UNIVERSITY OF LEEDS

This is a repository copy of *Effects of carbonation on mechanical properties of concrete under high temperature and impact*.

White Rose Research Online URL for this paper:
https://eprints.whiterose.ac.uk/183641/

Version: Accepted Version

Article:

Wang, J, Lord, T, Wang, Y et al. (2 more authors) (2022) Effects of carbonation on mechanical properties of concrete under high temperature and impact. Proceedings of the Institution of Civil Engineers - Smart Infrastructure and Construction, 175 (1). pp. 44-56. ISSN 2397-8759

https://doi.org/10.1680/jsmic.21.00021

© ICE Publishing: All rights reserved. This is an author produced version of an article published in Proceedings of the Institution of Civil Engineers - Smart Infrastructure and Construction. Uploaded in accordance with the publisher's self-archiving policy.

Reuse

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

White Rose
university consortium
Universities of Leeds, Sheffield & York

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk/

Smart Infrastructure and Construction (Proceedings of the ICE)

Effects of carbonation on mechanical properties of two types of concrete under extreme loadings of high temperature and impact

SMIC-2021-021-R1 | Paper

Submitted on: 06-12-21

Submitted by: Jiaming Wang, Toby Lord, Yong Wang, Leon Black, Qingming Li, Weiguo Guo, longyang chen

Keywords: CARBONATION, CONCRETE STRUCTURES, HIGH STRAIN-RATE, HIGH TEMPERATURE, SHPB

PDF auto-generated using **ReView**
from
RIVER VALLEY
TECHNOLOGIES

Effects of carbonation on mechanical properties of two types of concrete under extreme loadings of high temperature and impact

Wang et al.

ice | proceedings

Proceedings of the Institution of Civil Engineers
Pages 1–15

Keywords: Concrete/Carbonation/High strain-rate/High temperature/SHPB

ICE Publishing: All rights reserved

Effects of carbonation on mechanical properties of two types of concrete under extreme loadings of high temperature and impact

Jiaming Wang Department of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester, UK
Toby Lord School of Civil & Structural Engineering, The University of Leeds, Leeds, UK
Yong Wang* Department of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester, UK
Leon Black** School of Civil & Structural Engineering, The University of Leeds, Leeds, UK
Q.M. Li Department of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester, UK
Weiguo Guo School of Aeronautics, Northwestern Polytechnical University, Xi'an 710072, China
Longyang Chen School of Aeronautics, Northwestern Polytechnical University, Xi'an 710072, China

This paper presents the results of an experimental study to investigate changes in mechanical properties of two types of concrete under normal and extreme loading conditions pre- and post-carbonation. Specimens of CEM I and CEM II concrete (concrete prepared with 20% replacement cement with PFA) were cured for 28 days before accelerated carbonation under 4% CO_2 for 28 days at 20 °C and 57% relative humidity. Static compressive mechanical tests at ambient temperature were carried out for both concrete types. For CEM I concrete, static compressive mechanical tests were performed at elevated temperatures of 300, 500 and 650 °C, and high strain-rate tests at ambient and elevated temperature of 500 °C. The results show that the mechanical performance of CEM I concrete was improved after carbonation, i.e. increase of static compressive strength at ambient and elevated temperatures, and higher dynamic strength than fresh concrete at the same strain-rate at both ambient and elevated temperatures. However, CEM II concrete suffers reductions in compressive strength after carbonation.

1. Introduction

At £8.8 billion, the cost of repair and maintenance of existing infrastructure in the UK is about 30% of the UK's total annual infrastructure spend (Martin (2018)). While safety of aging infrastructure is of paramount importance, unnecessary repair and strengthening is costly, so should be avoided. Making a well-judged decision on the critical issue of cost-effective repair and maintenance of the nation's infrastructure demands a thorough understanding of long-term infrastructure material performance. Concrete is the most widely used infrastructure material. Over its lifetime, concrete may react with atmospheric CO_2 in a process known as carbonation. This process causes changes in phase assembly, porosity and pore size distribution, which in turn affects its mechanical performance (Šavija and Luković (2016)).

The hydration of Portland cement in concrete produces calcium hydroxide, (also known as portlandite, or CH in standard cement nomenclature). Subsequently, carbon dioxide dissolved in pore water may react with portlandite to produce calcium carbonate, which precipitates in the pore space. Since the volume of $CaCO_3$ is greater than that of portlandite, the porosity of concrete is reduced, leading to increases in strength. However, other phases within the hardened cement paste are also susceptible to carbonation. Their carbonation may lead to increases or decreases in volume. Therefore, overall changes in performance are dependent on the phase assemblage of the hardened cement paste.

To reduce the environmental impact of concrete and to alleviate the problem of thermal cracking during cement hydration, pulverised fuel ash (PFA) or fly ash, an industrial by-product of pulverized coal combustion, has been used to replace some of the OPC in cement for about the past 50 years (Teychenne´ *et al.* (1975)), and replacement of about 20% of the Portland cement with PFA is common, constituting a CEM II concrete. In such systems, portlandite is consumed by PFA in the pozzolanic reaction to yield more calcium silicate hydrate. Carbonation of such systems can thus lead to slight shrinkage, typically less than 1% (Kamimura *et al.* (1965)) and an increase in porosity due to abstraction of calcium from the calcium silicate hydrate structure. While the addition of silica fume to concrete has been shown to reduce carbonation shrinkage (Persson (1998)), this fell outside of the immediate scope of this paper.

There have been some studies investigating the effects of carbonation on the mechanical properties of CEM I and CEM II concrete under quasi-static loadings (e.g. Šavija and Luković (2016); Ashraf (2016)). Chang *et al.* (2003) reported that the compressive strength, split tensile strength and elastic modulus of CEM I concrete were all enhanced after carbonation.

Many types of infrastructure are at risk of fire and explosion, which can happen in isolation or simultaneously. Studies of mechanical properties and microstructure changes of fresh concrete at high temperatures (Ma *et al.* (2015); Klingsch *et al.* (2009); Novak and Kohoutkova (2018); Fan *et al.* (2019); Zhai *et al.* (2017); Su *et al.* (2014); Liang *et al.* (2019)) indicate that the compressive strength of fresh concrete is maintained or increases slightly from room temperature to about 300 °C; then decreases dramatically between 300 and 800 °C; and is almost completely lost at temperatures above this. Furthermore, with increasing temperature, porosity and pore sizes increase; the hardened cement matrix expands first then shrinks with increasing temperature due to loss of water, which is lost completely at 400 °C. Meanwhile aggregates expand with increasing temperature. These effects of high temperatures tend to oppose those of carbonation for CEM I concrete.

The dynamic behaviour of concrete at high strain-rates is important for impact and blast loads. The Split Hopkinson Pressure Bar (SHPB) test is widely used to determine the dynamic compressive strength of concrete-like materials (Davies and Hunter (1963); Sudheera *et al.* (2018)) although structural effects, such as specimen geometry (i.e. diameter), end interface friction and material inertia, may influence the determination of unconfined uniaxial compressive strength in a SHPB test (Li and Meng (2003); Zhang *et al.* (2009); Li *et al.* (2009); Flores-Johnson and Li (2017)). In the present study, SHPB testing results was used directly to demonstrate the effect of carbonation on concrete's dynamic behaviour.

Carbonation also affects concrete's high-temperature performance. It is known that portlandite decomposes at about 450 °C, while calcite does not decompose until about 700 °C. Thus, while non-aged concrete is expected to show loss of strength as portlandite decomposes, this strength loss may not be observed in carbonated specimens. Given that the effects of carbonation and high temperature may oppose one another, there is a need to investigate how carbonation and high temperature effects interact. Furthermore, there is a paucity of research to investigate performance of aged/carbonated concrete under extreme loadings of high temperatures and high strain-rates. When designed for protection against accidental loading, the current practice uses mechanical properties of fresh concrete. It is necessary to investigate whether this is safe and the conditions that this practice can be applied. This is the main focus of this paper.

This paper will present some preliminary results of mechanical properties of CEM I and CEM II concretes at ambient and elevated temperatures with and without high strain-rate effects.

2. Materials and experimental procedures

2.1. Materials

As mentioned, this research investigates concrete prepared from CEM I and CEM II (CEM I with 20% replacement with PFA), prepared with 5mm quartzite aggregate. The concrete was designed according to the method of Teychenne´ *et al.* (1975) to achieve a characteristic cube strength of 20 or 40 MPa, designated

Table 1. The mix design of concrete specimens (unit: kg/m³)

Concrete type	Water	OPC	PFA	Aggregate
CEM I 20 MPa concrete	225	343	-	1716
CEM I 40 MPa concrete	230	493	-	1555
CEM II 20 MPa concrete	210	246	88	1797

(a) RDP Howden Stiff Tester (b) Hoek triaxial loading cell

Figure 1. Experimental setup for uniaxial quasi-static compression tests

hereafter as C20 and C40 respectively. Water/cement ratios were chosen to achieve the required characteristic strength with constant workability. No superplastisizer was added in the tested concrete. For CEM I concrete, two concrete strengths were used. Table 1 provides detailed information of mix designs. Concrete was cast into cylindrical moulds of 50 mm diameter and 100 mm length, ensuring a 10:1 sample to aggregate size ratio. The 50 mm diameter was chosen to facilitate complete specimen carbonation. After 7 days curing at 99 ± 1% RH and 20 ± 1 °C, the specimens were moved to ambient laboratory conditions and cured for further 21 days.

After 28 days, half of the specimens underwent accelerated carbonation for 28 days, at 4 ± 0.5% CO_2, and 57 ± 5% RH. These conditions are optimum to accelerate carbonation while simulating natural carbonation reactions (Leemann and Moro (2017)). The non-carbonated control samples were stored under laboratory ambient conditions. Both CEM I and CEM II C20 concrete specimens were fully carbonated after exposure, while the CEM I 40 MPa concrete specimens were subsequently found to require exposure for 35 days to reach full carbonation (but were still tested after 28 days).

2.2. Experimental set-up and methodology

Tables 2-4 summarise the quasi-static and impact experiments and their results. For each concrete, three specimens were tested under quasi-static loading at ambient temperature, one or two specimens were tested at elevated temperatures, as indicated in Tables 2 and 3. Only one specimen was tested in SHPB experiments.

It is possible for concrete to be subject to multi-axial loading condition. Therefore, the effect of confinement was investigated in this research. However, in this study, the confinement stress could only be applied by a cylindrical load cell for the cylindrical test specimens. It was not possible to apply confinement stress to the 100 mm cubes.

The quasi-static loading experiments were carried out via an RDP Howden Stiff Tester, as shown in Fig. 1 (a), under unconfined and

Table 2. Summary of test specimens and results for quasi-static (Q-S) testing at ambient temperature

Concrete grade	Carbonation	Q-S strength (MPa)	Q-S critical strain	5 MPa Confinement
CEM I C20 cylinder	fresh	22.5±3.8	0.00196±0.0005	-
		66.7±2.3	0.02109±0.0087	confined
	carbonated	26.0±1.9	0.00159±0.0007	-
		87.6±11.8	0.04223±0.0263	confined
CEM I C40 cylinder	fresh	41.3±2.1	0.00197±0.0008	-
	carbonated	54.1±6.1	0.00206±0.003	-
CEM II C20 cylinder	fresh	34.4±5.1	0.00200±0.006	-
		62.0±4.5	0.01351±0.0081	confined
	carbonated	26.3±7.0	0.00273±0.0007	-
		58.7±0.0	0.01663±0.0000	confined
CEM I C20 disk	fresh	27.9±0.7	-	-
	carbonated	28.3±0.3	-	-

Table 3. Summary of specimens and results for quasi-static (Q-S) loading tests at elevated temperatures

Concrete grade	Carbonation	Q-S strength (MPa)	Q-S critical strain	T (°C)
CEM I C20 cube	fresh	33.8±0.0	0.0025±0.0000	20
		31.6±0.3	0.0067±0.0018	300
		24.9±3.1	0.0303±0.0044	500
		22.1±0.0	0.0404±0.0000	650
	carbonated	35.9±0.0	0.00312±0.0000	20
		40.4±2.3	0.0107±0.0054	300
		46.2±3.0	0.0069±0.0063	500
		37.6±0.0	0.0185±0.0000	650

Table 4. Summary of specimens and results for SHPB tests at ambient and elevated temperatures on CEM I 20 MPa concrete disk specimens

Carbonation	Strain-rate (s^{-1})	Dynamic strength (MPa)	Dynamic critical strain	T (°C)
fresh	50	36.4	0.01586	20
	100	41.4	0.01843	
	200	43.6	0.04197	
	300	44.1	0.06044	
	450	50.7	0.08040	
	550	65.6	0.10257	
	200	41.4	0.00970	500
	450	62.9	0.01535	
carbonated	50	39.2	0.01215	20
	100	37.0	0.03581	
	200	48.5	0.03466	
	300	46.9	0.05347	
	450	48.5	0.08249	
	550	69.5	0.11551	
	100	33.6	0.02238	500
	200	46.3	0.01890	
	300	45.8	0.02542	
	450	59.0	0.01948	

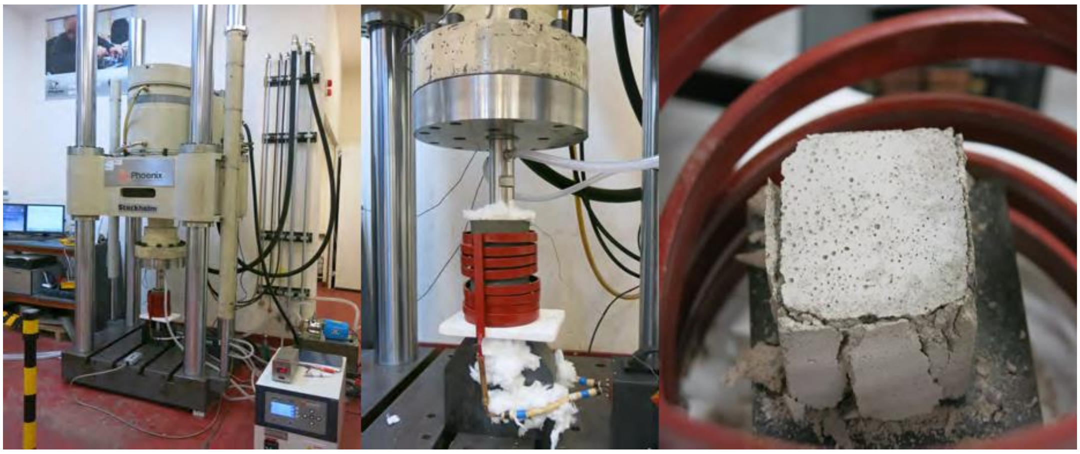

(a) Experimental setup (b) Induction heating (c) Concrete specimen

Figure 2. High temperature testing facility with induction heating

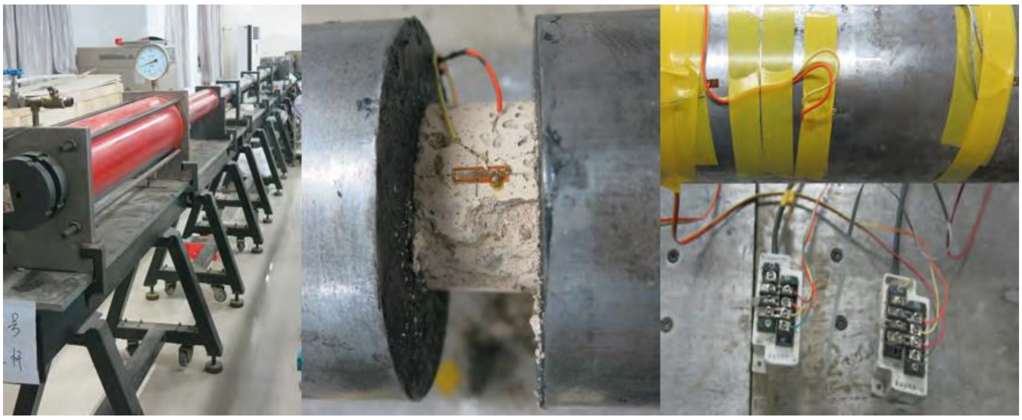
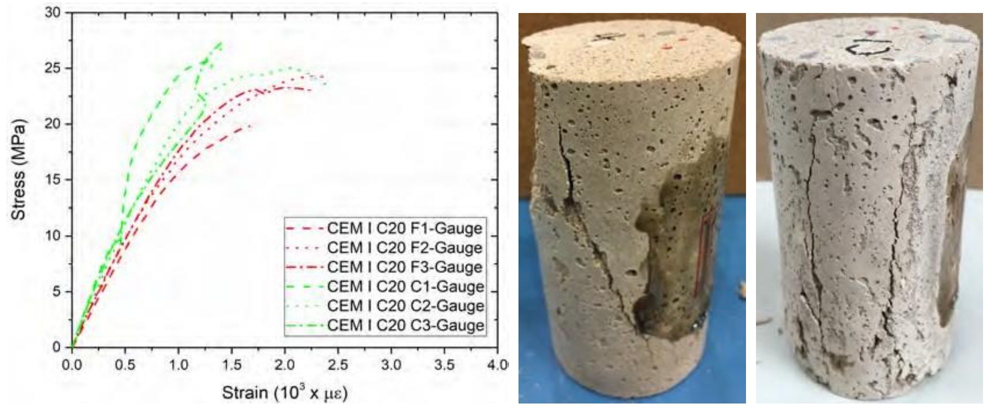

(a) SHPB apparatus (b) Concrete specimen (c) Strain gauges

Figure 3. a) Split Hopkinson Pressure Bar system and strain gauges on b) concrete specimen and c) incident/transmission bar

confined conditions as indicated in Table 2. For the tests with a confinement stress of 5 MPa, the confinement stress was achieved using a Hoak pressure cell confinement sleeve (see Fig. 1 (b)). The unconfined and confined compressive loading rate was 2 mm per minute.

20 mm long strain gauges were attached to the concrete specimens at the mid-point on opposite sides of the cylinder samples. Both force and strain data were recorded. Displacements measured in mechanical tests consisted of specimen and loading frame deformation. The actual displacement of the specimen was determined after correction for other displacements associated with machine compliance (Gruber (2018)).

Concrete compression at elevated temperatures was carried out on 50 mm cubes in the high temperature testing facility by induction heating, as seen in Fig. 2. No confinement stress was applied. Specimens were heated to 300, 500 and 650 °C. To check



(a) CEM I 20 MPa concrete (b) Fresh sample (c) Carbonated sample

Figure 4. (a) Stress-strain curves and (b-c) failure patterns of fresh (F1-F3) and carbonated (C1-C3) CEM I 20 MPa concrete under unconfined compression

temperature uniformity within the sample, a hole was drilled in the centre of each specimen and a wire thermocouple was installed inside. The heating rate was 10 °C per minute, with the specimens held at the target temperature for 30 minutes, following a similar procedure to Chen *et al.* (2015). Afterwards, mechanical loading was applied at a rate of 2 mm per minute. Load-displacement curves obtained by linear variable displacement transducers (LVDT) were converted into stress-strain curves after removing any machine deformation.

The high strain-rate loading experiment was carried out using an SHPB facility, as shown in Fig. 3 (a). Disk samples with size D50*30 mm were obtained by cutting a 100 mm length cylinder into three. Special care was taken to ensure that the two ends of the specimen were parallel with each other and perpendicular to the disk axis. Strain-rates varying from 50 to 550 s^{-1} were applied. Molybdenum disulfide lubricant was evenly smeared on the end surfaces of the incident and transmitted bars attached with the specimen, as shown in Fig. 3 (b), to minimize any structural effect due to interface friction at the ends (Flores-Johnson and Li (2017)). 10 mm semiconductor strain gauges were installed on the D50*30 mm concrete disk, and the incident and transmitted bars. Pulse shaper made of thin copper sheet was attached to the impact end of the incident bar in order to generate a ramp pulse with sufficient raising time to ensure that the stress balance was achieved in the specimen to ensure valid SHPB test (Chen *et al.* (2013); Lv *et al.* (2017); Hassan and Wille (2017)).

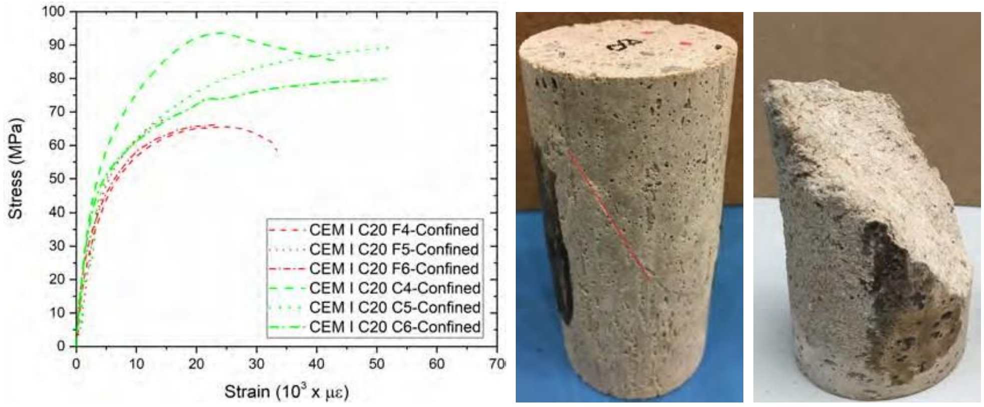
Any inaccuracy of measurement, i.e. strain at ambient or high temperatures under quasi-static or dynamic loading, or temperature, is less than 1% of the recorded value.

3. Results and discussion

3.1. Quasi-static loading results at ambient temperature

Figures 4-8 present detailed results of stress-strain curves and failure modes for the quasi-static loading results of unconfined fresh (hardened) and carbonated concrete for different cement types and strength grades. Tables 2 and 3 summarise the recorded compressive strengths.

For CEM I 20 MPa concrete, carbonation led to increases in both compressive strength and Young's modulus, as noted previously (Hussain *et al.* (2017); Ashraf (2016)). The extent of the increase in strength and Young's modulus is dependent on the degree of carbonation (Hussain *et al.* (2017)). The fully carbonated specimens in this study showed, from Figure 4 (a), increases of 16 and 19% respectively. This compares to a 25% increase in compressive strength observed by Hussain *et al.* (2017), following exposure to 5% CO_2. In both instances, carbonation was complete, but in this study, the mass of paste constituted a slightly smaller proportion



(a) CEM I 20 MPa concrete (b) Fresh sample (c) Carbonated sample

Figure 5. (a) Stress-strain curves and (b-c) failure patterns of fresh (F4-F6) and carbonated (C4-C6) CEM I 20 MPa concrete under confined compression

than in the work of Hussain *et al.* (2017) (25 vs 27%). Figure 4 (b) shows a diagonal crack running in the direction of the loading, indicating failure by shear for the fresh concrete specimen, but the crack direction for the carbonated specimen was in the direction of loading. Vertical cracking of the carbonated specimens was possibly due to the smoother specimen end surfaces after carbonation. This reduced friction between the loading platens and the specimen (Talaat *et al.* (2021)). However, the inclined angle to the horizontal for the carbonated specimen is so large that the crack is almost vertical.

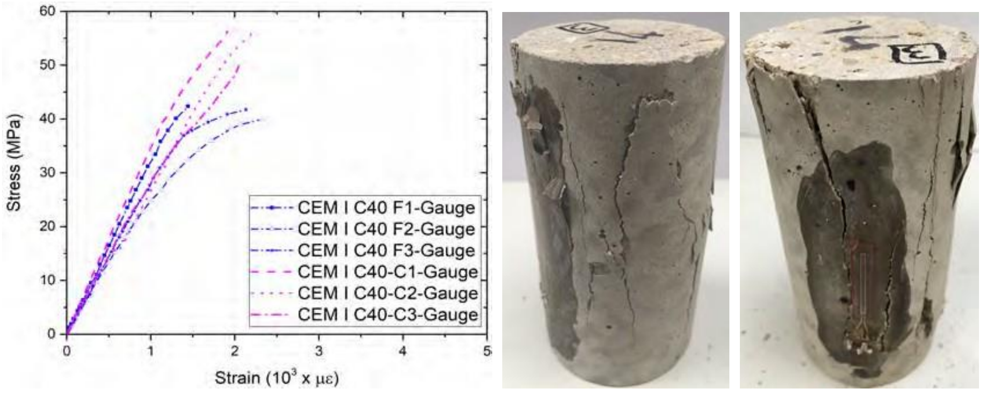
Figure 5 presents results for confined CEM I 20 MPa concrete, which should be compared with the results in Figure 4 for unconfined concrete. The effects of carbonation are similar, with increases of 31% and 11% in compressive strength and Young's modulus respectively. But remarkably, just 5 MPa confinement stress resulted in approximately three-fold increase in compressive strength. This is similar to the results reported by others such as Wang *et al.* (2016)) who tested concrete compressive strength under varying confining stress and found that the compressive strength increased to 3 to 7 times of that of unconfined concrete when the confining ratio (the ratio of confining stress to unconfined concrete strength) increased from 0.5 to 2. This is also in agreement with calculated results based on the equation relating compressive strength of confined (f_{cc}) and unconfined concrete (f_c) (Wang *et al.* (2016)):

$$\frac{f_{cc}}{f_c} = 1 + k * \frac{f_{con}}{f_c} \quad (1)$$

where f_{con} is the confining stress, and k = 30 for fresh concrete and k=50 for carbonated concrete (Wang *et al.* (2016)). Using this equation gives f_{cc}/f_c ratios of 2.74 and 3.26 respectively for fresh and carbonated concrete.

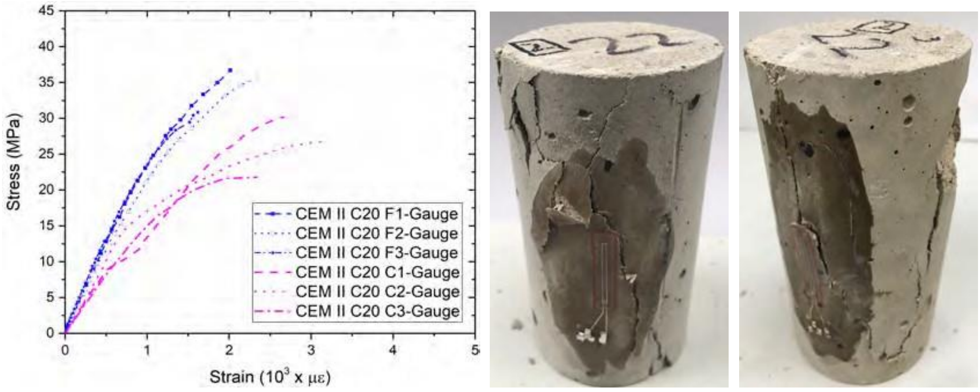
Due to lateral confinement, the failure mode in both fresh and carbonated specimens was shear failure (Figure 5 (b-c)), because the angle between the crack line and the horizontal is much smaller than that of the unconfined specimens in Figure 4 (b-c).

The denser microstructure of the 40 MPa CEM I concrete (Figure 6) meant that its carbonation depth was less than that of the weaker specimen. This correlates with a lower increase in Young's modulus of 7% after carbonation, compared to a 19% increase in CEM I 20 MPa concrete. However, this contrasts with the compressive strength data, with carbonation leading to 31% increase in compressive strength compared to a 16% increase upon carbonation of the weaker specimen. Nevertheless, it is more important to note the increase in strength and stiffness upon carbonation of CEM I concrete rather than the exact values, because the extent of the increase, in all cases, is modest. The failure patterns of unconfined CEM I 40 MPa concrete are similar to those of



(a) CEM I 40 MPa concrete (b) Fresh sample (c) Carbonated sample

Figure 6. (a) Stress-strain curves and (b-c) failure patterns of fresh (F1-F3) and carbonated (C1-C3) CEM I 40 MPa concrete under unconfined compression



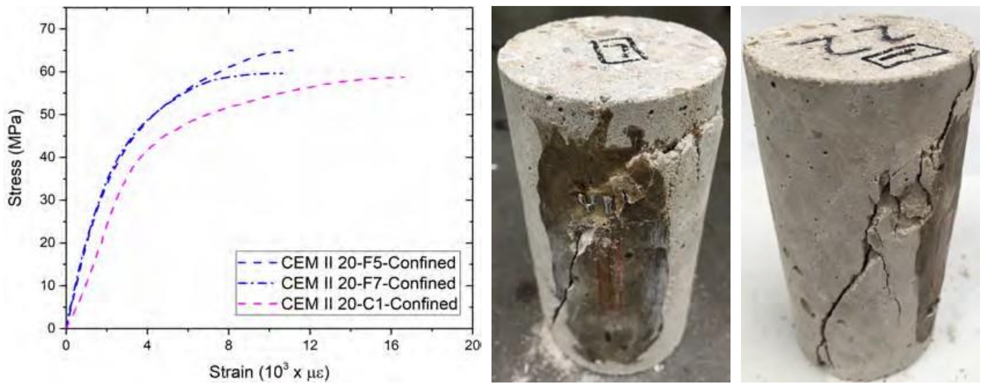
(a) CEM II 20 MPa concrete (b) Fresh sample (c) Carbonated sample

Figure 7. (a) Stress-strain curves and (b-c) failure patterns of fresh (F1-F3) and carbonated (C1-C3) CEM II 20 MPa concrete under unconfined compression

unconfined CEM I 20 MPa concrete, with cracks in the loading direction (vertical).

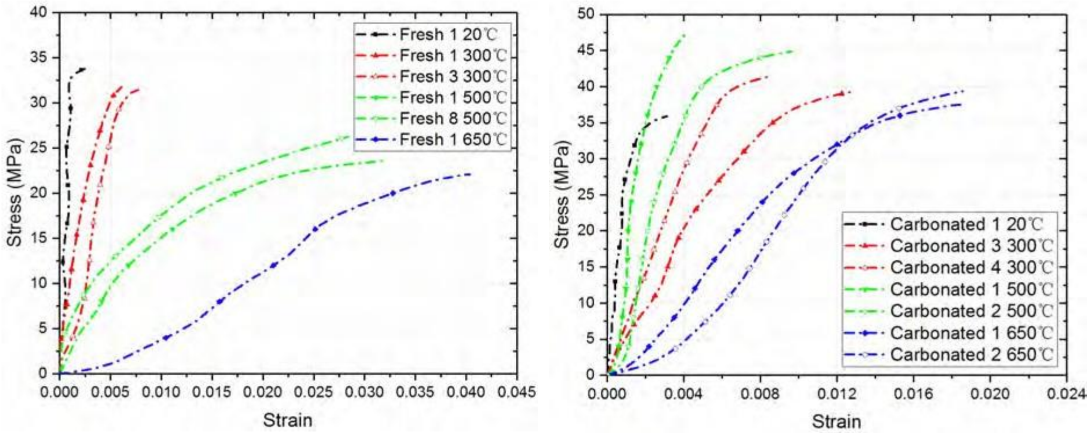
To summarise, carbonation of CEM I concrete leads to modest increases in compressive strength and elastic modulus. Because of uncertainty in the degree of carbonation in real life, it is unlikely that such modest increase would be taken into consideration in quantitative assessment of carbonated CEM I concrete load carrying capacity. However, what is more important is that it can be taken for granted that CEM I concrete structures will not suffer reduction in load carrying capacity after carbonation.

In contrast, the CEM II concrete suffered a decrease in compressive strength and elastic modulus after carbonation, as shown in Figure 7 for the unconfined specimen. The post-peak part of the stress-strain curve is not shown in Figure 7, therefore the peak stress is taken at the very end of the stress-strain curve shown here. As explained earlier, the portlandite in CEM II concrete is consumed by PFA during hydration and carbonation of C-S-H leads to shrinkage.



(a) CEM II 20 MPa concrete (b) Fresh sample (c) Carbonated sample

Figure 8. (a) Stress-strain curves and (b-c) failure patterns of fresh (F5, F7) and carbonated (C1) CEM II 20 MPa concrete under confined compression



(a) Fresh concrete (b) Carbonated concrete

Figure 9. (a) Stress-strain curves of fresh and (b) carbonated CEM I C20 concrete cubes at 20, 300, 500 and 650 °C

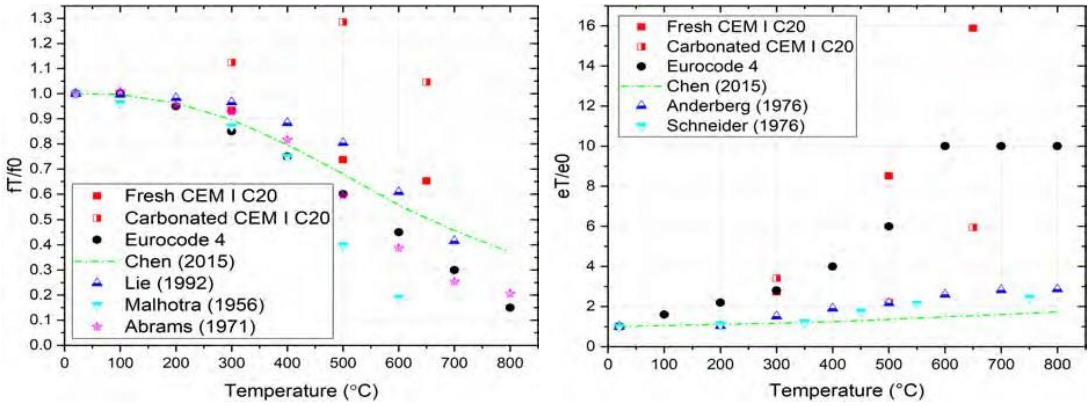
Therefore, carbonated CEM II concrete will increase porosity, resulting in reduction in strength and stiffness. These results are contrary to those of Hussain *et al.* (2017) who observed modest increases in compressive strength (20%) and in elastic modulus (9%).

Confinement has similar effects on CEM II concrete as on CEM I concrete, as seen by comparing Figures 7 and 8 with Figures 4 and 5, with an increase in compressive strength and elastic modulus, plus a change in crack pattern, upon confinement.

It is important to note that this study deliberately designed concretes which would carbonate completely so as to assess the impact of carbonation. In practice, this should not occur in infrastructure. However, given the widespread use of PFA in concrete over the past 40-50 years, there is a need to consider possible reductions in concrete's mechanical properties due to carbonation.

3.2. High temperature loading results

Figure 9 shows the stress-strain curves of fresh and carbonated CEM I 20 MPa concrete under compression at 20, 300, 500 and 650



(a) Normalized compressive strength (b) Normalized critical strain

Figure 10. Relationship between temperature and a) normalized quasi-static compressive strength and b) normalized critical strain at peak stress

°C. The average compressive strength of the fresh cube specimens at 20 °C was 33.8 MPa, increasing by 6% to 35.9 MPa after carbonation. For fresh concrete, there was a gradual reduction in peak compressive stress with increasing temperature similar to that described in Eurocode EN 1994-1-2 and by others (Chen *et al.* (2015); Lie (1992); Malhotra (1956); Abrams (1971); Anderberg and Thelandersson (1976); Schneider (1976)).

Meanwhile, the carbonated CEM I concrete showed a different behaviour as a function of temperature (Figure 10 (a)). Increasing the temperature to 300 and then 500 °C led to an increase in peak stress. While the fresh specimens showed a reduction in performance due to the decomposition of portlandite from about 450 °C, the conversion of portlandite to calcite upon carbonation meant that there was no such decomposition in the carbonated specimens, and the only changes would have been the removal of water from the hydrated cement paste. This will lead to slight contraction of the specimens. However, by 650 °C (the onset of carbonate decomposition) peak stress started to drop a little.

Figure 10 (b) indicates that the recorded strains at peak stresses of this research for both fresh and carbonated concrete are similar at elevated temperatures and follow those in Eurocode EN 1994-1-2. However, they are higher than those from a few other researchers (Chen *et al.* (2015); Anderberg and Thelandersson (1976); Schneider (1976)). The failure patterns of fresh and carbonated concretes are similar at different temperatures, as shown in Figure 11.

3.3. High strain-rate loading results

The SHPB tests were carried out 6 months after the concrete was cast due to late delivery of the testing facility. To eliminate any effect of storage on strength, control specimens of CEM I 20 MPa concrete were tested under uniaxial compression just before the SHPB test, and their results are compared in Fig. 12. They indicate that there was very little change in both compressive strength and elastic modulus of the fresh concrete (less than 5%) after 6 months storage. This is expected with a CEM I system, where a degree of hydration approaching 90% would be expected after 28 days (Whittaker *et al.* (2014)).

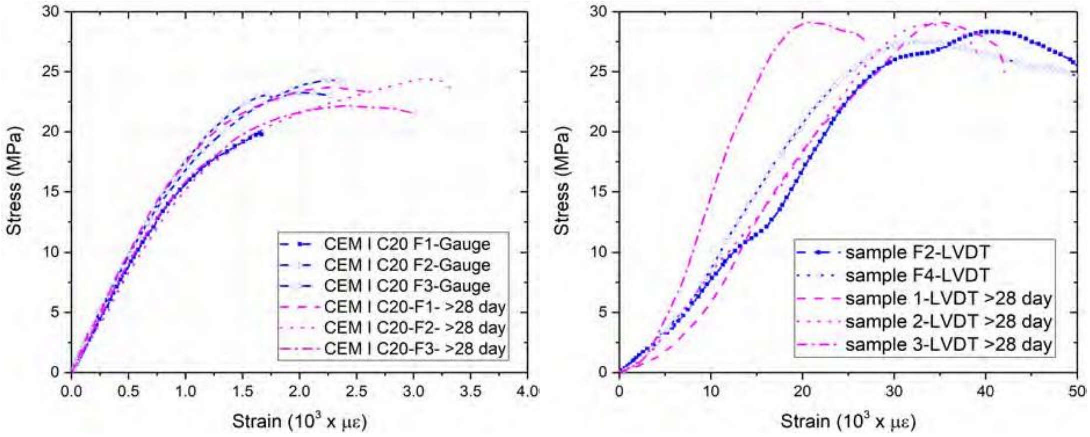
Cylindrical concrete specimens were required in SHPB experiments, with cylinders used for quasi-static testing and disks for dynamic testing. The cylinders had the same diameter as the disks but with a length/diameter (L/D) ratio of 2.0 to satisfy the requirement of ASTM C 192 standard (Wang *et al.* (2012)).

Results confirmed that SHPB specimens were in a state of dynamic stress equilibrium, thus validating the SHPB results. This is done by comparing the stresses at the two ends of the specimen and the stress equilibrium is achieved when their relative difference is less than 7%. Quasi-static compressive cylinder strengths were then

(a) 20 °C (b) 300 °C (c) 500 °C (d) 650 °C

(e) 20 °C (f) 300 °C (g) 500 °C (h) 650 °C

Figure 11. Failure patterns of fresh (a-d) and carbonated (e-h) CEM I 20 MPa concrete at various temperatures



(a) D50*100 mm cylinder (b) D50*30 mm disk

Figure 12. Control sample quasi-static test results at 28 day and 6 months at ambient temperature for CEM I 20 MPa fresh concrete: stress-strain curves of the sample in shape of a) D50*100 mm cylinder and b) D50*30 mm disk

used to calculate dynamic increase factors. The dynamic increase factor (DIF) is used to express the increase in a material's strength due to a high strain rate. Structural design using a material's dynamic strength will give the true resistance of structures under blast loading, whilst using the static strength may underestimate resistance of the structure.

It has been reported that various structural effects lead to the pseudo strain-rate effect of concrete-like materials and that lateral confinement in concrete-like specimens is responsible for the structural effect (or pseudo strain-rate effect) in the SHPB test (Flores-Johnson and Li (2017)). Therefore, the direct use of the SHPB results as material properties should be considered with caution.

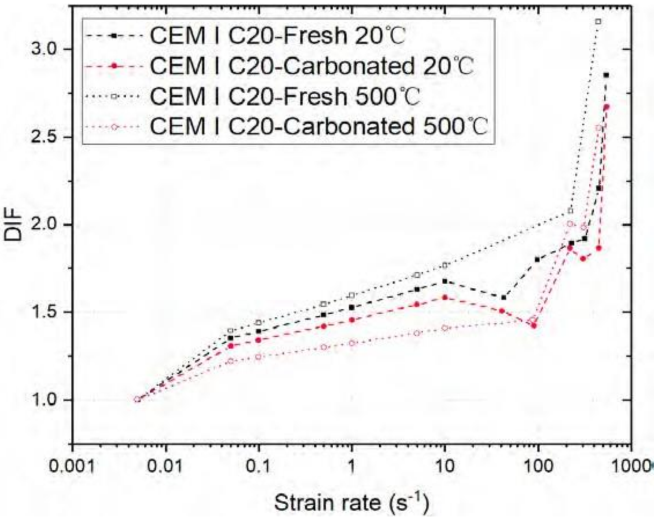


Figure 13. Dynamic increase factor (DIF) - strain-rate dependence based on dynamic disk strength and quasi-static cylinder strengths of fresh and carbonated CEM I 20 MPa concrete at 20 and 500 °C


(a) 50 s^{-1} (b) 100 s^{-1} (c) 200 s^{-1} (d) 300 s^{-1} (e) 450 s^{-1}

(f) 50 s^{-1} (g) 100 s^{-1} (h) 200 s^{-1} (i) 300 s^{-1} (j) 450 s^{-1}

Figure 14. Failure patterns of fresh (a-e) and carbonated (f-j) CEM I 20 MPa concrete under various strain-rates

To calculate the dynamic increase factor (DIF), the CEB 1993 standard (Code (1993)) gives the following equation for strain-rates up to 30 s^{-1}:

$$(2) \quad DIF = \left(\frac{\varepsilon_d}{\varepsilon_s}\right)^{1.026\alpha} \; for \; \varepsilon_d \text{ � } 30 \text{ s}^{-1}$$

where $\alpha = 1/(10 + 6f_c/10)$, in which f_c is the quasi-static compressive strength in MPa and $\varepsilon_s = 3 * 10^{-6} s^{-1}$.

When calculating the DIF, the cylinder strength should be used to normalize the dynamic measurements. However, the high temperature SHPB tests were carried out on disk samples at 500

°C for demonstration purposes only, with the results summarised in Table 4. These results were used to calculate the DIF. High temperature quasi-static concrete cylinder strengths are not available in this study. Therefore, in order to use the same series of results to calculate DIFs at both ambient and high temperatures, the quasi-static compressive cube strengths at 20 and 500 °C (Table 3) were used to estimate cylinder values. The cylinder strength of a concrete specimen is approximately 0.8 that of an equivalent cube at 20 °C, but 0.5 that at 500 °C (Razib and Rahman (2017)).

Figure 13 shows the DIF calculated from dynamic disk strengths and quasi-static cylinder specimens at 20 and 500 °C for both fresh and carbonated CEM I 20 MPa concrete. All results follow the same trend, with only moderate difference between different specimens. This suggests that the DIF-strain rate relationship for fresh concrete at ambient temperature may be used for elevated temperatures and for carbonated concrete. However, further tests are necessary to confirm this observation and to establish more precise quantitative relationships.

The failure modes were similar for both fresh and carbonated concretes, as shown in Figure 14. The disk specimen remained intact at a strain-rate loading of 50 s^{-1} but was increasingly fragmented as the strain-rate increased.

4. Conclusion

This paper has presented the results of a preliminary experimental study into the effects of carbonation on mechanical properties of concrete under high strain-rate and high temperature loading conditions. Concrete mixes were prepared with (CEM II) and without (CEM I) PFA. For CEM I concrete, the experiments were performed to obtain quasi-static compressive properties of unconfined and confined concrete at ambient temperature, static compressive properties of unconfined concrete at various temperatures (20, 300, 500 and 650 °C), and SHPB tests with strain-rate ranging from 50 to 550 s^{-1} at ambient temperature and at 500 °C. For CEM II concrete, the same static tests were performed, but just at ambient temperatures. For dynamic properties, the experimental results were used to assess the prediction method in CEB 1993 standard (Code (1993)) for calculating dynamic increase factor (DIF). The main findings of this study are as follows:

(1) For CEM I concrete, carbonation results in increased compressive strength and elastic modulus under static and dynamic loading at both ambient and elevated temperatures. However, the extent of the increase is moderate at ambient temperature, therefore, it is prudent not to take advantage of such increases because the precise level of carbonation may be difficult to determine in practice.

(2) However, at elevated temperatures, the static compressive strength of CEM I concrete after carbonation does not seem to suffer any reduction, unlike for non-carbonated concrete. Should this finding be confirmed to hold true in all cases, it implies that the load carrying capacity of carbonated CEM I concrete structure would not deteriorate under fire attack where the temperature was below 650 °C.

(3) For CEM II concrete, carbonation led to deterioration of the static mechanical properties of concrete. However, this study was just a preliminary one and due to limited resources, no investigation was carried out for CEM II concrete at elevated temperatures or under dynamic loading.

(4) Apart from the aforementioned absence of strength loss at elevated temperatures, the mechanical properties of carbonated CEM I concrete can be predicted using the same method as for non-carbonated concrete provided that the static compressive strength of carbonated concrete is used as a reference value. The dynamic increase factors for carbonated and non-carbonated concrete at ambient temperatures and 500 °C all follow the same trend, indicating the same equation for fresh concrete at ambient temperature can be used for other cases with only small modifications. Nevertheless, more extensive investigations are needed to confirm the general applicability of this conclusion.

Over its lifetime, infrastructure may be subjected to different loading conditions, including extreme loading conditions of high temperature and high strain-rates. This preliminary research has revealed that depending on the mix, long-term environmental exposure can cause complex changes in properties of concrete. It is imperative that further research should be carried out to establish a comprehensive database of concrete properties under different possible combinations of environmental exposure and loading conditions so that the service of concrete infrastructure can be maximised without compromising safety.

Acknowledgements

The authors would like to thank the EPSRC for funding this research, through the PLEXUS project (EP/R013535/1), as part of the UKCRIC programme (EP/R017727/1 and EP/P017169/1). We would like to thank Dr. Stephen Burley, Mr. Lawrence Bailey and Mr. Ross Holmes in The University of Manchester for performing the quasi-static experiments.

REFERENCES

Abrams MS (1971) Compressive Strength of Concrete at Temperatures to 1600F. *ACI special publication* **25**: 1–11.

Anderberg Y and Thelandersson S (1976) Stress and deformation characteristics of concrete: experimental investigation and material behaviour model. *Bull Div Struct Mech Concr Constr Bull* **54**.

Ashraf W (2016) Carbonation of cement-based materials: Challenges and opportunities. *Construction and Building Materials* **120**: 558–570, 10.1016/j.conbuildmat.2016.05.080.

Chang JJ, Yeih W, Huang R and Chi JM (2003) Mechanical properties of carbonated concrete. *Journal of the Chinese Institute of Engineers* **26(4)**: 513–522, 10.1080/02533839.2003.9670804.

Chen L, Fang Q, Jiang X, Ruan Z and Hong J (2015) Combined effects of high temperature and high strain rate on normal weight concrete. *International Journal of Impact Engineering* **86**: 40–56, 10.1016/j.ijimpeng.2015.07.002.

Chen X, Wu S and Zhou J (2013) Experimental and modeling study of dynamic mechanical properties of cement paste, mortar and concrete. *Construction and Building Materials* **47**: 419–430, 10.1016/j.conbuildmat.2013.05.063.

Code CFM (1993) *CEB-FIP model code for concrete structures, euro-international committe for concrete*. Thomas Telford Publishing.

Davies EDH and Hunter SC (1963) The Dynamic Compression Testing of Solids by the Methed of the Split Hopkinson Pressure Bar. *J. Mech. Phys. Solids* **11**: 155–179.

Fan K, Li D, Damrongwiriyanupap N and Li Ly (2019) Compressive stress-strain relationship for fly ash concrete under thermal steady state. *Cement and Concrete Composites* **104(June)**: 103371, 10.1016/j.cemconcomp.2019.103371.

Flores-Johnson EA and Li QM (2017) Structural effects on compressive strength enhancement of concrete-like materials in a split Hopkinson pressure bar test. *International Journal of Impact Engineering* **109**: 408–418, 10.1016/j.ijimpeng.2017.08.003.

Gruber JA (2018) Accurate Data Reduction for the Uniaxial Compression Test. *Experimental Techniques* **42(2)**: 209–221, 10.1007/s40799-017-0215-0.

Hassan M and Wille K (2017) Experimental impact analysis on ultra-high performance concrete (UHPC) for achieving stress equilibrium (SE) and constant strain rate (CSR) in Split Hopkinson pressure bar (SHPB) using pulse shaping technique. *Construction and Building Materials* **144**: 747–757, 10.1016/j.conbuildmat.2017.03.185.

Hussain S, Bhunia D and Singh SB (2017) Comparative study of accelerated carbonation of plain cement and fly-ash concrete. *Journal of Building Engineering* **10**: 26–31, 10.1016/j.jobe.2017.02.001.

Kamimura K, Sereda PJ and Swenson EG (1965) Changes in weight and dimensions in the drying and carbonation of Portland cement mortars. *Magazine of Concrete Research* **17(50)**: 5–14, 10.1680/macr.1965.17.50.5.

Klingsch E, Frangi A and Fontana M (2009) Experimental Analysis of Concrete Strength at High Temperatures and after Cooling. *Acta Polytechnica* **49(1)**, 10.14311/1087.

Leemann A and Moro F (2017) Carbonation of concrete: the role of CO_2 concentration, relative humidity and CO_2 buffer capacity. *Materials and Structures* **50(1)**: 30, 10.1617/s11527-016-0917-2.

Li Q, Lu Y and Meng H (2009) Further investigation on the dynamic compressive strength enhancement of concrete-like materials based on split Hopkinson pressure bar tests. Part II: Numerical simulations. *International Journal of Impact Engineering* **36(12)**: 1327–1334, 10.1016/j.ijimpeng.2009.04.009.

Li QM and Meng H (2003) About the dynamic strength enhancement of concrete-like materials in a split Hopkinson pressure bar test. *International Journal of Solids and Structures* **40(2)**: 343–360, 10.1016/S0020-7683(02)00526-7.

Liang X, Wu C, Yang Y and Li Z (2019) Experimental study on ultra-high performance concrete with high fire resistance under simultaneous effect of elevated temperature and impact loading. *Cement and Concrete Composites* **98(July 2018)**: 29–38, 10.1016/j.cemconcomp.2019.01.017.

Lie T (1992) *Structural Fire Protection*. American Society of Civil Engineers, New York.

Lv TH, Chen XW and Chen G (2017) Analysis on the waveform features of the split Hopkinson pressure bar tests of plain concrete specimen. *International Journal of Impact Engineering* **103**: 107–123, 10.1016/j.ijimpeng.2017.01.004.

Ma Q, Guo R, Zhao Z, Lin Z and He K (2015) Mechanical properties of concrete at high temperature-A review. *Construction and Building Materials* **93**: 371–383, 10.1016/j.conbuildmat.2015.05.131.

Malhotra HL (1956) The effect of temperature on the compressive strength of concrete. *Magazine of Concrete Research* **8(23)**: 85–94.

Martin J (2018) Developing new statistics of infrastructure: August 2018. *Office for national statistics* : 1–19.

Novak J and Kohoutkova A (2018) Mechanical properties of concrete composites subject to elevated temperature. *Fire Safety Journal* **95(October 2017)**: 66–76, 10.1016/j.firesaf.2017.10.010.

Persson B (1998) Experimental studies on shrinkage of high-performance concrete. *Cement and Concrete Research* **28(7)**: 1023–1036, 10.1016/S0008-8846(98)00068-4.

Razib SA and Rahman FI (2017) Elevating the Effect of Temperature on Compressive and Tensile Strength of Concrete with Admixture. *International Journal of Advanced Structures and Geotechnical Engineering* **6(1)**: 12–20.

Šavija B and Luković M (2016) Carbonation of cement paste: Understanding, challenges, and opportunities. *Construction and Building Materials* **117**: 285–301, 10.1016/j.conbuildmat.2016.04.138.

Schneider U (1976) Behaviour of concrete under thermal steady state and non-steady state conditions. *Fire and Materials* **1(3)**: 103–115, 10.1002/fam.810010305.

Su H, Xu J and Ren W (2014) Experimental study on the dynamic compressive mechanical properties of concrete at elevated temperature. *Materials and Design* **56**: 579–588, 10.1016/j.matdes.2013.11.024.

Sudheera, Rammohan YS and Pradeep MS (2018) Split Hopkinson Pressure Bar Apparatus for Compression Testing: A Review. *Materials Today: Proceedings* **5(1)**: 2824–2829, 10.1016/j.matpr.2018.01.071.

Talaat A, Emad A, Tarek A, Masbouba M, Essam A and Kohail M (2021) Factors affecting the results of concrete compression testing: A review. *Ain Shams Engineering Journal* **12(1)**: 205–221, 10.1016/j.asej.2020.07.015.

Teychenné D, Franklin R, Erntroy H and Marsh B (1975) *Design of normal concrete mixes*. HM Stationery Office.

Wang S, Zhang MH and Quek ST (2012) Mechanical behavior of fiber-reinforced high-strength concrete subjected to high strain-rate compressive loading. *Construction and Building Materials* **31**: 1–11, 10.1016/j.conbuildmat.2011.12.083.

Wang YB, Liew JY, Lee SC and Xiong DX (2016) Experimental study of ultra-high-strength concrete under triaxial compression. *ACI Materials Journal* **113(1)**: 105–112, 10.14359/51688071.

Whittaker M, Zajac M, Ben Haha M, Bullerjahn F and Black L (2014) The role of the alumina content of slag, plus the presence of additional sulfate on the hydration and microstructure of Portland cement-slag blends. *Cement and Concrete Research* **66**: 91–101, 10.1016/j.cemconres.2014.07.018.

Zhai C, Chen L, Fang Q, Chen W and Jiang X (2017) Experimental study of strain rate effects on normal weight concrete after exposure to elevated temperature. *Materials and Structures* **50(1)**: 40, 10.1617/s11527-016-0879-4.

Zhang M, Wu HJ, Li QM and Huang FL (2009) Further investigation on the dynamic compressive strength enhancement of concrete-like materials based on split Hopkinson pressure bar tests. Part I: Experiments. *International Journal of Impact Engineering* **36(12)**: 1327–1334, 10.1016/j.ijimpeng.2009.04.009.

Response to reviewers

Dear Editor,

We would like to thank the reviewers for their valuable and constructive comments on our paper and suggestions for improvement. We have thoroughly revised our paper to address all of their comments. Our changes in the manuscript are colour coded in blue. Our point-by-point replies to the comments are given below, colour coded in blue.

Yours sincerely,

Jiaming Wang, Toby Lord, Yong Wang, Leon Black, Qingming Li, Weiguo Guo, Longyang Chen

Reviewer 1:

The topic of the paper is interesting and suits the Journal of ICE. However, a major revision is required before this manuscript is qualified to be published in this prestigious journal. The manuscript is needed to be revised grammatically. The authors are required to check the whole manuscript with a grammar specialist as it has several grammatical errors. Only after revising the manuscript based on the comments, the paper is suggested to be published in ICE. Further information on various issues identified in the manuscript appears below:

Response: We have thoroughly proofread our paper and corrected any grammatical mistakes.

Page 1 Abstract:

1. "before and after carbonation. Specimens of CEM I concrete and CEM II concrete (CEM I concrete prepared" has been rewritten as "pre- and post-carbonation. Specimens of CEM I and CEM II concrete (concrete prepared"
2. "cured for 28 days then underwent accelerated carbonation for 28 days at 20 °C and 57% relative humidity under 4% CO_2." has been rewritten as "cured for 28 days before accelerated carbonation under 4% CO_2 for 28 days at 20 °C and 57% relative humidity."

Page 1 Paragraph 1:

"Concrete is the most used infrastructure material and is subject to carbonation throughout its service life. Carbonation of concrete causes" has been rewritten as "Concrete is the most widely used infrastructure material. Over its lifetime, concrete may react with atmospheric CO_2 in a process known as carbonation. This process causes"

Page 1 Paragraph 2:

1. "During the hydration of Portland cement (or CEM I) concrete, portlandite (calcium hydroxide or CH, i.e. $Ca(OH)_2$) is produced." has been rewritten as "The hydration of Portland cement in concrete produces calcium hydroxide, (also known as portlandite, or CH in standard cement nomenclature)."
2. "pore water reacts with portlandite" has been rewritten as "pore water may react with portlandite"

Page 2 Paragraph 1:

1. “greater than that of the reactant portlandite” has been rewritten as “greater than that of portlandite,”
2. “leading to increases in mechanical properties.” has been rewritten as “leading to increases in strength.”

Page 2 Paragraph 2:

1. “thermal cracking during hydration of cement, Pulverised fuel ash (PFA) or fly ash, which is an industrial by-product” has been rewritten as “thermal cracking during cement hydration, pulverised fuel ash (PFA) or fly ash, an industrial by-product”
2. “replace some of the OPC in cement since about 50 years ago (Teychenn´e et al. (1975)). Replacement of up to 20% Portland cement with PFA would constitute a CEM II concrete. In such systems,” has been rewritten as “replace some of the OPC in cement for about the past 50 years (Teychenn´e et al. (1975)), and replacement of about 20% of the Portland cement with PFA is common, constituting a CEM II concrete. In such systems,”

Page 2 Paragraph 3:

1. “studies to investigate the effects of carbonation on mechanical properties of carbonated CEM I” has been rewritten as “studies investigating the effects of carbonation on the mechanical properties of CEM I”
2. “were enhanced after hardened samples are carbonated.” has been rewritten as “were all enhanced after carbonation.”

Page 2 Paragraph 4:

1. “due to hydration of unhydrated cement” has been deleted
2. “almost completely lost at temperatures higher than 800 °C.” has been rewritten as “almost completely lost at temperatures above this.”
3. “porosity and pore size increases; capillary water is lost completely at 400 °C; the hardened cement matrix expands first and shrinks with increasing temperature due to loss of water, while aggregates keep expansion all the time. The above effects” has been rewritten as “porosity and pore sizes increase; the hardened cement matrix expands first then shrinks with increasing temperature due to loss of water, which is lost completely at 400 °C. Meanwhile aggregates expand with increasing temperature. These effects”

4. “tend to be opposite to” has been rewritten as “tend to oppose”
5. “Therefore, it is necessary to investigate how carbonation and high temperature effects interact.” has been moved to Page 2 Paragraph 6, and rewritten as “Given that the effects of carbonation
6. and high temperature may oppose one another, there is a need to investigate how carbonation and high temperature effects interact.”

Page 2 Paragraph 5:

1. “behavior” has been corrected as “behaviour”
2. “The” has been added before “Split Hopkinson Pressure Bar (SHPB)”
3. “, such as specimen geometry (i.e. diameter), end interface friction and material inertia,” has been added after “although structural effects”
4. “of the unconfined” has been rewritten as “of unconfined”
5. “will be directly used to” has been rewritten as “was used directly to”
6. “on the dynamic behavior of concrete.” has been rewritten as “on concrete’s dynamic behaviour.”

Page 2 Paragraph 6:

1. “Carbonation will also affect the high-temperature performance of concrete.” has been rewritten as “Carbonation also affects concrete’s high-temperature performance.”
2. “this strength loss should not be observed” has been rewritten as “this strength loss may not be observed”
3. “There is however a paucity of research” has been rewritten as “Furthermore, there is a paucity of research”

Page 2 Paragraph 7:

1. “CEM II types of concrete” has been rewritten as “CEM II concrete”
2. “with or without” has been rewritten as “with and without”

Page 2 Paragraph 8:

“, with the aggregate being quartzite-based 5 mm aggregate” has been moved to the 1st sentence of the paragraph and rewritten as “, prepared with 5mm quartzite aggregate.”

Page 3 Paragraph 1:

1. “two concrete grades” has been rewritten as “two concrete strengths”

2. "The 50 mm diameter was chosen to ensure complete carbonation of specimens." has been rewritten as "The 50 mm diameter was chosen to facilitate complete specimen carbonation."
3. "After 7 days curing under ideal conditions of 99 ± 1% relative humidity" has been rewritten as "After 7 days curing at 99 ± 1% RH"

Page 3 Paragraph 2:

1. "After 28 days curing," has been rewritten as "After 28 days,"
2. "for additional 28 days, with 4 ± 0.5% CO_2 content, and 57 ± 5% RH, according to the highest CO_2 concentration and optimum humidity to simulate natural carbonation" has been rewritten as "for 28 days, at 4 ± 0.5% CO_2, and 57 ± 5% RH. These conditions are optimum to accelerate carbonation while simulating natural carbonation"
3. "The control samples" has been rewritten as "The non-carbonated control samples"
4. "to rule out any effect of further ageing" has been moved to the last sentence of the paragraph and rewritten as "(but were still tested after 28 days)."
5. "Both CEM I and CEM II concrete" has been rewritten as "Both CEM I and CEM II C20 concrete"
6. "exposure. Note that the CEM I 40 MPa concrete specimens required exposure" has been rewritten as "exposure, while the CEM I 40 MPa concrete specimens were subsequently found to require exposure"

Page 4 Paragraph 1:

"Quasi-static loading experiments" has been rewritten as "The quasi-static loading experiments"

Page 4 Paragraph 2:

1. "20 mm strain gauges were attached to the concrete samples" has been rewritten as "20 mm long strain gauges were attached to the concrete specimens"
2. "were tested to failure under compression" has been deleted
3. "the specimen deformation and the deformation of the loading frame deformation" has been rewritten as "specimen and loading frame deformation"
4. "determined when the other displacements associated with the machine compliance were removed (Gruber (2018))." has been rewritten as "determined after correction for other displacements associated with machine compliance (Gruber (2018))."

Page 6 Paragraph 1:

1. “Concrete cubes with size 50 mm” has been moved to the 1st sentence of the paragraph and rewritten as “on 50 mm cubes”
2. “Concrete cubes with size 50 mm were heated” has been rewritten as “Specimens were heated”
3. “temperature uniformity with the sample, … in the centre of the specimen” has been rewritten as “temperature uniformity within the sample, … in the centre of each specimen”
4. “10 °C per minute. After reaching the target temperature, the sample was sustained at the temperature for 30 minutes following a similar procedure as in Chen et al. (2015).” has been rewritten as “10 °C per minute, with the specimens held at the target temperature for 30 minutes, following a similar procedure to Chen et al. (2015).”
5. “stress-strain curves of the sample after” has been rewritten as “stress-strain curves after”

Page 6 Paragraph 4:

“Table 2 and 3” has been rewritten as “Tables 2 and 3”

Page 6 Paragraph 5:

1. “For CEM I 20 MPa concrete, carbonation led to … Hussain et al. [34], under similar 5% CO_2 concentration.” has been moved before “Figs. 4 (b) shows inclined crack direction to the loading direction, … as for the carbonated specimen.”
2. “as noticed by a number of previous researchers, such as Hussain et al. (2017) and Ashraf (2016).” has been rewritten as “as noted previously (Hussain et al. (2017); Ashraf (2016)).”
3. “The amount of increase is a function of the carbonation depth and intensity, with increased carbonation leading to higher gains in compressive strength and Young’s modulus. For example, the results in Figure 4 (a) show increases of 16% and 19% respectively in compressive strength and elastic modulus of this research, compared to 25% increase in compressive strength from Hussain et al. [34], under similar 5% CO_2 concentration.” has been rewritten as “The extent of the increase in strength and Young’s modulus is dependent on the degree of carbonation (Hussain et al. (2017)). The fully carbonated specimens in this study showed, from Figure 4 (a), increases of 16 and 19% respectively. This compares to a 25% increase in compressive strength observed by Hussain et al. (2017), following exposure to 5% CO_2.”

Page 7 Paragraph 1:

1. “Figs. 4 (b) shows inclined crack direction to the loading direction, indicating” has been rewritten as “Figure 4 (b) shows a diagonal crack running in the direction of the loading, indicating”

2. “due to the smoother surfaces at specimen ends after carbonation, which reduced” has been rewritten as “due to the smoother specimen end surfaces after carbonation. This reduced”
3. “between the loading platens and specimen (Talaat et al. (2021)). However, for the fresh concrete specimen the inclined angle to the horizontal is large so the crack is almost vertical as for the carbonated specimen.” has been rewritten as “between the loading platens and the specimen (Talaat et al. (2021)). However, the inclined angle to the horizontal for the carbonated specimen is so large that the crack is almost vertical.”

Page 7 Paragraph 2:

1. “However, what is remarkable is that the 5 MPa” has been rewritten as “But remarkably, just 5 MPa”
2. “This is in agreement with calculation results using the following equation (Wang et al. (2015)) that relates the compressive strength of confined concrete f_{cc} to that of the unconfined concrete f_c:” has been rewritten as “This is also in agreement with calculated results based on the equation relating compressive strength of confined (f_{cc}) and unconfined concrete (f_c) (Wang et al. (2016)):”

Page 7 Paragraph 3:

“both fresh and carbonate concrete samples was shear failure (Figure 5 (b-c)), with much smaller angles to the horizontal compared to the unconfined specimens” has been rewritten as “both fresh and carbonated specimens was shear failure (Figure 5 (b-c)), because the angle between the crack line and the horizontal is much smaller than that of the unconfined specimens”

Page 7 Paragraph 4:

1. “For CEM I 40 MPa concrete, due to denser microstructure, its carbonation depth was less than that of CEM I 20 MPa concrete. This seems to correlate with a lower increase in Young’s modulus after carbonation – 7% increase compared to 19% increase” has been rewritten as “The denser microstructure of the 40 MPa CEM I concrete (Figure 6) meant that its carbonation depth was less than that of the weaker specimen. This correlates with a lower increase in Young’s modulus of 7% after carbonation, compared to a 19% increase”
2. “However, this seems to be in contrast with the recorded compressive strength with carbonation leading to … compared to 16% increase in CEM I 20 MPa concrete.” has been rewritten as “However, this contrasts with the compressive strength data, with carbonation leading to … compared to a 16% increase upon carbonation of the weaker specimen.”

3. “note the increase in mechanical properties due to carbonation on CEM I concrete, rather than the exact values because the magnitude of increase in all cases is modest.” has been rewritten as “note the increase in strength and stiffness upon carbonation of CEM I concrete rather than the exact values, because the extent of the increase, in all cases, is modest.”

Page 8 Paragraph 2:

“leads to modest increase in its compressive strength” has been rewritten as “leads to modest increases in compressive strength”

Page 8 Paragraph 3:

“for unconfined CEM II 20 MPa concrete.” has been rewritten as “for the unconfined specimen.”

Page 9 Paragraph 1:

“These results are opposite to those of Hussain et al. (2017) who obtained modest increases” has been rewritten as “These results are contrary to those of Hussain et al. (2017) who observed modest increases”

Page 9 Paragraph 2:

1. “Confinement seems to have” has been rewritten as “Confinement has”
2. “concrete , by comparing the results between Figure 8 and Figure 7 vs. Figure 5 and Figure 4, in changes in compressive strength and elastic modulus, and in failure patterns from near vertical crack for unconfined concrete to inclined crack for confined concrete.” has been rewritten as “concrete, as seen by comparing Figures 7 and 8 with Figures 4 and 5, with an increase in compressive strength and elastic modulus, plus a change in crack pattern, upon confinement.”

Page 9 Paragraph 3:

“In summary, when assessing CEM II concrete structures, it is important to carefully quantify possible reductions in mechanical properties of concrete due to carbonation.” has been rewritten as “It is important to note that this study deliberately designed concretes which would carbonate completely so as to assess the impact of carbonation. In practice, this should not occur in infrastructure. However, given the widespread use of PFA in concrete over the past 40-50 years, there is a need to consider possible reductions in concrete’s mechanical properties due to carbonation.”

Page 10 Paragraph 1:

“For fresh concrete, the change (reduction) in peak compressive stress with increasing temperature is similar to that in Eurocode EN 1994-1-2 and results by others” has been rewritten as “For fresh concrete, there was a gradual reduction in peak compressive stress with increasing temperature similar to that described in Eurocode EN 1994-1-2 and by others”

Page 10 Paragraph 2:

“In contrast, the carbonated CEM I concrete specimens did not suffer any reduction in peak stress at elevated temperatures, as shown in Figure 10 (a). As mentioned previously, the possible reason is that portlandite decomposes at about 450 °C, while calcite does not decompose until about 700 °C. Thus, while non-aged concrete is expected to show loss of strength as portlandite decomposes, this strength loss should not be observed in carbonated specimens.” has been rewritten as “Meanwhile, the carbonated CEM I concrete showed a different behaviour as a function of temperature (Figure 10 (a)). Increasing the temperature to 300 and then 500 °C led to an increase in peak stress. While the fresh specimens showed a reduction in performance due to the decomposition of portlandite from about 450 °C, the conversion of portlandite to calcite upon carbonation meant that there was no such decomposition in the carbonated specimens, and the only changes would have been the removal of water from the hydrated cement paste. This will lead to slight contraction of the specimens. However, by 650 °C (the onset of carbonate decomposition) peak stress started to drop a little.”

Page 10 Paragraph 3:

1. “Figure 10 (b) indicates … as shown in Figure 11.” has been moved to the last paragraph of Section 3.2
2. “are similar at different temperatures” has been rewritten as “are similar at elevated temperatures”
3. “However, there are higher than those from a few other researchers.” has been rewritten as “However, they are higher than those from a few other researchers (Chen et al. (2015); Anderberg and Thelandersson (1976); Schneider (1976)).”

Page 10 Paragraph 5:

"Concrete specimens in shapes of disk and cylinder were required in the SHPB experiment, with the cylinder specimens used for quasi-static testing and the disk specimens for dynamic testing." has been rewritten as "Cylindrical concrete specimens were required in SHPB experiments, with cylinders used for quasi-static testing and disks for dynamic testing."

Page 11 Paragraph 2:

"It has been reported that … concrete-like materials and the lateral confinement in concrete-like specimen" has been rewritten as "It has been reported that … concrete-like materials and that lateral confinement in concrete-like specimens"

Page 12 Paragraph 1:

"SHPB results as material properties should be with caution." has been rewritten as "SHPB results as material properties should be considered with caution."

Page 12 Paragraph 3:

1. "When calculating DIF," has been rewritten as "When calculating the DIF,"
2. "at 500 °C only for demonstration purpose (results are summarized in Table 4) and their results are used in calculations of DIF. Furthermore, under quasi-static loading, cylinder strengths of the concrete at elevated temperatures are not available" has been rewritten as "at 500 °C for demonstration purposes only, with the results summarised in Table 4. These results were used to calculate the DIF. High temperature quasi-static concrete cylinder strengths are not available"
3. "the quasi-static compressive strength of cube specimens at 20 and 500 °C in Table 3 was used to obtain cylinder values. The cylinder strength of concrete is approximately 0.8 that of cube strength at 20 °C" has been rewritten as "the quasi-static compressive cube strengths at 20 and 500 °C (Table 3) were used to estimate cylinder values. The cylinder strength of a concrete specimen is approximately 0.8 that of an equivalent cube at 20 °C"

Page 12 Paragraph 4:

1. "dynamic disk strength" has been rewritten as "dynamic disk strengths"
2. "All results follow the same trend with moderate difference in quantities, suggesting that" has been rewritten as "All results follow the same trend, with only moderate difference between different specimens. This suggests that"

3. “for elevated temperatures as well as for carbonated concrete with some minor modification.” has been rewritten as “for elevated temperatures and for carbonated concrete.”
4. “precise quantitative relations.” has been rewritten as “precise quantitative relationships.”

Page 14 Paragraph 2:

“PLEXUS (EP/R013535/1) project, as part of the UKCRIC programme” has been rewritten as “PLEXUS project (EP/R013535/1), as part of the UKCRIC programme (EP/R017727/1 and EP/P017169/1)”

1. The introduction section needs to be revised. A paragraph should be dedicated to the importance of your work.

Response: We have added the following paragraph in the Introduction 1st paragraph.

“At £8.8 billion, the cost of repair and maintenance of existing infrastructure in the UK is about 30% of the UK’s total annual infrastructure spend (Martin (2018)). While safety of aging infrastructure is of paramount importance, unnecessary repair and strengthening is costly, so should be avoided. Making a well-judged decision on the critical issue of cost-effective repair and maintenance of the nation’s infrastructure demands a thorough understanding of long-term infrastructure material performance.”

2. More information on this topic materials can be found here, and can certainly add value to the literature review:

"An accelerated test method of simultaneous carbonation and chloride ion ingress: durability of silica fume concrete in severe environments." Advances in Materials Science and Engineering (2016).

Response: There is a more relevant, and earlier paper. We have added the following sentence at the end of Page 2 Paragraph 2.

“While the addition of silica fume to concrete has been shown to reduce carbonation shrinkage (Persson (1998)), this fell outside of the immediate scope of this paper.”

Reference:

Persson, B. (1998). Experimental studies on shrinkage of high-performance concrete. Cement and Concrete Research, 28(7), 1023-1036.

3. Please provide the exact specification of the concrete material and strengths.

Response: We have provided the requested details in Page 3 Table 1.

4. Please provide more detailed reasoning behind the structure behavior. The details should include rigid numbers or percentages.

Response: We have provided the requested detailed experimental results in Page 4 Tables 2-4.

We have added the following sentence to further explain the possible reason of the strength increase difference compared with literature in Page 7 1st paragraph.

"In both instances, carbonation was complete, but in this study, the mass of paste constituted a slightly smaller proportion than in the work of Hussain et al. (2017) (25 vs 27%).“

We have added the following sentence to further explain the effect of confinement on concrete strength in Page 7 2nd paragraph, see the second comment of reviewer 3.

“This is similar to the results reported by others such as Wang et al. (2016)) who tested concrete compressive strength under varying confining stress and found that the compressive strength increased to 3 to 7 times of that of unconfined concrete when the confining ratio (the ratio of confining stress to unconfined concrete strength) increased from 0.5 to 2.”

We have rewritten the 2nd paragraph in Page 10 to further explain the concrete structural behaviour at elevated temperatures.

“Meanwhile, the carbonated CEM I concrete showed a different behaviour as a function of temperature (Figure 10 (a)). Increasing the temperature to 300 and then 500 °C led to an increase in peak stress. While the fresh specimens showed a reduction in performance due to the decomposition of portlandite from about 450 °C, the conversion of portlandite to calcite upon carbonation meant that there was no such decomposition in the carbonated specimens, and the only changes would have been the removal of water from the hydrated cement paste. This will lead to slight contraction of the specimens. However, by 650 °C (the onset of carbonate decomposition) peak stress started to drop a little.”

We have added the following sentence to further explain why the compressive strength changes slightly after storage in Page 10 paragraph 4.

“This is expected with a CEM I system, where a degree of hydration approaching 90% would be expected after 28 days (Whittaker et al. (2014)).”

Reference:

Whittaker, M., Zajac, M., Haha, M. B., Bullerjahn, F., & Black, L. (2014). The role of the alumina content of slag, plus the presence of additional sulfate on the hydration and microstructure of Portland cement-slag blends. Cement and Concrete Research, 66, 91-101.

5. The theoretical analysis needs a more in-depth discussion.

Response: As our response to point 4 above, we have added paragraphs to explain the theoretical basis of our observed experimental results.

6. What is the reason for choosing those W/C ratios and the percentage of SP? Please explain it in the manuscript.

Response: We have added the following sentences on Page 2 last paragraph.

"The concrete was designed according to the method of Teychenn´e et al. (1975) to achieve a characteristic cube strength of 20 or 40 MPa, designated hereafter as C20 and C40 respectively. Water/cement ratios were chosen to achieve the required characteristic strength with constant workability. No superplastisizer was added in the tested concrete."

Reference:

Teychenné, D. C., Franklin, R. E., Erntroy, H. C., & Marsh, B. K. (1975). Design of normal concrete mixes. HM Stationery Office.

7. Please indicate how many samples for each experiment have been used. Please revise the other experiments respectively.

Response: We have added the following text in Page 3 Section 2.2 1st paragraph for the missing information.

"For each concrete, three specimens were tested under quasi-static loading at ambient temperature, one or two specimens were tested at elevated temperatures, as indicated in Tables 2 and 3. Only one specimen was tested in SHPB experiments.

8. Please describe the process of each experiment. Also indicate the model of each tool that is used in the experiment. What is the accuracy of each machine? Please explain them accurately.

Response: In our original manuscript (Section 2.2), we provided detailed descriptions of the experiments, including their tools . Furthermore, we have added the following text in Page 6 Section 2.2 last paragraph for the missing information.

“Any inaccuracy of measurement, i.e. strain at ambient or high temperatures under quasi-static or dynamic loading, or temperature, is less than 1% of the recorded value.”

9. Please add error bars to the figures. Please do this for the rest of the figures.

Response: Error bars are not appropriate in every instance. This is because some samples were only ran once, or that error bars are confusing when showing stress strain curves and that they would detract and clutter the figures. However, errors are included in the tables of results.

10. Conclusion needs to be more concise. Please use fewer sentences containing percentages and illustrate the main conclusions in the manuscript. Please paraphrase your results and discussions and use them in the conclusion part.

Response: We have revised the conclusion section to make it concise.

“ This paper has presented the results of a preliminary experimental study into the effects of carbonation on mechanical properties of concrete under high strain-rate and high temperature loading conditions. Concrete mixes were prepared with (CEM II) and without (CEM I) PFA. For CEM I concrete, the experiments were performed to obtain quasi-static compressive properties of unconfined and confined concrete at ambient temperature, static compressive properties of unconfined concrete at various temperatures (20, 300, 500 and 650 °C), and SHPB tests with strain-rates ranging from 50 to 550 s^{-1} at ambient temperature and at 500 °C. For CEM II concrete, the same static tests were performed, but just at ambient temperatures. For dynamic properties, the experimental results were used to assess the prediction method in CEB 1993 standard (Code (1993)) for calculating dynamic increase factor (DIF). The main findings of this study are as follows:

(1) For CEM I concrete, carbonation results in increased compressive strength and elastic modulus under static and dynamic loading at both ambient and elevated temperatures. However, the extent of the increase is moderate at ambient temperature, therefore, it is prudent not to take advantage of such increases because the precise level of carbonation may be difficult to determine in practice.

(2) However, at elevated temperatures, the static compressive strength of CEM I concrete after carbonation does not seem to suffer any reduction, unlike for non-carbonated concrete. Should this finding be confirmed to hold true in all cases, it implies that the load carrying capacity of carbonated CEM I concrete structure would not deteriorate under fire attack where the temperature was below 650°C.

(3) For CEM II concrete, carbonation led to deterioration of the static mechanical properties of concrete. However, this study was just a preliminary one and due to limited resources, no investigation was performed for CEM II concrete at elevated temperatures or under dynamic loading.

(4) Apart from the aforementioned absence of strength loss at elevated temperatures, the mechanical properties of carbonated CEM I concrete can be predicted using the same method as for non-carbonated concrete, provided that the static compressive strength of carbonated concrete is used as a reference value. The dynamic increase factors for carbonated and non-carbonated concrete at ambient temperatures and 500 °C all follow the same trend, indicating the same equation for fresh concrete at ambient temperature can be used for other cases with only small modifications. Nevertheless, more extensive investigations are needed to confirm the general applicability of this conclusion.

Over its lifetime, infrastructure may be subjected to different loading conditions, including extreme loading conditions of high temperature and high strain- rates. This preliminary research has revealed that depending on the mix, long-term environmental exposure can cause complex changes in properties of concrete. It is imperative that further research should be carried out to establish a comprehensive database of concrete properties under different possible combinations of environmental exposure and loading conditions so that the service of concrete infrastructure can be maximised without compromising safety."

Reviewer 2:

This paper presents an experimental study on the mechanical properties of carinated concrete under the effect of high strain rate and elevated temperature. The results are presented in detail and discussed reasonably. The topic will be of interest to areas of appraisal of aged concrete members after being exposed to actions like fire or impact. The authors are congratulated.

This reviewer has the following comments for the authors to consider.

1. Section 3.1. 'However, for the fresh concrete specimen the inclined angle to the horizontal is large so the crack is almost vertical as for the carbonated specimen.' The authors may wish to reword this sentence.

Response: We have reworded the sentence as follows: "However, the inclined angle to the horizontal for the carbonated specimen is so large that the crack is almost vertical." in Page 7 paragraph 1.

2. 'compressive strength from Hussain et al. [34],' a different style of referencing is found here.

Response: We have corrected the reference in Page 7 paragraph 1.

3. '…was shear failure (Figure 5 (b-c)), with much smaller angles to the horizontal compared to the unconfined specimens in Figure 4 (b-c).' this reviewer is confused with the reason why the angles to the horizontal are small here; the angle appears to be great instead. Also, it would be helpful to indicate the crack in figure 5b using an arrow/line.

Response: The angle to the horizontal is the angle between the horizontal line and the crack. For clarification, we have reworded the sentence to read "… was shear failure (Figure 5(b-c)), because the angle between the crack line and the horizontal is much smaller than that of the unconfined specimens in Figure 4(b-c) …" in Page 7 paragraph 3.

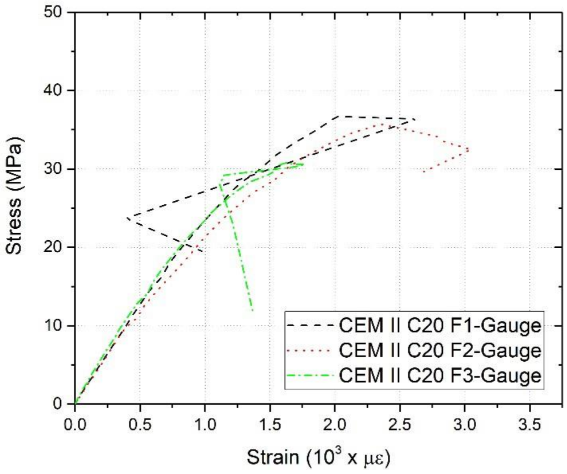
A line is drawn in Figure 5b to indicate the crack in Page 7.

4. Figure 6 may be mentioned in the text.

Response: We have added "(Figure 6)" in Page 7 paragraph 4.

5. How were the peak stress determined for curves CEM II C20 F1 to 3 in figure 7a? Were the very end viewed as the peak?

Response: Post-peak stress is not shown in the figure. Therefore, the peak stress is taken at the very end of the curve in the original manuscript, as shown in the figure below. We have added the following sentence for clarification: ” The post-peak part of the stress-strain curve is not shown in Figure 7, therefore the peak stress is taken at the very end of the stress-strain curve shown here.” in Page 8 Paragraph 3.

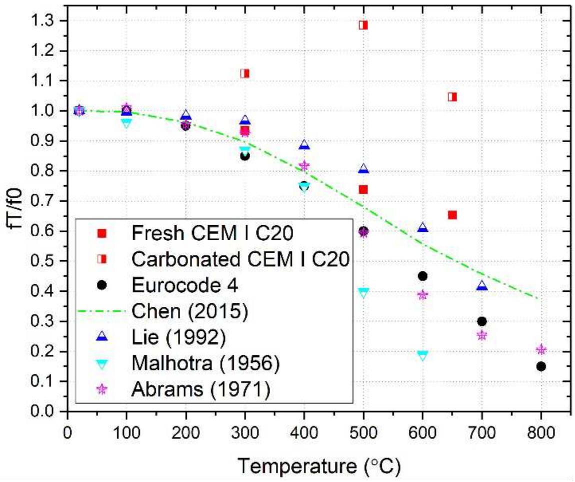


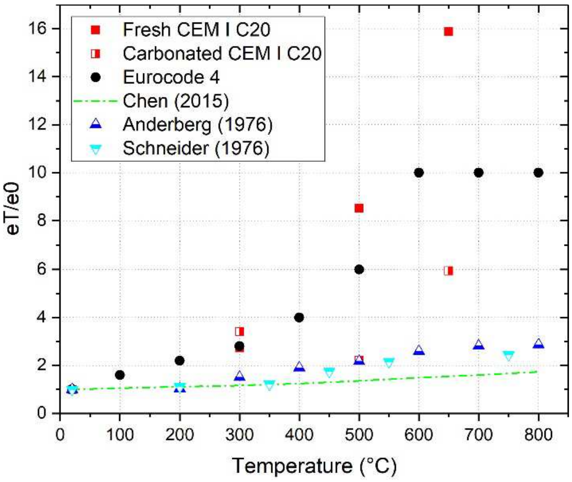
6. ‘However, there are higher than those from a few other researchers.’ It is better to give some references here.

Response: We have added the following references in Page 10 3rd paragraph.

“(Chen et al. (2015); Anderberg and Thelandersson (1976); Schneider (1976))”

The references in Figure 10 have been updated in Page 10.





7. Please consider if it is necessary to present Figure 13 or all the subfigure in Figure 13.

Response: We have removed all the figures in Figure 13.

We have added the following sentence for clarification: “This is done by comparing the stresses at the two ends of the specimen and the stress equilibrium is achieved when their relative difference is less than 7%.” in Page 11 paragraph 1.

"Figure 13 shows that the SHPB test specimens were in a state of dynamic stress equilibrium, validating the SHPB test.“ has been rewritten as “Results confirmed that SHPB specimens were in a state of dynamic stress equilibrium, thus validating the SHPB results.”

“Later, the quasi-static compressive strengths of the cylinder specimens were used to calculate dynamic increase factors (DIFs).” has been rewritten as “Quasi-static compressive cylinder strengths were then used to calculate dynamic increase factors.”

8. It would be better to put Figure 15 in front of Figure 14, as the sequence they are mentioned.

Response: We have moved the paragraph “The failure modes were similar … The disk specimen stayed as a whole piece at strain-rate loading of 50 s^{-1} but fragmented into increasing number of smaller pieces as strain-rate increased.” to Page 12 as the last paragraph of Section 3, and rewritten as “The failure modes were similar … The disk specimen remained intact at a strain-rate loading of 50 s^{-1} but was increasingly fragmented as the strain-rate increased.”. This is because crack propagation results always come after the stress-strain or DIF vs. strain-rate curve results in this paper. There is no need to change the order of figures.

9. Section 3.3, it is helpful to describe the use of dynamic increase factor. What is the implication of this factor from a structural point of view?

Response: We have added the following sentence for clarification: ”The dynamic increase factor (DIF) is used to express the increase in a material’s strength due to a high strain rate. Structural design using a material’s dynamic strength will give the true resistance of structures under blast loading, whilst using the static strength may underestimate resistance of the structure.” in Page 11 paragraph 1.

10. The first paragraph in Conclusion appears a duplicate of the second paragraph.

Response: We have deleted the first paragraph of Section 4 Conclusions. Please refer to comment 10 of reviewer 1.

11. Bullet point (1) in Conclusion ‘Carbonation was achieved by xxx’ please revise the missing information ‘xxx’.

Response: Sorry, this text has been carried over from a draft version of the manuscript and is superfluous. It has therefore been deleted.

12. Bullet point (2) in conclusion, the ‘at elevated temperatures’ at the end of the first sentence appears to be a duplicate.

Response: We have deleted the second ‘at elevated temperatures’.

13. Bullet point (4) in conclusion, this reviewer is not sure if this is meaningful, as it is well predicted by theory and has little to do with the topic of this paper.

Response: We have deleted bullet point (4).

Reviewer 3:

Page 2, Paragraph 1: "Carbonation of such system can thus lead to slight shrinkage.....". Instead of slight can you be more specific with increase or decrease?

Response: We have added “Their carbonation may lead to increases or decreases in volume. Therefore, overall changes in performance are dependent on the phase assemblage of the hardened cement paste.” at the end of Page 2 Paragraph 1. We have added “typically less than1% (Kamimura et al. (1965))” after shrinkage in Page 2 Paragraph 2.

Reference:

Kamimura, K., Sereda, P. J., & Swenson, E. G. (1965). Changes in weight and dimensions in the drying and carbonation of Portland cement mortars. Magazine of Concrete Research, 17(50), 5-14.

Page 6, Paragraph 3: Can you articulate further on the reason for 3X increase in compressive strength. If you had cast 100 mm cube specimens, can you also include those test results.

Response: We have added the following sentence for clarification in Page 7 2nd paragraph.

“This is similar to the results reported by others such as Wang et al. (2016)) who tested concrete compressive strength under varying confining stress and found that the compressive strength increased to 3 to 7 times of that of unconfined concrete when the confining ratio (the ratio of confining stress to unconfined concrete strength) increased from 0.5 to 2.”

In this study, confinement was applied by the cylindrical load cell. It was not possible to apply any confinement stress to the 100 mm cubes. We have clarified this point in Page 3 section 2.2 2nd paragraph.

“It is possible for concrete to be subject to multi-axial loading condition. Therefore, the effect of confinement was investigated in this research. However, in this study, the confinement stress could only be applied by a cylindrical load cell for the cylindrical test specimens. It was not possible to apply confinement stress to the 100 mm cubes. ”

Page 10, Paragraph 1: The loss of strength due to decomposition of Portlandite. Do you expect similar behaviour if silica fume is also present in the concrete? Any comments to clarify the limitations of your initial findings.

Response: The behaviour of a PFA-containing concrete would differ. It might be expected that the carbonated CEM II concrete would not have shown the same loss of strength at elevated temperature, since the fresh CEM II concrete had a very low portlandite content.

Page 13: "Carbonation was achieved by xxx." Please correct this sentence.

Response: See earlier comment item 11 from reviewer 2. It was carried over from an earlier draft and should be deleted.

Page 13, Paragraph 2: "....this finding has important implications on infrastructures...." . Please consider modifying to "....implications for infrastructure "

Response: We have rewritten bullet point (2) in Page 13. Please refer to comment 10 of reviewer 1.

"(2) However, at elevated temperatures, the static compressive strength of CEM I concrete after carbonation does not seem to suffer any reduction, unlike for non-carbonated concrete. Should this finding be confirmed to hold true in all cases, it implies that the load carrying capacity of carbonated CEM I concrete structure would not deteriorate under fire attack where the temperature was below 650 °C."

Page 13, Paragraph 5: "CEM I concrete, except for the impressive effect"…". Not sure what impressive effect means. Can you please modify?

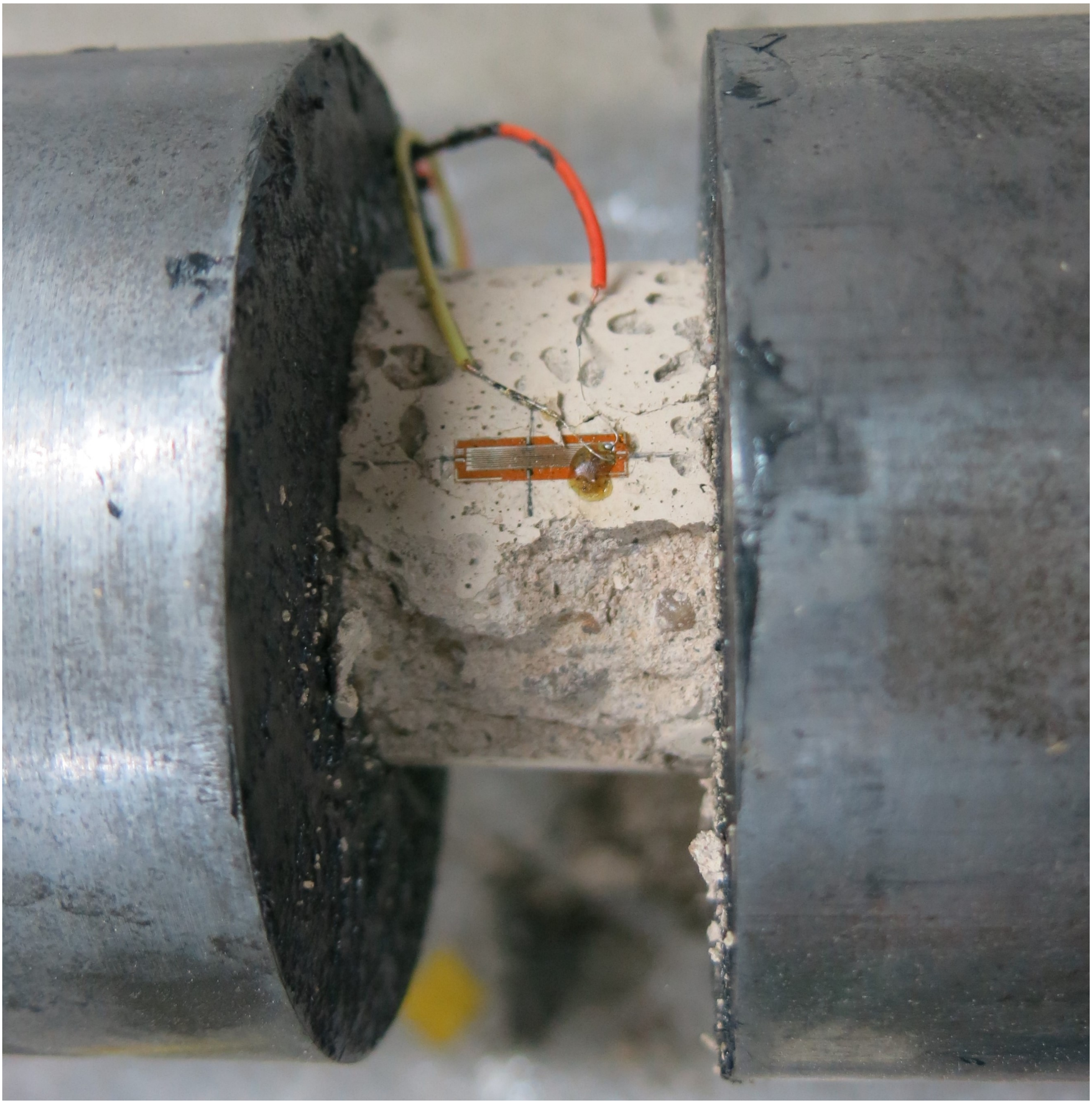
Response: We have rewritten bullet point (4) in Page 13. Please refer to comment 10 of reviewer 1.

"(4) Apart from the aforementioned absence of strength loss at elevated temperatures, the mechanical properties of carbonated CEM I concrete can be predicted using the same method as for non-carbonated concrete provided that the static compressive strength of carbonated concrete is used as a reference value. The dynamic increase factors for carbonated and non-carbonated concrete at ambient temperatures and 500 °C all follow the same trend, indicating the same equation for fresh concrete at ambient temperature can be used for other cases with only small modifications. Nevertheless, more extensive investigations are needed to confirm the general applicability of this conclusion."

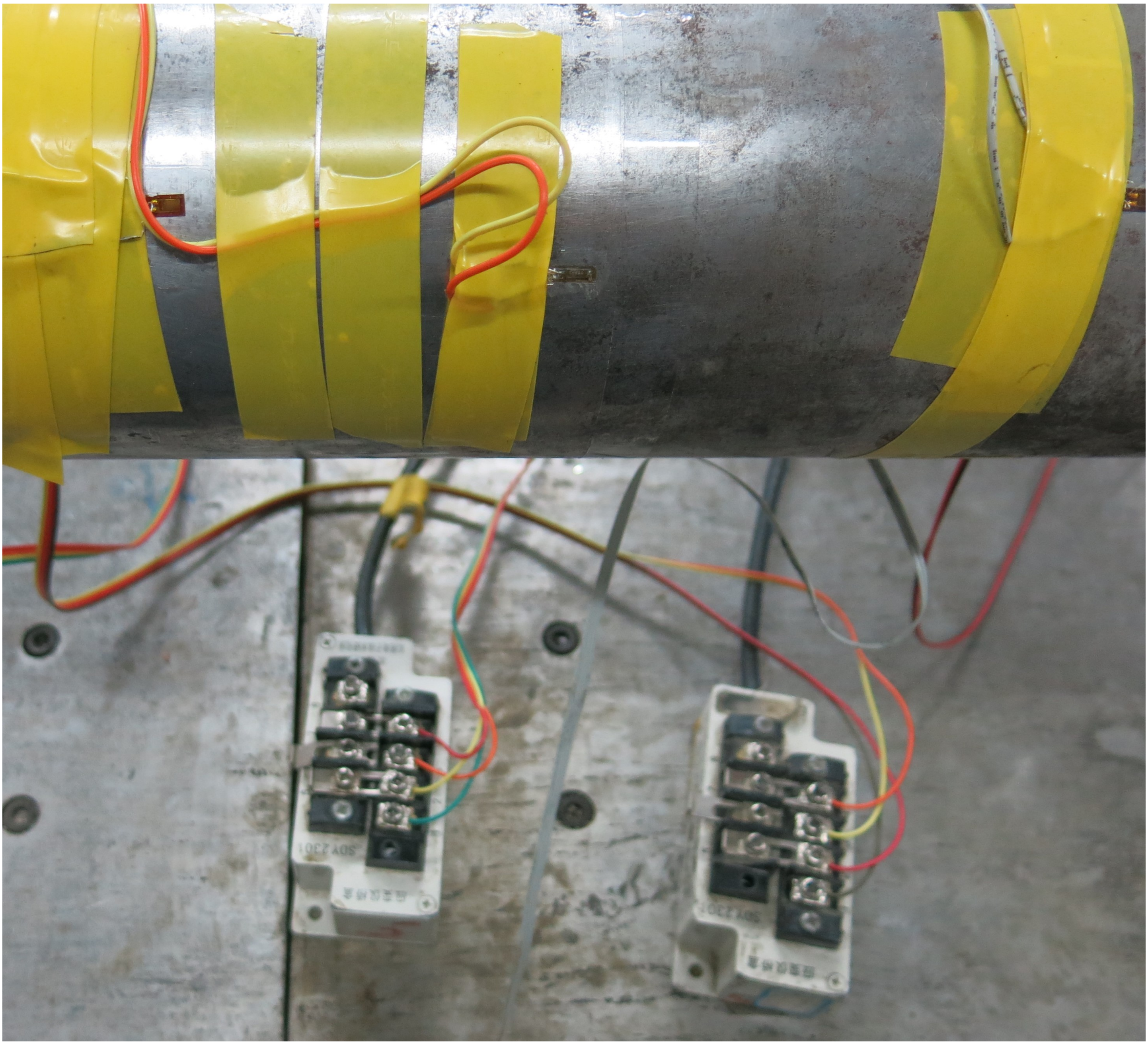

RDP GROUP
Do not operate this equipment unless technically qualified
IMPORTANT
RISK ASSESSMENTS
RCN0202
0.01
-307
217
036


CONTROLS
Model 45-D0556
DANGER
Live busbars


0.8
0.4
压力表
1.2
MPa
0
1.6
号
杆

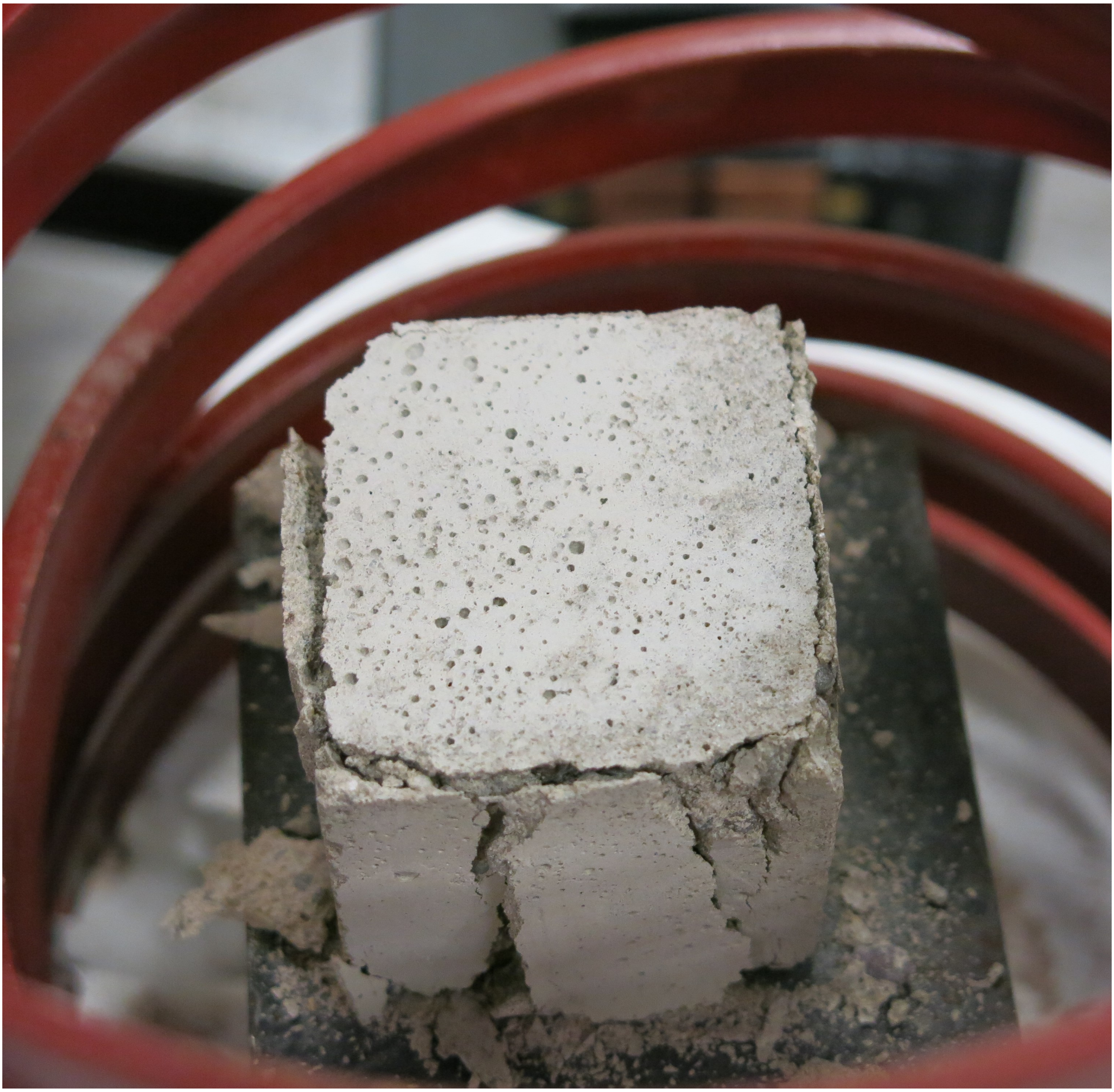


2b.jpg *Figure*

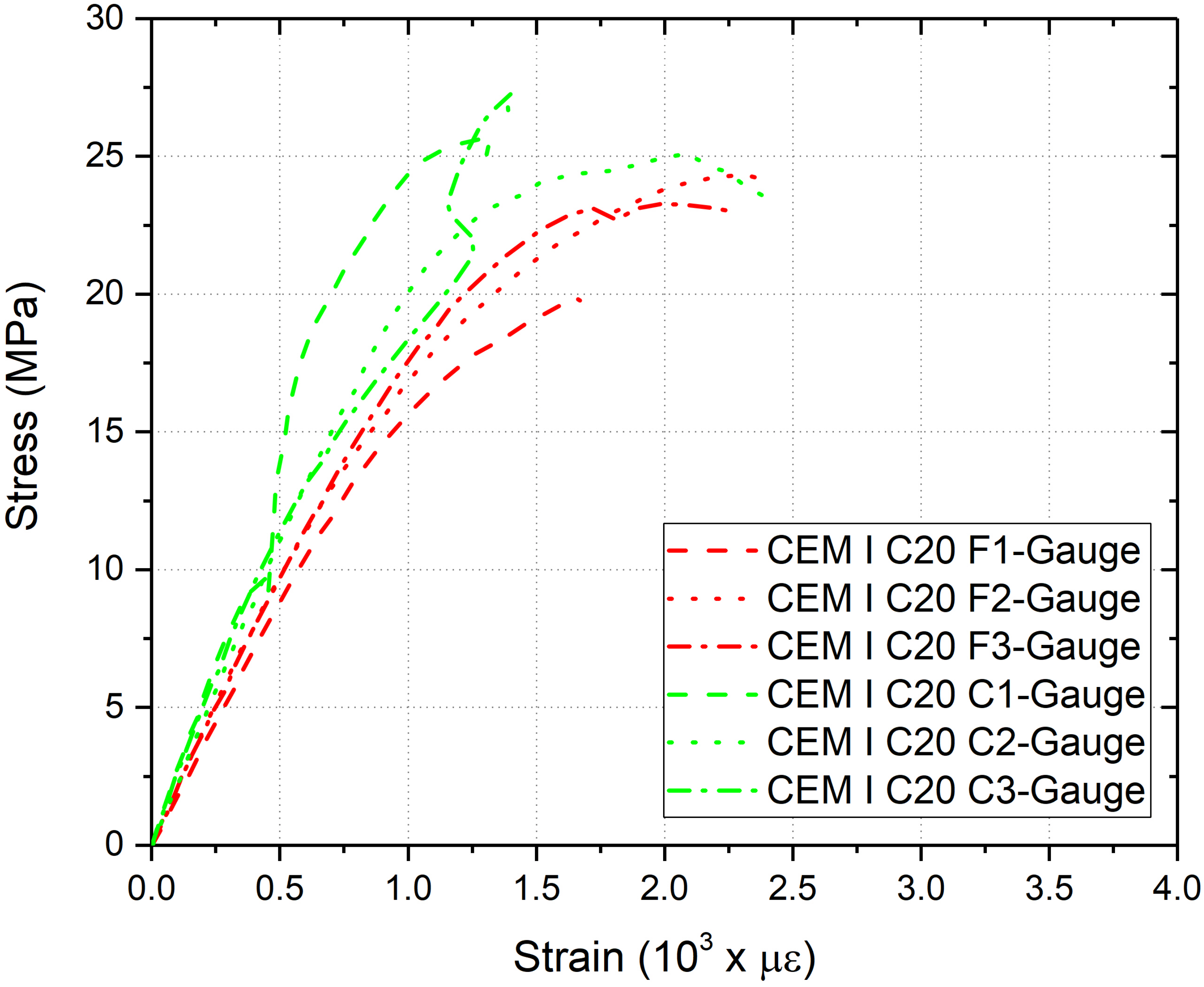


2c.jpg *Figure*

3a.jpg Figure

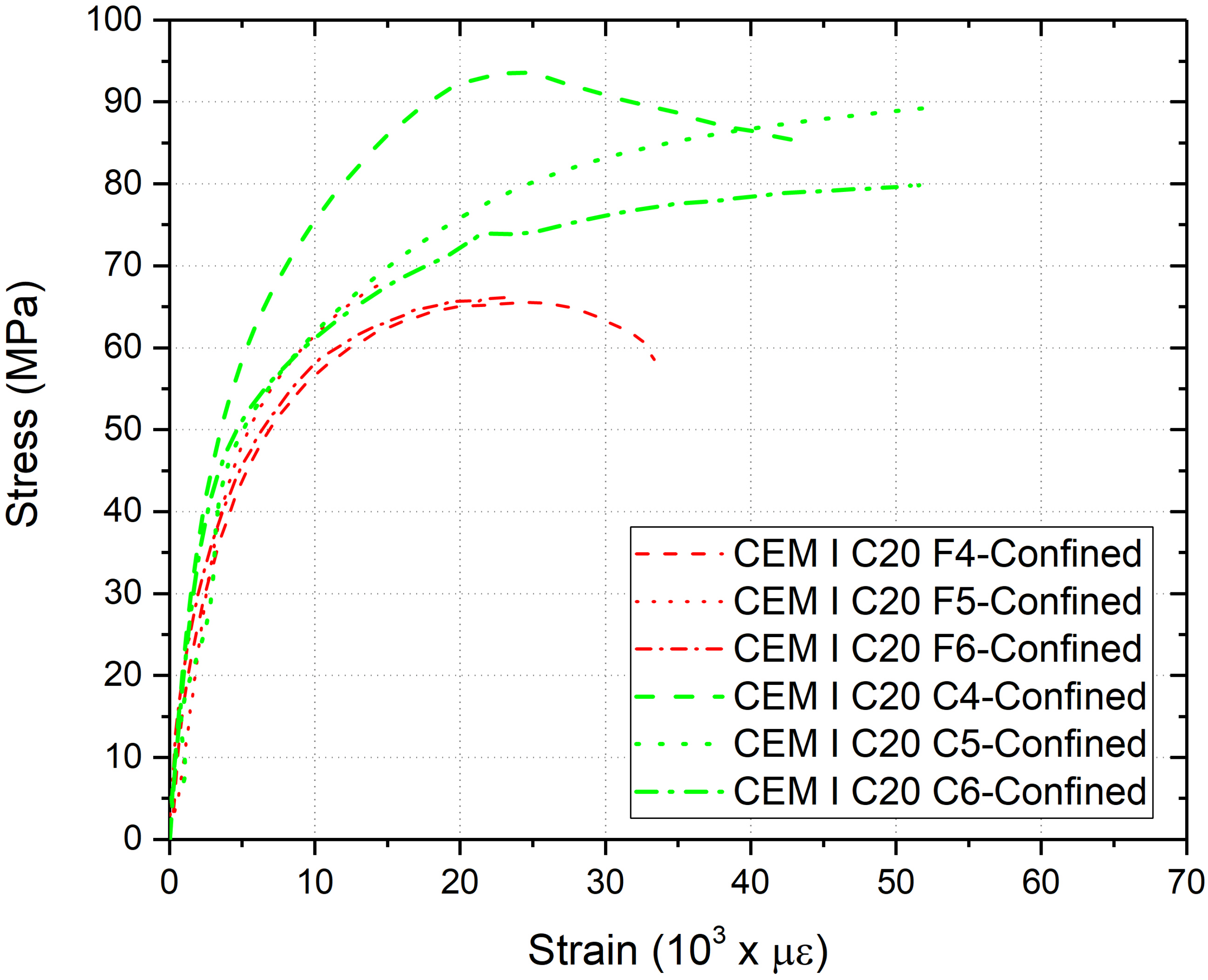


3c.jpg Figure


Stress (MPa)
30
25
20
15
10
5
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Strain (10³ x με)
CEM I C20 F1-Gauge
CEM I C20 F2-Gauge
CEM I C20 F3-Gauge
CEM I C20 C1-Gauge
CEM I C20 C2-Gauge
CEM I C20 C3-Gauge

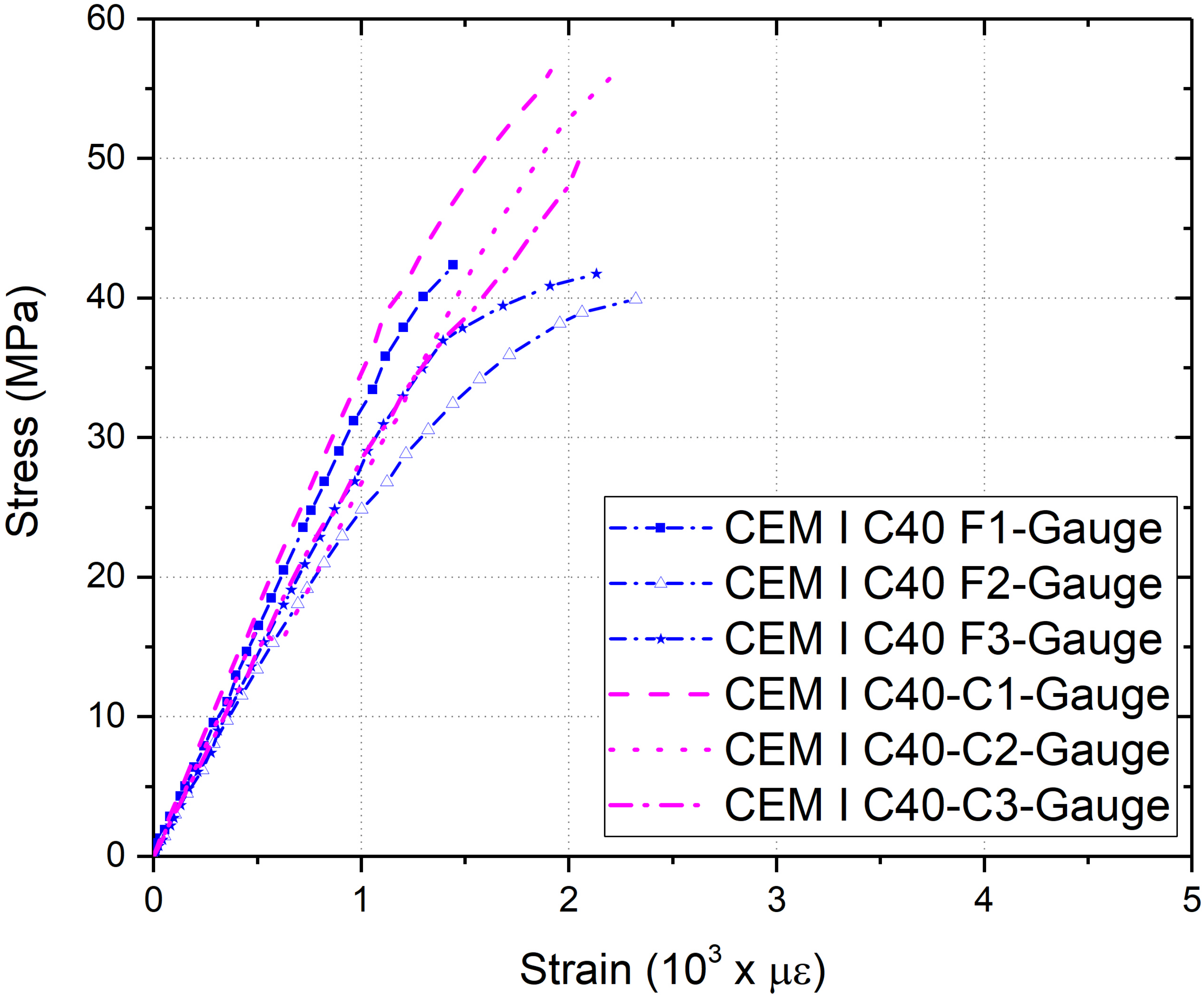
4b.jpg Figure

4c.jpg Figure


Stress (MPa)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
Strain (10^3 x με)
CEM I C20 F4-Confined
CEM I C20 F5-Confined
CEM I C20 F6-Confined
CEM I C20 C4-Confined
CEM I C20 C5-Confined
CEM I C20 C6-Confined

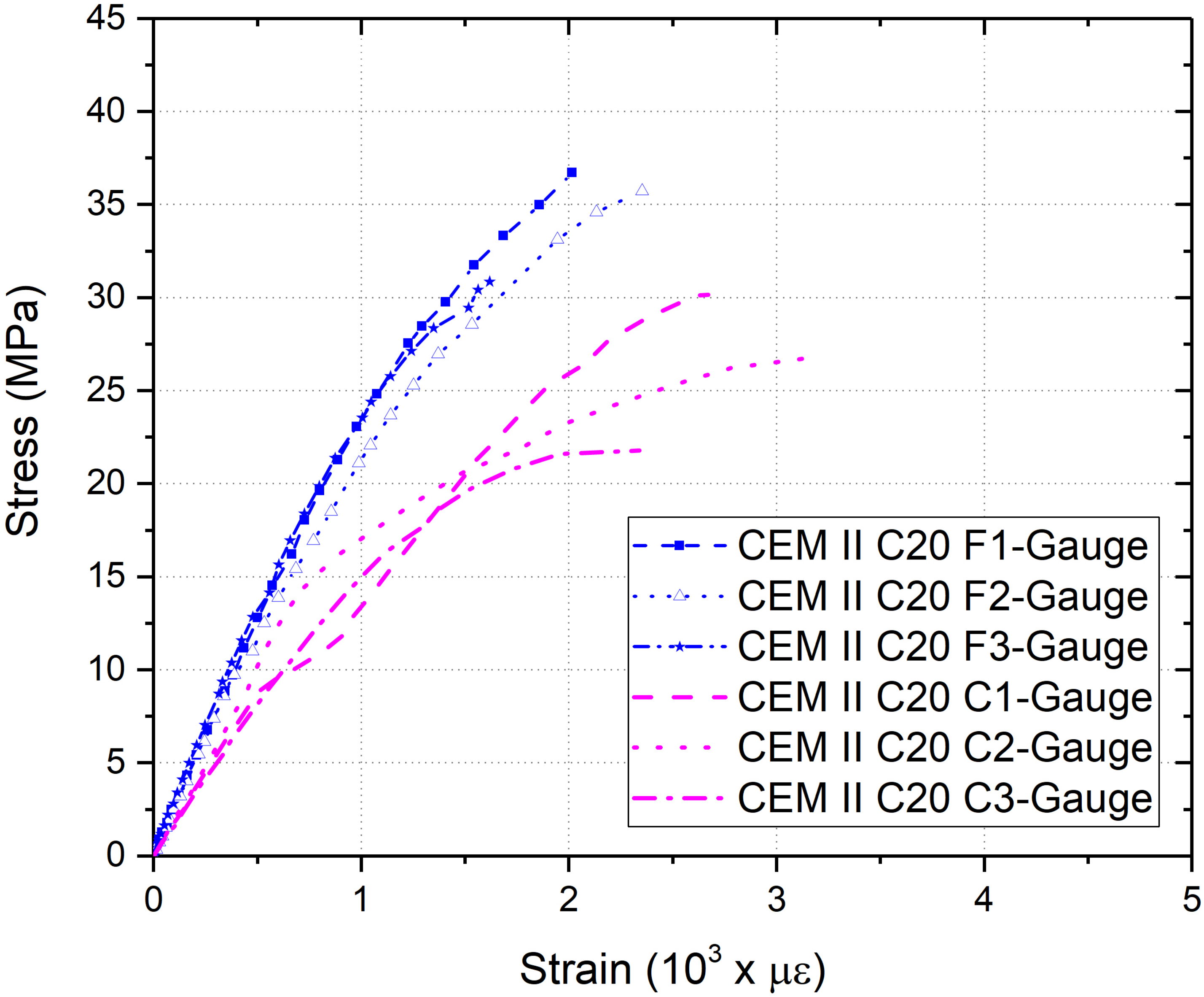
5b.jpg Figure

5c.jpg *Figure*


Stress (MPa)
60
50
40
30
20
10
0
Strain (10^3 x με)
0
1
2
3
4
5
CEM I C40 F1-Gauge
CEM I C40 F2-Gauge
CEM I C40 F3-Gauge
CEM I C40-C1-Gauge
CEM I C40-C2-Gauge
CEM I C40-C3-Gauge

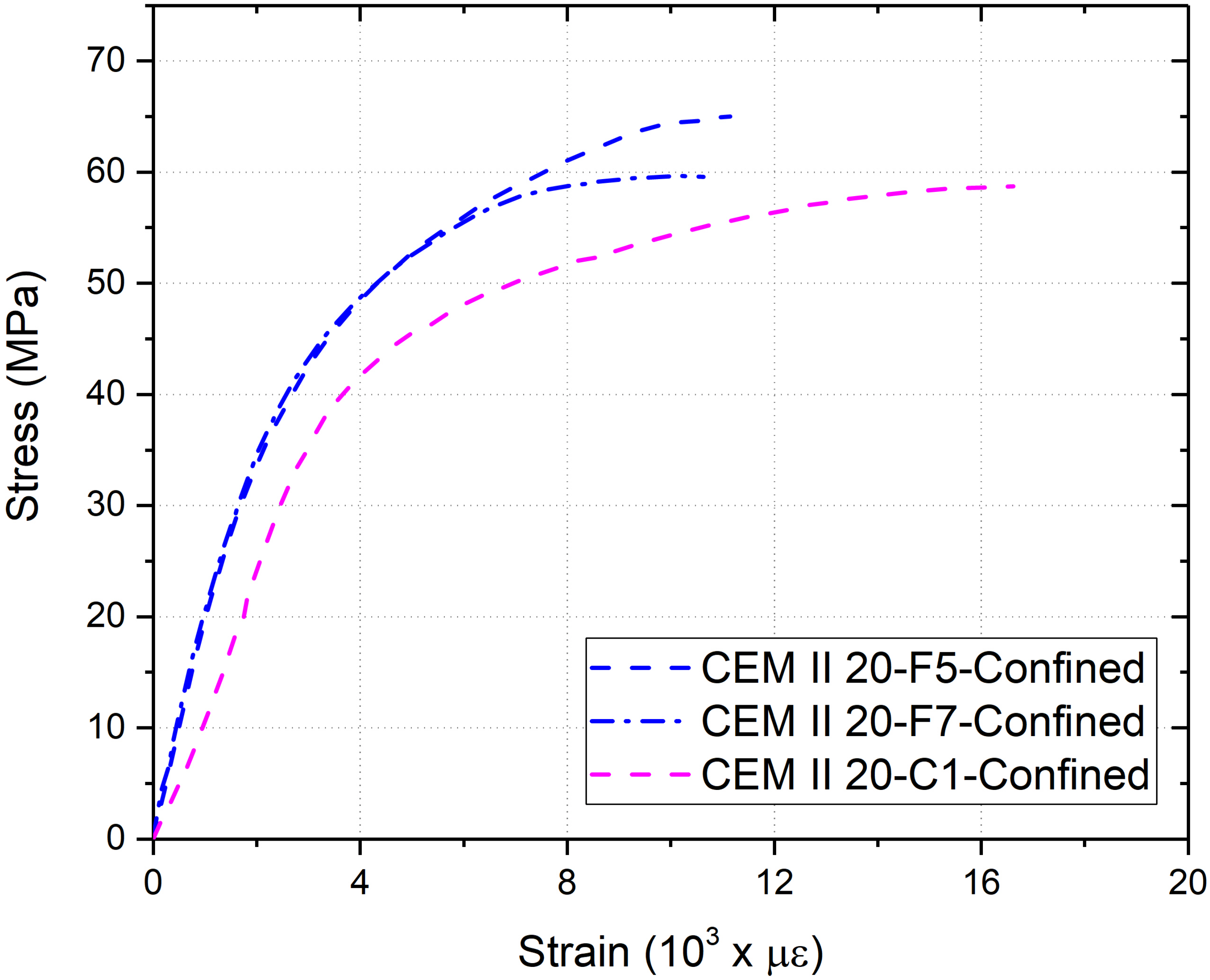
6b.jpg *Figure*

6c.jpg Figure

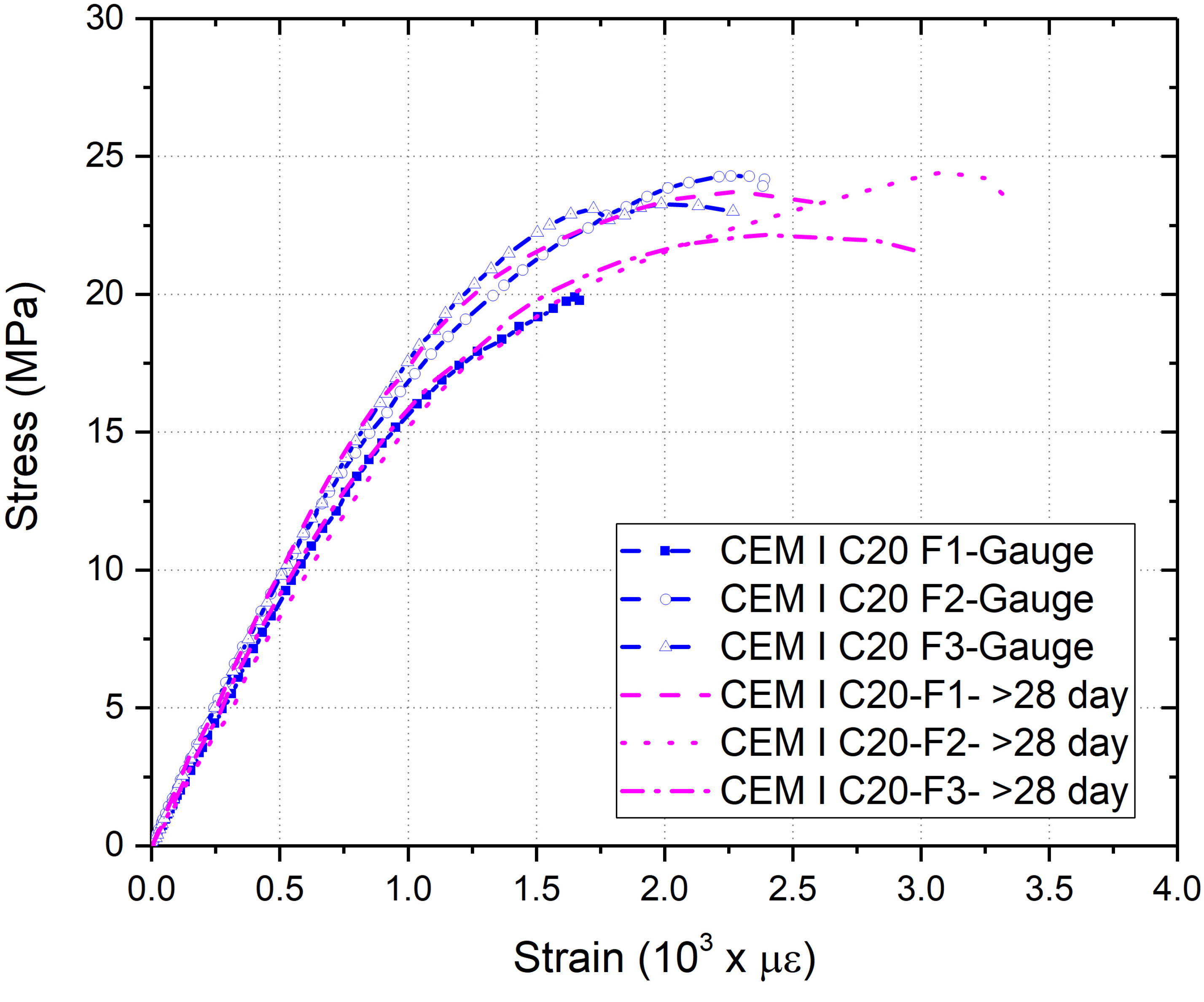

Stress (MPa)
0
5
10
15
20
25
30
35
40
45
Strain (10^3 x $\mu\varepsilon$)
0
1
2
3
4
5
CEM II C20 F1-Gauge
CEM II C20 F2-Gauge
CEM II C20 F3-Gauge
CEM II C20 C1-Gauge
CEM II C20 C2-Gauge
CEM II C20 C3-Gauge

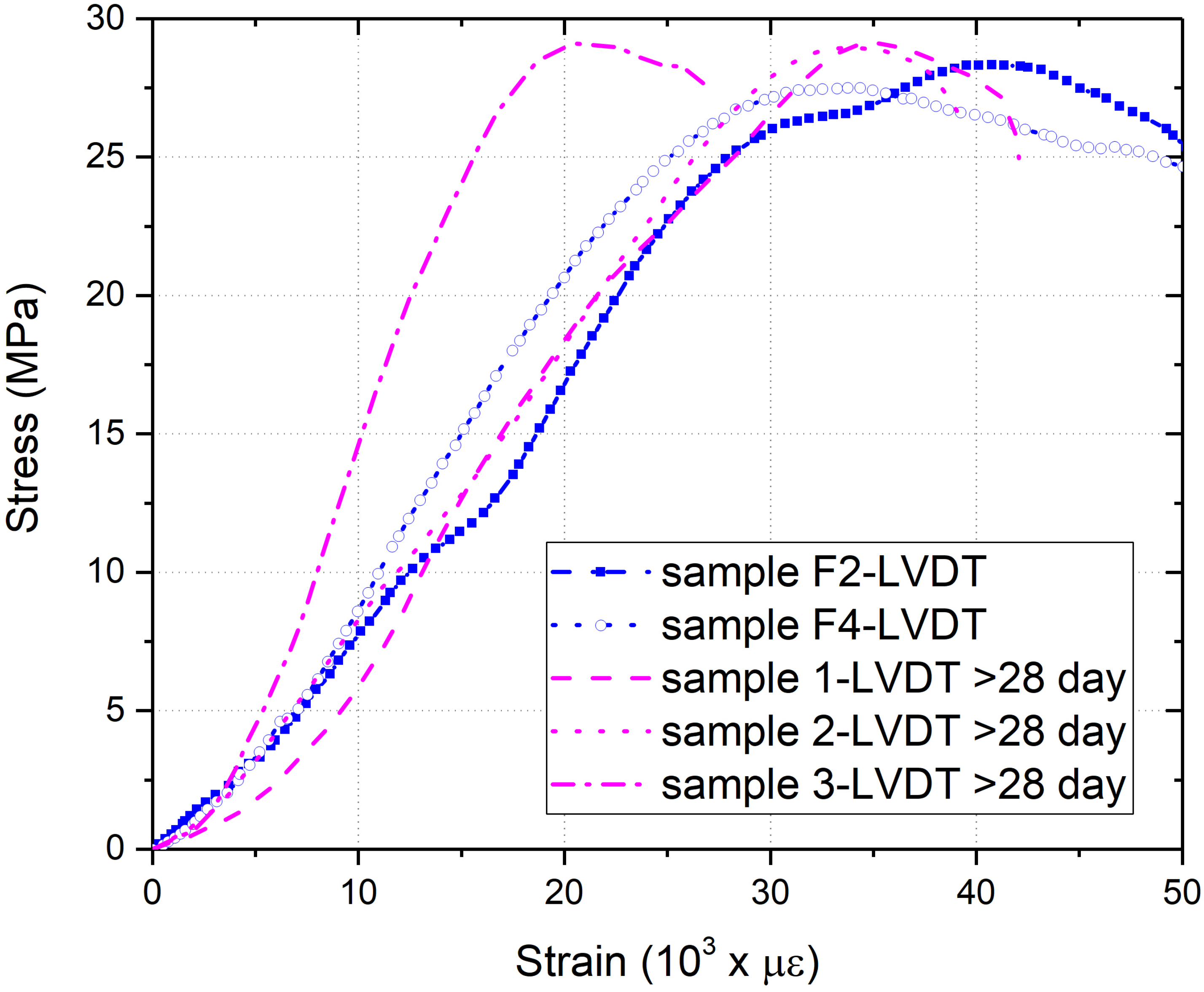
7b.jpg Figure

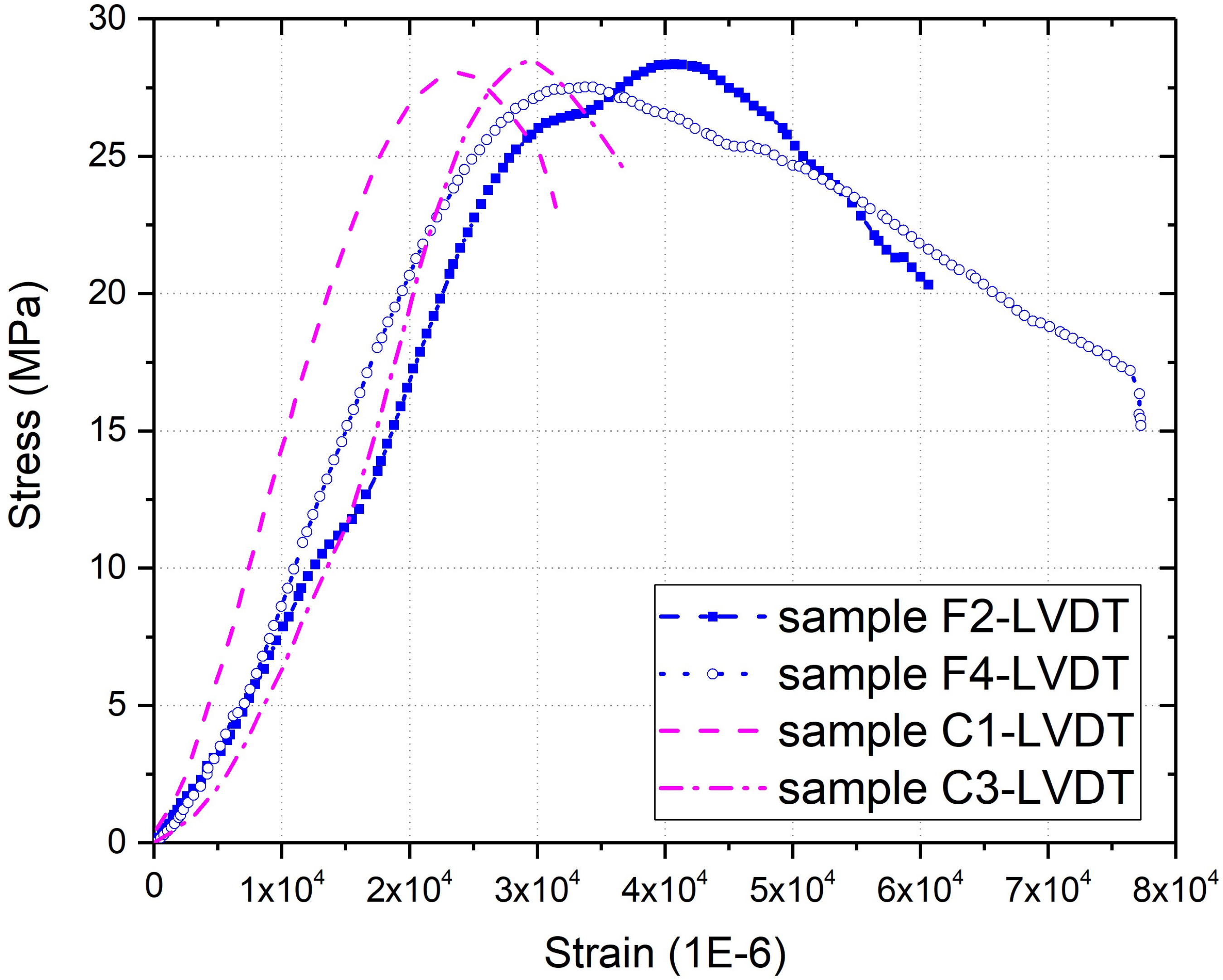
7c.jpg *Figure*

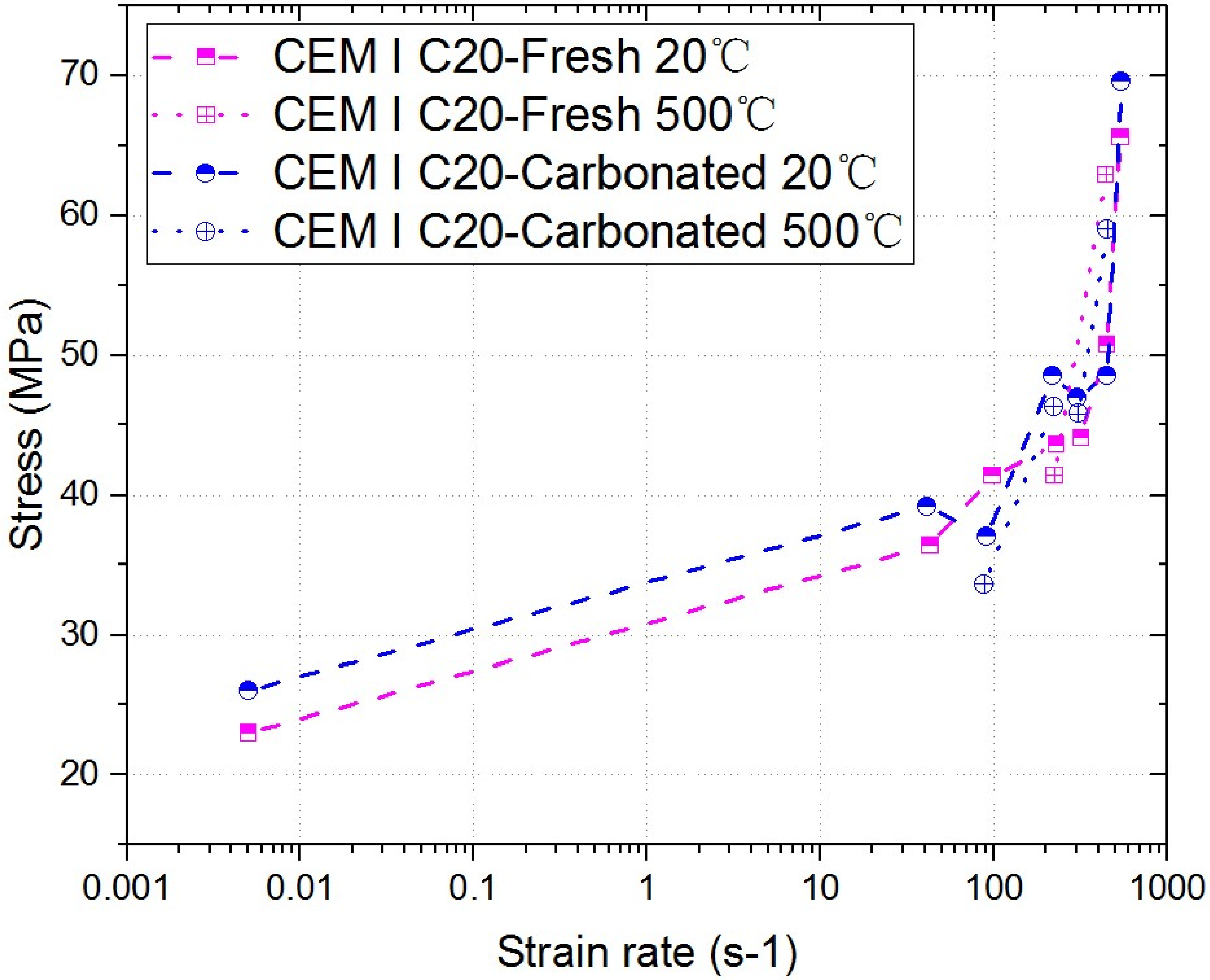

Stress (MPa)
0
10
20
30
40
50
60
70
Strain (10^3 x με)
0
4
8
12
16
20
CEM II 20-F5-Confined
CEM II 20-F7-Confined
CEM II 20-C1-Confined

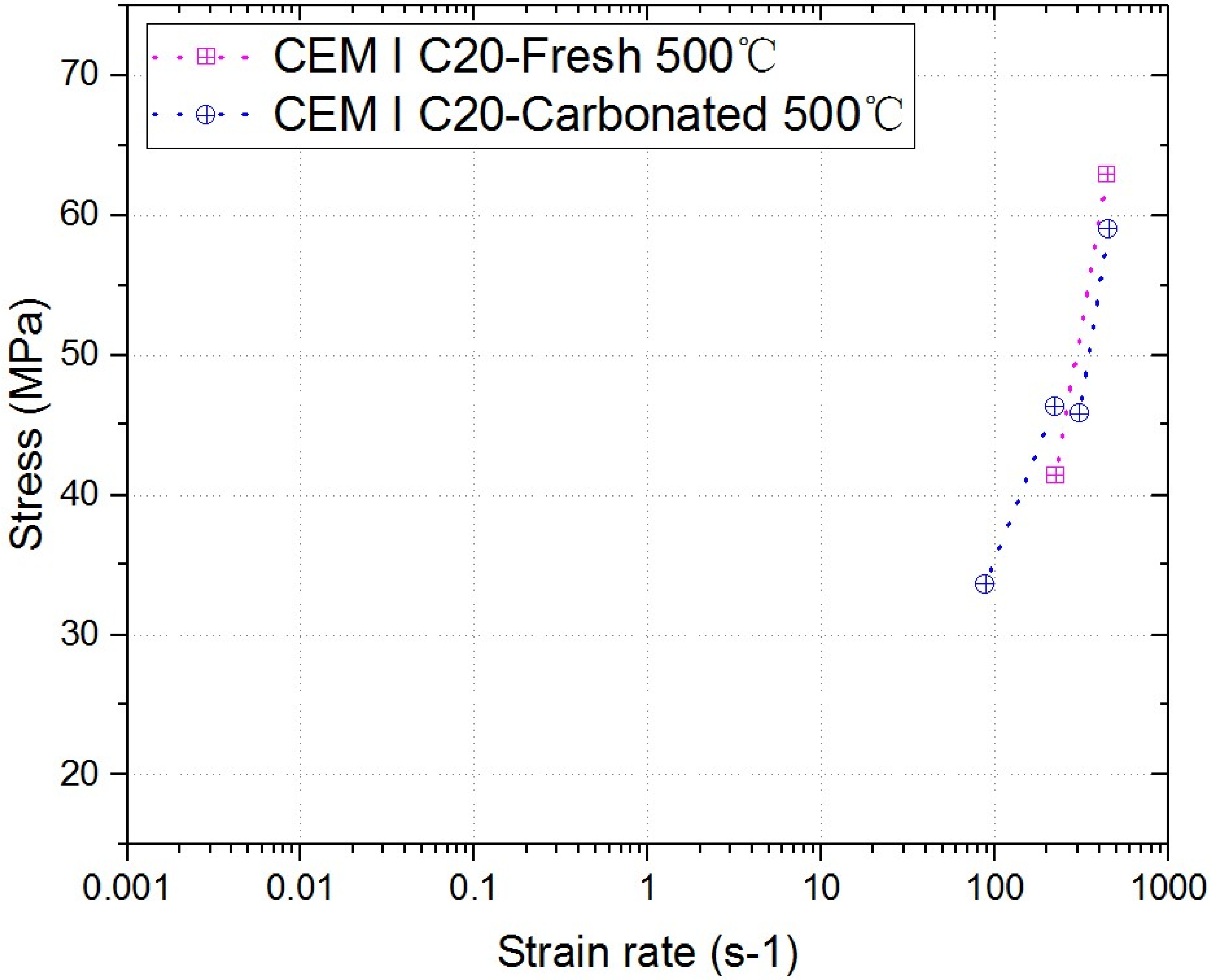
8b.jpg Figure

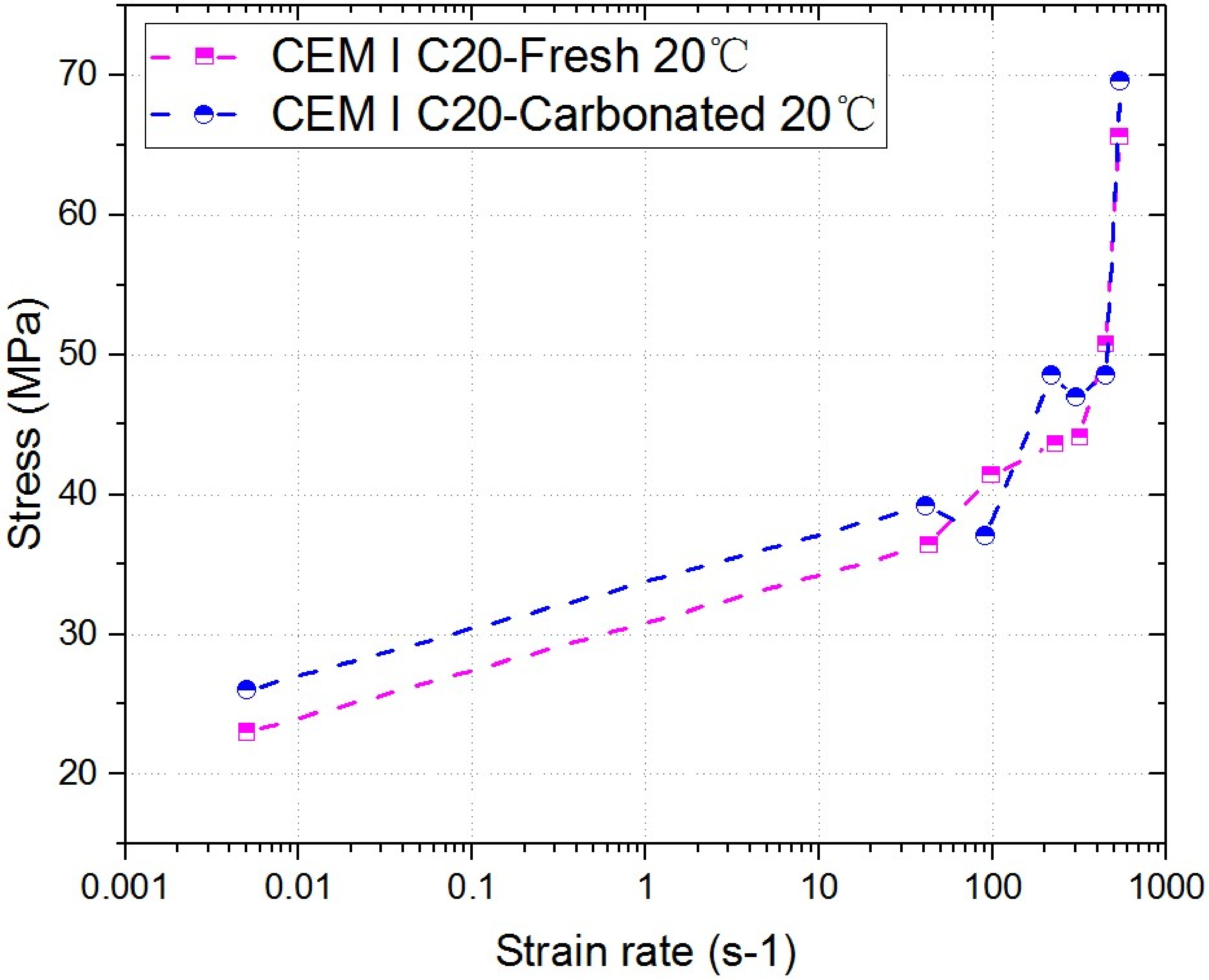

Stress (MPa)
Strain (10^3 x με)
0
5
10
15
20
25
30
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
CEM I C20 F1-Gauge
CEM I C20 F2-Gauge
CEM I C20 F3-Gauge
CEM I C20-F1- >28 day
CEM I C20-F2- >28 day
CEM I C20-F3- >28 day

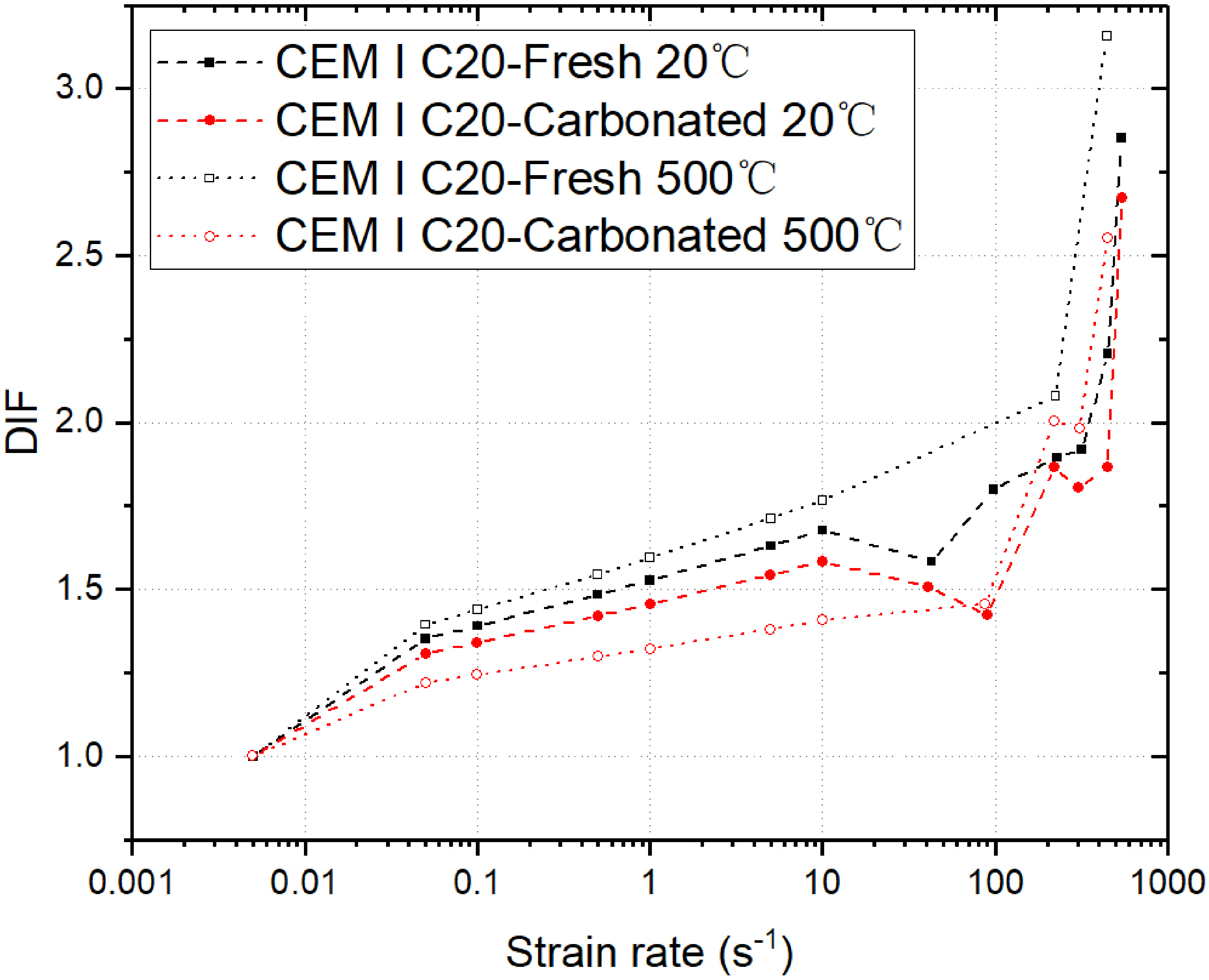

Stress (MPa)
30
25
20
15
10
5
0
0
10
20
30
40
50
Strain (10^3 x $\mu\varepsilon$)
sample F2-LVDT
sample F4-LVDT
sample 1-LVDT >28 day
sample 2-LVDT >28 day
sample 3-LVDT >28 day


Stress (MPa)
30
25
20
15
10
5
0
Strain (1E-6)
0
1x10^4
2x10^4
3x10^4
4x10^4
5x10^4
6x10^4
7x10^4
8x10^4
sample F2-LVDT
sample F4-LVDT
sample C1-LVDT
sample C3-LVDT


CEM I C20-Fresh 20℃
CEM I C20-Fresh 500℃
CEM I C20-Carbonated 20℃
CEM I C20-Carbonated 500℃
Stress (MPa)
70
60
50
40
30
20
0.001
0.01
0.1
1
10
100
1000
Strain rate (s-1)


CEM I C20-Fresh 500℃
CEM I C20-Carbonated 500℃
Stress (MPa)
70
60
50
40
30
20
0.001
0.01
0.1
1
10
100
1000
Strain rate (s-1)


CEM I C20-Fresh 20℃
CEM I C20-Carbonated 20℃
Stress (MPa)
20
30
40
50
60
70
Strain rate (s-1)
0.001
0.01
0.1
1
10
100
1000



11d-1.jpg Figure


F

14b.jpg *Figure*

14c.jpg *Figure*

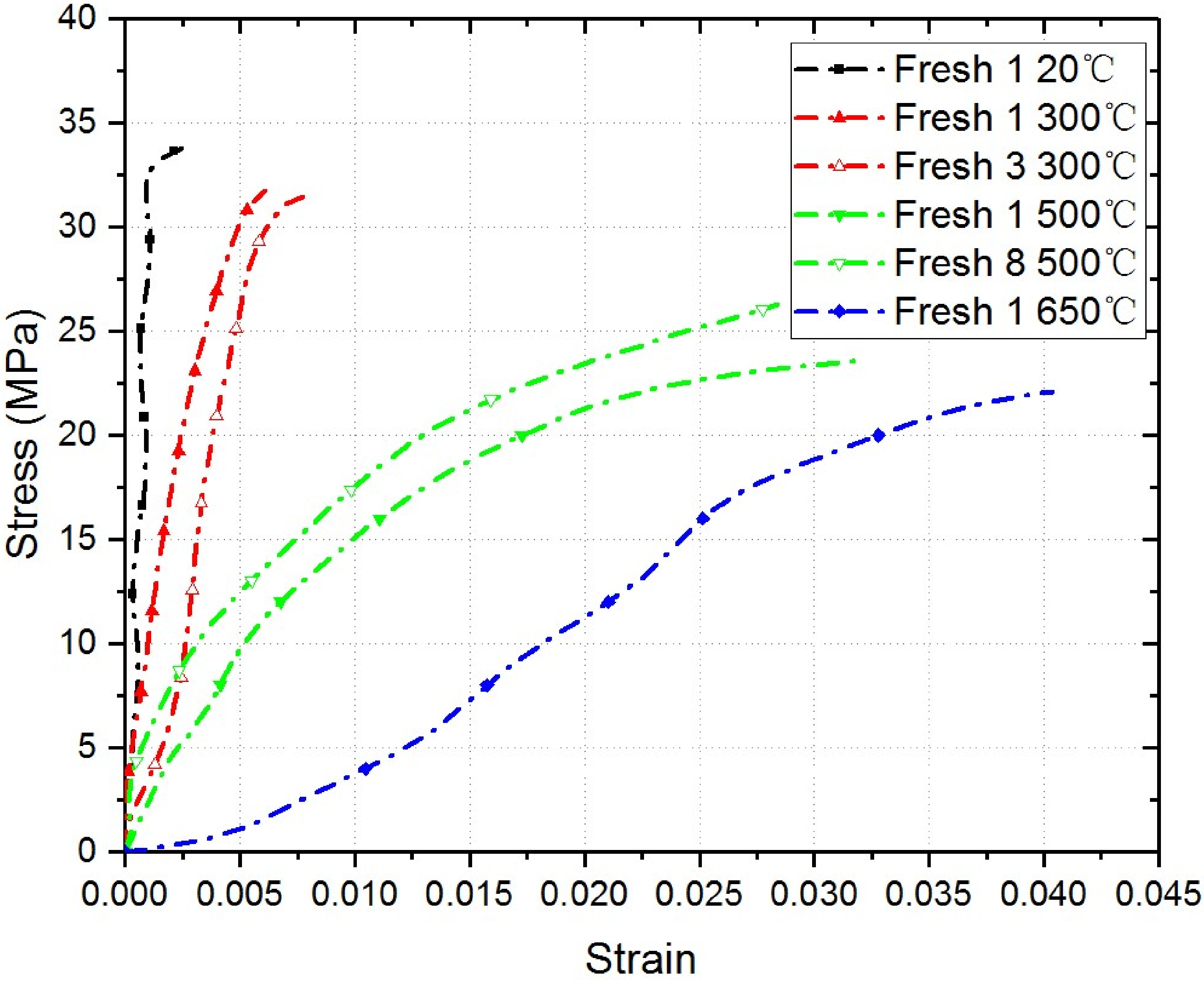
14d.jpg Figure

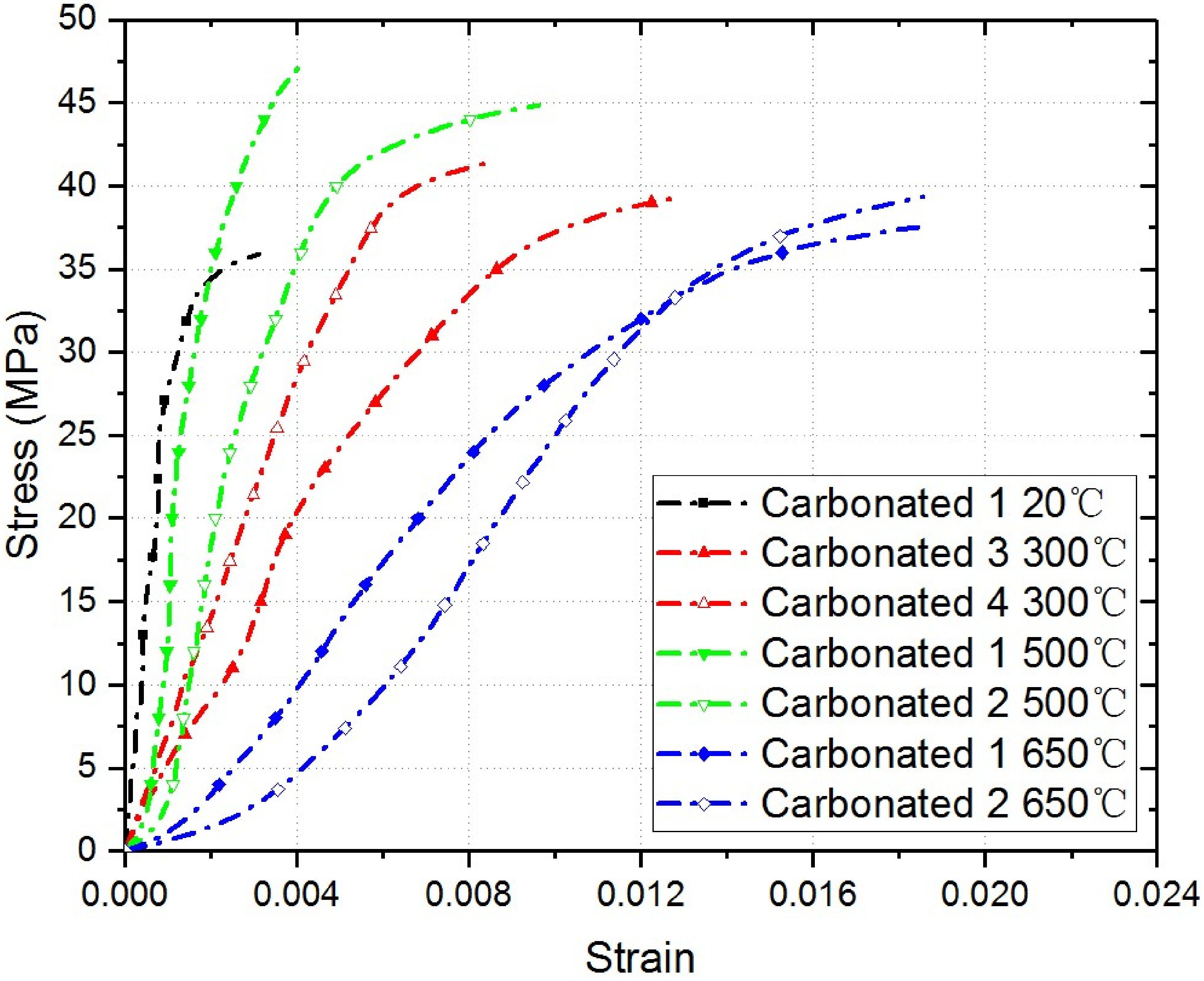
14e.jpg *Figure*

14f.jpg Figure

14g.jpg *Figure*

14h.jpg *Figure*


Fresh 1 20℃
Fresh 1 300℃
Fresh 3 300℃
Fresh 1 500℃
Fresh 8 500℃
Fresh 1 650℃
Stress (MPa)
Strain
0
5
10
15
20
25
30
35
40
0.000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045


50
45
40
35
30
25
20
15
10
5
0
Stress (MPa)
0.000
0.004
0.008
0.012
0.016
0.020
0.024
Strain
Carbonated 1 20℃
Carbonated 3 300℃
Carbonated 4 300℃
Carbonated 1 500℃
Carbonated 2 500℃
Carbonated 1 650℃
Carbonated 2 650℃

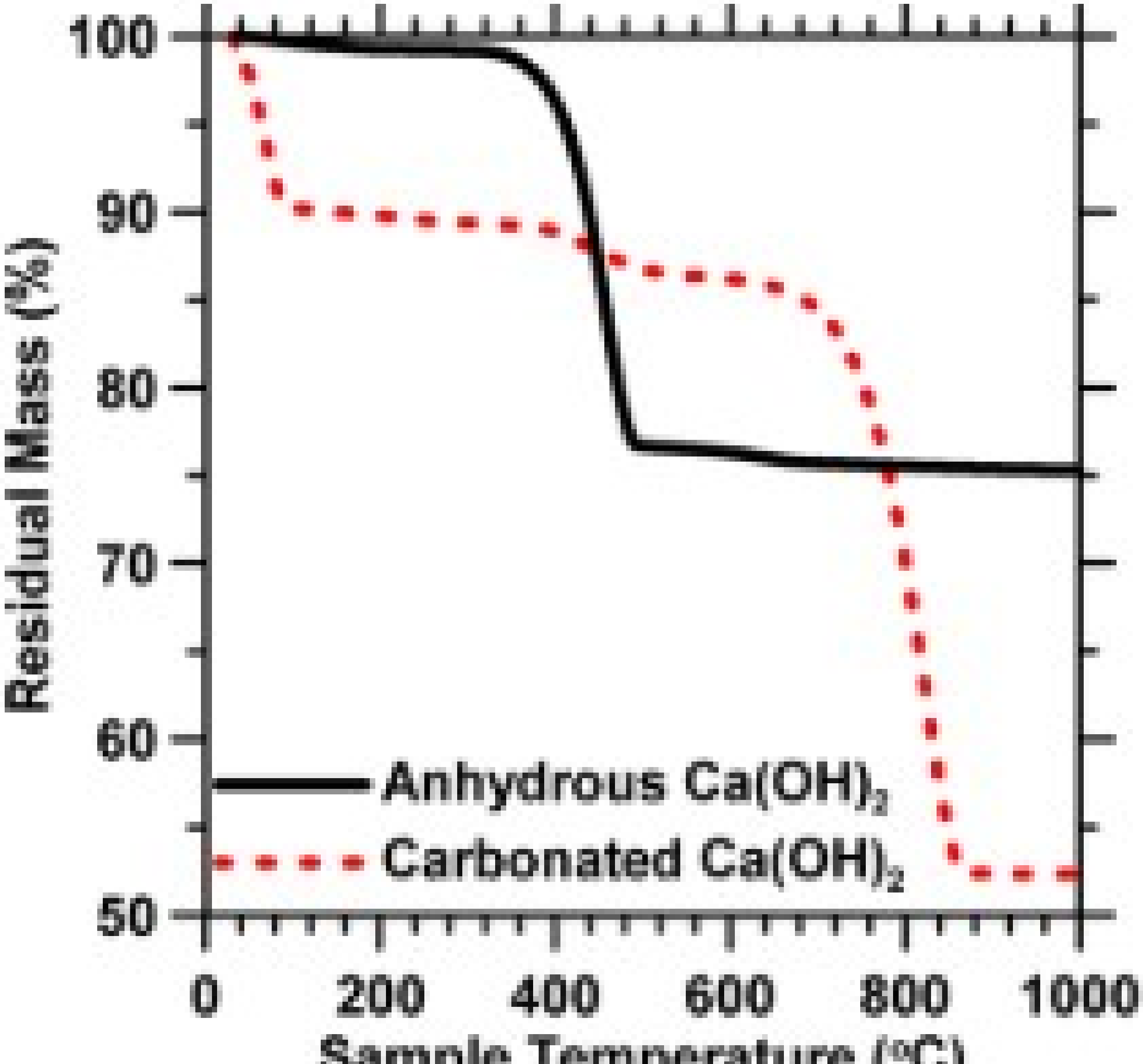
16a.jpg *Figure*

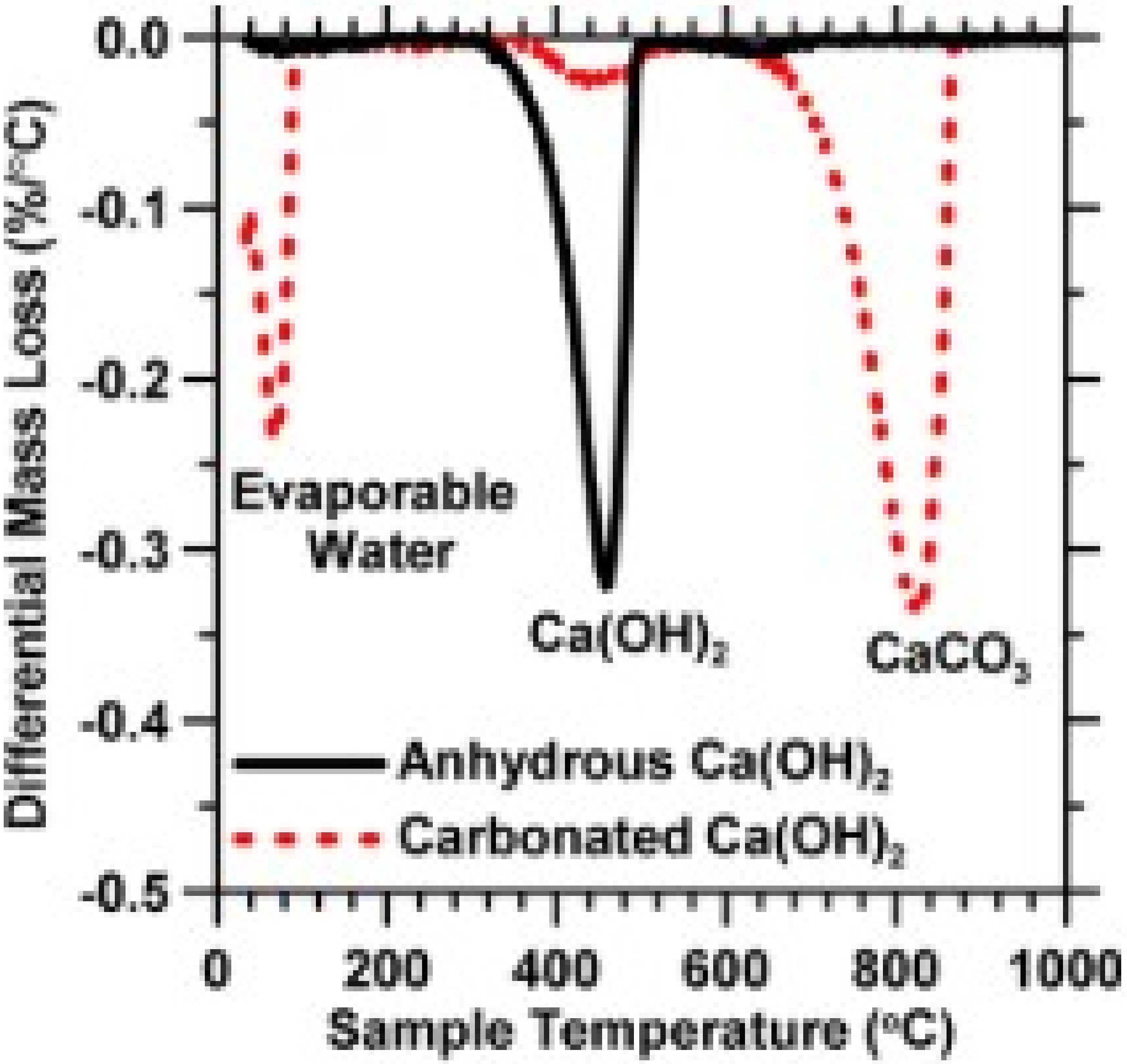
16b.jpg Figure

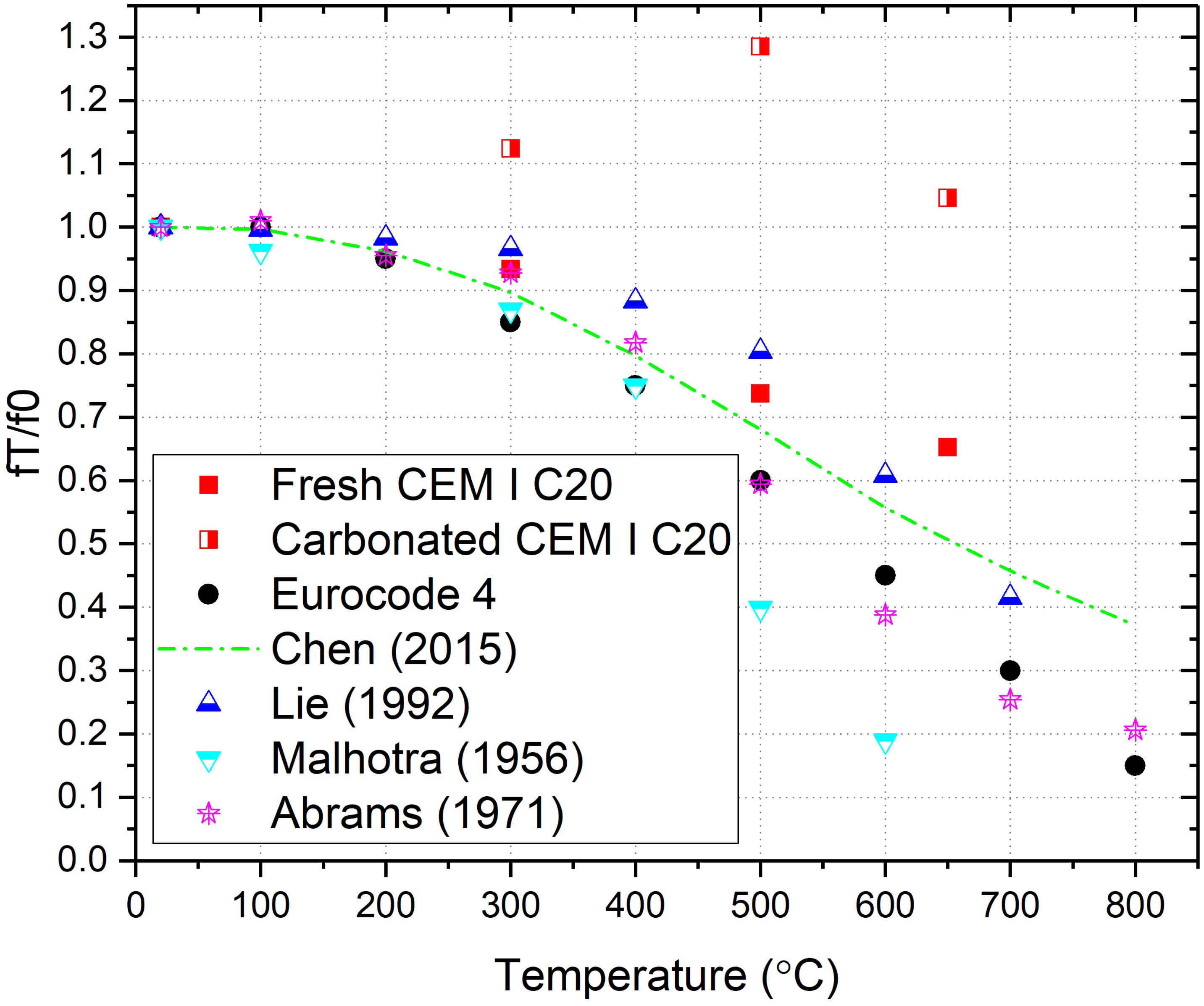
16c.jpg *Figure*

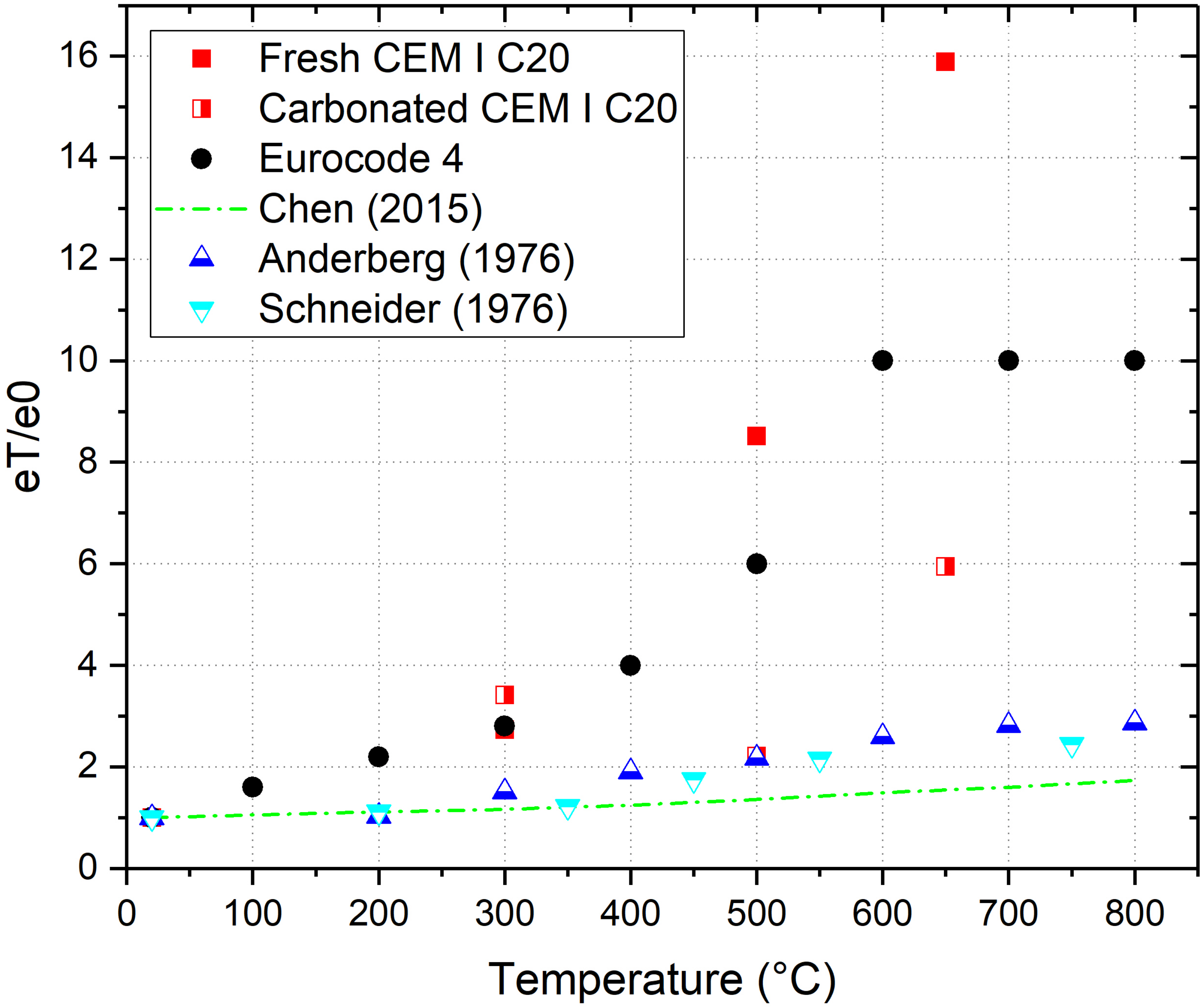
16e.jpg *Figure*

16h.jpg Figure


Residual Mass (%)
100
90
80
70
60
50
0
200
400
600
800
1000
Sample Temperature (°C)
Anhydrous Ca(OH)₂
Carbonated Ca(OH)₂


0.0
-0.1
-0.2
-0.3
-0.4
-0.5
Differential Mass Loss (%/°C)
0
200
400
600
800
1000
Sample Temperature (°C)
Evaporable Water
Ca(OH)₂
CaCO₃
Anhydrous Ca(OH)₂
Carbonated Ca(OH)₂


1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
fT/f0
0
100
200
300
400
500
600
700
800
Temperature (°C)
Fresh CEM I C20
Carbonated CEM I C20
Eurocode 4
Chen (2015)
Lie (1992)
Malhotra (1956)
Abrams (1971)



18b-1.jpg Figure