Minireview Article

Research Progress of Geopolymer Recycled Concrete

Abstract: Geopolymer concrete has the outstanding characteristics of low carbon emissions and low energy consumption while utilizing industrial solid waste, and is expected to replace cement as a new generation of green building materials. Moreover, with the continuous increase in the amount of concrete, the environmental damage and resource depletion caused by the mining of sand and gravel aggregates have become increasingly serious. It is imminent to seek substitutes for natural sand and gravel aggregates. Combining green and environmentally friendly geopolymer concrete with recyclable recycled concrete technology is expected to reduce the negative impact of recycled aggregates. This paper summarizes and analyzes the relevant research results, comprehensively discusses the mechanical properties of geopolymer concrete and recycled concrete from the aspects of alkali activator, curing method, curing age, and raw materials, finally the research status of mechanical properties of geopolymer concrete mixed with recycled aggregate is summarized.

Key words: Geopolymer concrete；Recycled aggregate；Mechanical properties；

introduction

In order to minimize the consumption of natural resources and energy and reduce carbon emissions, the impact of the structure on the environment is minimized in the whole life cycle. In this paper, cement consumption is reduced by using a lower carbon emission cementitious material instead of cement. Because the main raw materials of geopolymers are industrial wastes such as fly ash and slag, the production process consumes less energy, CO_2 emissions are small, and the mechanical properties, high-temperature resistance and acid and alkali corrosion resistance are excellent[1,2]，it is considered It is the cement substitute with the most development potential in the 21st century [3]。

Geopolymer is a new type of high-performance inorganic polymer, which produces less waste in the production process, and its CO_2 emission is 80%~90% lower than Portland cement[4]，Moreover, the firing of cement clinker requires a high temperature of 1400°C, but the raw materials of geopolymers can be obtained directly or processed at a lower temperature (350-750°C), and its production energy consumption is about 1/6-1/4 of that of cement [1]，Compared with ordinary portland cement concrete, the carbon emission in the preparation process of geopolymer concrete is reduced by 26%~45%[5]。At the same time, geopolymer raw materials are widely available and the price is low. Due to the development of industrialization in my country, the treatment of mine tailings and fly ash has become more and more severe. Using this as raw material to prepare geopolymers can not only reduce the amount of cement, but also has a beneficial effect on waste reuse and environmental protection.

With the continuous increase of the amount of concrete, the environmental damage and resource depletion caused by the mining of sand and gravel aggregates have become increasingly serious. Therefore, from the perspective of sustainable development and resource development and utilization, it is imminent to seek substitutes for natural sand and gravel aggregates. Concrete is the most widely used man-made construction material in the world, and once a building or structure disintegrates, it will accordingly become part of construction waste. The amount of construction waste in my country has accounted for

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30%-40% of the total amount of urban waste, while the overall recycling rate of construction waste in my country is less than 10%, and the treatment methods are still in the stage of extensive landfill and stacking. The disintegrated concrete is crushed and screened into coarse aggregate and fine aggregate to replace part of natural aggregate to prepare mixed recycled aggregate concrete（RAC）, which can save natural mineral resources and reduce the environmental pollution caused by solid waste.

Combining green and environmentally friendly geopolymer concrete（GPC）with recyclable recycled aggregate technology. That is, the use of industrial by-products such as mineral powder and construction waste can combine the advantages of RAC and GPC to make up for their respective shortcomings. In addition to simply superimposing the two technologies, the research on geopolymer recycled concrete (GRAC) is expected to achieve a role in transforming negative effects into positive effects [6]. Since a large amount of alkaline mortar from old buildings will be attached to the surface of the recycled aggregate, these alkaline mortars used in ordinary concrete will produce a double transition interface and greatly reduce the performance of the concrete. However, if this type of mortar is used in GPC, although it will still result in a double transition section, the alkaline components of the old mortar will also have an alkali-activated effect on the geopolymer raw materials. Therefore, unfavorable factors may be transformed into advantages, thus achieving the effect of killing multiple birds with one stone.

At present, the existing research mainly focuses on the raw material composition, preparation technology, reaction mechanism and microscopic mechanism of mineral formation of geopolymers, and a relatively complete research system has been formed. However, less research has been done on GPC. Due to the wide range of sources of geopolymer materials and the large differences in mineral components in different regions, a lot of research work is still needed to implement large-scale promotion and application nationwide. To use concrete in building structures, the study of its mechanical properties is essential. Therefore, in order to promote the use of GRAC in structural engineering, this paper comprehensively and deeply summarizes the influence of GPC and the addition of recycled aggregate on its performance.

1、Research progress on mechanical properties of GPC

The raw materials of GPC include ground blast furnace slag, fly ash, metakaolin and industrial waste powder rich in activated aluminosilicate minerals, among which slag and fly ash are the most commonly used [7]. With the decrease of the average particle size, the specific surface area of fly ash with good particle size distribution increases, the reaction speed of alkali excitation accelerates, and the accumulated voids can be filled with fine particles, the microstructure is denser, and the strength of GPC prepared is higher[8]. The critical value of positive influence of slag on compressive strength of GPC is 30%[9]. Slag is a highly active raw material, and the early strength and compactness of GPC can be significantly improved by mixing slag with silicon-rich aluminum raw materials such as fly ash or volcanic ash [10]. Even if it is the same raw material, there will be great differences due to different sources. At present, the research status mainly focuses on the differences of raw materials, activators, ages and curing conditions, which leads to significant differences in mechanical properties of GPC.

The alkali content in the activator will significantly affect the compressive strength of GPC. Fang et al.[11] studied the influence of NaOH concentration on the strength of slag-based polymer concrete, and found that the critical concentration of stimulating effect was 12 mol; Soutsos et al.[12] believes that too high alkali concentration reduces the free water molecules in the alkali activator, affects the dissolution rate or degree of SiO_2 and Al_2O_3 in raw materials, and then affects the strength of concrete. Usually, when sodium hydroxide is used to adjust the modulus of water glass to 1-2, the excitation effect is the best. Water glass provides soluble silicate ions for the formation of gel, making the microstructure denser and conducive to the improvement of strength [7].

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The preparation of geopolymer concrete needs to choose the appropriate curing system according to the different raw materials. For raw materials with high activity (such as slag), high temperature curing is not suitable. High temperature curing is often needed to improve the early strength of fly ash-based GPC, mainly because of the high activation energy of fly ash, which can provide the energy needed for the reaction and accelerate the hydration reaction [13]. The compressive strength of fly ash-based GPC is also sensitive to temperature. Under the curing condition of 60°C, the early compressive strength increases rapidly, and it can reach a higher strength after curing for 24 h, but it increases slowly after 48 h, but too high temperature will cause volume expansion, so the curing temperature below 70°C is the most suitable [14]. Wen Tian [15] studied the influence of different curing methods on the mechanical properties of fly ash-slag-based geopolymer concrete, and found that increasing humidity before 7 d is beneficial to improve the development speed of specimen strength, and too high humidity after 7~28 d will hinder the continued hydration of geopolymer concrete, which is not conducive to its later strength development; High temperature curing will significantly improve the early strength; In addition, high temperature curing will increase the brittleness of geopolymer concrete.

The strength of GPC with different raw materials has different laws with the development of age.Huang Hua [16] By investigating the compressive strength of geopolymer concrete with different mix proportions at different ages, it can be found that reducing the modulus of sodium silicate and increasing the proportion of slag can promote the polymerization reaction and improve the mechanical properties and microstructure compactness of geopolymer concrete. Mao [17] studied the fly ash-based GPC, and found that the geopolymer concrete can reach the design strength in 3 days under the high temperature curing of 50℃ and 80℃. However, under standard curing, the strength within 7 days has been lower than the design strength.

The degradation law of high temperature compressive strength of GPC varies with its chemical composition, but the overall degradation law is basically the same as that of ordinary concrete. Zhang H Y [18] used potassium sodium silicate to excite the mixture of metakaolin and fly ash to prepare geopolymer concrete. The mechanical properties of GPC were tested with different water-binder ratio, sand ratio and bone-binder ratio as variables. The results showed that with the increase of temperature, the compressive strength and splitting tensile strength of GPC gradually decreased, especially at 300~500℃. Compared with ordinary concrete, GPC has better high temperature resistance.Zhu S Q [19] The damage law of GPC after high temperature is studied. It is found that with the increase of temperature, the compressive strength of the specimen generally decreases, and 600℃ is the inflection point of the curve change. Before 600℃, the compressive strength changes gently and the loss rate does not exceed 20%. However, when the temperature exceeds 600℃, the loss rate rises sharply, and at 1000℃, the loss rate of compressive strength reaches 85%.Yan Jia’s [20] research found that the compressive strength and splitting tensile strength of GPC basically do not decrease when the temperature is less than 300 °C, and when the temperature is 500 °C, the compressive strength and splitting tensile strength of GPC decrease respectively. 20% and 55% of that at normal temperature. At 700°C, the compressive strength drops significantly, about 56% of normal temperature, and the loss of splitting tensile strength is even more serious, about 36% of normal temperature. Compared with the compressive strength, the tensile strength of geopolymer concrete decreases more obviously after high temperature, and the degradation rate is faster, because the crack connection and the porosity of the concrete have more influence on the split tensile strength than the compressive strength [18].

2、Research progress on mechanical properties of RAC

It is found that the water-cement ratio and the replacement rate of recycled aggregate have great

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influence on the mechanical properties of RAC. With the increase of water-cement ratio, the compressive strength of RAC tends to decrease obviously [21]. Because recycled aggregate has high water absorption, large porosity and residual waste mortar, the performance of RAC is weaker than that of natural aggregate concrete [22]. Bai et al.[23] research shows that if the strength of recycled concrete is equal to that of ordinary concrete, the water-cement ratio of recycled concrete should be 5%~10% smaller than that of ordinary concrete. The replacement rate of recycled aggregate also has a significant impact on the mechanical properties of recycled concrete. Most scholars [21,24-28] have conducted systematic research and showed that the mechanical properties of RAC weaken with the increase of the replacement rate of recycled aggregate.

To sum up, the water-cement ratio and recycled aggregate replacement rate have great influence on the mechanical properties of recycled concrete, and the mechanical properties of RAC weaken with the increase of water-cement ratio and recycled aggregate replacement rate.

Zega[29] test found that the residual compressive strength of recycled concrete after high temperature was slightly lower than that of natural aggregate concrete, and only under the condition of low water cement ratio, the residual compressive strength was higher than that of ordinary concrete after exposure at 500℃ for 1 hour. Salah[30] found that when the replacement rate of recycled aggregate is more than 50% and the temperature is higher than 250℃, the residual mechanical properties of RAC are higher than that of ordinary concrete. This is because with the increase of substitution rate, the amount of residual mortar and broken limestone attached to recycled aggregate increases, which leads to a better match of thermal expansion performance between aggregate and cement slurry. Kou[31] concluded that the relative residual compressive strength of concrete containing RA is higher than that of concrete prepared with natural aggregate, because the expansion coefficient of the interface between old and new mortar is similar, and its compatibility reduces the micro/macro cracks of cement mortar. Vieira[32] concluded that the residual compressive strength of RAC is not significantly different from that of ordinary concrete.

3、Research progress on mechanical properties of GRAC

Due to the weak characteristics of recycled aggregate, its utilization rate is low, but the combination of geopolymer and recycled aggregate can not only be more environmentally friendly and save resources, but also have better durability and mechanical properties than ordinary concrete. At present, the slump, setting time, compressive strength, elastic modulus, Poisson's ratio, toughness and failure mode of geopolymer recycled concrete have been studied experimentally. Currently, the main influencing factors are raw materials, activator, replacement rate of recycled aggregate, curing temperature and curing time.

Effect of alkali activator on mechanical properties of GRAC. Ding Z Y [33] studied the mechanical properties of GRAC with different water glass modulus, and obtained that the compressive strength of GRAC was inversely proportional to the water glass modulus. The decrease of water glass modulus will lead to the increase of the diffusion layer of electric double layer structure in concrete, which will stimulate more Ca^{2+}, Si^{4+} and Al^{3+} in raw materials, and improve the strength of geopolymer. At high modulus, the diffusion layer of water glass is small, the content of free Na+ and OH- is low, the dissolved Ca^{2+}, Si^{4+} and Al^{3+} in mineral raw materials are less, and the content of hydration products formed by polycondensation is low, which leads to the cementation between particles. Nuaklong[34] studied the influence of NaOH with different content on the compressive strength and density of GRAC, and found that NaOH concentration slightly increased the density of GRAC. When NaOH concentration was 8M, 12M and 16 M, the compressive strength of GRAC was 30.6 MPa, 38.4 MPa and 34.8Mpa, respectively. The splitting tensile strength and flexural strength had the same law as the compressive strength. The optimum concentration of alkali activator was 12M, and low concentration led to weak chemical reaction and low compressive

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strength. The increase of alkali concentration promotes the strength development of geopolymer, but excessive hydroxide ion concentration leads to the precipitation of early aluminosilicate products, so the strength of GRAC decreases.

Effect of curing temperature on mechanical properties of GRAC. Ding Z Y [35] found that with the increase of curing temperature, the compressive strength of GRAC increased first and then decreased. This is because more water glass can be solidified at a proper temperature, and the formed network skeleton is more complete, which improves the early strength of GRAC. However, too high temperature (80℃ and 100℃) will make the water in the system turn into gas, form a large number of holes, and reduce the strength of the whole test block. Moreover, too high temperature will also inhibit the polymerization reaction of silicon and aluminum substances in the system, which seriously reduces the later strength of geopolymer cementitious materials. It is found that the best curing system of GRAC is 60℃.

Effect of curing time on mechanical properties of GRAC。Ding Z Y 's [35] test results show that the maximum strength appears when the curing time is 4 hours, and the strength will gradually decrease if the curing time is prolonged. This is attributed to the fact that with the extension of curing time, in the initial stage of the reaction, there are constantly siloxane tetragonal monomers and aluminum-oxygen tetrahedron in the gelation system, and polycondensation occurs after the concentration is saturated. The longer the curing time, the more polycondensation reactions occur, and the higher the early strength. However, if the curing time is too long, the active silicon and aluminum substances in the system will be overdrawn, which will reduce the amount of free silicon-oxygen tetragonal monomers and aluminum-oxygen tetragonal monomers which can undergo polycondensation in the later stage, thus reducing the later strength.

Effect of replacement rate of recycled aggregate on mechanical properties of GRAC. Long Tao[36] research shows that the compressive strength of GRAC is obviously higher than that of RAC at all ages. Compared with the substitution rate of 0%, the compressive strength of 50% and 100% decreased by 16% and 36% respectively. Shi's [37] experimental results show that the compressive strength of GRAC with different recycled aggregate content is significantly higher than that of RAC. With the increase of recycled aggregate, the compressive strength of RAC and GRAC decreases, but the replacement rate of RA has a greater influence on the compressive strength of GRAC. Shi[37] analyzed the microscopic properties of GRAC, and found that with the increase of recycled aggregate in concrete, the microstructure became looser, and there were more pores and cracks. GRAC is denser, more uniform and has higher strength. It is because fly ash particles can be well embedded in the pores of concrete, and the function as pore filler improves the strength of GRAC.

4、Conclusion

1. GPC has a denser microstructure than ordinary concrete, which leads to its better performance than ordinary concrete.
2. The poor performance of RAC is attributed to the mortar attached to recycled aggregate, which leads to lower density, higher water absorption and weaker strength.
3. The combination of GPC and recycled aggregate is not only more economical and environmentally friendly, but also can reduce the negative impact of recycled aggregate and achieve the effect of complementary advantages.
4. Due to the lack of standards and application specifications, and the standard system for durability testing and evaluation of GPC, its utilization rate is low.
5. Because there are many raw materials for GPC, and for the same kind of raw materials, different sources will also lead to differences in GPC. Due to the complexity of composition, the general mix design method

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of geopolymer concrete has not been fully established, which is a difficult point in our application.

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