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Influence of Desert Sand and Cooling Regime on the Compressive Strength of High Strength Concrete after High Temperatures

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Abstract: An experimental investigation is conducted to analyze the influence of desert sand replacement ratio and cooling regime on the compressive strength of desert sand-based high strength concrete (DS-HSC). According to the design of experiment, six desert sand replacement ratios (0%, 20%, 40%, 60%, 80% and 100%) are employed to concrete mixture. DS-HSCs are subjected to two cooling regimes (air cooling and water cooling) and various temperatures (20℃, 400℃, 500℃, 600℃, 700℃ and 850℃, respectively) in this paper. The results indicate that the compressive strength of DS-HSC with air cooling is higher than that with water cooling. Moreover, the highest compressive strength appears with the desert sand replacement ratio of 20%. The compressive strength of DS-HSC gradually decreases with the increase of desert sand replacement ratio when the desert sand replacement ratio is more than 20%.

1. Introduction

Sand is a non-renewable resource and plays a significant role in building. The ordinary material of concrete has a huge demand every year in building domain, which leads to the excessive consumption of sand. It is important to find a new material to solve this problem. Plentiful desert sand place in China. If desert sand has a good workability in concrete, it will promote the development of local economy. Researchers have already performed some research on desert sand these years [1-5]. Dune sand from Tenggeli and Mu Us desert could be used as fine aggregate in concrete construction [6]. Properties of drying shrinkage cracking of concrete using dune sand and crushed sand were investigated [7]. It was found that the maximum value of compressive and tensile strength occurred when the dune sand replacement was 20%. Moreover, the compressive and tensile strength increased firstly and then decreased with increasing dune sand. The physical characteristics and mechanical performance test of concrete for pavement application containing Sahara dune sand were carried out [8]. It was found that the concrete for pavement application had a good workability with a mix of 60% dune sand and 40% crushed sand. The relationship of dune sand replacement ratio on mechanical properties of concrete was also surveyed [5, 9, 10]. These above indicate desert sand has a potential to be used in building domain.

Recent years, the requirement of high-rise building is huge due to the rapid development of economy. High strength concrete is widely used in building domain according to its characteristic of high durability, stiffness and strength. Meanwhile, the trend of high-rise building fire gradually grows with increasing the high-density population and quantity of high-rise building. Fires frequently cause the damage of building structure and threaten the safety of people. The pictures of high-rise building fire are displayed in figure 1. Some researcher have already focused on this status and performed some work. The mechanical properties of fiber high-strength concrete exposed to high temperature were performed [11-12]. The different grades of high-strength concrete and normal concrete were researched on their compressive strength, splitting tensile strength and flexural strength [13]. High-strength concrete exposed to high temperature lost its mechanical strength in a manner similar to that of normal concrete [14]. Moreover, some works were conducted to other properties of high-strength concrete. The influence of eccentric loading on mechanical property of high-strength concrete column, tube and bar was investigated [15-16]. It was found that eccentric loading significantly affected the axial stress-strain behavior of FRP-confined high-strength concrete. Some researchers concerned the effect of experimental condition on compressive properties of high-strength concrete. Curing method and curing time had a close relationship with mechanical property of high-strength concrete [17-18]. It was found that the compressive strength of high-strength concrete increased with increasing curing temperature and curing time. The cooling regime had a significant effect on mechanical properties of high-strength concrete [19]. It was illustrated that water cooling caused only a bit more deterioration in compressive strength than that of furnace cooling.

In this paper, the compressive strength of DS-HSC exposed to different high temperatures is investigated. The influence of desert sand replacement ratio and cooling regime on the compressive strength of DS-HSC exposed to high temperature is analyzed. In addition, the optimal value of desert sand replacement ratio is found.

Figure 1. High-rise building fire

2 Experimental methods

2.1. Materials

In this paper, the raw materials, used to produce DS-HSC element, contained: cement, fly ash, stone, mountain sand and desert sand. The 42.5R grade of Ordinary Portland cement, provided by Saima cement plant, was used in DS-HSC element. The stone was purchased from local stone plant as coarse aggregate. The maximum value of stone was 25mm. The apparent density, bulk density, void content and mud content of coarse aggregate were 2698kg/m^3, 1430kg/m^3, 47% and 0.78%, respectively. Desert sand from Mu Us desert and local mountain sand were employed as fine aggregate. The apparent density, bulk density and mud content of desert sand were 2624kg/m^3, 1400kg/m^3 and 0.14%, respectively, while those of mountain sand were 2636kg/m^3, 1570kg/m^3 and 0.6%, respectively. The fineness modulus of desert sand and mountain sand were 0.194 and 2.59, respectively, so desert sand was super-fine sand in accordance with Chinese National Standard JGJ52-2006[20]. The appearance of desert sand from Mu Us desert is displayed in figure 2. The fly ash of class I provided by local power plant was used to make elements and the ignition loss ratio was 2.8%. In this work, the water used was local running water. Polycarboxylate superplasticizer in power was used and the ratio of reducing water ranged from 25% to 30%. Moreover, the dosage of Na_2SO_4 was below 3%.

Figure 2. Appearance of desert sand from Mu Us desert

2.2. Mix proportion and element preparation

Mix proportion has a significant influence on workability of concrete in test. In this paper, the water-cement ratio and sand ratio were 0.28 and 0.35, respectively. Six desert sand replacement ratios (0%, 20%, 40%, 60%, 80% and 100%) were employed to make DS-HSC elements of grade C60. Moreover, the 10% content of fly ash was placed in all concrete elements. The mix proportion of DS-HSC is shown in Table 1. The name meaning of every group is expressed in Table 2.

According to GB/T50081-2002[21], raw materials of DS-HSC were successively placed into the agitator mixing different time, coarse aggregate and fine aggregate mixing 1min, Ordinary Portland cement and fly ash mixing 0.5min, water mixed with superplasticizer mixing 2min. After the mixing process, concrete mixture was put into molds and then vibrated 2min on the vibrator in order to shape and discharge bubbles of elements. In total, 216 cubic elements (100mm×100mm×100mm) were made in this paper. All elements were removed to the curing room (18~22℃, humidity of 95% above) maintaining 28 days after elements demolded.

Table 1. Mix proportion of DS-HSC.

Materials	Mass (kg/m^3)
Cement	643
Fine aggregate	553
Coarse aggregate	1024
Water	180

Table 2. The name meaning of every group.

Group	Content description
C1	0% desert sand and 10% fly ash
C2	20% desert sand and 10% fly ash
C3	40% desert sand and 10% fly ash
C4	60% desert sand and 10% fly ash
C5	80% desert sand and 10% fly ash
C6	100% desert sand and 10% fly ash

2.3. Testing

In order to research the mechanical property of DS-HSC on fire, DS-HSC at the age of 28 days was exposed to different high temperatures(20℃, 400℃, 500℃, 600℃, 700℃ and 850℃). The heating process was conducted with a muffle furnace (10℃/min) and maintained DS-HSC element in target temperature for 1h to keep thermal stability of element. The specific heating process of DS-HSC is shown in figure 3. After the heating process, DS-HSC element was subjected to two cooling regime (air cooling, water cooling). In particular, DS-HSC element with water cooling were put into water(20℃) for 0.5h before placing room for 1 day. Finally, all DS-HSC elements were conducted to the compressive test until damage according to Chinese National Standard GB50081-2002[21]. The loading rate was 0.8~1.0MPa/s. The pictures of heating furnace and compressive machine are shown in figure 4.

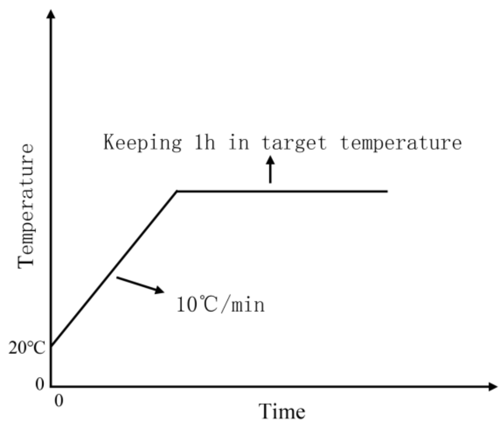

Figure 3. Curve of DS-HSC exposed to heating temperature

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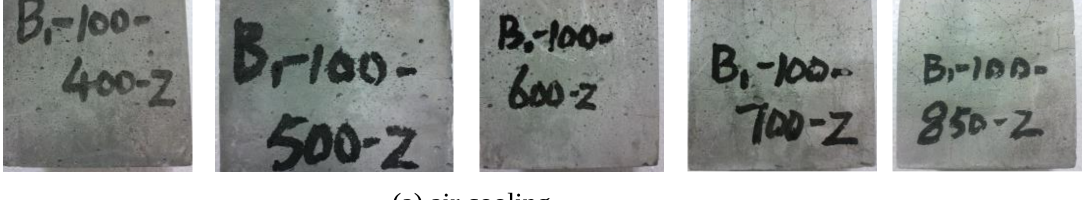
Figure 4. Muffle furnace and compressive machine.

3. Results and discussions

3.1. Physical characteristic

3.1.1. Appearance. DS-HSCs exposed to different high temperatures are subjected to air cooling and water cooling, respectively. The apparent characteristics of DS-HSC C6 exposed to high temperature with two cooling regimes are shown in figure 5. For DS-HSC with air cooling and water cooling, micro-cracks appear for DS-HSC element exposed to 400℃. Crack widens and increases its quantity with increasing temperature. The effect of temperature and cooling regime causes the difference of DS-HSC elements in colors. The colors of DS-HSC exposed to 400℃, 500℃, 600℃, 700℃ and 850℃ with air cooling are dark grey, bluish grey, grey with yellow little, off-white with yellow little and off-white, respectively, while these with water cooling are dark grey, bluish grey, off-grey, grey with yellow little and off-white, respectively.

DS-HSC element exposed to 850℃ with water cooling arises the phenomenon of scaling while it does not arise for DS-HSC element with air cooling. It may be attributed to the scouring effect of stream. DS-HSC element exposed to 600℃ above arises the spalling. This phenomenon can be explained as follow: DS-HSC element has a great compaction and produces evaporating pressure for DS-HSC element exposed to high temperature. The evaporating pressure of DS-HSC element does not have an efficient way to discharge due to the great compaction of DS-HSC element. Therefore, the evaporating pressure of DS-HSC element increases with increasing temperature until spalling.



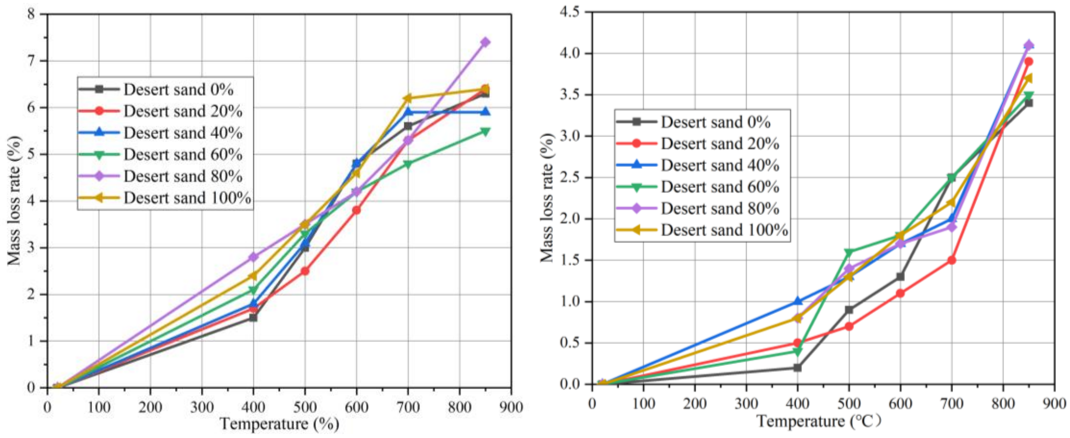
(a) air cooling

(b) water cooling

Figure 5. Apparent characteristics of DS-HSC C6 exposed to high temperature with two cooling regime.

3.1.2. Mass loss rate. All cubic elements were weighed before burning and after removing from furnace for placing 24h. The ratio of the difference in mass of DS-HSC before and after high temperature to the mass of DS-HSC before high temperature is defined as mass loss rate. The relationship between temperature and mass loss rate of DS-HSC is displayed in figure 6. The mass losses of DS-HSC are different levels under different temperatures and cooling regimes. As shown in figure 6, the mass loss rates of DS-HSCs with air cooling and water cooling gradually increase with increasing temperature. For instance, the mass loss rates of DS-HSC C2 exposed to 400℃, 500℃, 600℃, 700℃ and 850℃ with air cooling are 1.7%, 2.5%, 3.8%, 5.3%, 6.4%, respectively, while these with water cooling are 0.5%, 0.7%, 1.1%, 1.5%, 3.9%, respectively. This phenomenon is due to the evaporation of water and decomposition of C-S-H and $Ca(OH)_2$[22].

The relationship between desert sand replacement ratio and mass loss rate of DS-HSC exposed to 700℃ is shown in figure 7. It can be found from figure 7 that the mass loss rate of DS-HSC with air cooling is higher than that with water cooling. This can be explained as follow: Water comes into DS-HSC when DS-HSC exposed to high temperature performs water cooling. Therefore, the DS-HSC can continue to hydration.



(a) air cooling (b) water cooling

Figure 6. Relationship of temperature and mass loss rate of DS-HSC

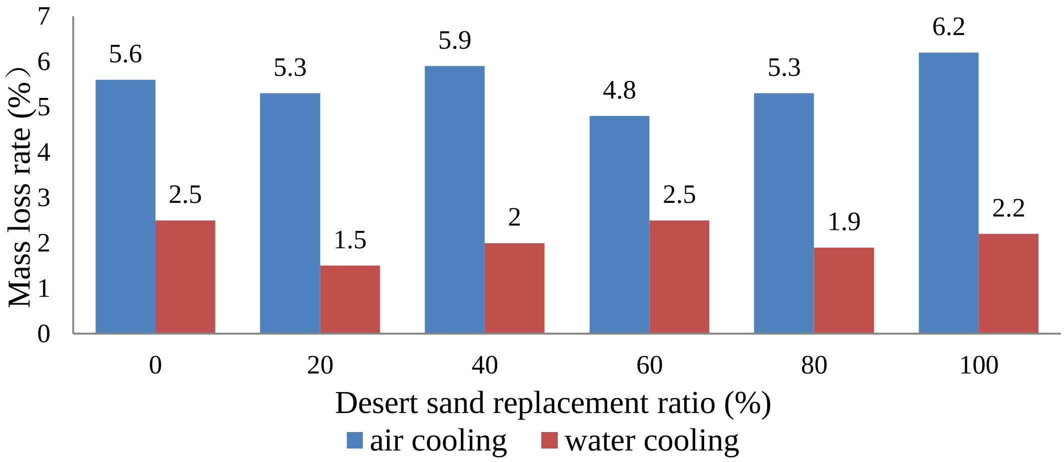
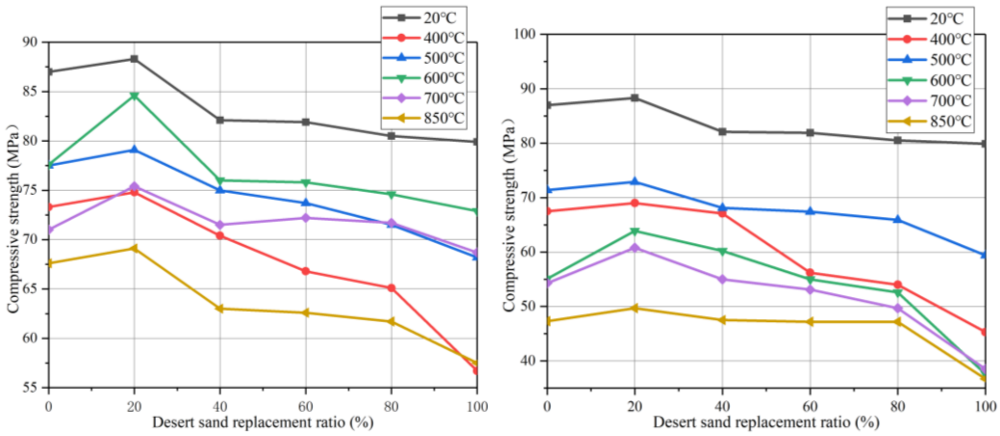


Figure 7. Relationship between desert sand replacement ratio and mass loss rate of DS-HSC exposed to 700℃.

3.2. Compressive strength

3.2.1. Desert sand replacement ratio. The relationship between desert sand replacement ratio and compressive strength of DS-HSC exposed to high temperature is shown in figure 8. As displayed in figure 8, no matter which cooling regime is employed, the compressive strength of DS-HSC increases with the desert sand replacement ratio to be the maximum value at 20% and gradually decreases after the desert sand replacement ratio is over 20%. This phenomenon can be explained as follow. Due to the characteristic of small particle for desert sand, desert sand improves the gradation of fine aggregate and then enhances the cohesive force between cementitious material and fine aggregate. Therefore, the compressive strength of DS-HSC increases with increasing the desert sand replacement ratio. At the same time, the strength of desert sand is lower than that of mountain sand. In the second region, as the desert sand replacement ratio increases, the effect of desert sand on cohesive force is smaller than effect of strength of desert sand on compressive strength of DS-HSC. Therefore, the compressive strength of DS-HSC decreases with increasing the desert sand replacement ratio.



(a) air cooling (b) water cooling

Figure 8. Relationship of desert sand replacement ratio and strength exposed to high temperature

3.2.2. Cooling regime. The influence of cooling regime on the compressive strength of DS-HSC is measured in every desert sand replacement ratio and high temperature. Experimental results of DS-HSC with desert sand replacement ratio of 20% are taken for an example, which is plotted in figure 9. It is clearly displayed in figure 9 that the influence of cooling regime on compressive strength is significant for the DS-HSC exposed to high temperature. The compressive strength of DS-HSC exposed to high temperature with air cooling is higher than that with water cooling. This phenomenon can be explained as follow. The DS-HSC element with air cooling slowly finishes the process of thermal release. At the same time, DS-HSC element produces drastic thermal shock in the rapid process of water cooling, so the internal DS-HSC element with water cooling produces some residual stresses which increase cracks [23-24]. Therefore, the damage of DS-HSC element with water cooling is higher than that with air cooling.

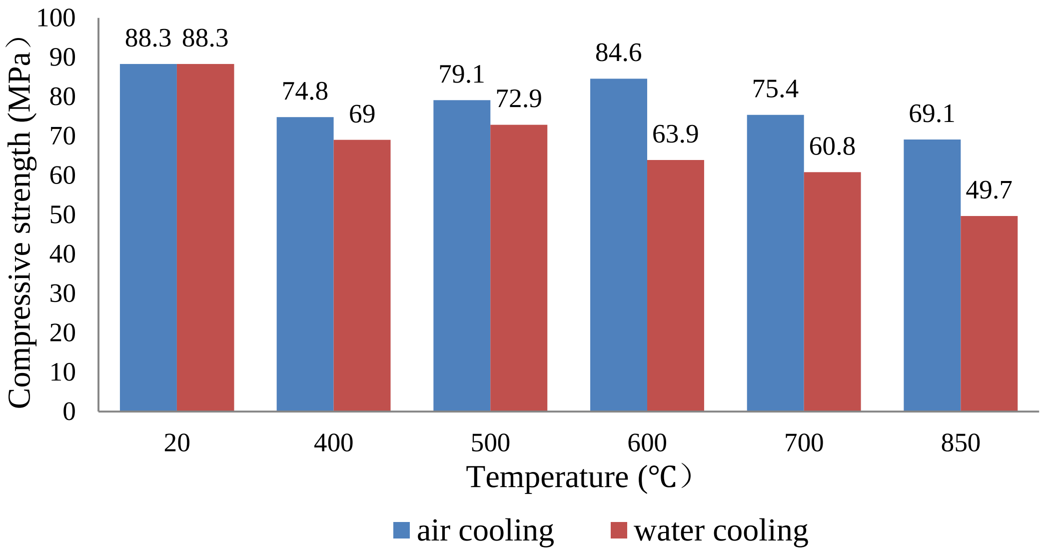


Figure 9. The influence of cooling regime on the compressive strength of DS-HSC with desert sand replacement ratio of 20%

4. Conclusions

This paper made 216 cubic DS-HSC elements (100mm×100mm×100mm) totally and carried out an experiment to investigate the influence of desert sand replacement ratio and cooling regime on the compressive strength of DS-HSC exposed to high temperature. According to experimental results, these conclusions can be found: When DS-HSC is exposed to high temperature, the compressive strength of DS-HSC increases with the desert sand replacement ratio to be the maximum value at 20% and gradually decreases after the desert sand replacement ratio is over 20%. Moreover, the compressive strength of DS-HSC exposed to high temperature with air cooling is higher than that with water cooling.

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