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Dynamic tests of cemented paste backfill: effects of strain rate, curing time, and cement content on compressive strength

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Abstract This article investigates the compressive strength of cemented paste backfill (CPB) under dynamic loading. To accommodate the low impedance CPB, a modified split Hopkinson pressure bar (SHPB) system is adopted. In contrast to traditional solid steel transmitted bar, a hollow aluminum transmitted bar is introduced to reduce the impedance. With this system, the dynamic stress equilibrium is achieved, which guarantees the valid dynamic material testing condition. The dynamic tests are conducted for CPB with different cement contents and curing time. It is observed that: (1) for CPB with the same curing time and cement content, the dynamic strength increases with the strain rate, (2) for CPB with the same cement content, the dynamic strength increases with the curing time, and (3) for CPB with the same curing time and tested under similar strain rate, the dynamic strength increases with the percentage of cement. This observation can be understood by considering the hydration process of cements.

Introduction

Cemented paste backfill (CPB), a relatively new backfill technique, plays an important role in underground mines all over the world [1, 2]. From the economic and environmental considerations, the main solid component of CPB is mine tailings generated by mineral extraction processes. The additives such as Portland cement, fly ash, lime, and smelter slag are used in CPB with varying percentages from mine to mine to meet different requirements. Transportation through a pipeline was adopted as the main method to deliver CPB underground with water typically taking 15 to 30% of the total weight. During the last decade, CPB has become increasingly popular in underground mining operations for preventing caving, roof falls, supporting pillows, walls, and enhancing the recovery of pillars.

In order to provide safety while mining in adjacent stopes, CPB must remain stable during the mining operation period. The mechanical stability of CPB is thus the most important quality control parameter. The quasi-static compressive strengths of CPB were extensively investigated in the literature. Kesimal et al. [3] measured the compressive strength of CPB; the effects of cement ratio and curing time on the strength were considered. Kesimal et al. [4] later compared the short term and long term compressive strength of CPB. Klein and Simon [5] discussed the dependence of uniaxial compressive strength of CPB on the fly ash additive or selected chemical admixtures. The triaxial and uniaxial compressive strength tests of CPB were reported by Fall et al. [6]. The foregoing works came to the conclusion that the binder and the curing time are the two key factors controlling the compressive strength of CPB.

It is noted that by far the characterization of mechanical behavior of CPB has been exclusively carried out under quasi-static condition (strain rate $\sim 10^{-4}$ s^{-1}). However, CPB may be subjected to dynamic loading induced by blasting, earthquakes or rock bursts, where the strain rate involved is in the range of 10^2 to 10^3 s^{-1} [7, 8] and the peak particle velocity is usually larger than 0.1 m s^{-1} for high ground motion events [9]. It is therefore necessary to

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study the response of CPB under dynamic loading conditions.

In this work, the split Hopkinson pressure bar technique (SHPB) is adopted to examine CPB under higher strain rates. Originally developed by Kolsky [10] for testing metals, SHPB has been widely accepted as a standard testing machine for characterizing engineering materials [11]. The conventional SHPB technique is usually used to test high strength materials such as metals, rocks, and concretes, whose impedance is similar to bar materials. To measure low strength/impedance materials, Chen et al. [12] developed a modified SHPB system, which has successfully obtained the dynamic compressive behavior of silicone rubber (with strength lower than 15 MPa). This technique has been well accepted to measure the dynamic compressive strength of soft materials [13, 14]. Following this technique, a modified SHPB system is constructed to measure the dynamic compressive strength of CPB under dynamic loading, simulating the load encountered in the field due to earthquakes, blasts, and rock bursts. It is noted that for the larger and longer the specimen, the higher is the risk that the simplified assumption are not valid anymore to justify the SHPB analysis due to inertial effects [15]. This is specially the case for testing SHPB tests of concretes, where large samples are used and the failure strain is small. As described in the following section, we use pulse shaping technique to achieve a ramped loading pulse, which will ensure dynamic stress equilibrium and in addition, it will help reduce both the axial and radial inertial effects [16].

A solid knowledge of the CPB dynamic behavior in compression is vital for a rational design and a safe and efficient analysis of the stability of CPB structures. Therefore, the main objectives of this study are: to study the stress–strain properties of CPB in compression under dynamic conditions; to evaluate the influence of the cement content and to investigate the effect of curing time.

Sample preparation

The CPB used in this study consists of mine tailings, deionized water, and Portland cement. The mine tailings were provided as a filter cake from a gold mine. The filter cake is dewatered mine waste produced during the flotation and dewatering processes of gold-bearing ores. The chemical composition and particle size distribution of the tailings were reported by Klein and Simon [5]. There are ~50% of the particles smaller than 20 μm. The cement used in this study is normal Portland cement (Canadian Standards Association type 10) from Lafarge, Canada. The mineralogical and chemical compositions of the Portland cement were presented also by Klein and Simon [5].

In this article, water content was fixed at 28% of total mass. Five different Portland cement contents (1, 3, 5, 7 and 10% of solid mass) were used to study the influence of cement content on the dynamic compressive strength of CPB. Water, Mine tailings and Portland cement were mixed by a handheld electric mixer. After mixture, the fresh CPB was poured into Flotemp CPVC 4130 SDR11 pipes with inner diameter 22.04 mm, outer diameter 25 mm, and height 70 mm. Then, the pipes were sealed with water-resisting tapes and cured under ~100% humidity with room temperature. Before the experiments, samples were extracted from pipes, cut and polished into a cylindrical shape with diameter 22.04 mm and height 10 mm.

Modified SHPB system

The conventional SHPB system is composed of a striker bar, an incident bar and a transmitted bar. A gas gun launches the striker bar which impacts the incident bar and produces an elastic compression wave. The wave travels in the incident bar toward the sample. At the interface of incident bar and specimen, the incident compressive wave will separate into two waves: (i) an elastic tensile wave, which is reflected into the incident bar, and (ii) an elastic compressive wave, which is transmitted into the transmitted bar. The incident wave ε_i, reflection wave ε_r and transmitted wave ε_t are measured using strain gauges on the incident bar and the transmitter bar. Conventional SHPB technique is usually used to test high strength materials, whose impedance is similar to incident bar and transmitted bar (typically made of steel). However, the mechanical impedance of CPB is less than 10% of that of a steel bar. It is thus not appropriate to use the conventional SHPB technique to test CPB. Therefore, a modified technique is introduced [12, 17]. Instead of conventional steel bars, an aluminum solid incident bar and an aluminum hollow transmitted bar are used (Fig. 1).

During the test, we assume that the wave-motions in the bars obey 1D stress wave theory. The forces P_1 and P_2 on both ends of the specimen can be calculated:

$$P_1(t) = \mathrm{EA}_1[\varepsilon_i(t) + \varepsilon_r(t)] \quad (1)$$

$$P_2(t) = EA_2\varepsilon_t(t) \quad (2)$$

And the stress σ_s, strain ε_s and strain rate $\dot{\varepsilon}$ of the specimen are:

$$\sigma_s(t) = \frac{EA_2}{A_s}\varepsilon_t(t) \quad (3)$$

$$\varepsilon_s(t) = \frac{C}{L_0}\left\{\int_0^t \left[2\varepsilon_i(\tau) - \frac{A_2}{A_1}\varepsilon_t(\tau)\right]\mathrm{d}\tau - \int_0^t \varepsilon_t(\tau)\mathrm{d}\tau\right\} \quad (4)$$

$$\dot{\varepsilon}(t) = \frac{C}{L_0}\left\{2\varepsilon_i(t) - \frac{A_2 - A_1}{A_1}\varepsilon_t(t)\right\} \quad (5)$$

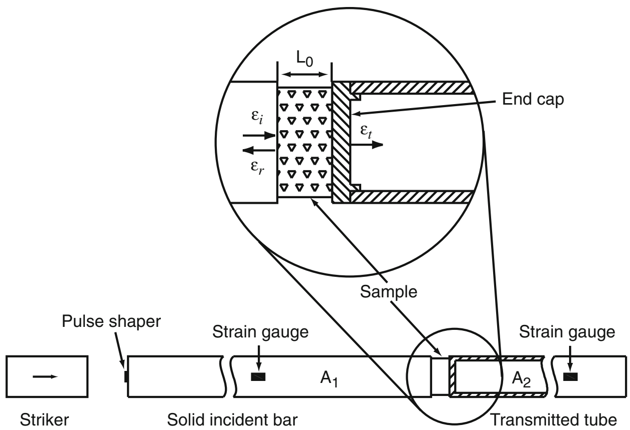


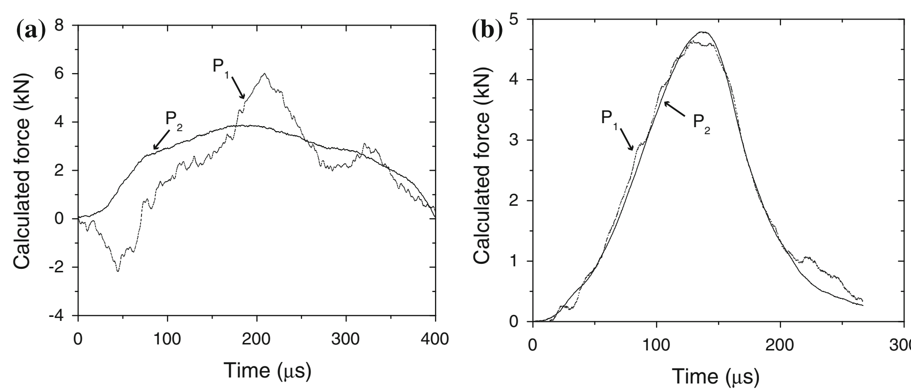
Fig. 1 Schematic of the modified split Hopkinson pressure bar system

where E and C are the Young's modulus and wave speed of the bar material, A_1 and A_2 are the cross section area of the incident bar and transmitter tube, respectively, L_0 is the length of the sample, and A_s is the area of the sample.

In our design, the striker bar, incident bar and transmitter bar are made of 6061 Aluminum, which has the modulus of 68.9 GPa, density of 2700 kg m^{-3} and wave speed of 5051 m s^{-1}. The diameter of both the striker bar and the incident bar is 25 mm. The outer diameter and inner diameter of the transmitter bar are 25 and 20 mm, respectively. The lengths of the striker bar, incident bar, and transmitter bar are 250, 3000, and 2000 mm, respectively.

To achieve the stress equilibrium of the samples, pulse shaper technique is utilized [18]. Compared with the static test, it is harder to achieve the balance of the dynamic loading forces in a dynamic test of soft materials (Fig. 2a); during the test, stress waves need three to four round-trips in the sample before the stress reaches an equilibrium state. Because the wave speed of the CPB is very low ($\sim$1500 m/s), it takes longer for the sample to reach the equilibrium state than metals. In this study, a composite pulse shaper made of a rubber disc and a copper disc was used to modify the incident wave (Fig. 1). The rubber (nature Latex) is 0.15 mm in thickness and the copper (A110) is 0.35 mm in thickness; both were purchased from McMaster-Carr. The diameter of shaper discs is 6.4 mm and the overall thickness is 0.5 mm. It can be seen from Fig. 2b that with the pulse shaper technique, the dynamic force balances and the stress equilibrium in the CPB sample during the dynamic test has been achieved.

Fig. 2 Typical SHPB test: **a** without pulse shaper, **b** with pulse shaper



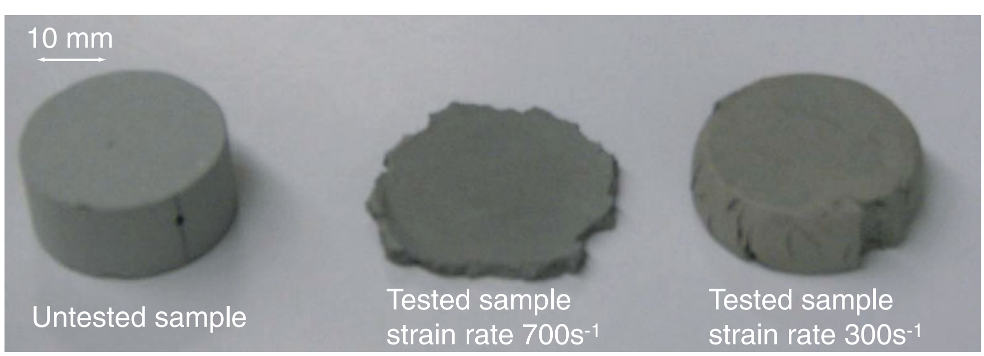


Fig. 3 Typical tested and untested samples

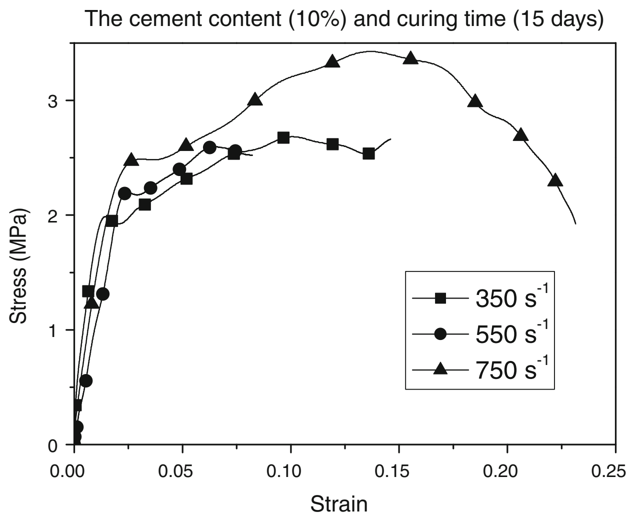


Fig. 4 Stress-strain curves of CPB (cured for 15 days, 10% cement) at different strain rate

Results and discussions

A total of 135 samples with different curing times (15, 30, and 60 days) and five types of cement content (1, 3, 5, 7, and 10% of solid mass) were tested under three different strain rates ($\sim$300, $\sim$500, and $\sim$750 s^{-1}). Three samples were tested under every test condition and the reported strength is given as the average. Figure 4 shows typical samples before and after tests. The deformation of the samples increases with the strain rate. Microcracks can be observed on the tested CPB samples (Fig. 3). Creation and accumulation of microcracks in the deforming CPB sample absorb the loading energy.

Strain rate effect

Three different strain rates were used in this work. The effect of strain rate on the stress–strain curve of CPB is illustrated in Fig. 4. For CPB samples cured for 15 days with 10% cement, the yield strength is 2.0 MPa at the strain rate of 350 s^{-1}. When the strain rate is increased to 750 s^{-1}, the yield strength is 2.5 MPa. The yield strength of CPB thus increases with the strain rate. Results for other CPB samples are summarized in Fig. 5.

For one type of CPB sample (curing time of 30 days and 5% cement) the dynamic strength values are compared with the static value (Fig. 6). The static test results were for same CPB that was prepared the same way [5], the strain rate was about 2×10^{-4}. It can be seen that the strength at high strain rates is about 4 times the static strength. The dynamic values are found to be higher than the static strength of a CPB sample with the same cement content and one year curing time (1 MPa at 10^{-3} s^{-1} strain rate). Although the strain rate enhancement of CPB on strength has not been reported elsewhere, similar results were found

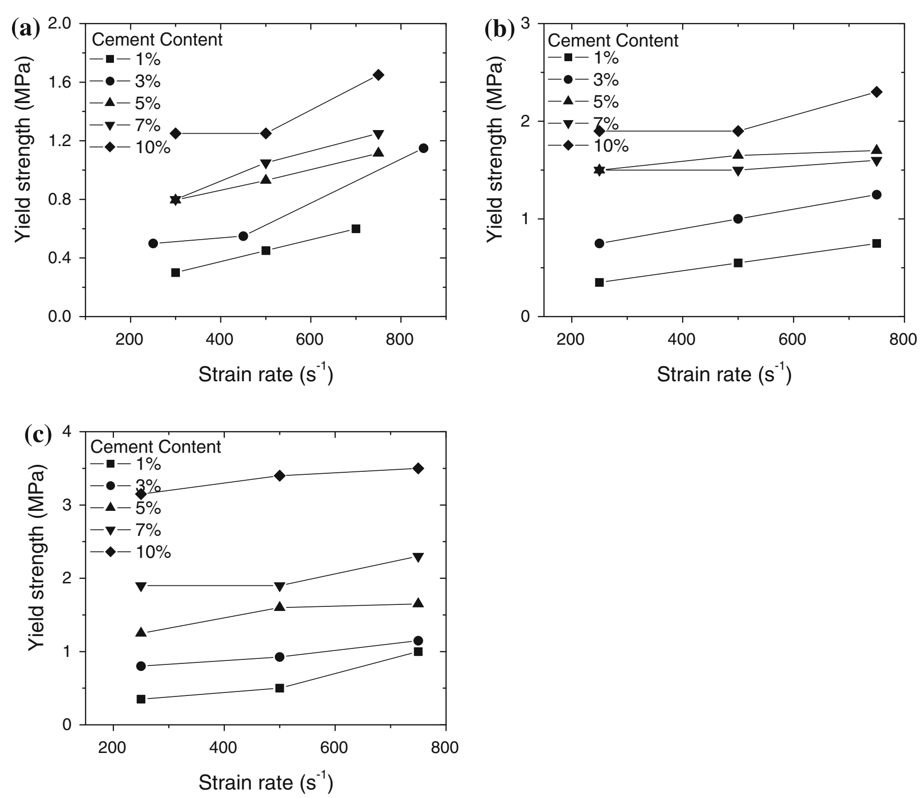


Fig. 5 Yield strength of different cement contents and strain rates for: **a** 15 curing days, **b** 30 curing days, and **c** 60 curing days

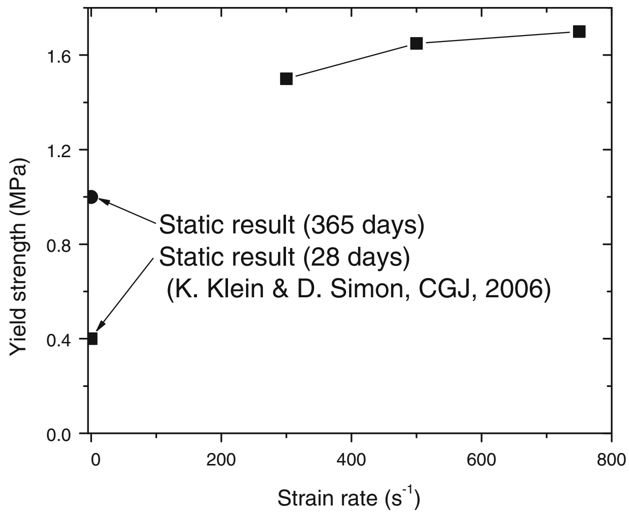


Fig. 6 Dynamic strengths (cured for 30 days, 5% cement) compared with static results

for concretes [19, 20]. For concretes, the strain rate dependent behavior was explained as a transition from the creep phenomenon under static loading to the tensile micro-cracking during dynamic loading. More microcracks generated during impacting require more energy to overcome the inertial resistance of the material. Hence compared with the static loading, dynamic failure occurs at higher stress level because of the generation of a large amount of microcracks before the onset of the major crack/failure. The strain rate effect of CPB can be qualitatively explained in the same way.

Binder effect

Existing investigations pointed out that the cement content is one of the most important factors to influence the

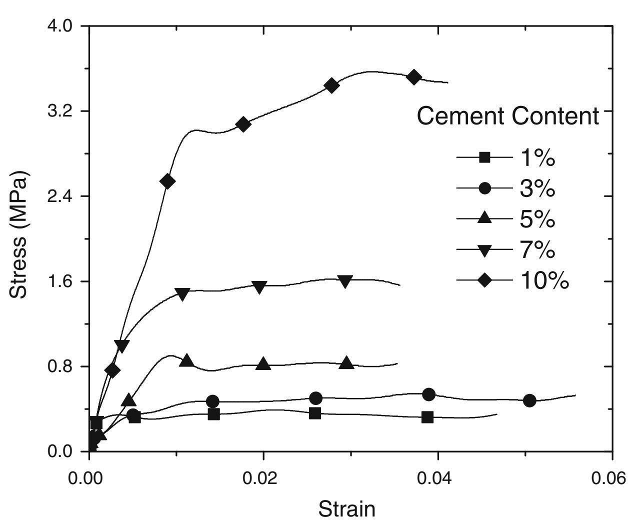


Fig. 7 The strain–stress curves of CPB cured for 30 days at 750 s^{-1} strain rate

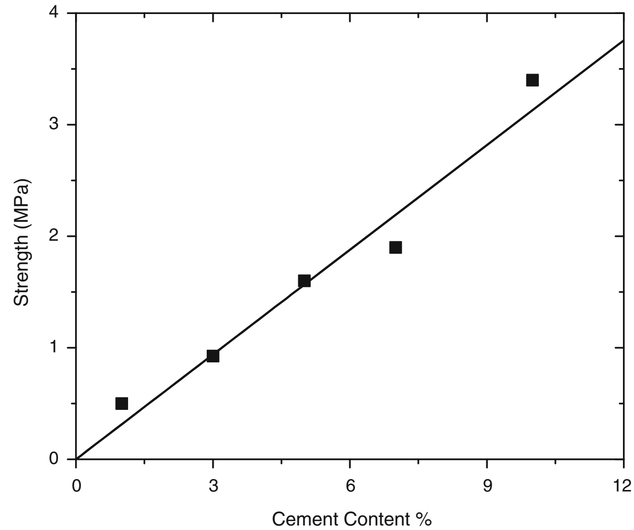


Fig. 8 The strength with different cement content cured for 60 days old at 750 s^{-1} strain rate

compressive strength of CPB [3, 5, 6]. The same conclusion can be drawn from this work: the dynamic strength of CPB increases with the cement content. Figure 7 shows the stress–strain curve of CPB with different cement content. CPB has a typical elastic–plastic behavior, and the yield strength of CPB increases with the content of cement as shown in Fig. 7. A linear fit in Fig. 8 shows that the strength of CPB is proportional to the cement content. For the same curing time and strain rate, higher binder content leads to the formation of more cement hydration products, which result in stronger CPB.

Curing effect

The effect of curing time with different cement content is shown in Fig. 9. Under the same strain rate, the strength for CPB with 1, 3, and 5% cement increases with curing time before 60 days. For CPB with 7 and 10% cement, the strength approximately increases linearly with the curing time. This observation is attributed to the hydration of cement. For CPB with low cement content, the hydration of cement nearly finished around 30 days; the strength thus does not change much afterwards. For CPB with higher cement content, there is enough cement available to be hydrated for longer curing time. The strength thus continues to increase after 60 days of curing. Ercikdi et al. [21] reported similar results on the static tests. They found that the UCS of CPB with 5% cement remains constant after 30 days, while the strength of CPB with 7% cement keeps increasing till 60 days. Klein and Simon [5] measured the shear velocity of CPB during curing to investigate the hydration progress of cement. They reported that the shear velocity of 5% CPB increases with curing time till 600 h, this study indicates that the 5% cement completes hydration

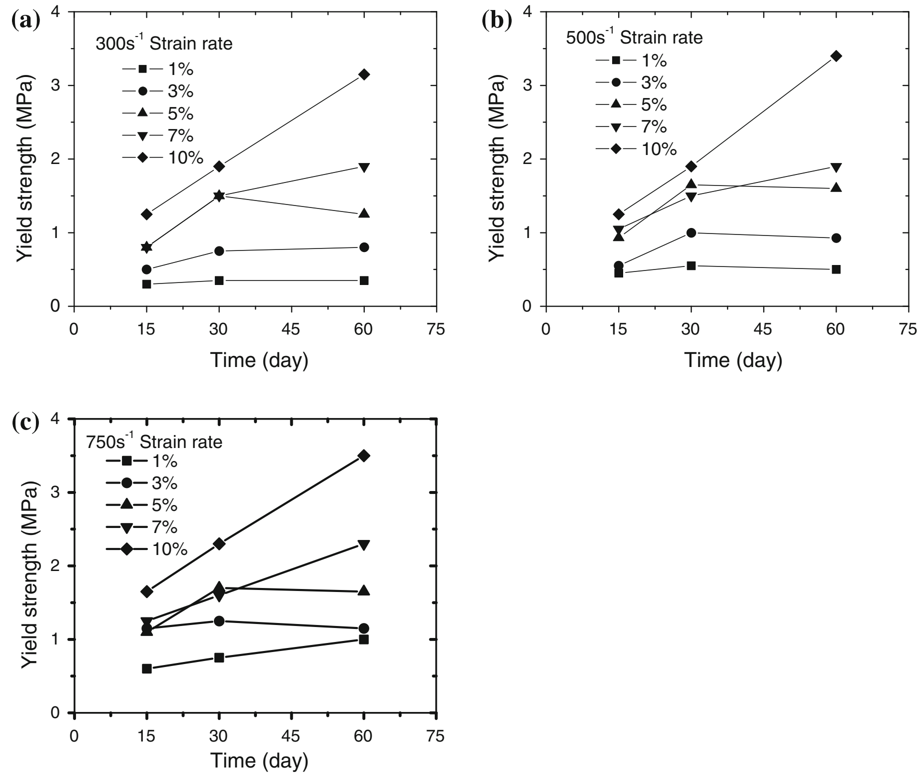


Fig. 9 Strength with different curing time at: **a** 300 s^{-1} strain rate, **b** 500 s^{-1} strain rate, and **c** 750 s^{-1} strain rate

after 600 h (25 days) of curing, which agrees very well with our results.

Conclusion

In this article, a modified SHPB technique is adopted to test the dynamic properties of CPB. This technique uses an aluminum bar as incident bar and a hollow aluminum tube as transmitted bar instead of traditional steel bar to accommodate testing of low impedance CPB. Five different cement contents of CPB are tested. From the results, CPB shows a clear strain rate effect for samples with the same curing time and cement content. The content of cement is also an important factor that influences the strength. The strength of CPB increases almost linearly with the cement content. The effect of curing time on the dynamic strength shows a saturation phenomenon. This phenomenon was explained using the hydration process of cement.

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References

1. Belem T, Benzaazoua M (2004) In: Villaescusa and Potvin (eds) The 5th International Symposium on Ground Support in Mining and Underground Construction. Taylor & Francis Group, Perth, Australia, p 637
2. Landriault D, Lidkea W (1993) In: Bawden and Archibald (eds) Innovative mine design for the 21st century: Proceedings of the International Congress on Mine Design, Kingston, Canada, p 111
3. Kesimal A, Yilmaz E, Ercikdi B (2004) Cem Concr Res 34:1817
4. Kesimal A, Yilmaz E, Ercikdi B, Alp I, Deveci H (2005) Mater Lett 59:3703
5. Klein K, Simon D (2006) Can Geotech J 43:310
6. Fall M, Belem T, Samb S, Benzaazoua M (2007) J Mater Sci 42:3914. doi: 10.1007/s10853-006-0403-2
7. Chong KP, Hoyt PM, Smith JW, Paulsen BY (1980) Int J Rock Mech Min Sci 17:35
8. Cai M, Kaiser PK, Suorineni F, Su K (2007) Phys Chem Earth 32:907
9. Kaiser PK, McCreath DR, Tannant DD (1996) Rockburst research handbook. CAMIRO Mining Division, Sudbury
10. Kolsky H (1949) Proc R Soc A B62:676
11. Nemat-Nasser S (2000) In: Kuhn H and Medlin D (eds) ASM metals handbook, vol 8: mechanical testing and evaluation. ASM International, Materials Park, p 3
12. Chen W, Zhang B, Forrestal MJ (1999) Exp Mech 39:81
13. Luo H, Lu H, Leventis N (2006) Mech Time-Depend Mater 10:83
14. Mulliken AD, Boyce MC (2006) Int J Solid Struct 43:1331
15. Li QM, Meng H (2003) Int J Solid Struct 40:343
16. Forrestal MJ, Wright TW, Chen W (2007) Int J Impact Eng 34:405
17. Chen W, Lu F, Frew DJ, Forrestal MJ (2002) J Appl Mech 69:214
18. Frew DJ, Forrestal MJ, Chen W (2002) Exp Mech 42:93
19. Fu HC, Erki MA, Seckin M (1991) J Struct Eng 117:3645
20. Bischoff PH, Perry SH (1991) Mater Struct 24:425
21. Ercikdi B, Kesimal A, Cihangir F, Deveci H, Alp I (2009) Cem Concr Res 31:268