

A Review of Compressive Properties and Size Effects of Geopolymers in Recycled Concrete

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ABSTRACT

Geopolymer recycled aggregate concrete (GRAC), a green material, has dual functions. It uses industrial waste to replace cement in geopolymeric cementitious materials, reducing CO₂ emissions, and substitutes natural aggregates with recycled aggregates to solve problems like construction waste disposal and over - consumption of sand and gravel, meeting global carbon neutrality goals. However, GRAC is a semi-brittle material with size - dependent effects, where mechanical properties decline as dimensions increase. Due to the unique features of geopolymer materials and recycled aggregates, its size-dependent behavior differs from conventional concrete, restricting its engineering applications. Also, experimental limitations in testing conditions and costs often hinder detailed microscopic investigation of concrete's size effects, while numerical simulation is effective. This paper comprehensively reviews the impact of size effects on GRAC compressive performance through theoretical studies and numerical simulations, offering theoretical support for recycled aggregate recycling in the construction industry.

KEYWORDS; agglomerated recycled concrete; compressive performance; size effect; numerical simulation

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I. INTRODUCTION

Traditional Portland cement (OPC) has been an indispensable material for building production. It is a hydraulic cementitious material made by grinding limestone and an appropriate amount of gypsum. Its production mainly depends on the calcination of CaCO₃, which produces a large amount of CO₂ and a large amount of energy consumption [1][2]. About 0.66-0.82kg of CO₂ is produced per 1kg of OPC, accounting for 5-7% of global anthropogenic CO₂ emissions [3]. Compared with ordinary Portland cement, the carbon dioxide emission per unit mass of geopolymers is reduced by 80%-90%, and the energy consumption is also reduced by 75%-85%. These significant environmental characteristics make geopolymers favored in the construction industry and widely used in various construction projects.

Meanwhile, the construction of massive infrastructure and buildings consumes vast amounts of concrete. The extraction of sand and gravel from concrete production triggers soil erosion, terrain degradation, and river pollution, causing severe environmental impacts. To address the growing risks posed by increasing sand and gravel mining and construction waste, the concept of recycled aggregates has emerged as a research hotspot. Consequently, scholars have begun exploring the combination of geopolymers and recycled aggregates to create geopolymer-reclaimed concrete (GRAC). Due to its eco-friendly characteristics and diverse sourcing options, research on geopolymer-reclaimed concrete is gaining momentum. As applications continue to mature, it's foreseeable that this material will soon see widespread implementation in real-world engineering projects, demonstrating remarkable potential for future development.

II. THE IMPACT OF SIZE EFFECT ON ENGINEERING

Size effect refers to the phenomenon where a material's mechanical properties no longer remain constant but vary with geometric dimensions[4]. The strength obtained through testing is no longer a repetitive property of the material, but rather depends on structural geometric parameters. In civil engineering and hydraulic engineering, practical structures often have large dimensions that make full-scale model testing impractical, typically requiring scaled-down simulations. However, whether these scaled test results possess broad applicability and practical significance has become one of the major challenges faced by most researchers.

The study of size effects in large-scale concrete materials and specimens holds significant engineering implications for the scientific and rational design of large components. To elucidate these principles, researchers

must systematically organize experimental data, employ mathematical models, and validate findings through laboratory tests or practical applications. However, previous studies have predominantly focused on macroscopic perspectives while overlooking the intricate microstructural complexities within concrete materials. This oversight has hindered the revelation of fundamental physical mechanisms underlying material failure, particularly the impact of internal micro-defects on both mechanical properties and size effects. Therefore, conducting systematic research on size effects in concrete mechanics at the microscale carries substantial theoretical significance and practical value for engineering practice.

III. SIZE EFFECT OF GEOPOLYMER RECYCLED CONCRETE

To study the size effect of GRAC, it is necessary to first analyze the influencing factors of concrete size effect. Scholar Jin proposed that concrete initial defects, weak areas and internal inhomogeneity of materials will affect the size effect of concrete[5].

Grout-reinforced concrete (GRAC) utilizes recycled aggregates instead of conventional aggregates. However, the presence of residual mortar inevitably introduces inherent defects in recycled aggregates. Through extensive experimental studies, researchers have identified that both the substitution rate of recycled aggregates and aggregate particle size significantly influence size effects. Zhou conducted experimental and numerical simulations using the substitution rate of recycled aggregates as a parameter[6]. Experimental findings indicate that increasing the substitution rate reduces the nominal strength of concrete while producing more pronounced size effects. In addition, Jin also found that the increase of the maximum particle size of aggregate can improve the sensitivity of size to strength and make the size effect more obvious[7]. However, Kim found in the experiment that with the increase of aggregate size, the skeleton effect of the aggregate becomes more obvious and the size effect decreases[8]. In addition to the defects of recycled aggregate itself, the initial crack also has an impact on the size effect of concrete. Wang discovered that variations in aggregate spatial distribution lead to different initial crack locations and crack propagation patterns under external loads, which subsequently results in differences in mechanical properties of concrete with varying sizes. The aforementioned research reveals that the substitution rate of recycled aggregates, aggregate particle size, and the distribution of recycled aggregates all significantly influence the size effect[9].

The presence of weak zones can affect the size effect in concrete. For concrete, these weak zones include mortar pores and interface transition areas. Musket pointed out that the presence of old mortar is the main reason for the poor performance of recycled concrete[10]. The weak strength of the interface transition area between old and new mortar further impacts the overall strength of recycled concrete. The poor performance of both old and new interface transition areas stems from their high porosity. Peng used the numerical simulation method to describe the nonlinear mechanical behavior of concrete with the multi-linear damage model[11]. The results show that the interface transition zone is the unit where microcracks originate, and the influence of the interface transition strength on the size effect is investigated by changing the strength of the interface transition zone.

Internal material inhomogeneity also affects the size effect of concrete. Zhong et al. investigated the size effects on flexural strength, splitting strength, and torsional strength of high-strength concrete using both conventional and lightweight aggregates. Their study revealed that concrete with lightweight aggregates exhibited greater brittleness and more pronounced size effects[12]. Gao discussed the influence of aggregate composition on the size effect of concrete uniaxial compressive performance, and the results showed that coarse aggregate had a greater influence on the size effect of concrete, while fine aggregate had a smaller influence[13].

For GRAC, the combination of ground aggregates and recycled aggregates makes the reasons for concrete's size effect more complex. The material's size effect is caused by low-strength internal units within the material. However, the performance of interfacial transition zones in recycled aggregate concrete is significantly lower than that of ordinary concrete, making the low strength of these transition zones the primary factor triggering the size effect. Generally speaking, the adverse effects of recycled aggregates on GRAC differ considerably from those on ordinary concrete[14]. Due to the distinct matrix formation processes, geopolymer materials alter internal homogeneity. Their high bonding strength creates a more compact interfacial transition zone with aggregates. Khedmati also demonstrated that these materials can effectively fill pre-existing incomplete interfaces in recycled aggregates[15].

IV. DIMENSIONAL EFFECT THEORY

At present, there are many size effect theories in solid mechanics, among which Weibull statistical size effect theory and Bazant size effect theory based on energy release criterion are mainly used.

The Bazant size effect formula is shown in Equation (1), and the asymptotic analysis curve is shown in Figure 1.

$$\sigma_N = \frac{Bf_t}{\sqrt{1 + D/D_0}} \quad (1)$$

Where:

- σ_N —— Nominal strength related to size at the time of specimen failure;
D—— Structural dimensions of specimen characteristics;
D0—— Constants related to structural geometric dimensions;
B—— Dimensionless constant;
 f_t —— Tensile strength of the material.

The study of the Weibull statistical size effect theory can be traced back to Leonardo da Vinci's discussions during the Renaissance. Later, Fisher revised and improved Tippet's extreme value statistical theory, expressing the weakest link model of chains through mathematical formulas[16]. Building on previous research, Weibull proposed the renowned Weibull distribution model in statistics. Zaitsev refined, applied, and validated this model, ultimately establishing the Weibull statistical size effect theory. This theory posits that as concrete characteristic dimensions increase, the probability of encountering low-strength materials within the structure rises, thereby increasing the likelihood of low-strength units developing microcracks and macrocracks. Consequently, concrete becomes more prone to failure. However, some scholars have raised objections, arguing that the Weibull statistical size effect theory only applies to brittle materials, while concrete is a quasi-brittle material with distinct differences from typical brittle materials. Building on nonlinear fracture mechanics, Bazant proposed a simplified formula for the size effect law. Subsequently, this formula was refined by researchers including Belytschko, Cabot, and Chang, ultimately forming Bazant's size effect theory based on the energy release principle. The theory posits that the instability propagation of crack zones causes damage in quasi-brittle materials like concrete, with crack development being governed by energy dissipation and the release of stored energy[4]. Concrete exhibits a fracture process zone at the front edge of cracks, composed of microcracks. In this zone, crack propagation involves both energy release and dissipation processes. The disproportionate relationship between energy consumption and crack size gives rise to the size effect.

V. NUMERICAL SIMULATION OF SIZE EFFECT OF CONCRETE MATERIALS

Most current studies on concrete size effects rely on experimental approaches. However, these experiments are constrained by economic limitations, experimental conditions, and human errors, resulting in inherent variability in results. With the advancement of computer technology, numerical simulations have emerged as a viable method for studying size effects, offering a way to overcome some of the limitations imposed by experimental constraints.

Numerical simulation can effectively address the limitations of experimental conditions. Lim developed a three-dimensional lattice model of concrete to analyze the energy scaling effect in compressive failure, establishing specimens with V-shaped notches (50mm, 100mm, 200mm) and non-V-shaped notched specimens. Simulation results indicate that both notched and unnotched specimens exhibit size effects, but the notched specimens demonstrate significantly more pronounced scaling behavior[17].

Compared to conventional concrete microscale finite element models, research on microscale finite element models for geopolymer concrete remains limited. Tam utilized the damage model in ABAQUS software to conduct finite element analysis of geopolymer-reinforced concrete structures, focusing on the effects of explosion-induced loads on geopolymer concrete beams. The study demonstrated the feasibility of applying ABAQUS's damage model for numerical simulation of geopolymer concrete[18]. Pham et al. established a mesoscale finite element model to determine the stress-strain relationship of fiber-reinforced polyurethane concrete. The material parameters of their finite element model were determined through experiments, with an elastic modulus of 25.4GPa and a Poisson's ratio of 0.128. The simulation results were consistent with the experimental results[19].

VI. CONCLUSION

1) The replacement rate of recycled aggregate, aggregate size and distribution of recycled aggregate, porosity and strength of interface transition zone all have a significant influence on the size effect of ordinary concrete and recycled concrete.

2) The size effect is not only related to the dimensions of specimens but also to crack formation and weak zones within them. For geopolymer-reinforced recycled concrete, crack generation and weak zones are associated with the replacement rate of recycled aggregates, aggregate distribution, maximum aggregate particle size, porosity, and strength of interfacial transition zones. However, Bazant's size effect law does not account for these factors, necessitating modifications to Bazant's size effect law.

3) The finite element model of microparticle concrete is feasible, and the numerical analysis results are reliable. When the model is established, the material parameters need to be modified. The damage model adopts the damage model in ABAQUS software, and the geometric model is still established according to the random aggregate model.

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