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Research Status and Development Trend of 3D Printing Recycled Concrete

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Abstract: As a new construction technology, 3D printing concrete has the advantages of mechanization and model-free. Waste brick is an important part of construction waste. Its disposal not only consumes land but also pollutes the environment. At the same time, cement is the main raw material in concrete materials. Cement production consumes resources, produces greenhouse gases and is not environmentally friendly. Therefore, grinding brick waste into recycled brick powder and replacing cement to produce 3D-printed concrete is considered a feasible method. This paper reviews the effects of recycled brick powder on hydration, workability, mechanical properties and durability of 3D-printed concrete, analyzes its mechanism, and points out some problems to be further studied at present.

Keywords: 3D printed concrete; Recycled powder; Mechanical properties.

1. Introduction

With the continuous advancement of the urbanization process, the acceleration of the industrialization process and the continuous improvement of people's living standards, the construction waste generated by various cities in China has been increasing, accounting for 30%-50% of the total urban waste [1]. It is estimated that the annual urban output of construction waste in China is about 600 million tons. In addition, in the past 100 years, a large number of masonry structures were constructed in our country, resulting in the waste brick accounting for more than 30% of the construction waste. Its recycling and utilization is an important aspect to make the construction industry realize sustainable development, build a circular economy and build a conservation-oriented society.

Producing one ton of cement releases about 222 kilograms of carbon dioxide. Excessive carbon emissions can lead to climate change and global warming. In addition, 3D printed concrete buildings have the advantages of high mechanization, personalization and model-free [2,3,4,5,6,7]. Therefore, converting waste brick into recycled powder instead of cement and using it in the preparation of 3D printed concrete can bring both environmental and economic benefits [8].

In order to systematically analyze the application of recycled brick powder (RBP) in 3D printing, based on the latest research results, this paper summarizes the impact of RBP as a cement substitute on the performance of 3D printed concrete, in order to provide reference for the future development of recycled brick powder in 3D printed concrete。

2. The Basic Properties of Recycled Brick Powder

2.1. Physical properties

RBP is a kind of powder with small particle size, loose texture and certain congenital adhesion and plasticity, and the surface of brick powder particles is rough and irregular [9]. Its specific surface area is 450-608m2/kg, its bulk density is 1817-1860kg/m3, and its optimal water content is 17%[10,11,12]. Figure 1 shows the preparation process of RBP, which mainly includes recovery, crushing, crushing and screening [13]. In addition, by changing the grinding time of the ball mill, RBP of different fineness can be obtained [14].

2.2. Chemical and mineral composition

The chemical components of RBP are mainly SiO_2, Al_2O_3 and Fe_2O_3, etc. [3] It can be seen that the total amount of active components SiO_2, Al_2O_3 and Fe_2O_3 exceeds 70%, which meets the requirements of ASTM C618 on the content of main chemical components of volcanic ash materials [17]. Therefore, RBP can be considered as a pozzolanic material used as a substitute for cement [18,19,20]. In addition, particle size has an important effect on the activity of recycled brick powder. The finer the particles, the larger the specific surface area, and the more favorable the volcanic ash reaction [21,22]. Brick powder has irregular shape and angular porous surface, and its particles are in an amorphous state. From the perspective of the phase structure of brick powder [23], its crystals show an indefinite form, have an active basis, and contain a large number of ultrafine particles, which can play a good filling effect. Studies show [24,25] that with the increase of grinding time, RBP tends to be refined and spherical, which is conducive to the increase of RBP pozzolanic activity and specific surface area. In addition, the dried brick slag has a better grinding efficiency than the undried brick slag. The reason is that the dry brick slag is pulverized to form the brick powder, which is harder than the brick powder that is not dried, and can be used as the grinding body to play a role in the subsequent grinding and improve the grinding efficiency. Studies show that [26,27], fine grinding brick powder is superimposed by volume grinding model and surface grinding model. In the early stage, the main performance is volume crushing with high crushing efficiency. In the later stage, the main performance is surface grinding, and the grinding efficiency is greatly reduced. In addition [28], too long grinding time will lead to RBP agglomeration and increase energy consumption, so the grinding time is not easy to be too long. Due to comprehensive consideration, the appropriate time should be selected.

3. Performance of Freshly Mixed 3D Printed Concrete Containing RBP

3.1. Water requirement of normal consistency

Water consumption is the most important factor affecting the workability of 3D printed concrete. RBP has the characteristics of high water absorption, which will reduce the working performance of 3D printed concrete. The irregular shape and rough surface of RBP [29] will seriously affect the water consumption of the standard consistency of RBP. With the increase of the amount of RBP, the water consumption of the standard consistency of recycled concrete will increase. The relative water demand increases in direct proportion to the RBP replacement rate. RBP's irregular microstructure and high specific surface area result in increased water requirements. Under the same RBP replacement condition, the increase of RBP fineness will lead to the decrease of the water requirement of the mixture. After deep grinding [30], the initial pores of the RBP particles are destroyed, and their microstructure becomes regular rather than angular, providing obvious lubrication effect and offsetting the increase in water requirement caused by the increase in specific surface area. The microstructure of RBP is improved and the workability of RBP mixture is improved with the increase of fineness.

3.2. Mobility

Hou et al. [31] conducted an experimental analysis on the change rule of 3DPM fluidity with RP added over time. The results show that the liquidity loss rate of 3DPM added to RP is larger in the first 60 min, and the longer the time, the greater the liquidity loss. And with the increase of RP replacement rate, liquidity loss will also increase. The reason is that the chemical reaction between RBP and cement hydration product $Ca(OH)_2$ requires more water to complete the reaction, resulting in increased water demand and poor fluidity [32,33]. In addition, the fluidity of concrete is also related to RBP fineness. The smaller the RBP particle size, the more significant the slump reduction of the mixture [34,35,36].

3 Effect of recycled brick powder on hydration reaction of 3D printed concrete

The hydration process of cement slurry shows that with the increase of RBP content, its peak temperature decreases, indicating that RBP has a delayed effect on the hydration reaction of cement [37], and the content of $Ca(OH)_2$ also decreases, indicating that the pozzolash effect of RBP consumes $Ca(OH)_2$ in the later stage of hydration. In addition, fineness has an important effect on hydration reaction. The finer particles in the RP disperse the cement particles, increasing the contact area between the cement particles and the water, and increasing the hydration rate.

The hydration of cement is an exothermic process. The change of hydration heat with time can be analyzed. Duan et al. [38] found that C_3A of cement clinker made a great contribution to the high hydration rate of cement in the early stage. At the same time, the trace elements in RP promote the hydration of C_3A and increase its hydration rate. Sulfate content has an important effect on the hydration of C_3A, C3A reacts with CaS04 to produce ettringite. The lower the SO_3 content in RP, it will lead to rapid hydration of C_3A and water, and the hydration heat will increase. In addition, higher base content also has a positive effect on the reactivity of C3A, which can promote the reaction of C_3A with sulfate. The reactivity of RP is lower than that of cement, which is caused by the lower CaO content.

4. Effect of Recycled Brick Powder on Mechanical Properties of 3D Printed Concrete

4.1. Compressive strength

Ge et al. [39] studied the long-term performance of concrete, and the results showed that the long-term performance (400 days) of concrete mixed with 10% or 20%RBP as a substitute for clinker was better, even better than ordinary Portland cement without RBP. Schackow et al. [40] found that compared with the control group, the 28-day and 90-day compressive strength of mortar with RBP of 40% increased by 130% and 82%, respectively, and the compressive strength was inversely proportional to the apparent porosity. This indicates that the pozzolanic reaction [41] and micro-aggregate filling effect of RBP promote the development of compressive strength of mixed mortar when the content of RBP is appropriate. SiO2 and Al2O3 with higher activity in RBP reacted with CH after 28 days, and correspondingly produced more C-A-H and C-A-S-H gels. In addition, the small RBP also fills the pores, and the two work together to form a dense microstructure and improve the compressive strength.

4.2. Flexural and tensile strength

Studies have shown that excess RBP can significantly reduce the bending and tensile strength of 3D printed concrete. Xue et al. found that the 28-day flexural strength decreased linearly with the increase of RBP replacement rate. Zheng 's study showed that the 28-day bending strength of concrete with different RBP content (10%, 20%, 30%) was similar to that of the control concrete, and similar conclusions were also reached about the tensile strength of concrete with RBP content. Naceri et al. showed that the bending strength of mortar mixed with 5% and 10% RBP at 90 days was higher than that of the control group. However, with the increasing of RBP dosage, the bending strength of mortar will gradually decrease. That is, the addition of appropriate RBP has no significant effect on the tensile and bending strength of 3D printed concrete .

5. Effect of Recycled Brick Powder on Durability of 3D Printed Concrete

5.1. Carbonization resistance

Carbonization resistance is one of the important indicators of durability of 3D printed concrete. Gao et al. found that the carbonization depth increased with the increase of RBP substitution rate, and the carbonization resistance decreased. The addition of RBP has a great influence on the carbonization after 7 days, and the carbonization depth increases by 8.4%, 20% and 46.6%, respectively, when 10%, 20% and 30% RBP are added. When the curing period is increased to 28 days, the carbonization depth of RBP with addition of 10%, 20% and 30% increases by 36.81%, 59.72% and 72.22%, respectively.

The carbonization effect is affected by the permeability of CO_2 gas and the content of $Ca(OH)_2$ and C-S-H. On the one hand, the finer particles of RBP have a filling effect on the mortar, making the structure of the mortar more dense and slowing down the penetration of CO_2. This is beneficial to the carbonization resistance of mortar. The lower the CaO content, the lower the RBP activity, the lower the hydration products $Ca(OH)_2$ and C-S-H. In addition, the secondary hydration of RBP reduces the content of $Ca(OH)_2$, which reacts with CO_2 to form $CaCO_3$. As a result, less CO_2 gas is consumed and more CO_2 gas will penetrate deep into the recovered mortar sample. On the other hand, lower $CaCO_3$ content is produced, resulting in relatively loose tissues, resulting in increased carbonization depth.

6. Conclusion and Prospect

(1) RBP contains a large number of chemical components such as SiO_2 and Al_2O_3, and its micro-aggregate and volcanic ash effect can significantly improve the microstructure of 3D printed concrete, which has the potential to be used as an auxiliary cementing material.

(2) Due to the porosity and high water absorption of recycled micro-powder, it will significantly affect the working performance of 3D printed concrete, increasing the consistency and water demand.

(3) The hydration process of cement slurry shows that the peak temperature decreases with the increase of RBP content, indicating that RBP has a delayed effect on the hydration reaction of cement.

(4) Adding an appropriate amount of RBP is conducive to improving the mechanical properties of 3D printed concrete. Studies have shown that 3D printed concrete mixed with 10% to 20%RBP has better long-term (400 days) performance, even better than ordinary Portland cement without the addition of RBP.

(5) Incorporation of RBP can increase the carbonization depth.

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