Impact properties of geopolymeric concrete: a state-of-the-art review

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Abstract. The application of geopolymer instead of cement in construction engineering provides an effective way to achieve sustainable development. A large number of studies have shown that geopolymeric concrete (GC) has excellent static performance. However, there are relatively few studies on the dynamic performance of GC which is of dominate importance in cases such as explosion, earthquake and other impact loads. This paper presents a brief review of recent research on the impact properties of GC, in order to facilitate the research development in this field. The effects of strain rate, fiber type, alkali type, elevated temperature, water environment and flow state on the impact resistance performance of GC were analysed. Research findings revealed that GC exhibited better impact properties than ordinary Portland concrete (OPC).

1. Introduction

China is a large resource-consuming country, the economic growth of which is increasingly constrained by shortage of resources and environmental pollution. In 2015, the cement production over the whole world was 4 billion tons and China consumed about 2.5 billion tons, that is to say, 60% of all cement are poured on China's land. It should be mentioned that the production of each 1 ton of Portland cement requires about 1.5 tons of limestone, and consumes a lot of coal and electricity, and emits about 1 ton of CO$_2$. At the same time, the amount of solid wastes increases dramatically in China. For example, every 1 ton of steel production is accompanied by the output of dozens of tons of steel slag, slag and other wastes. The accumulation of these solid wastes not only occupies a large amount of land, but also causes serious environmental pollution. In order to significantly reduce CO$_2$ emissions and recycle industrial wastes to achieve sustainable development in China, using geopolymer instead of cement to develop green concrete is one of the efficient methods. Geopolymer is considered as the third generation cement after lime and ordinary Portland cement, which is generically used to describe a amorphous alkali aluminosilicate. A variety of aluminosilicate materials such as kaolinite, feldspar and industrial solid residues such as fly ash, metallurgical slag, mining wastes etc. have been used as solid raw materials in the geopolymerization technology [1]. Geopolymeric concrete (GC) is a new kind of concrete material prepared by geopolymer used as cementing material [2]. The production process of GC not only consumes less energy and emits low CO$_2$, but also recycles solid wastes and conserves land resources. Thus, GC generates more environmental benefits than ordinary Portland concrete (OPC). Moreover, GC has been widely reported to exhibit high resistance to fire and acids, and does not produce the high evolution of reaction heat associated with OPC, reducing cost and potential cracking issues when the material is placed in large volumes [3].
Nowadays, numerous studies have been conducted on the mechanical properties of geopolymer concrete [1-4]. However, the majority of these studies are focused on geopolymer concrete under monotonic loading, with a limited number under dynamic loading, very limited information is available for the impact performance of GC which is of dominate importance in cases such as pile driving. Thus, To facilitate the research development in this field and promote the application of this new type of green concrete in civil engineering, this paper reviews the performance of GC under impact loading, and presents the recommendations for future research.

2. Impact Resistance of GC
Geopolymer has unique three-dimensional network structure of inorganic polycondensation, and its microstructure and physical-chemical properties are relatively better than traditional cement. Therefore, the bonding property between the geopolymer and aggregate is superior to that between the cement and aggregate. Many experimental results indicated that compared with the cement concrete, GC has less inherent defects and a denser internal structure resulting in a stronger impact resistance [1,4-6].

2.1. Effect of Strain Rate on Impact Performance
The strain rate range of Split Hopkinson Pressure Bar (SHPB) test is usually $10^2-10^4/s$, which can represent the strain rate sensitivity of in-site engineering material. Thus, many researchers conducted SHPB test to investigate the effect of strain rate on the impact performance of GC [4-6], as shown in Table 1. The findings have reached a consensus that strain rate affects significantly the impact performance of GC. It can be indicated from these experiments [4-6] that the compressive strength, deformation properties and impact toughness of GC under impact loading increase with the increase of strain rate.

| Data sources       | Test number | Strain rate ($s^{-1}$) | Dynamic compressive strength (MPa) | Critical strain ($10^{-3}$) | Specific energy absorption (kJ·m$^{-2}$) |
|--------------------|-------------|------------------------|-----------------------------------|-----------------------------|----------------------------------------|
| Fan et al. [4]     | 1           | 34.6                   | 72.3                              | 5.60                        | 340                                    |
|                    | 2           | 54.8                   | 87.1                              | 6.77                        | 690                                    |
|                    | 3           | 76.4                   | 98.1                              | 11.97                       | 1070                                   |
| Xu et al. [5]      | 1           | 38.5                   | 62.2                              | 8.20                        | 174.4                                  |
|                    | 2           | 55.9                   | 73.3                              | 9.44                        | 393.2                                  |
|                    | 3           | 73.0                   | 86.5                              | 9.96                        | 658.1                                  |
| Lu and Zheng [6]   | 1           | 39.3                   | 62.2                              | 8.20                        | 250.9                                  |
|                    | 2           | 54.7                   | 72.4                              | 10.23                       | 548.3                                  |
|                    | 3           | 83.2                   | 86.6                              | 10.26                       | 730.2                                  |

2.2. Effect of Fibre Type on Impact Performance
GC is a quasi-brittle material as same as OPC. Usually, adding fibre into concrete is an efficient method to enhance toughness, including basalt fibre and carbon fibre. In order to investigate the effect of basalt fiber on the impact resistance of GC, Li et al. [7] conducted the impact test of the GC with volume fraction of 0.3% basalt fibre by SHPB. This result revealed that fibre had no significant improvement in 28-day-old compressive strength, but it could obviously enhance the deformation and energy absorption capacity of GC. Xu et al. [8,9] studied the deformation characteristics of the GC with 0.1%, 0.2% and 0.3% basalt fibre and carbon fibre under impact loading, and then found that the optimal addition of fibre is 0.2%. Similarly, Zhu et al. [10] conducted a series of impact tests of the GC with different carbon fibre content, and then pointed out that the optimal addition of fibre is 0.3%. It can be seen that the addition of the appropriate amount of basalt fibre and carbon fibre can effectively improve the impact resistance of GC, and its optimal addition is 0.2%-0.3%.

To compare the effects of basalt fibre and carbon fibre on the impact resistance of GC, Luo et al. [11] found that the early impact properties of 3-day-old and 7-day-old GC with basalt fibre is better than
that with carbon fibre, while Xu et al. [12] poited out that of 28-day-old GC is just on the contrary. The role of the fibre in the impact mechanism and its quantitative effect are complex and require further investigation.

2.3. Effect of Alkali Type on Impact Performance
The use of alkali activator is one of the key procedures in the preparation of GC. Undoubtedly, the type of alkali activator is critical to the performance of GC. Luo et al. [13,14] conducted some impact tests on slag and fly ash based GC to compare the effect of NS activator (NaOH and sodium silicate) and NN activator (NaOH and Na2CO3) on the dynamic performance. The results indicated that NN is more beneficial than NS to enhance the compressive strength of GC, while NS is more beneficial than NN to improve the deformation capacity. The reason may be that different alkali could change the hydration-producing substance and microstructures of GC. Therefore, suitable alkali-activator should be chosen to use in practical application according to the specific engineering requirements.

2.4. Effect of Water Environment on Impact Performance
Liu et al. [15] and Ren et al. [16] conducted a series of tests to investigate the influence of long-time water environment on the dynamic mechanical properties of GC. These experimental results shown that the dynamic compressive strength of GC increased after exposure to water environment (180 days), but the quasi-static strength of the specimens decreased. It can be seen that water environment enhance the strain rate sensitivity of the dynamic compressive strength of GC, which is the same as OPC in water environment [17]. Moreover, the higher dynamic elastic modulus indicated that water environment has a stiffening effect on GC. It should be noted that the influence of water environment on the impact toughness of GC is relatively small. Thus, it can be concluded that GC has a good impact resistance in water environment. Further research is required to investigate others environments such as saltwater erosion and freezing-thawing on the impact resistance of GC.

2.5. Effect of Temperature on Impact Performance
To investigate the effect of elevated temperature on the impact resistance of GC, Su et al. [18] designed high temperature SHPB system to conduct a series of impact test (200°C-800°C). As shown in Figure 1 [18], the dynamic compressive strength of GC grows higher at 200°C than at room temperature, but suffers a dramatic drop at 800°C. However, at 400°C and 600°C, it is close to that at room temperature. It indicates that GC could keep its integrity when exposed to temperatures from 200°C to 600°C, resulting in a good mechanical properties. For GC, the elevated temperature may promote the dissolution and polycondensation of aluminosilicate that has not reacted previously, leading to more compact structure and higher strength at 200°C [18]. With the temperature increases, free water vaporizes and the polycondensation terminates, so the strength decreases dramatically after 800°C. A similar observation was also reported for GC static test [19]. For OPC, calcium hydroxide decomposes after 400°C and most strength is lost after 600°C. Thus, it can be seen the impact energy absorption ability of GC is better than that of OPC subjected to elevated temperature.

Figure 1. The increase ratio of dynamic compressive strength compared to room temperature [18].
2.6. Impact Performance of Highly-fluidized GC

GC usually is lowly-fluidized because the setting and hardening of geopolymer is fast. To popularize the application of GC, highly-fluidized GC (HFGC) is receiving increasing attentions [20,21]. Xin et al. [20,21] conducted an experimental study on the impact properties of HFGC. The results revealed that the dynamic strength of HFGC exhibits significant strain rate correlation, which is similar to lowly-fluidized GC and OPC. Compared with lowly-fluidized GC, the strain rate sensitivity threshold of HFGC is higher. However, limited information is available for HFGC. Therefore, further research is needed to investigate of impact resistance of HFGC leading to improved design methodologies.

3. Summary

Geopolymeric concrete, as a kind of green concrete, produces significant environmental benefits, which can not only effectively recycle solid waste and save a lot of resources, but also can reduce CO2 emissions. In addition, it exhibits good static and impact resistance performance. The dynamic compressive mechanical properties of GC has strong strain rate dependency. Compared with OPC, the impact resistance of GC is better subject to elevated temperature or in water environment. To improve the impact resistance of GC, adding basalt fibre or carbon fibre into it is an efficient method. Therefore, it can be concluded that GC has unique advantages and broad application prospect in cases such as heat-resistance structure, hydraulic structure and rapid-repair of pavement and so on. However, the impact resistance of GC is not clear yet. Further research is required to investigate the effects of alkali dosage, curing conditions, various environments, etc. In addition, the application of recycled aggregates from construction and demolition waste currently has become a hot focus in civil engineering. Consequently, the impact resistance of GC mixed with recycled aggregates should be further investigated.

4. References

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