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The effect of supplementary cementitious material systems on dynamic compressive properties of ultra-high performance concrete paste

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1. Introduction

Ultra-high-performance concrete (UHPC) is a relatively advanced cementitious composite with superior mechanical properties, excellent durability, and good impact resistance [1–3]. The low water-to-binder ratio (0.16 ~ 0.22) and high cement content are often used to achieve ultra-high strength, resulting in high cost, energy consumption and intensive CO$_2$ emission [4]. Current research indicates that CO$_2$ emissions from the Portland cement (PC) production process account for approximately 5–7% of the total emissions [5]. To achieve low carbon footprint and low costs of UHPC, the construction industry and researchers have been making ever more substantial efforts to reduce and optimize the use of PC in concrete [6,7]. Therefore, supplementary cementitious materials (SCMs), such as fly ash, glass powder, ground granulated blast furnace slag (GGBS), micro-silica (MS) and fillers, i.e., limestone powder (LP) are used to replace PC in UHPC partially.

As an industrial by-product, GGBS has proved to be a promising supplementary material thanks to its much lower CO$_2$ emission and superior durability than those of PC. Due to its fine particle size and high pozzolanic activity, the incorporation of MS can remarkably reduce porosity and permeability, consequently leading to enhanced strength and durability [8]. Nevertheless, due to the workability problem, the replacement of cement by MS is limited, normally less than 20%. In addition, very low water-to-cement ratios are generally utilized to decrease the porosity and promote the strength in UHPC. It means that there is still a large quantity of incompletely hydrated cement particles. Therefore, replacing parts of cement with an unreactive powder such as LP as filler is reasonable to enhance environmental and economic sustainability [9,10]. The use of LP in UHPC is widespread since it reduces cement consumption and improves the rheological properties of the mixes [11,12]. However, excessive content of LP would cause a larger total free shrinkage and reduced strength of UHPC pastes because of the dilution effect. In contrast, the addition of MS is an effective countermeasure to combat those deficiencies because of the effects of nucleation, pozzolanic and filling [6].

Compared with binary system (PC-GGBS), ternary system (PC-MS-LP) can improve the relative water-binder ratio of PC and GGBS, consequently improving the hydration degree of them. Burroughs et al. [13] reported that the pozzolanic effect of MS, and the filler effect and high sustainability of LP can offer great potential for ternary system to

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improve the sustainability and strength of UHPC. Since limestone powder can provide sites for C-S-H and CH crystallization nucleation, the quaternary system (PC-GGBS-MS-LP) slightly accelerates the hydration process of cement in general, and significantly improves the hydration degree and efficiency of cement in UHPC paste [14,15]. Li et al. [6] found that compared with binary (PC-GGBS) and ternary (PC-MS-LP), the quaternary system (PC-GGBS-MS-LP) had a positive synergistic effect on strength, fiber to matrix bonding and total free shrinkage. However, the majority of previous studies have focused on the hydration kinetics, microstructure, rheology, quasi-static mechanical properties and durability of different SCM systems [16–19], while the study on their dynamic mechanical properties is still very limited. During the service life, concrete structures (e.g., airstrip, piers and military facilities) are vulnerable to impact loads such as weight fall, vehicle impact and explosion [20–22]. UHPC materials are ideal for civil and national defense engineering due to their ultra-high strength and excellent impact resistance. Previous research has demonstrated that UHPC under dynamic impact loading responds differently from conventional quasi-static loads [20,23,24]. Additionally, the current research on dynamic compressive characteristics of UHPC mainly focuses on the effect of steel fibers, such as content [25,26], type [27], orientation [28] and hybrid [29]. Besides the steel fiber, the matrix also plays an essential role in the dynamic performance of UHPC. Therefore, it is of great intrinsically scientific and engineering significance to study the influence of SCMs on the dynamic compressive properties of UHPC paste for analyzing and designing UHPC structures under impact loads. Nevertheless, the synergistic effect of SCMs on the dynamic performance of UHPC has not been well understood. In comparison to the swinging pendulum, drop-weight machine, and blast test, the split Hopkinson pressure bar (SHPB) can determine the stress-strain relationship of the tested material precisely, which can be used to determine the dynamic strength, peak strain, and energy absorption. Therefore, the SHPB has been widely utilized to measure dynamic compressive behaviour under strain rates ranging from 10 to $10^4$ s$^{-1}$ [30].

In this study, the UHPC pastes of binary (PC-GGBS), ternary (PC-MS-LP) and quaternary (PC-MS-GGBS-LP) systems are prepared by partially replacing PC with MS, GGBS and LP. The workability is of great significance to engineering applications and the pore structure of UHPC pastes can benefit the comprehension of quasi-static compressive strength and dynamic compressive properties. Therefore, this paper firstly investigates the effect of SCMs on workability, pore structure and quasi-static compressive strength. Subsequently, the influence of strain rate and different SCMs on the dynamic compressive characteristics of UHPC pastes are investigated deeply by using a 50 mm SHPB system. The
UHPC pastes. The research results can provide theoretical guidance for the large-scale engineering application of SCMs in UHPC under impact loading.

2. Experimental program

2.1. Materials

The raw materials include cement PI-52.5 (PC), micro-silica (MS), ground granulated blast furnace slag (GGBS), limestone powder (LP), polycarboxylate-based superplasticizer (SP) with a solid content of 30%. The PC contains about 4% LP (data provided by the cement manufacturer and self-confirmed by a synchronous thermal analyzer). The particle size distributions of powders tested by laser particle analyzer are presented in Fig. 1. The scanning electron microscopy (SEM) images of the powders are shown in Fig. 2. The MS exhibits small finer and spherical characteristics, and appropriate dosage can benefit the workability, pore structure and quasi-static compressive strength, which will be discussed in detail in Section 3.1-3.3. The chemical properties and the specific surfaces area are listed in Table 1.

2.2. Mixture design

A total of six UHPC pastes with a water-powder ratio (w/p) of 0.18 are prepared in this study. Pure cement is used as the reference binder, whereas the other binders are binary (SC), ternary (PC-MS-LP) and quaternary (SC-MS-LP) cementitious blends. Here SC represents the mixture containing 50% PC and 50% GGBS. Considering the content of GGBS in slag cement is generally between 20% and 70%, and the slag cement with 50% GGBS content is widely used, 50% PC and 50% GGBS are used as a binary binder (SC) [31]. The substitution of LP is 10% and 30% of the total powder mass, whereas the replacement of SF is 5% of the whole powder mass. The detailed mix design is shown in Table 2, and SP represents the content of the polycarboxylate-based superplasticizer. For instance, the amount of SP in M1 is 1.5 % by the mass of PC. Considering that the influence of steel fiber on the mechanical performance of UHPC varies with the SCM system, steel fiber is not used in this study.

2.3. Mixing procedure and sample preparation

The mixing progress of UHPC pastes is shown in Fig. 3. After 24 h of casting, specimens are de-molded and then cured in the standard curing condition (20 ± 2 °C and 95% RH) until the testing age. The specimens for dynamic experiments SHPB test are cut into 50 mm (diameter) × 25 mm (height) through the process of coring, slicing and polishing after 28 days of curing. The aspect ratio of the test specimens is 0.5 to minimize the friction and inertia effect [32]. The fabricated specimens are shown in Fig. 4. The specimens are polished at both surfaces with roughness less than 0.02 mm to keep contact as perfect as possible and minimize the frictional effect between the specimen and bars. The prepared specimens are cured under the above defined curing condition until 56 days for the dynamic test. To investigate the strain rate effect of UHPC paste, four different impact velocities are used in each mix design. Five specimens are prepared for each mix design at the same impact velocity to ensure the validity of experimental data and the average value is taken as the test result. Hence, a total of 120 samples are used for the SHPB test in this study.

2.4. Testing methods

2.4.1. Flow test

The spread flow of UHPC pastes is determined by a truncated mini-cone (height: 60 mm, upper inner diameter: 70 mm, bottom diameter: 100 mm). SP dosage is adjusted to obtain the target fluidity of 270 ± 20 mm for the self-consolidating mix [33]. The mini-slump cone is placed at the center of the plate. The fresh paste is filled in the cone and then it is smoothly lifted straight upwards without jolting. The mini-
slump flow spread is recorded by calculating the mean value of two perpendicular spread diameters.

2.4.2. Quasi-static compressive tests

The quasi-static compressive tests are conducted on a servo hydraulic pressure testing machine. Cubic specimens $70.7 \times 70.7 \times 70.7$ mm$^3$ are prepared for the tests. A loading rate of 1.2 MPa/s is used for these tests. Three specimens are prepared and tested for each design mix at 7 d, 28 d and 56 d, and the average of the experimental results are recorded.

2.4.3. Mercury intrusion porosimetry

The pore structure of the UHPC pastes is performed by mercury intrusion porosimetry (MIP) after 56 days of standard curing. The UHPC pastes are cored and sliced into small pieces with a diameter between 3 mm and 5 mm from the center of the pastes, and approximately 3.5 g samples are utilized for measurement. The samples are dried in the oven at 50 °C until a constant mass is reached.

2.4.4. Split Hopkinson pressure bar (SHPB) tests

Fig. 5(a) shows a schematic illustration of a 50 mm SHPB system utilized in this study, which is made of superior alloy steel and Fig. 5(b) shows the picture of the device used in this study. The specimen is sandwiched between the incident bar and the transmitted bar. Grease is used at the specimen–bar interfaces to minimize the end friction confinement. The strain gauges are installed on the device at the center of the incident bar and transmitted bar to measure the incident pulses ($\varepsilon_i$), reflected ($\varepsilon_r$) and transmitted pulse ($\varepsilon_t$), respectively. The typical pulse signals of the SHPB test are shown in Fig. 6.

The following assumptions are often made in SHPB tests: (1) The wave propagation through the bars follows one-dimensional wave theory; (2) The stress and strain states within the specimen are uniaxial and uniform [35]. The stress equilibrium condition and uniform deformation during the dynamic loading are assumed (i.e., $P_1 = P_2$, $\varepsilon_i(t) + \varepsilon_r(t) = \varepsilon_t(t)$). Stress $\sigma_i(t)$, strain $\varepsilon_i(t)$ and strain rate $\dot{\varepsilon}_i(t)$ can be calculated by the following equations:

$$\sigma_i(t) = \frac{P_1 + P_2}{2A_s} = \frac{E_0 A_0}{2A_s}[\varepsilon_i(t) + \varepsilon_r(t) + \varepsilon_t(t)] \quad (1a)$$

$$\varepsilon_i(t) = \frac{C_0 L_s}{L_0} \frac{1}{A_s} \int_0^t [\varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_t(t)] \, dt \quad (1b)$$

$$\dot{\varepsilon}_i(t) = \frac{C_0 L_s}{L_0} [\varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_t(t)] \quad (1c)$$

where $P_1, P_2$ refer to the dynamic forces on the incident end and the transmitted end of the specimen. $E_0, C_0$ and $A_0$ refer to the Young’s modulus, wave velocity and cross-sectional area of the bars, respectively. $A_s$ and $L_s$ represent the cross-sectional area and length of the specimen, respectively.

2.4.5. Sieving tests of UHPC fragment distribution

Previous studies on the dynamic performance of UHPC were mainly concentrated on mechanical properties. However, damage caused by debris is also essential to be considered in the protection design. Therefore, a more comprehensive evaluation considering fractal characteristics under dynamic loading can benefit the design of protective engineering [36]. The fractal theory is an excellent tool for studying and revealing the laws underlying the complex phenomenon of UHPC fragmentation caused by impact loading [37].

To quantify the fragmentation distribution of UHPC in SHPB test, fractal dimension is used to characterize the fragments of UHPC. Initially proposed by Mandelbrot and Wheeler, fractal geometry theory has been proved to be effective in describing highly irregular and self-
similar objects [38]. The macroscopic breakage of concrete materials is characterized by large fragments, while minor fracture is characterized by smaller cracks and aggregation, which result in fragments with self-similar behavior and energy dissipation [39]. The fractal theory is employed to quantitatively analyze the distribution of UHPC fragments under dynamic loads. The fractal dimension (D) of UHPC fragments can be determined by the following formula [40,41]:

$$D = 3 - \frac{\log(M_d/M_T)}{\log(d/d_m)}$$  \hspace{1cm} (2)

where $M_d$ is the cumulative mass of fragments with a diameter smaller than $d$; $M_T$ is the total mass of fragments; $d$ and $d_m$ represent the diameter and the maximum diameter of fragments, respectively.

The fragments of UHPC specimen subjected to the SHPB test are collected. Then, standard sieves with mesh sizes of 2.5 mm, 5 mm, 10 mm, 16 mm, 20 mm, 25 mm, 31.5 mm, 40 mm, and 50 mm are utilized to measure the size distribution of UHPC fragmentation. The weight of the fragments that remained on each grade of the standard sieve are measured utilizing a balance with a precision of 0.05 g. Finally, the fractal dimension of fragments is calculated by equation (2).

3. Results and discussion

3.1. Workability

Fluidity is an important property of UHPC, and insufficient fluidity will have a negative impact on its mechanical properties [42]. The dosage of SP is crucial in regulating the flow performance of UHPC. The amount of SP is adjusted to secure the target fluidity spread value of $270 \pm 20$ mm [33], and the fluidity test is shown in Fig. 7(a). Fig. 7(b) shows the amount of SP required for the target fluidity of different pastes. It can be seen that UHPC pastes prepared by different powders, especially those with different GGBS and LP replacement rates, have a significant difference in fluidity. After partially replacing PC with GGBS and LP, the fluidity of UHPC pastes is significantly improved.

For M1 ~ M3, with the increase of LP from 10% to 30%, SP dosage is reduced to 1.17% and 0.917%, respectively. For M4 ~ M6, when the replacement rate of LP is increased by 10% and 30%, SP dosage is decreased to 0.75% and 0.625%, respectively. The LP mainly consists of $\text{Ca}_2^+$ and $\text{CO}_3^{2-}$, resulting in a neutral surface. In an aqueous solution, the $\text{OH}^-$ groups preferably concentrate on the $\text{Ca}_2^+$ surface, leading to electrostatic repulsion between particles, enhancing the fluidity and declining particle flocculation [43,44]. Moreover, the incorporation of LP leads to an increased effective water-cement ratio, which promotes the fluidity of UHPC pastes. When GGBS is added at 50%, the SP dosage of M4 is reduced by $38.87\%$ compared with M1. This is because the
water dispersion of GGBS presents a higher alkalinity (pH = 12 ~ 12.6) and releases a large amount of calcium ions, thus making the surface of GGBS positively charged distribution, which in turn can adsorb negatively charged superplasticizers molecules, promoting the dispersion of superplasticizers in the cementing system and increasing the fluidity of pastes [45,46]. In addition, the small fineness, glassy and spherical nature of MS provides a “ball bearing” effect that helps displace water trapped in coarse and fine particles, which improves the flow of UHPC pastes [47].

3.2. Pore structure analysis

Many previous studies have confirmed that incorporating SCMs would lead to the different pore structures of UHPC [48–51]. The result of MIP is presented in Fig. 8 to analyze the influence of SCMs on the pore size distribution [52]. The pores of UHPC pastes designed in this study are mainly concentrated between 5 nm and 100 nm, and the pores between 100 nm and 100 μm are very few and analogical to each other. Therefore, the pore size distribution between 5 nm and 100 nm is mainly discussed. The small capillary pores of 8 to 50 nm are regulated primarily by the amount of water and hydration products [53].

As shown in Fig. 8, with the substitution rate of 5% MS and 10% LP, M2 has a finer pore size and the volume of capillary pores of M2 is slightly lower compared to M1. This indicates that the microstructure of M2 becomes denser. The MS reacts pozzolanically with calcium hydroxide, resulting in an increased calcium silicate hydrate gel volume, further reducing capillary porosity during hydration [54]. Additionally, the better filling and nucleation effect of finer LP also leads to a denser microstructure. However, with the substitution rate of 30% LP, M3 exhibits significantly more gel pores and the pore size becomes large, indicating that more low-density and porous C-S-H gel are generated due to the dilution effect of LP.

In general, despite the addition of MS and LP, the mixtures with GGBS all have the larger critical pore diameter (the maximum peak on the pore size distribution curve) and cumulative pore volume than that without GGBS, which indicates that the addition of larger content GGBS results in the higher porosity of UHPC pastes. Due to the low water amount, the produced portlandite and free water is quite limited. Thus, no sufficient saturated calcium hydration solution can touch and activate the GGBS. It cannot participate in hydration to reduce the porosity of UHPC pastes [16]. Additionally, the incorporation of GGBS changes the packing distribution of particles, which may also cause increasing porosity.

3.3. Quasi-static compressive strength

The compressive strength of UHPC pastes is measured at the ages of 7 d, 28 and 56 d, as shown in Fig. 9. When LP is finer than PC particles, LP mainly exhibits filling and nucleation effects. LP mainly shows a dilution effect when the LP particle size is similar to or larger than the PC particles [55]. As shown in Fig. 1, the D50 of LP and PC used in this test is 7.82 μm and 15.85 μm, respectively, i.e., the average particle size of PC is about twice that of LP. When the LP substitution rate is 10%, there is almost no decrease in strength due to the nucleation effect and the excellent filling effect of the finer LP, which optimizes the bulk density of the UHPC paste. When 30% LP is used as a substitute, the admixture of excessive LP causes a reduction in compressive strength due to the dilution effect. Nevertheless, the 28-day compressive strength of M3 declines by 13.4% compared to M1 and only 9.4% at 56 days. The 28-day compressive strength of M3 declines by 10.9% compared to M2 due to the dilution effect of LP. The 28-day strength of M6 decreases by 11.2% compared to M4, which is a smaller decrease in strength. In addition, attributed to the incorporation of 5% MS, the MS consumed Ca

![Fig. 9. Quasi-static compressive strength of UHPC pastes.](image)

![Fig. 10. (a) Relationship between dynamic compressive strength and strain rate; (b) Relationship between DIF and strain rate for UHPC pastes.](image)
3.4. SHPB test

3.4.1. Dynamic strength and dynamic increase factor (DIF)

Fig. 10 (a) shows the relationship between dynamic compressive strength and strain rate of UHPC pastes at the strain rate of 53.9 – 170.7 s⁻¹. It can be found that the dynamic compressive strength of UHPC pastes increase with increasing strain rate. The conclusion has been consistently reported by previous studies [21,24,30]. The macroscopic strength sensitivity to strain rate can be ascribed to the growth of time-dependent micro-cracks [57]. There is sufficient time for micro-cracks to develop into macro-cracks under quasi-static loading [29,58,59]. Nevertheless, the loading time is extremely transient under the impact loading. Micro cracks are nucleated and enlarged before they become macro cracks with more consumption of energy and higher compressive strength. In addition, the lateral confinement also leads to the enhancement of dynamic compressive strength [60].

Fig. 10(b) shows the relationships between the strain rate and DIF for UHPC pastes at the strain rate of 53.9 – 170.7 s⁻¹. It can be clearly observed from Fig. 10(b) that the values of DIF increase approximately linearly with the rising of strain rate. The incorporation of LP and GGBS lead to different microstructure and microscopic pore structure, consequently, affecting quasi-static compressive strength and dynamic compressive strength. As analysed in sections 3.2 and 3.3, with the substitution rate of 30% LP, the pore size of M3 becomes larger and more low-density and porous C-S-H gel are generated, consequently resulting in lower quasi-static compressive strength, leading to higher strain rate sensitivity. The addition of larger content GGBS also leading to the higher porosity of UHPC pastes and dilution effect of the clinker result in a lower quasi-static compressive strength compared with the pastes without GGBS. At the similar strain rate, the DIF values of each pastes are compared, M6 > M5 > M4 > M3 > M2 > M1. It can be concluded that the DIF value increases with the increase of GGBS and LP.

Fig. 11 shows the comparison of DIF values of different types of concrete with experimental data in this study. It can be observed that DIF values of normal strength concrete are larger than that of high-strength concrete, while high-strength concrete are larger than that of UHPC pastes [61], which is consistent with the conclusion of Bischoff and Perry, who found that lower quality concrete exhibited higher DIF values [62]. It could be attributed to that the concrete with low strength level has a more heterogeneous microstructure. Li et al. [63] confirmed that a higher heterogenous microstructure would lead to a higher DIF.

The following formula was established by the fib Model Code 2010 [64]:

\[
\text{DIF} = \frac{\sigma_d}{\sigma_s} = \left(\frac{\dot{\varepsilon}_d}{\dot{\varepsilon}_s}\right)^{0.014} \quad \dot{\varepsilon}_d \leq 30 \text{s}^{-1}
\] (3a)

\[
\text{DIF} = \frac{\sigma_d}{\sigma_s} = 0.012 \left(\frac{\dot{\varepsilon}_d}{\dot{\varepsilon}_s}\right)^{0.2} \quad \dot{\varepsilon}_d > 30 \text{s}^{-1}
\] (3b)

where \(\dot{\varepsilon}_d\) ranges from \(3 \times 10^{-5}\) to 300 s⁻¹ and \(\dot{\varepsilon}_s = 3 \times 10^{-5}\) s⁻¹. \(\sigma_s\) is the dynamic strength at \(\dot{\varepsilon}_s\), \(\sigma_d\) is the compressive strength in quasi-static loading.

Ren et al. [27] proposed a DIF formula for UHPC with 2% short straight steel fiber:

\[
\text{DIF} = \left(\frac{\dot{\varepsilon}_d}{\dot{\varepsilon}_s}\right)^{0.014} \quad \dot{\varepsilon}_d \leq 92 \text{s}^{-1}
\] (4a)

\[
\text{DIF} = 0.51 \left(\log \dot{\varepsilon}_d\right)^2 - 1.23 \left(\log \dot{\varepsilon}_d\right) + 1.6892 \dot{\varepsilon}_d < 328.4 \text{s}^{-1}
\] (4b)

Zhou and Hao [65] put forward a DIF formula by linear regression of experimental data:

\[
\text{DIF} = 0.0225 \log \dot{\varepsilon}_d + 1.12 \dot{\varepsilon}_d \leq 10 \text{s}^{-1}
\] (5a)

\[
\text{DIF} = 0.2713 \left(\log \dot{\varepsilon}_d\right)^2 - 0.3563 \left(\log \dot{\varepsilon}_d\right) + 1.2275 \dot{\varepsilon}_d > 10 \text{s}^{-1}
\] (5b)

As shown in Fig. 10, the Model proposed by the fib Model Code 2010.
and Zhou and Hao [65] overestimated the DIF value obtained in this study. These two models were proposed for normal strength concrete, while the DIF of UHPC was relatively small at the same strain rate. However, the model established by Ren et al. [27] underestimated the DIF value obtained in this test. The addition of steel fibers can improve the quasi-static compressive strength and significantly enhance the toughness, thus improving the impact resistance. However, the growth rate of the dynamic strength relative to the quasi-static strength of UHPC incorporated with steel fibers decreases compared with that of UHPC pastes. The three models mentioned above do not apply to UHPC pastes, but the fitting model suggested by the literature [27, 65] has similar variation laws to the test data in this study. Therefore, the model parameters proposed in the literature [27, 65] are re-fitted, and the fitting results are shown in Eq. (6). It can be seen that the empirical formula fitted agrees well with the test results and can be used to predict the DIF value of UHPC pastes under impact loading. The fitting formula is compared with reactive powder concrete (the dynamic strength ranges from 167.36 MPa to 224.81 MPa) tested by Huang et al. [66], and it is in agreement with the test results.

Fig. 13. Stress–strain curves at four different strain rates.
good agreement, which further verifies that the model proposed in this study could be used to predict the DIF value of UHPC.

\[
DIF = 1.19\left(\log\dot{\varepsilon}_d\right)^2 - 3.79\left(\log\dot{\varepsilon}_d\right) + 4.1353.9s^{-1} \leq \dot{\varepsilon}_d \leq 170.7s^{-1} (R^2 = 0.9) \]

(6)

3.4.2. Peak strain

Peak strain is defined as the strain when the dynamic compressive stress reaches the peak, which is used to describe the deformation property. Bischoff and Perry [62] concluded that the peak strain increased with the increasing strain rate. Fig. 12 shows the relationship between the peak strain and the strain rate. The peak strain increases with the rising strain rate. This finding agrees well with the conclusion of Li et al. [67], who attribute the strain rate effect of peak strain to the development progress of cracks. With the increase of the strain rate, the failure with several macroscopic cracks were transformed into the overall failure of microscopic cracks, which improves the cumulative strain. Nevertheless, Harsh et al. [68], Harris et al. [69] and Wang et al. [70] found that the peak strain kept almost constant with the rising strain rate.

Compared with M1, the peak strain of M2 remains almost constant. However, the peak strain of M3 at the four strain rates is significantly increased compared with that of M1. Compared with M1, the peak strain of M4 increases by 14.2% when the strain rate is 139.2 s^{-1}. Compared with M1, the peak strain of M6 increases by 17.7% when the strain rate is 139.9 s^{-1}. It can be summarized that the peak strain increases with the rising of the replacement rate of GGBS and LP. This may be due to a large amount of GGBS and LP incorporation, resulting in the increase of the porosity, which is analyzed in Section 3.2. More pores are compressed during the impact process, resulting in the increase of the peak strain, which is similar to the findings of Li et al. [71], who considered that the increasing pores are expanded under the impact loading, leading to the fully development of cracks. As a result, the peak strain continually accumulated under the dynamic loading.

3.4.3. Dynamic stress-strain relationships and energy absorption capacity

The stress–strain relationships of the specimen at strain rates from 53.9 to 170.7 s^{-1} are shown in Fig. 13. All the stress–strain curves of the specimen show the same trend in the rising stage. In the initial stage, the stress increases linearly with the rising strain and rapidly reaches the peak. In the ascending phase, the slope increases with the increasing strain rate. However, there are two different trends in the descending stage. When the strain rate is low, the strain increases first and then reduces after reaching the peak stress. A similar phenomenon has been reported in the previous study [72]. The specimen is not damaged completely under the relatively low strain rate (53.9–58.8 s^{-1}); thus, the deformation has a certain recovery after the impact. Under the relatively high strain rate (58.8 – 170.7 s^{-1}), the strain increases with the decrease of stress after the peak stress is reached. All UHPC pastes show a noticeable strain rate effect, which can be ascribed to the combined effect of the Stefan effect, rate sensitivity of crack propagation and inertial effects [23]. For M1, as the strain rate increases from 56.3 to 167.8 s^{-1}, the dynamic strength increases from 167.75 MPa to 237.9 MPa, and the dynamic strength increases by 41.8%. The excellent pozzolanic reaction and filling effect of M5 have played a role in enhancing the strength, making up for the reduction of strength caused by excessive LP, which resulted in a smaller decrease in dynamic strength of M3. At the strain rate of 170.7 s^{-1}, the dynamic strength of M6 only decreases by 17.7% compared with M1. In the quaternary system, 32.5% of GGBS and 30% of LP are replaced, while the dynamic compression strength is reduced relatively slightly, which indicates that it is feasible to use GGBS and LP with large dosage in engineering applications.

In the SHPB test, the kinetic energy is absorbed in the fragmentation process of the concrete specimen [73]. Toughness is an important index to characterize the ability of the concrete to resist impact loading, which can be calculated by [74]:

\[
W = \int \sigma(\varepsilon)d\varepsilon
\]

(7)

where $W$ denotes toughness, $\sigma$ and $\varepsilon$ represent stress and strain, respectively.

With the rising of the strain rate, the energy absorption capacity increases approximately linearly, as shown in Fig. 14. It could be attributed to that the micro cracking process of UHPC evolves with the strain rate [75]. At a lower strain rate, the number of cracks generated is less, the damage degree of the specimen is lower, and the energy consumption is less. With the increasing strain rate, the number of internal cracks increases, the damage of the specimen is aggravated, and the energy absorption increases. Energy absorption capacity is a comprehensive index reflecting the dynamic strength and strain of materials [30]. Compared with M1, the dynamic strength of M2 is almost unchanged, while the peak strain is slightly larger than that of M1. As a result, the energy dissipation capacity of M2 is similar to M1, and the energy absorption value of M2 even exceeds M1 when the strain rate is 136.2 s^{-1}. Although the peak strain and ultimate strain of M3 increase, while the dynamic strength decreases, leading to a slight decline in energy absorption capacity compared with M1. Compared with M1, the energy absorption capacity of M4 decreases by 20.5%. The incorporation of 50% GGBS would lead to the decline of energy absorption capacity. The addition of GGBS increases the porosity, resulting in better deformation capacity of UHPC paste under impact loading, which is consistent with the finding in the previous study [71]. Therefore, the reduction of energy absorption capacity is limited. With the rising of GGBS and LP content, the energy absorption capacity of M6 decreased significantly compared with M1. Although the strain of M6 is greater than that of M1 at the same strain rate, the apparent decrease of its strength leads to reduced energy absorption capacity. At the strain rate of 170.7 s^{-1}, it decreases by 30.7%.

3.4.4. Failure modes

The failure modes of UHPC pastes exposed to impact loading with different velocities are shown in Fig. 15. The micro-pores and initial cracks develop together under impact, leading to the fracture of the specimen and significant brittle failure. Internal pores and initial cracks coalesce to form cracks under impact load. As the appearance of stresses exceeds the local strength of the concrete material, cracks form and
propagate in the weakest part [76]. The size and number of fragments after impact are directly related to the strain rate and quasi-static compressive strength of the specimen. As shown in Fig. 15, in the case of M1, at the strain rate 56.3 s\(^{-1}\), there are only a few visible fractures, and the dynamic compressive strength is 167.75 MPa, which increases by 10% compared with the quasi-static compressive strength. When the strain rate increases to 167.8 s\(^{-1}\), the specimen is broken into smaller fragments. M2 has almost the same damage pattern as M1. Due to the
In the work [77], apparent damage has occurred to normal strength concrete pastes at the strain rate of 33 s\(^{-1}\). At the strain rate of 33.7 s\(^{-1}\), the damage degree of ultra-high-performance cement-based material prepared by Lai et al. [70] was lower than normal concrete pastes. The UHPC paste prepared in this study began to crack at 53.9 s\(^{-1}\), while the normal concrete paste was broken into small pieces at the strain rate of 99 s\(^{-1}\). The damage degree of the UHPC paste prepared in this study was significantly lower than that of the normal strength concrete paste at the same strain rate. The denser microstructure and higher strength of UHPC pastes lead to this phenomenon. It confirms that the UHPC paste prepared in this study has excellent impact resistance.

3.4.5. Quantification of UHPC fragment distribution using fractal dimension

Fig. 16(a) shows the fragments with various sizes of M1 after sieving at 138.7 s\(^{-1}\). Based on the results of sieving test, the relationships between \(\log(M_d/M_T)\) and \(\log(d/d_m)\) of M1 are illustrated in Fig. 16(b). The correlation coefficient \(R^2\) of fitted lines is greater than 0.90, indicating that the fragment size distribution of UHPC pastes after dynamic impact exhibits a significant fractal feature. As shown in Fig. 16(b), the fractal dimension of M1 at the strain rate of 56.3 s\(^{-1}\) is 0.85 and that of M1 at 167.8 s\(^{-1}\) is 1.88. With the increasing strain rate, the number of fitting data points decreases, which indicates finer fragments are formed at a higher strain rate. It can be concluded that a higher strain rate leads to a smaller mean size and a larger values of fractal dimension, consequently resulting in a greater degree of UHPC fragmentation.

Fig. 17 shows the relationships between fractal dimension and strain rate. The fractal dimension value ranges from 0.84 to 2.51, and it universally rises as strain rate rises for all mixes. The fractal dimension exhibits significant strain rate effect, and the fractal dimension and denary logarithms of the strain rate exhibit a positive linear correlation. The correlation between them can be expressed as follows:

\[
D = a \cdot \lg \varepsilon + b
\]

where \(a\) and \(b\) are fitting coefficients. The coefficient of association all surpass 0.91, indicating that at the strain rate range of 53.9–170.7 s\(^{-1}\), the variation relationship of the fractal dimension and the denary logarithms of the strain rate can be well expressed by linear fitting equations, as shown in Table 3. The coefficient \(a\) can represent the sensitivity of fractal dimension to strain rate. With the same increase of
strain rate and the same values of coefficient $b$, the larger value of $a$ means the higher fractal dimension.

It can be clearly seen that the fractal dimension increases with the rising of GGBS and LP. Compared with that of M1 at the strain rate of 138.7 s$^{-1}$, the D of M4 at the strain rate 139.2 s$^{-1}$ increases by 15.2% and that of M6 increases by 44.3% at the strain rate 139.9 s$^{-1}$. Replacing a large amount of GGBS and LP leads to a higher porosity and a larger pore size, consequently a decrease in quasi-static strength. Thus, the fragmentation of M3 and M6 are more severe than that of M1, which is consistent with the results illustrated in Fig. 15. A similar conclusion was found in [37], in which a higher strength concrete can be assigned to a denser microstructure. Hence, a higher strength concrete possessed higher stress levels of crack initiation and expansion, resulting in a smaller fragmentation degree and fractal dimension for higher strength concrete.

4. Conclusions

In this study, MS, GGBS and LP are used to partially substitute cement to fabricate UHPC. The flow property, pore structure, quasi-static compressive strength, and dynamic compressive properties of UHPC are investigated. The main conclusions can be drawn as follows:

(1) The increase of the substitution rate of GGBS and LP increases the fluidity of UHPC paste. With the substitution rate of 10% LP, the microstructure of M2 becomes denser. The further addition of LP and GGBS increases porosity. Compared with the cement paste, the quasi-static compressive strength of the ternary system (LP replacement rate 10%) remains the same level, and the 56-day compressive strength of the ternary system (LP replacement rate 30%) is only reduced by 9.4%. The 56-day compressive strength of the binary system decreases by 14.9% when 50% GGBS is used.

(2) The UHPC paste with different SCMs exhibits a noticeable strain rate effect. Compared with the cement paste, the dynamic strength of the ternary system (with 10% LP substitution) decreases insignificantly. With the rising of GGBS and LP substitution, the dynamic compressive strength decreases while the peak strain increases. When 67.5% cement is replaced in the quaternary system, the dynamic compressive strength only decreases 17.7% compared with the cement paste, and the peak strain increases by 11.8% at the strain rate of 170.7 s$^{-1}$.

(3) A new DIF model of UHPC with different SCM systems is established at the strain rate range of 53.9 – 170.7 s$^{-1}$. The empirical results agree with experimental data in the literature, which indicates that the proposed model in this study can reasonably predict the DIF value of UHPC. The DIF value increases with the increasing substitution of GGBS and LP.

(4) Compared with cement pastes, the energy dissipation capacity of the ternary system (LP replacement rate is 10%) only decreases slightly. With the increase of the content of GGBS and LP, the energy consumption capacity decreases, but the decrease is limited. A higher strain rate leads to a smaller mean size of fragments and a larger fractal dimension. The fractal dimension has a positive linear relationship with the denary logarithms of the strain rate. The fractal dimension increases with the increment of GGBS and LP contents.

(5) Replacing 10% LP does not reduce the dynamic and quasi-static compressive strength. As the substitution rate of GGBS and LP increases, the dynamic and quasi-static compressive strength decreases, but the decline range is limited. Therefore, considering the fluidity quasi-static and dynamic compressive properties, replacing cement with GGBS and LP to prepare UHPC is suggested.


