | 29.04            |
|                    | 100%                  | 12.66             | 16.06            |
|                    | 0%                    | 45.31             | 53.94            |
| 0.5                | 50%                   | 28.09             | 31.56            |
|                    | 100%                  | 14.98             | 20.33            |
3.2. Characteristic parameters of microscopic pore structure

Table 5 shows the characteristic parameters of the microscopic pore structure of MSWI BA replacement sand concrete.

3.3. Correlation analysis between microstructure parameters and compressive strength

The test results of compressive strength in Table 4 and the bubble parameters of hardened concrete in Table 5 were fitted linearly, and the fitting formula was shown in Table 6 ($a_y$ represents the air content of hardened concrete (%); $\alpha$ Represents specific surface area of bubble /mm$^{-1}$; $d$ represents the bubble chord length (mm); $L$ represents the bubble spacing coefficient (mm)). The compressive strength of the three kinds of sand-replacement ratios of MSWI BA replacement sand concrete is negatively related to its air content, bubble chord length and bubble spacing coefficient, that is three kinds of sand-replacement ratios of MSWI BA replacement sand concrete compressive strength decreases with the increase of its air content, bubble chord length and bubble spacing coefficient. The compressive strength of the three kinds of sand-replacement ratios of MSWI BA replacement sand concrete is positively related to the specific surface area of its bubbles, three kinds of sand-replacement ratios of MSWI BA replacement sand concrete compressive strength increases with the increase of specific surface area and the bubbles, MSWI BA replacement sand concrete compressive strength with the air change rate decreases with the increase of replacement of sand ratio.

### Table 5. Characteristic parameters of concrete micro-pore structure

| water-binder ratio | Sand replacement rate | Air content (%) | Specific bubble surface area (mm$^{-1}$) | Bubble spacing coefficient (mm) | Bubble chord length (mm) |
|--------------------|-----------------------|-----------------|----------------------------------------|-------------------------------|---------------------------|
|                    |                       | 28d 90d         | 28d 90d                                | 28d 90d                       | 28d 90d                   |
| 0.6                | 0%                    | 5.44 5.29       | 16.26 17.78                            | 0.348 0.197                   | 0.246 0.165               |
|                    | 50%                   | 9.76 8.37       | 21.61 19.86                            | 0.237 0.165                   | 0.182 0.145               |
|                    | 100%                  | 10.29 9.98      | 22.57 25.09                            | 0.196 0.158                   | 0.185 0.138               |
|                    | 0%                    | 5.01 4.45       | 19.59 20.27                            | 0.277 0.195                   | 0.222 0.155               |
| 0.5                | 50%                   | 8.42 7.06       | 22.00 23.30                            | 0.230 0.146                   | 0.177 0.113               |
|                    | 100%                  | 9.03 8.54       | 24.90 25.52                            | 0.173 0.122                   | 0.161 0.092               |
|                    | 0%                    | 4.49 4.10       | 20.06 20.98                            | 0.268 0.189                   | 0.204 0.093               |
| 0.4                | 50%                   | 6.26 6.98       | 26.42 23.56                            | 0.207 0.133                   | 0.153 0.084               |
|                    | 100%                  | 8.07 7.88       | 26.14 26.98                            | 0.129 0.113                   | 0.151 0.075               |
|                    | 0%                    | 9.76 3.73       | 25.89 27.78                            | 0.226 0.143                   | 0.155 0.053               |
| 0.3                | 50%                   | 4.58 4.47       | 32.98 33.24                            | 0.108 0.118                   | 0.134 0.043               |
|                    | 100%                  | 5.63 5.19       | 29.76 30.18                            | 0.116 0.101                   | 0.110 0.058               |
|                    | 0%                    | 3.89 3.47       | 35.95 37.64                            | 0.145 0.112                   | 0.123 0.039               |
| 0.2                | 50%                   | 4.42 4.03       | 36.33 37.20                            | 0.095 0.109                   | 0.111 0.040               |
|                    | 100%                  | 5.15 4.60       | 32.53 33.12                            | 0.104 0.087                   | 0.105 0.044               |
MSWI BA were 50% and 100% for sand concrete with the air change rate close and far less than 0% of MSWI BA replacement sand concrete (ordinary concrete); MSWI BA replacement sand concrete compressive strength with the increase of the specific surface area of bubbles, the chord length of bubbles and the change rate of bubble spacing coefficient.

Table 6. Fitting formula of compressive strength and pore structure parameters of MSWI BA replacement sand concrete

| Parameter                  | Sand replacement rate | Fitting formula | $R^2$ |
|----------------------------|-----------------------|-----------------|-------|
| Gas content                | 0                     | $fc=-14.84ay+118.12$ | 0.87  |
|                            | 50%                   | $fc=-4.87ay+68.97$  | 0.86  |
|                            | 100%                  | $fc=-4.43ay+58.66$  | 0.95  |
| Specific bubble surface area| 0                     | $fc=1.21\alpha+23.24$ | 0.86  |
|                            | 50%                   | $fc=1.53\alpha-4.78$ | 0.95  |
|                            | 100%                  | $fc=2.63\alpha-47.05$ | 0.96  |
| Bubble chord length        | 0                     | $fc=-130.87d+71.70$  | 0.74  |
|                            | 50%                   | $fc=-166.13d+57.21$  | 0.62  |
|                            | 100%                  | $fc=-172.45d+45.05$  | 0.69  |
| Bubble spacing coefficient | 0                     | $fc=-135.61L+81.13$  | 0.96  |
|                            | 50%                   | $fc=-169.54L+63.81$  | 0.90  |
|                            | 100%                  | $fc=-256.28L+59.04$  | 0.93  |

3.4. Fractal dimension of bubble distribution
This experiment uses fractal dimension to express the pore structure of MSWI BA replacement sand concrete to better analyze the mechanical properties of MSWI BA replacement sand concrete with different sand replacement ratios. In this test, based on the data characteristics of the hardened concrete pore structure tester, combined with the box dimension concept, the box dimension calculation method is used to calculate the fractal dimension of the bubble distribution of the MSWI BA replacement sand concrete. The calculation formula is shown in Eq.1. The calculation results of the fractal dimension of bubble distribution of MSWI BA replacement sand concrete are shown in Table 7, and the fitting formula is shown in Table 8.

$$\lg N_c = -D_b \lg d + C \quad (1)$$

- $d$ ——— Bubble diameter/mm,
- $N_c$ ——— Conversion number of bubbles with bubble diameter,
- $C$ ——— Constant,
- $D_b$ ——— Fractal dimension of bubble distribution.

Table 7. Fractal dimension of bubble distribution of sand concrete

| Curing age | Sand replacement rate | Water-binder ratio |
|------------|-----------------------|--------------------|
|            |                       | 0.6    | 0.5    | 0.4    | 0.3    | 0.2    |
| 28(d)      | 0                     | 2.138  | 2.264  | 2.364  | 2.402  | 2.477  |
|            | 50%                   | 2.064  | 2.100  | 2.213  | 2.259  | 2.369  |
|            | 100%                  | 1.833  | 1.926  | 2.044  | 2.170  | 2.248  |
| 90(d)      | 0                     | 2.314  | 2.374  | 2.427  | 2.437  | 2.495  |
|            | 50%                   | 2.131  | 2.205  | 2.222  | 2.341  | 2.390  |
|            | 100%                  | 2.002  | 2.042  | 2.078  | 2.258  | 2.259  |
It can be seen from Table 7 and Table 8 that the fractal dimension of bubble distribution of MSWI BA 0% sand replacement is between 2.138 and 2.495; the fractal dimension of MSWI BA 50% sand replacement concrete is between 2.064 and 2.390; The fractal dimension of bubble distribution of MSWI BA 100% sand replacement concrete is between 1.833–2.259. The compressive strength of MSWI BA replacement sand concrete increases with the increase of the fractal dimension of bubble distribution.

4. Conclusion
Compared with natural sand, the particle gradation curve of MSWI BA is gentler, and there is no obvious sudden change in the slope. The MSWI BA fineness modulus is 2.26, and the natural sand fineness modulus is 2.64. According to the results of crushing value, natural sand is 21%, which is relatively strong, and the MSWI BA is only 69%, and its crush resistance is weak. The moisture content of MSWI BA and the water absorption are higher than natural sand.

The compressive strength of MSWI BA replacement sand concrete is negatively correlated with air content, bubble chord length and bubble spacing coefficient, that is, the compressive strength decreases with the increase of air content, bubble chord length and bubble spacing coefficient. It is positively correlated with the specific surface area of the bubble, that is, the compressive strength increases with the increase of the specific area of the bubble.

The fractal dimension of bubble distribution of MSWI BA replacement sand concrete is between 1.833–2.259, and that of ordinary concrete is between 2.138–2.495. The compressive strength of MSWI BA replacement sand concrete changes with its bubble fractal dimension, which is consistent with that of ordinary concrete, and is positively correlated with its bubble distribution fractal dimension, that is, its compressive strength increases with the increase of its bubble distribution fractal dimension.

In addition, combined with this test and previous experimental research on MSWI BA replacement sand concrete in this area, it is believed that the compressive strength of MSWI BA replacement sand concrete is relatively low, in fact, it is not suitable that 100% MSWI BA were used as fine aggregate in concrete. The MSWI BA replacement rate should be controlled at 50%.

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