## The Influence of Biomass Power Plant Ash on the Mechanical Properties of Recycled Aggregate Concrete: A Review

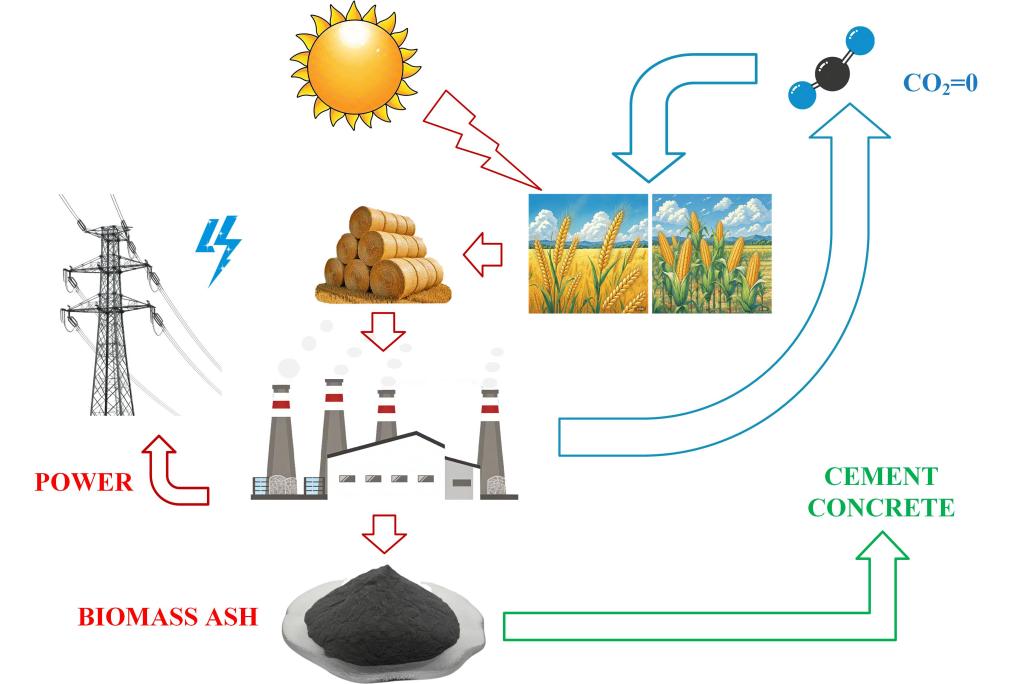
Abstract:

With the increasing installed capacity of biomass power generation in China and the evolution of urbanization, the disposal of biomass power plant ash and construction waste, mainly concrete, has become extremely urgent. Through biomineralization, biomass power plant ash theoretically contains highly active volcanic ash active substances such as silica, which has the potential to be developed as a new type of auxiliary cementitious material for cement concrete. However, the preparation conditions of biomass power plant ash differ greatly from the optimal preparation conditions in the laboratory, and the physical and chemical properties of biomass power plant ash are not stable. Therefore, it is challenging to apply biomass power plant ash as an auxiliary cementitious material in concrete systems. Secondly, the building materials industry has high energy consumption and carbon emissions. The use of recycled aggregates and auxiliary cementitious materials to replace cement is a key measure to address global climate change. This article provides comments on the physical and chemical properties of biomass ash and its impact on the mechanical properties of concrete, the mechanical properties of recycled aggregate concrete, and the influence of auxiliary cementitious materials on the mechanical properties of recycled aggregate concrete. The aim is to inspire research on the mechanical properties of biomass power plant ash recycled aggregate concrete.

## Keywords: Biomass Power Plant Ash; Recycled Aggregate Concrete; Mechanical Properties; Supplementary Cementitious Materials (SCMs).

## 1 Introduction

In the past decade, China's total straw production has stabilized at 800 million tons per year, of which about 84% of the total amount of straw can be collected, and the total amount of straw that can be used for large-scale industrial production is about 700 million[1]. In traditional agricultural production, open burning has long been the main method of straw disposal, resulting in serious air[2]. In addition, the treatment methods commonly used at present also have mechanized returning to the field, returning to the field over the abdomen, being used as the base material for cultivating edible fungi, making biogas, etc., but the absorption capacity of these methods is very limited, and it is difficult to adapt to the requirements of the development of industrialized society. In fact, agricultural wastes such as straw are a kind of biomass fuels with stable output, and the use of crop straw to generate electricity is one of the main ways of biomass energy power generation. After nearly 20 years of development, China's installed biomass power generation capacity has increased year by year, and a relatively complete equipment manufacturing capacity and collection, storage and transportation service system has been[3]. However, a large amount of biomass power plant ash produced by generator sets is often disposed of as landfill, which not only causes a waste of land resources, but also poses a risk of environmental[4]. At present, the treatment of ash (slag) of biomass power plants has become a new problem that disturbs the development, and it is extremely urgent to find corresponding solid waste absorption methods.



**Fig. 1 Scheme of the energy recovery of biomass and the material recovery of biomass**

**power plant ashes in cement/concrete[5]**

In China, more than 2 billion of concrete waste is generated annually due to demolitions, and the direct landfill of waste concrete occupies a considerable area of land and also poses potential environmental hazards [6]. In May 2020, the Ministry of Housing and Urban-Rural Development issued the "Guiding Opinions on Promoting the Reduction of Construction Waste" and the "Guidance Manual for the Reduction of Construction Waste at the Construction Site (Trial)" as important documents to guide the source reduction of construction waste at present and in the future, and vigorously promote the recycling of construction waste to "turn waste into treasure". At the end of 2018, eight departments, including the Shanghai Municipal Housing and Urban-Rural Development Management Commission, jointly issued the "Shanghai Construction Waste Concrete Recycling Management Measures" (hereinafter referred to as the "Measures"), which came into force on January 1, 2019, and established China's first mandatory use system for recycled bone (powder). However, recycled aggregate concrete still requires the use of a large amount of cement as a cementitious material. On 22 September 2020, President Xi announced that China would strive to peak carbon dioxide emissions before 2030 and strive for 2060 achieve carbon neutrality [7, 8]. The carbon dioxide content produced by the production of cement accounts for about 5%~7% of the total greenhouse gases every year[9], so the emission reduction of carbon dioxide in the cement industry has become the focus. In order to meet the huge demand for cement in the construction industry, it is necessary to optimize the cement production process to reduce carbon emissions and energy consumption, and on the other hand, it is necessary to strengthen the research of cement alternative materials such as supplementary cementitious materials (SCMs) or alkali activated materials. In fact, the ash of biomass power plants with straw as the main fuel is theoretically rich in amorphous SiO2, and through biomineralization, thin amorphous SiO2 such as opal SiO2·nH2O in the soil is enriched in biological structures such as straw and chaff [10], and biomass power plant ash has the potential to be developed as a new type of cement-concrete high-activity auxiliary cementitious material. As shown in Fig.1, the biomass power plant directly burns a huge amount of agricultural and forestry wastes such as straw and chaff to generate electricity, realizing the resource utilization of controllable environmental pollution risks.

At present, the basic and application research of biomass power plant ash as a new type of cement concrete auxiliary cementitious material is still in its infancy in general, and the research mostly focuses on the influence of biomass ash on the performance of mortar or ordinary concrete, and the relevant research on the mixing of biomass power plant ash into the recycled aggregate concrete system is less, and the existing conclusions are difficult to apply to the recycled aggregate concrete of biomass power plant ash. As a kind of porous calcined biomass solid waste, biomass power plant ash and recycled aggregate are both absorbent, and the coupling effect of the two in terms of working performance, mechanical properties, and microstructure is not clear, and related research needs to be carried out urgently.

2 Properties of biomass ash materials and their influence on the mechanical properties of concrete

Biomass ash is a solid residue produced in the process of biomass energy utilization (such as combustion and gasification), and its sources include agricultural wastes (rice husks, straw), forestry residues (sawdust, bark), energy crops (switchgrass, miscanthus grass) and organic wastes (food processing residues), etc., and its volcanic ash activity is manifested in the ability to react with calcium hydroxide to form hydrated calcium silicate (C-S-H) gel at room temperature, making it have the ability to replace traditional volcanic ashpotential of materials such as fly ash[11]. The main components of this activity are silicon, calcium, potassium, magnesium, and phosphorus oxides, among which the SiO2 content of rice husk ash is as high as 80%~90%, while the wood ash is mainly CaO and K2O, and contains trace heavy metals (Pb, Cd, Cu) and alkali metals (Na, K)[12]. High temperature treatment (> 800℃) promotes the formation of silicate glass[13], and the melting properties are negatively correlated with alkali metal[14]. For example, Rajamma et al.[15] studied two biomass ashes (F1 and F2) with SiO2+Al2O3+Fe2O3 of 52.9% and 36.4%, respectively, and CaO content of 11.4% and 25.4%, respectively, which still met the EN 450 Class C fly ash standard. Wang et al. [16] pointed out through SEM-EDS analysis that the biomass ash particles were irregular in shape but could continuously form C-S-H gels. Cordeiro et al. [17] found that the Chapelle activity of sugarcane ash (SCBA) reached 421 mg/g (28% higher than the minimum limit of volcanic ash material) after calcination at 600℃, and the volcanic ash activity index (PAI) increased first and then decreased due to the change of SiO2 crystallinity.

In order to improve the activity of volcanic ash, pretreatment methods such as screening, grinding and chemical excitation are widely used. Ahmad J et al. [18] sieved wheat straw ash at 75 μm to achieve 69.94% SiO2+Al2O3+Fe2O3, which met the standard of Class F fly ash. Rößler et al. [19] and Cordeiro et al. [20] showed that rice husk ash (RHA) grinding had an optimal time to balance the specific surface area (SSA) with compressive strength, and that too long (e.g., 240 minutes) would reduce SSA. Qudoos et al. [21-23] proposed that the morphology of wheat straw ash particles could be homogenized≥60 min by ball milling. de Lima et al. [24] removed contaminants such as K2O and CaO and increased the amorphous SiO2 content by soaking and finely grinding corn straw ash with citric acid. Wang et al. [25] confirmed the addition of 5% Na2SO4 or CaCl2·H2O can improve the performance of switchgrass ash-cement systems.

The content of biomass ash significantly affects the performance of cement concrete. Rajamma et al. [26] found that the water requirement spiked when the biomass ash (BFA) content was > 20%. Liu et al. [27] pointed out that the increase of rice husk ash (RHA) content would reduce the fluidity of mortar, but Liu Li [28] showed that RHA could improve concrete workability and prepare C40 self-compacting concrete with a larger water-cement ratio (W/B≥0.5). In terms of mechanical properties, Li et al. [29] found that 4% corn straw ash (CSA) could maintain the early strength of fly ash/cement systems. Agwa et al. [30] and Aksoğan et al. [31] confirmed that the content of 5%~10% straw ash (RSA) or straw ash could increase the strength, while the high content (20%~30%) led to the decrease of strength. Amin et al.[32] found that the increase in wheat straw ash (WSA) content reduced the compressive strength of mortar and concrete, but the strength activity index still met the ASTM-C618 standard. Bheel et al. [33] and Nagrockiene et al. [34] showed that the compressive strength could be optimized by 5%~10%, and the compressive strength was increased by 17.8% at 7d with 5% content. Martinez-Lage I et al. [35] further pointed out that 10% biomass ash content can make the 7d strength of concrete reach 92% of the 28d strength, which is better than the 87% of the benchmark concrete.

In summary, the pozzolana activity of biomass ash is affected by the characteristics of raw materials, pretreatment process and dosage, and the working and mechanical properties of concrete can be effectively balanced by optimizing the calcination temperature (such as 600℃), mechanical grinding (controlling SSA) and chemical excitation (Na2SO4/CaCl2), and controlling the dosage (5%~15%).

3 Characteristics of recycled aggregate concrete and its effect on mechanical properties

Recycled aggregate (RA) is an aggregate formed from the recycling of construction and demolition waste, and its physical properties (such as density, water absorption, porosity, particle morphology and gradation, etc.) directly affect the properties of building materials such as concrete. The apparent density of recycled aggregates is usually lower than that of natural aggregates, mainly due to the significant increase in porosity due to the adhesion of old mortar, and the uneven pore distribution weakens the compressive strength of recycled concrete [36]. Due to the significant differences in the capillary structure of the old mortar, the water absorption rate of recycled coarse aggregate reached 3%~10% in 24 hours [36]. In order to improve the above defects, different researchers have proposed different preparation and modification methods. Zhang et al. [37] successfully balanced the workability and strength of recycled concrete by measuring the water absorption of waste concrete aggregate in 10 minutes to optimize the pre-water absorption. Tam et al. [38, 39] developed a two-stage mixing method (TSMA) to improve performance by adding water in steps to preferentially wrap the aggregate with low water-cement over the slurry. Etxeberria et al. [40] pointed out that the recycled coarse aggregate needs to be moistened with water before use due to its high water absorption, so as to avoid the reduction of the effective water-cement ratio due to its absorption of slurry water, but emphasized that the wetting should not reach a saturated state, otherwise it may lead to the failure of the effective interface transition zone between the saturated recycled coarse aggregate and the new cement slurry. Poon[41] found that the water content of natural and recycled aggregates significantly affected the slump and compressive strength of concrete by comparing the three aqueous states of air-drying (AD), drying (OD) and saturated surface drying (SSD), among which the initial slump was directly related to the free water content, and the slump loss was closely related to the aqueous state of the aggregate, especially when the replacement rate of recycled aggregate reached 100%, the slump loss in the AD or OD state was particularly significant. Fathifazl et al. [42] then proposed the same amount mortar method, by precisely regulating the volume ratio of recycled coarse aggregate and natural mortar, so that the total volume of new and old mortar in recycled aggregate concrete is kept equal to the volume of ordinary concrete mortar, so as to obtain recycled aggregate concrete with similar performance to natural aggregate concrete; Gayarre et al. [43] further discussed the influence of curing conditions, and found that the 28-day compressive strength of recycled aggregate concrete under standard curing conditions is basically the same as that of natural aggregate concrete, but the compressive strength loss can reach 20% under open-air curing conditions, revealing the key role of curing environment on the performance stability of recycled concrete. Li et al. [44] found that the carbonization of recycled coarse aggregate could significantly improve the mechanical properties of recycled concrete, and the microhardness of the interface transition zone (ITZ) and the old mortar of the cement mortar after carbonization was higher than that of the benchmark group, which increased the compressive strength of the recycled aggregate concrete by 34%, and the higher the water-glue ratio, the more significant the increase in compressive strength. Wang et al. [45] compared the carbonization and slurry wrapping modification methods, and found that the strengthening effect of carbonization on the old ITZ was significantly better than that of the new ITZ, while the mud wrapping had a limited effect on the new and old ITZ, which confirmed that the carbonization treatment had more advantages in improving the mechanical properties of recycled concrete. For the recycled aggregate combination method, Bui et al. [46] innovatively adopted the particle size layered substitution strategy, using natural aggregate at the particle size of 7.93, 6.73, and 5.60 mm above, and using recycled aggregate below to prepare concrete with 70%, 50%, and 30% substitution rates, breaking through the traditional 30% substitution rate limit, and achieving a significant improvement in mechanical properties under 50% recycled aggregate content. Wang et al. [47] treated the recycled aggregate mortar layer with crystallizer (CA), which effectively enhanced the aggregate-mortar adhesion, increased the density of concrete and the content of hydrated calcium silicate (C-S-H), and strengthened the performance of new and old ITZ, so as to comprehensively improve the mechanical indexes of recycled concrete. Kazmi S M S et al. [48] systematically compared five modification methods, including carbonation, acetic acid immersion and its composite process, and found that the split tensile strength and flexural resistance of the treated recycled aggregate concrete strength increases linearly, and the stress-strain curve of the recycled aggregate concrete of acetic acid impregnation + mechanical friction and lime impregnation + carbonation treatment is the closest to that of natural aggregate concrete, which proves that a specific composite process can effectively improve the mechanical properties of recycled concrete.

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Rahal [49] studied the mechanical properties of recycled coarse aggregate concrete (RAC) at 1, 3, 7, 14, 28 and 56 days of age, and found that the 28-day cubic compressive strength, cylindrical compressive strength, and indirect shear strength were 90% of those of natural aggregate concrete (NAC), while the elastic modulus was only 3% lower, and the strength development trend was consistent with NAC. Padmini AK et al. [50] pointed out that the water absorption rate of recycled aggregate increases with the increase of the strength of the parent concrete, but decreases with the increase of the maximum particle size, and a lower water-cement ratio and higher cement content are required to match the design strength, and its splitting tensile strength, flexural resistance and elastic modulus are lower than those of the parent concrete. Kou and Poon [51] prepared RAC from 30~100 MPa matrix concrete, and found that the compressive strength of RAC prepared from 80~100 MPa matrix was equal to or slightly better than NAC, which could completely replace natural aggregates. Xiao et al. [52] showed that the increase in the substitution rate of recycled coarse aggregate led to a decrease in the compressive strength, ductility and elastic modulus of RAC by up to 45%, but the prismatic/cubic strength ratio was higher than that of ordinary concrete. Silva et al. [53] found that the tensile strength of RAC decreased with the increase of substitution rate, but it could be improved by saturated surface drying or superplasticizer, and the tensile strength of RAC at one age could be equal to or exceed NAC. Casuccio et al. [54] revealed that the RAC stiffness was low, and the fracture energy, fracture zone size, and crack branching were significantly reduced. Mi et al. [55] proposed that the slump, strength and carbonization depth of the mortar could be optimized by adjusting the compressive strength ratio of the old and new mortars, and the inhomogeneity of the mortar could be reduced. Wang et al. [56] pointed out that the shear strength of RAC decreases with the increase of substitution rate, but increases with the increase of external compressive stress ratio, and the failure mode is affected by the substitution rate, compressive stress ratio and reinforcement ratio. Tang et al. [57] found that recycled aggregate and powder made the descending part of the stress-strain curve steeper or smoother, respectively, and the whole recycled coarse/fine segment elastic modulus of aggregate and powder concrete was reduced by 24%, 27% and 33%, respectively, compared with NAC. Kou et al. [58] have shown that the 5-year compressive strength of RAC (55.4 MPa) is close to NAC (58.9 MPa), and the strength increases by more than 60%, and the splitting tensile strength exceeds that of NAC. Geng et al. [59] found that the service time (1, 18, 40 years) of the parent concrete significantly affected the RAC strength, and the RAC strength prepared by the parent was reduced by 34% compared with NAC after 40 years of service at 100% substitution. The numerical simulations of Jayasuriya et al. [60] showed that the compressive strength and elastic modulus of RAC were reduced with the increase of adherent mortar content, and the stiffness of aggregate and mortar matrix was the main controlling factor for strength, and the old ITZ had a significant impact on the performance. In summary, the mechanical properties of RAC are regulated by multiple factors such as substitution rate, parent characteristics, aggregate treatment and age, and its mechanical properties can be improved by optimizing the mix ratio, aggregate strengthening and long-term curing.

4 Effect of auxiliary cementitious materials on the mechanical properties of recycled aggregate concrete

Dimitriou et al. [61] compared five groups of recycled aggregate concrete (RAC) tests (NA, 100% RAC, 50% RAC, 100% RAC + 25% fly ash (FA), 100% RAC + 25% FA + 5% silica fume (SF)), and found that the addition of FA and SF could reduce the amount of cement and the mechanical properties were similar to or even better than those of ordinary concrete. Qureshi et al. [62] further explored the effects of four auxiliary cementitious materials (SF, GGBS, FA, and rice husk ash (RHA)) when replacing ordinary cement with 10%~30%, and found that the compressive strength increase of 15% RHA and 10% SF (7~19%) was better than that of 20% FA and 30% GGBS, but the latter two increased the 90-day elastic modulus of RAC by 16%; Guo et al. [63] demonstrated that the recycled aggregate self-compacting concrete could significantly compensate for the defects of recycled aggregate and improve the mechanical properties by designing binary (FA), ternary (FA+GGBS) and quaternary (FA+GGBS+SF) composite admixtures. Wang et al. [64] found that the substitution of ground slag, red mud and glass powder for cement could increase the compressive strength of fully recycled coarse aggregate concrete by about 15%. However, Song et al. [65] pointed out that when waste glass powder (WGP) replaces cement, the compressive and splitting tensile strength of RAC continues to decrease with the increase of substitution rate, but the growth rate of 28 and 90 days of age shows an inverse trend. Fatiha et al. [66] compared the substitution effects of 20% natural volcanic ash (NP), 10% limestone powder (LP), 20% GGBFS, and 10% SF, and found that only GGBFS and SF increased strength by 9% and 28%, respectively, while LP reduced strength by only 3%. Dilbas et al. [67] confirmed that the 5% SF content can effectively improve the low compressive strength of RAC. Liu et al. [68] found that the synergistic effect of 30% RHA and fully recycled aggregate can meet the engineering needs while reducing costs and carbon emissions through a combination test of 0%~30% RHA and 0%~100% recycled coarse aggregate. In terms of long-term performance, Kou et al. [69] showed that the compressive strength and elastic modulus of RAC with 25%~55% FA instead of cement were still lower than those of the control group after 10 years. Kim et al. [70] pointed out that the 30% recycled aggregate content only slightly reduced the compressive strength, while FA improved the fluidity, but the negative effect of recycled aggregate and FA on tensile strength was more significant. In addition, Weng et al. [71] showed that the inclusion of fly ash (FA), slag powder (GGBS) and metakaolin (MK) could prolong the setting time of high-performance concrete (HPC), but the compressive strength could be improved by adjusting the ratio of FA to GGBS/MK, and the composite incorporation of FA+GGBS or FA+MK could inhibit drying shrinkage and self-shrinkage more than that of FA alone, and the shrinkage rate decreased with the increase of content due to the refinement of the microstructure of SCM.

5 Conclusion

Through the discussion in this article, there has been sufficient research on the physical and chemical properties of biomass power plant ash. Traditional auxiliary cementitious materials such as fly ash and slag have also been extensively studied in recycled aggregate concrete. The impact of biomass power plant ash as a new type of auxiliary cementitious material on the mechanical properties of recycled aggregate concrete is still unknown. This article points out the physical and chemical properties of biomass power plant ash and the influence of auxiliary cementitious materials on the mechanical properties of recycled aggregate concrete. It provides the mass substitution rate of biomass power plant ash for cement (0-20%) and the substitution rate of recycled aggregate for natural aggregate (50%, 100%) and research methods for mechanical properties and microscopic activity, which can promote the research on the influence of biomass power plant ash on the mechanical properties of recycled aggregate concrete.

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