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Test of Dynamic Mechanical Properties of Ambient-cured Geopolymer Concrete Using Split Hopkinson Pressure Bar (SHPB)

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Abstract: The application of geopolymer concrete (GPC) in construction could reduce a large amount of carbon dioxide (CO_2) emission, which is greatly beneficial to the environmental sustainability. Structures made of GPC might be subjected to extreme loading such as impact and blast loads. Therefore, a good understanding on the dynamic properties of GPC is essential to provide reliable predictions of performance of GPC structures subjected to dynamic loading. This study presents an experimental investigation on the dynamic compressive and splitting tensile properties of ambient-cured GPC using Split Hopkinson Pressure Bar (SHPB), with the strain rate up to 161.0 s^{-1} for dynamic compression and 10.3 s^{-1} for dynamic splitting tension. The failure mode and damage progress of GPC specimens, energy absorption and dynamic increase factor (DIF) were studied. Test results showed that ambient-cured GPC exhibited strain rate sensitivity. The compressive and splitting tensile DIFs increased with the strain rate and the ambient-cured GPC with lower quasi-static compressive strength exhibited higher DIFs under both dynamic compression and splitting

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tension. Empirical formulae were proposed to predict the DIF of ambient-cured GPC. Furthermore, the specific energy absorption of ambient-cured GPC under dynamic compression increased approximately linearly with the strain rate.

Keywords: Geopolymer concrete; SHPB; Compression; Splitting tension; Energy absorption; DIF

Introduction

Climate change due to greenhouse gas emission has attracted increasing attention in recent decades. The production of ordinary Portland cement concrete (OPC), one of the most widely used construction materials around the world, contributes to a large amount of greenhouse gas emission such as carbon dioxide (CO_2). The demand of OPC is still rising due to the booming of construction industry. Therefore, an alternative material with less CO_2 emission to replace OPC is deemed necessary. Geopolymer concrete (GPC), a potential alternative to OPC, uses industrial by-products such as fly ash and slag to replace cement as binder materials. The reuse of these industrial by-products can also save a lot of land areas for disposal and lead to great benefits to environment. In the past years, many studies have investigated the mechanical properties of GPC (Diaz-Loya et al. 2011; Ganesan et al. 2014; Noushini et al. 2016; Thomas and Peethamparan 2015; Xie et al. 2019). It is reported that GPC could behave similarly as OPC, or even better with respect to chemical resistance, fire resistance, chloride penetration, and freeze-thaw cycles (Li et al. 2019; Singh et al. 2015).

Concrete structures may be subjected to impact and blast loads during their service life. The failure modes and damage level of concrete structures are greatly affected by dynamic mechanical properties of concrete materials. Previous studies demonstrated that the dynamic mechanical properties of OPC is strain rate dependent (Al-Salloum et al. 2015; Grote et al. 2001; Li and Meng 2003; Lv et al. 2017; Trindade et al. 2020; Zhang et al. 2009). Under high loading rate, concrete materials exhibited a strength enhancement, including compressive and tensile strength, which could be quantified by the dynamic increase factor (DIF). The strength enhancement of concrete at high strain rate can be explained by the following reasons: (1) the Stefan effect that free water within concrete forms thin viscous films which can induce opposing viscous force to maintain the integrity of concrete (Rossi 1991a, b); (2) the inertia force that counters crack initiation and propagation, leading to lateral inertial confinement that restrains the deformation of concrete (Hao et al. 2010; Li and Meng 2003; Rossi and Toutlemonde 1996); and (3) the aggregates cleavage that cracks tend to cut through strong aggregates with short and straight paths (Brara and Klepaczko 2006; Wang et al. 2018). Over the past decades, intensive studies have been conducted to investigate dynamic mechanical properties of OPC (Al-Salloum et al. 2015; Brara and Klepaczko 2006; Chen et al. 2011; Grote et al. 2001; Kim et al. 2019; Li et al. 2009; Malvar and Crawford 1998; Zhang et al. 2009). Due to the different microstructures associated with the reaction processes between OPC and GPC, i.e. polymerization process for GPC and hydration process for OPC, dynamic mechanical properties of GPC might be different from those of OPC. Very limited studies, however, have been carried out to investigate the dynamic mechanical properties of GPC. Luo et al. (2013) and Luo and Xu (2013) conducted Split Hopkinson Pressure Bar (SHPB) tests on highly fluidized GPC with basalt fibres (with the slump of 188 mm). It is worth noting that the highly fluidized GPC had a relatively higher liquid (alkaline solution and water) content, which could lead to distinguished dynamic properties as compared to normal GPC with smaller slump. Moreover, sodium carbonate (Na_2CO_3) was used as one of alkaline solutions (the other one is sodium hydroxide, NaOH), causing different dynamic properties of GPC as compared to those of GPC activated by mixed alkaline solutions of sodium silicate (Na_2SiO_3) and NaOH (Luo et al. 2014). Feng et al. (2014, 2015) also found that the type of activators had a significant effect on the properties of GPC. Luo et al. (2014) suggested it was better to use Na_2SiO_3 and NaOH solutions as alkaline activators. Combining these two alkaline solutions as activators for geopolymer composites can also be found in many studies (Ganesan et al. 2014; Khan et al. 2018; Nath and Sarker 2014; Pham et al. 2020b; Tang et al. 2020). Tang et al. (2020) investigated the effect of recycled aggregates on the dynamic compressive properties of GPC and found that GPC with recycled aggregates exhibited higher compressive DIF (CDIF) than GPC with normal aggregates.

It is worth noting that the GPC specimens in the aforementioned studies (Feng et al. 2014, 2015; Tang et al. 2020) were heat cured at an elevated temperature (i.e. 60 ℃ or 75 ℃) for 24 h. Recently, the studies on the beams made of ambient-cured GPC under impact loads have been reported (Huang et al. 2020, 2021), but studies to quantify the dynamic mechanical properties of ambient-cured GPC, which are not necessarily the same as heat-cured GPC, are very limited. Understanding the dynamic mechanical properties of ambient-cured GPC is essential for accurate prediction of the dynamic response of such structures in numerical simulations. Therefore, it is imperative to conduct tests for quantifying the dynamic mechanical properties of ambient-cured GPC.

In the present study, ambient-cured GPC specimens were prepared and tested under quasi-static and impact loads. Dynamic compressive and splitting tensile tests on GPC specimens were conducted using SHPB. The failure mode, failure progress, energy absorption under dynamic compression, and both the dynamic compressive and splitting tensile strength were investigated. The test results of GPC from two mix designs with varying alkaline solution-binder ratios were compared and discussed. In addition, the empirical formulae were proposed to predict the CDIF and splitting tensile DIF (TDIF) of ambient-cured GPC at different strain rates.

Experimental programme

Raw materials and mix proportions

The raw materials used in this study consisted of fly ash and ground granulated blast-furnace slag (GGBS) as binder materials, sand as fine aggregates, gravels with the maximum size of 10 mm (50%) and 7 mm (50%) as coarse aggregates, and 12-M sodium hydroxide (NaOH) and D-grade sodium silicate (Na_2SiO_3) solutions as alkaline activators. **Table 1** gives two mix designs with different weight ratios of alkaline solution to binder (Deb et al. 2014; Huang et al. 2020; Tran et al. 2019). The labels of mix designs, i.e. C47 and C55, are named according to the tested compressive strength of GPC specimens. GPC C47 has been used for GPC beams subjected to impact load in the previous studies (Huang et al. 2020, 2021) whilst its dynamic mechanical properties are unknown. For comparison, GPC C55 with lower alkaline solution-binder ratio (i.e. lower workability) but higher compressive strength is also studied.

Specimens and test preparation

The mixing procedure of GPC follows the standard AS 1012.2 (2014). Cylinder moulds with two types of dimensions, i.e. 100 mm × 200 mm (diameter × height, for testing compressive strength and modulus of elasticity under quasi-static load) and 150 mm × 300 mm (for testing splitting tensile strength under quasi-static load), were used for casting the specimens. GPC cylindrical specimens were demoulded 24 h after casting and then were wrapped with cling wrap to preserve their moisture. Subsequently, these specimens were placed in a room with ambient temperature until the testing date. Quasi-static tests to determine the compressive strength (the loading rate of 0.33 MPa/s, corresponding to the strain rate of 1×10^{-4} s^{-1}), modulus of elasticity, and splitting tensile strength were conducted as per AS 1012.9 (2014), ASTM C469-14 (2014), and AS 1012.10 (2014), respectively. Cylindrical specimens with the diameter D of 100 mm and the length (or height) L of 50 mm were prepared and polished to ensure the parallel and smooth surfaces at both sides for SHPB test.

Split Hopkinson Pressure Bar tests

Fig. 1 shows the SHPB test apparatus with the bar diameter of 100 mm. It consists of an incident bar and a transmitted bar with the lengths of 5.5 m and 3.3 m, respectively. High speed camera was used to capture the failure progress of the specimens. Grease was used between the interfaces of specimen and bars to minimize friction effect. To achieve the stress equilibrium and eliminate high-frequency wave oscillation, a rubber pulse shaper was attached onto the surface of incident bar. Pressure with different levels was set to launch different impact velocities of striker bar, leading to different strain rates of specimen. Once the striker bar impacted the incident bar, the incident wave and reflected wave were recorded on the incident bar and the transmitted wave was captured on the transmitted bar.

Dynamic compressive test

For a specimen under dynamic compressive test, according to the theory of one-dimensional stress wave propagation, the stress σ, strain rate $\dot{\varepsilon}$, and strain ε of the specimen can be obtained based on the reflected wave (ε_r) and transmitted wave (ε_t) as follows (Lindholm 1964).

$$\sigma(t) = E_b \left(\frac{A_b}{A_s}\right) \varepsilon_t(t) \tag{1}$$

$$\dot{\varepsilon}(t) = -\frac{2C_b}{L_s} \varepsilon_r(t) \tag{2}$$

$$\varepsilon(t) = \int_0^t \dot{\varepsilon}(t)\, dt \tag{3}$$

where E_b and A_b are the modulus of elasticity and cross-sectional area of the bars (made of high strength steel material), respectively; C_b is the stress wave propagation velocity in the bars; A_s and L_s represent the cross-sectional area and length of the specimen, respectively.

Fig. 2 shows a typical stress equilibrium check of a dynamic compressive test with the “Transmitted” wave coinciding well with the “Incident + Reflected” wave. It is noted that the stress equilibrium has been checked for all the tests to validate the data. In this study, the strain rate was determined when the stress reached the peak value, as reported in the previous studies (Hao and Hao 2013; Li et al. 2021; Pham et al. 2020a; Yin et al. 2020).

Dynamic splitting tensile test

For a specimen under dynamic splitting tensile test, dynamic splitting tensile strength f_{td} of the specimen is proportional to the peak value of transmitted wave $\varepsilon_t(t)_{max}$ and can be calculated by using Eq. (4). Therefore, the stress rate $\dot{\sigma}$ and strain rate $\dot{\varepsilon}$ of the specimen can be estimated according to Eqs. (5) and (6), respectively (Tedesco and Ross 1993).

$$f_{td} = \frac{R_b^2 E_b}{R_s L_s} \varepsilon_t(t)_{max} \tag{4}$$

$$\dot{\sigma} = \frac{f_{td}}{\tau} \tag{5}$$

$$\dot{\varepsilon} = \frac{\dot{\sigma}}{E_s} \tag{6}$$

where R_b and E_b are the radius and modulus of elasticity of the bars, respectively; R_s, L_s, and E_s denote the radius, length, and modulus of elasticity of the specimen, respectively; τ represents the time interval of transmitted wave from the start to the peak value.

The data is only valid when the stress equilibrium is achieved. A typical stress equilibrium check of dynamic splitting tensile test is shown in **Fig. 3**, which illustrates a good agreement between the "Transmitted" wave and "Incident + Reflected" wave. In addition, it can be found that the magnitude of transmitted wave is much lower than those of incident and reflected waves, which is mainly due to the low tensile strength of the GPC specimen, leading to a significant portion of incident wave being reflected and turned into tensile wave after the failure of specimen (Khan et al. 2019). Similarly, stress equilibrium of dynamic splitting tensile tests for all the specimens were checked to ensure the valid results.

Test results and discussion

Quasi-static test results

Table 2 lists the quasi-static test results of two mix designs of GPC after 90-day curing, including compressive strength, modulus of elasticity and splitting tensile strength. The mix design C55 with lower ratio of alkaline solution to binder showed higher compressive strength, which agrees with the test results reported in the previous studies (Heah et al. 2012; Nath and Sarker 2014). It is understood that with higher alkaline solution-binder ratio, the strength of GPC decreases due to the higher content of water in the geopolymer composites, causing more blocked contact areas of polymerization reaction by water molecules and in turn leading to a lower compressive strength (Ng et al. 2018). However, it is noted that a lower alkaline solution-binder ratio would decrease the workability of GPC (Heah et al. 2012; Nath and Sarker 2014), which may lead to difficulties in mixing and compaction.

Dynamic compressive test results

Failure characteristics and progress

Fig. 4 shows the failure modes of the GPC specimens at different strain rates. It was observed that the specimens fractured into several large pieces when the strain rate was around 59.2 s^{-1} for C47 and 66.3 s^{-1} for C55. With the increase of strain rate, the specimens experienced severer damage and fractured into more numbers of small fragments. **Fig. 5** shows the failure progress of the specimens at different strain rates. Obviously, cracks appeared earlier as the strain rate increased. For example, a clear crack was observed along the axial direction of C55 specimen at 125 μs when the strain rate was 98.0 s^{-1}, whereas there was no crack observed at the strain rate of 70.3 s^{-1}. For the specimens at a relatively low strain rate, e.g., C47 at the strain rate of 48.4 s^{-1} and C55 at the strain rate of 70.3 s^{-1}, some main cracks developed and propagated along the axial direction through the whole specimens, which caused the rupture of the specimen into several relatively large pieces. At relatively high strain rate, e.g. 63.7 s^{-1} for C47 and 98.0 s^{-1} for C55, many numbers of micro cracks were observed on the surface of the specimens before 250 μs, and these micro cracks then extended and widened. Eventually, the specimens were shattered into many numbers of small fragments.

Dynamic compressive stress-strain curves and energy absorption

Fig. 6 shows the typical dynamic compressive stress-strain curves of the GPC specimens at different strain rates, which were derived from the test data according to Eqs. (1)-(3). All the stress-strain curves display a steep, almost linear increase at beginning, indicating the specimens were elastically compressed at this stage. The increase trend then slows down with a reduced slope of the stress-strain curves, which means the specimens entered into plastic deformation stage and minor damage occurred in the specimens as a result of the development of micro cracks. Subsequently, the peak stress is reached and the stress-strain curves exhibit a plateau with relatively constant stress and sharply increased strain, which indicates micro voids in the specimens were greatly compressed, leading to rapid damage accumulation of the specimens (Lv et al. 2017). Afterwards, the stress decreases faster with the increase of strain. It can be found that there is a slight decrease of strain in the tail of the stress-strain curves, e.g., C55 at the strain rate of 84.7 s^{-1}, suggesting the specimens experienced a slight recovery after separation from the incident bar. This observation can also be found in the references (Gao et al. 2015; Li and Xu 2009a, b; Luo et al. 2013; Lv et al. 2017) and it was named as “compression wave” phenomenon in the reference (Lv et al. 2017). It is more evident when strain rate is relatively low since specimens experience relatively low level of damage. With the increased strain rate, this phenomenon lessens due to severe damage of specimens. **Table 3** gives the dynamic compressive strength of all the specimens under impact loading. The dynamic compressive strength of GPC increases with the increase of strain rate, demonstrating GPC is a highly strain rate dependent material.

The energy absorption (Li and Xu 2009a; Luo et al. 2013; Su et al. 2014; Su et al. 2016) or impact toughness (Khan et al. 2018; Ren et al. 2015), which is defined as the area enclosed by the stress-strain curve, is also calculated and listed in **Table 3**. The relation between the energy absorption and strain rate is shown in **Fig. 7**. It is found that the energy absorption of C47 specimens is slightly higher than that of C55 specimens and both of them increased approximately linearly with the rising strain rate. The higher energy absorption at higher strain rate was due to more micro cracks and fracture surfaces (Ma et al. 2019; Tang et al. 2020) as illustrated in **Fig. 5**. The test data from the references (Luo et al. 2013; Tang et al. 2020) are also plotted for comparison. It is found that the trend of the energy absorption of the GPC specimens in the present study agrees with the test data of highly fluidized GPC by Luo et al. (2013). However, less energy was absorbed by the heat cured GPC specimens from the reference (Tang et al. 2020) at similar strain rate, owing to the smaller specimen size (i.e. diameter 75 mm × length 37.5 mm) as compared to the GPC specimens (diameter 100 mm × length 50 mm) in the present study. The relation of energy absorption *E* vs strain rate in the present study is fitted and given as follows.

$$\text{C47: } E = 25.21\dot{\varepsilon} - 421.73,\ 48.4\ \text{s}^{-1} \leq \dot{\varepsilon} \leq 98.3\ \text{s}^{-1} \qquad (7)$$

$$\text{C55: } E = 19.61\dot{\varepsilon} - 236.59,\ 66.3\ \text{s}^{-1} \leq \dot{\varepsilon} \leq 161.0\ \text{s}^{-1} \qquad (8)$$

Dynamic increase factor of the compressive strength

The dynamic increase factor (DIF), defined as the ratio of the dynamic strength to the static strength, is used to quantify the strength increment of concrete-like materials under dynamic loads. Concrete is a heterogeneous material, which includes mortar, aggregates, voids, and micro cracks. As mentioned in the Introduction section, three factors contribute to the increment of strength of concrete, one of which is the lateral inertial confinement induced by inertia force under dynamic loading (Hao et al. 2010; Li and Meng 2003). The lateral inertial confinement is considered as a structural effect. Therefore, the contribution of lateral inertia confinement to CDIF should be removed from the test data. Previous studies (Hao et al. 2010; Wang et al. 2018) showed that the lateral inertial confinement effect is specimen-size and density dependent. For instance, the cylindrical specimens with dimensions of 75 mm (diameter) × 37.5 mm (length), 100 mm × 50 mm, 100 mm × 100 mm, and 200 mm × 100 mm have the contribution of 0-5%, 4-13%, 13.68%, and 16.64% to dynamic strength increment, respectively. With the increase of strain rate, it increases slowly in low strain rate range but increases sharply after strain rate is higher than 200 s^{-1} (Hao et al. 2010). Since the strain rate in the present study was less than 200 s^{-1} and the specimen size was 100 mm × 50 mm, the contribution of lateral inertial confinement effect to dynamic compressive strength increment was adopted as 10%, which was also used in the reference (Pham et al. 2020a). The CDIFs after removing the lateral inertial contribution are listed in **Table 3** and illustrated in **Fig. 8**. As seen, the CDIFs of C47 are a bit higher than those of C55, which is consistent with the recommendation by CEB (1993) that OPC with lower compressive strength exhibits higher CDIF. The CDIF of C47 and C55 increased approximately linearly with the logarithm of strain rate as expressed below.

$$\text{C47}: CDIF = 1.98\log(\dot{\varepsilon}) - 1.67,\ \ 48.4\ \text{s}^{-1} \le \dot{\varepsilon} \le 98.3\ \text{s}^{-1} \quad (9)$$

$$\text{C55}: CDIF = 2.03\log(\dot{\varepsilon}) - 1.96,\ \ 66.3\ \text{s}^{-1} \le \dot{\varepsilon} \le 161.0\ \text{s}^{-1} \quad (10)$$

Fig. 9 compares the CDIFs of GPC obtained in this study and previous studies (Feng et al. 2015; Luo et al. 2013; Tang et al. 2020) with the CEB recommendation (1993) for OPC with the compressive strength of 47 MPa. It can be seen that the CDIFs of GPC from different studies (Feng et al. 2015; Luo et al. 2013; Tang et al. 2020) generally agree with the present data, and they also match well with the recommendation by CEB (1993) for OPC within the strain rate of 500 s^{-1}, although the test data from Feng et al. (2015) are a little bit dispersive. These results indicate that both the heat-cured and ambient-cured GPC have similar strain rate sensitivities, and they are also similar to those of OPC.

Dynamic splitting tensile test results

Failure characteristics and progress

Fig. 10 shows the failure modes of the specimens under dynamic splitting tension at different strain rates. As shown, all the specimens were split into two halves along the radial direction. With the increasing strain rate, more concrete was inevitably broken at both ends of the specimens. The failure progress of the specimens is shown in **Fig. 11**. Both C47 and C55 specimens show the similar failure characteristics. At low strain rate, for example 2.27 s^{-1} for C47 and 4.75 s^{-1} for C55, the cracks initiated in the middle of the specimens and could hardly be seen at 550 μs. When the time reached 800 μs, the disintegration of the specimens could be easily observed, which was characterized by a main crack in the middle of the specimens. Finally, the specimens failed into two halves with minor concrete crushing at both ends. As the strain rate increased, the disintegration occurred earlier which could be found at 550 μs for C47 specimens at the stain rate of 5.50 s^{-1} and C55 specimens at the strain rate of 9.74 s^{-1}. It should be noted that some minor cracks initiated from the edge near both ends besides a main crack. These additional minor cracks and more concrete failure at both ends caused more energy absorption by the specimens at high strain rate.

Dynamic increase factor of the splitting tensile strength

Fig. 12 shows the time histories of dynamic splitting tensile stress of C47 and C55. It is obvious that the peak splitting tensile stress of GPC increased with the strain rate, which confirms that the GPC is strain rate dependent. Moreover, the time to achieve the peak stress decreased in general as the strain rate increased. The test results of dynamic splitting tension are given in **Table 4**.

The relation between TDIF and strain rate of GPC specimens is plotted in **Fig. 13**. C47 has slightly higher TDIF than C55, which supports the recommendations by CEB (1993) and Malvar and Crawford (1998) that OPC with lower strength exhibits higher TDIF. The TDIF is nearly linearly proportional to strain rate in a logarithmical manner and the fitted curve can be expressed as

$$\mathrm{C47}: TDIF = 4.21\log(\dot{\varepsilon}) + 1.42,\ \ 2.08\ \mathrm{s}^{-1} \le \dot{\varepsilon} \le 9.80\ \mathrm{s}^{-1} \quad (11)$$

$$\mathrm{C55}: TDIF = 4.38\log(\dot{\varepsilon}) + 0.89,\ \ 3.19\ \mathrm{s}^{-1} \le \dot{\varepsilon} \le 10.33\ \mathrm{s}^{-1} \quad (12)$$

Fig. 14 compares the splitting TDIFs of GPC obtained in the present study and the previous studies (Feng et al. 2014; Luo and Xu 2013) with the CEB recommendation (1993) and the modified CEB recommendation by Malvar and Crawford (1998) for OPC with the compressive strength of 47 MPa. Besides, a predicted TDIF relation of GPC proposed by Feng et al. (2014) is also presented for comparison, which originates from the modified CEB recommendation by Malvar and Crawford (1998) based on the test data of GPC. It shows that the predictions by Malvar and Crawford (1998), CEB (1993), and Feng et al. (2014) significantly underestimate the TDIF of ambient-cured GPC with the compressive strength of 47 MPa in the present study by up to 45%, 40%, and 30% in the strain rate range of 2.0-10.0 s^{-1}, respectively. Moreover, the splitting TDIFs in the present study are higher than those from the studies by Luo and Xu (2013) and Feng et al. (2014). This considerable dispersion was also found for OPC as reported in the previous study (Malvar and Crawford 1998) that the TDIF of OPC in open literature ranged from about 1.2 to 6 at the strain rate of around 10 s^{-1}. One of the reasons could be due to the larger specimen size in the present investigation as compared to that in the previous studies (Feng et al. 2014; Luo and Xu 2013), i.e. 95 mm × 50 mm (diameter × length) in the reference (Luo and Xu 2013) and 90 mm × 45 mm in the reference (Feng et al. 2014), since it was reported that larger specimens exhibited higher TDIF under dynamic loading (Zhong et al. 2020). On the other hand, the addition of fibres in highly fluidized GPC (Luo and Xu 2013) might be the other reason since the test results (Khan et al. 2019; Li et al. 2020) showed that the concrete specimens without fibre exhibited higher TDIF than the specimens with fibres. Moreover, the distinction of the test data from different studies might also be resulted from the variations such as properties of coarse aggregates, moisture content within specimens (induced by curing conditions and mix proportions), and different types of alkaline activators that affect the microstructure of GPC.

Conclusion

In this study, dynamic properties including compression and splitting tension of ambient-cured geopolymer concrete (GPC) were examined by conducting SHPB tests, with the strain rate up to 161 s^{-1} under dynamic compression and 10.3 s^{-1} under dynamic splitting tension. Based on the test results, the main conclusions are drawn as below.

1. The ambient-cured GPC has similar strain rate sensitivity as heat-cured GPC and OPC under dynamic compression, but is more sensitive to strain rate than heat-cured GPC and OPC under dynamic splitting tension. The GPC with lower strength (or higher alkaline solution-binder ratio) is more sensitive to strain rate with higher DIF as compared to that with higher strength (or lower alkaline solution-binder ratio).

2. The CDIF of GPC in the present study at the strain rate up to 161.0 s^{-1} and splitting TDIF at the strain rate up to 9.80 s^{-1} can reach up to 2.5 and 6.0, respectively. The energy absorption under dynamic compression increases approximately linearly with strain rate, within the range of the considered strain rates. Empirical formulae for CDIF and TDIF, as well as energy absorption as a function of strain rate are derived from the test data.

3. The recommendation by CEB (1993) for OPC can reasonably predict the CDIF of ambient-cured GPC. However, the recommendation by CEB (1993) and the widely used modified CEB recommendation by Malvar and Crawford (1998) for OPC significantly underestimate the splitting TDIF of ambient-cured GPC obtained in the present study by up to 40% and 45% in the strain rate range of 2.0-10.0 s^{-1}, respectively.

Data Availability Statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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Figures

Fig. 1. Schematic diagram of SHPB setup

Fig. 2. Stress equilibrium check of the dynamic compressive test

Fig. 3. Stress equilibrium check of the dynamic splitting tensile test

Fig. 4. Failure modes of GPC specimens under dynamic compression at different strain rates

Fig. 5. Failure progress of GPC specimens under dynamic compression at different strain rates

Fig. 6. Dynamic compressive stress-strain curves of GPC specimens at different strain rates

Fig. 7. Relation between energy absorption and strain rate of GPC specimens

Fig. 8. Relation between CDIF and strain rate of GPC specimens

Fig. 9. Comparison of CDIF of GPC

Fig. 10. Failure modes of GPC specimens under dynamic splitting tension at different strain rates

Fig. 11. Failure progress of GPC specimens under dynamic splitting tension at different strain rates

Fig. 12. Time histories of dynamic splitting tensile stress of (a) C47 and (b) C55 specimens

Fig. 13. Relation between splitting TDIF and strain rate of GPC specimens

Fig. 14. Comparison of splitting TDIF of GPC

Tables

Table 1. Mix proportion of ambient-cured GPC (kg/m^3) (Deb et al. 2014; Huang et al. 2020; Tran et al. 2019)

Mix design	Coarse aggregates		Sand	Binder		Solution		Alkaline solution/binder ratio
	Maximum size: 7 mm	Maximum size: 10 mm		Fly ash	Slag	Na_2SiO_3	NaOH	
C47	598	598	644	360	40	173.7	59.4	0.6
C55	598	598	644	360	40	114.3	45.7	0.4

Table 2. Quasi-static test results after 90-day curing

Mix design	Modulus of elasticity (GPa)	Compressive strength f_c (MPa)	Splitting tensile strength f_t (MPa)
C47	34.3	47.0	4.2
C55	36.0	55.0	4.8

Table 3. Results of dynamic compressive tests

Samples	Strain rate (s^{-1})	Dynamic compressive strength (MPa)	CDIF (lateral inertial confinement removed)	Energy absorption E (kJ/m^3)
C-C47-1	48.4	87.9	1.7	937.8
C-C47-2	55.7	92.1	1.8	1125.0
C-C47-3	59.2	99.6	1.9	1057.1
C-C47-4	61.4	103.2	2.0	1389.4
C-C47-5	63.7	97.0	1.9	1237.3
C-C47-6	64.2	96.3	1.8	934.4
C-C47-7	68.6	97.2	1.9	1050.2
C-C47-8	74.8	102.9	2.0	1272.4
C-C47-9	78.1	109.3	2.1	1351.0
C-C47-10	79.3	107.1	2.1	1205.3
C-C47-11	82.3	108.2	2.1	2098.6
C-C47-12	93.9	123.2	2.4	2153.4
C-C47-13	98.3	117.9	2.3	2096.4

C-C55-1	66.3	109.8	1.8	966.8
C-C55-2	68.3	107.3	1.8	1580.3
C-C55-3	70.3	103.2	1.7	887.9
C-C55-4	78.1	117.8	1.9	1330.6
C-C55-5	84.7	116.4	1.9	1189.1
C-C55-6	95.7	125.2	2.0	1716.4
C-C55-7	98.0	127.9	2.1	1629.9
C-C55-8	110.9	136.7	2.2	2207.9
C-C55-9	117.5	138.2	2.3	1789.2
C-C55-10	161.0	151.8	2.5	2980.6

Table 4. Results of dynamic splitting tensile tests

Samples	Strain rate (s^{-1})	Dynamic splitting tensile strength (MPa)	TDIF
T-C47-1	2.08	11.96	2.9
T-C47-2	2.25	12.57	3.0
T-C47-3	2.27	12.25	2.9
T-C47-4	4.98	17.08	4.1
T-C47-5	5.08	18.74	4.5
T-C47-6	5.43	20.01	4.8
T-C47-7	5.48	19.27	4.6
T-C47-8	5.50	19.32	4.6
T-C47-9	5.56	16.69	4.0
T-C47-10	5.62	19.27	4.6
T-C47-11	5.89	20.70	4.9
T-C47-12	6.69	19.52	4.6
T-C47-13	6.83	19.34	4.6
T-C47-14	8.49	22.57	5.4
T-C47-15	9.80	25.22	6.0
T-C55-1	3.19	14.17	3.0
T-C55-2	4.61	18.36	3.8
T-C55-3	4.75	18.92	3.9
T-C55-4	7.14	21.33	4.4
T-C55-5	7.20	24.12	5.0
T-C55-6	7.42	23.51	4.9

T-C55-7	8.29	24.02	5.0
T-C55-8	8.52	23.13	4.8
T-C55-9	8.71	22.87	4.8
T-C55-10	9.32	25.31	5.3
T-C55-11	9.60	23.46	4.9
T-C55-12	9.61	25.22	5.3
T-C55-13	9.74	24.67	5.1
T-C55-14	10.33	26.18	5.5