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# Strength of Silica Fume Incorporated Mortar Specimens Exposed to High Temperature

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**ABSTRACT:** The effect of high temperature on the strength of mortar specimens having W/B ratios of 0.4, 0.5 and 0.7 was investigated. Silica fume (SF) was replaced with portland cement at 0, 5 and 10% by weight. After 7, 28 and 90-day standard moist curing, followed by a 7-day drying period in the laboratory, the specimens were exposed to 300 and 600°C for 24 hours. Regardless of the duration of moist curing, SF addition resulted in higher compressive strength of specimens cured and tested at 20 °C. The effect was more pronounced in specimens having higher SF content. Flexural strength upon SF incorporation was decreased at all W/B ratios. Exposure to 300°C increased the compressive strength of nearly all specimens. However, the effect of it on flexural strength was somewhat contradictory. All control and SF incorporated specimens showed a dramatic decrease in strength upon exposure to 600°C. However, the residual strengths of SF mortars were greater than control mixtures.

Keywords: Residual strength, high temperature, silica fume.

**ÖZET:** Yüksek sıcaklığın S/B oranı 0.4, 0.5 ve 0.7 olan harç numunelerinin dayanıma olan etkisi incelenmiştir. Karışımlara çimento yerine %0, 5 ve 10 oranında silis dumanı (SD) eklenmiştir. 7, 28 ve 90 gün standard bakım sonunda, numuneler 7 gün laboratuvarda kurutulmuş ve daha sonra 24 saat 300 ve 600°C sıcaklıkta tutulmuştur. Yüksek sıcaklığa maruz kalmayan numunelerde, bakım süresinden bağımsız olarak SD içeren numuneler daha yüksek basınç dayanımı göstermiştir. Bu etki SD içeriğinin artması ile çoğalmıştır. Bu numunelerin eğilme dayanımında SD eklenmesi ile azalma oluşmuştur. 300°C sıcaklığın etkisi ile tüm numunelerin basınç dayanımları artmıştır. Bu sıcaklık, eğilme dayanımında çelişkili sonuçlara yol açmıştır. 600°C sıcaklığın etkisi ile tüm numunelerin dayanımında çarpıcı azalmalar meydana gelmiştir. Fakat SD içeren numunelerin kalan dayanımı, kontrol numunelerinden daha yüksektir.

## Introduction

High performance concretes (HPC) containing mineral admixtures are extensively used due to their superior structural performance, environmental friendliness and energy conserving characteristics (Mehta, 1999). Apart from the usual risk of fire, in some structures such as the oil, gas, nuclear and power industries the concrete is exposed to high temperature and pressure for considerable periods of time. Although concrete has excellent resistance to high temperature, and is often used as a protective material for steel, many studies have shown extensive damage or even catastrophic failure at high temperatures, particularly in HPC (Poon et al, 2001). In addition to the level and duration of temperature exposure, the resistance of concrete to elevated temperatures depends on several factors, such as moisture content of concrete, the size and distribution of pores in the cement paste, aggregate type, the size of the concrete member and the stress acting upon (Khayat and Aïtcin, 1992; Neville, 1995). The composition of cement paste has a relatively less effect on the behavior of concrete at high temperature (Smith, 1994). However, it is known that at a temperature of 300$^o$C, the interlayer water and some of the chemically combined water from CSH and CSAHs may be lost. At 500$^o$C further dehydration begins due to decomposition of CH. At temperatures beyond 900$^o$C the complete dehydration of CSH occurs (Mehta, 1993). Smith (1994) reported that the dehydration of CH to calcium oxide and subsequent rehydration and carbonation of this compound causes a disruptive 14% expansion which is enough to cause distress and loss of strength. Thus, the preference is given to the use of cements releasing least amounts of CH or the use of fly ash and blast furnace slag cements.

Silica fume (SF) is also expected to show similar effect. Moreover, because of the fine pore structure and lower permeability in SF concrete, the lower rate of seepage of vapor may cause internal cracking, more strength reduction and sometimes spalling or even explosive spalling (Khayat and Aïtcin, 1992; Neville 1995). Hertz reported that 100×200 mm steel fiber reinforced high-strength concrete cylinder specimens exploded when heated between 200 and 400$^o$C. However, smaller specimens made from the same concrete did not explode. This explosive phenomenon was attributed to the size effect where thermal gradients are sharper in larger specimens, and the fact that internal moisture may easily migrate out of the concrete before high internal pressure begin to build up in small specimens as cited by Khayat and Aïtcin, (1992). Some investigators attributed the spalling to the thermal stress induced by rapid temperature rise or thermal shock (Sanjayan and Stocks, 1993; Felicetti and Gambarova, 1998). Others do not share the same idea (Luo et al, 2000).

Williamson and Rashed evaluated the residual compressive strength of low-strength, medium-strength and high-strength mortars containing 0, 8 and 16% SF at high temperatures. It was concluded that upon heating, the relative loses in compressive strength of low-strength control mortars were greater than that of mortars containing SF; whereas, high-strength SF mortars exhibited more strength reduction than non-SF mortars (Khayat and Aïtcin, 1992).

Jahsen (1989), in his comprehensive review concluded that there is little evidence to indicate that SF can have a negative effect on fire resistance of concrete. The damage of the high-strength concrete subjected to high temperature was attributed to dense structure of the material regardless of the presence or absence of SF. In order to reduce the risk of additional spalling potential of HSC, the author suggested addition of steel fibers for high-risk structures. Similar conclusions were verified by Luo et al (2000).

## Experimental Study

### Materials

The chemical composition of the ordinary portland cement (PÇ 42.5) and SF used in this study are given in Table 1.

Table 1. Chemical Composition and Physical Properties of Portland Cement and SF

| Item | | PÇ 42.5 | SF |
|---|---|---|---|
| CaO (%) | | 64.1 | 0.5 |
| $SiO_2$ (%) | | 20.4 | 92.8 |
| $Al_2O_3$(%) | | 5.1 | 0.8 |
| $Fe_2O_3$ (%) | | 3.5 | 0.7 |
| MgO (%) | | 1.0 | 0.6 |
| $Na_2O$ (%) | | 0.2 | 0.1 |
| $K_2O$ (%) | | 0.8 | 0.6 |
| $SO_3$ (%) | | 2.8 | - |
| S (%) | | - | 0.1 |
| C (%) | | - | 1.0 |
| LOI(%) | | 1.0 | 0.7 |
| IR (%) | | 0.4 | - |
| Specific Gravity | | 3.15 | 2.3 |
| Blaine Specific Surface ($cm^2/g$) | | 3760 | - |
| Le Chatelier Soundness (mm) | | 3 | - |
| Initial Setting Time (min.) | | 125 | - |
| Final Setting Time (min.) | | 180 | - |
| Compressive Strength (MPa) | 2-D | 33.5 | - |
| | 7-D | 44.2 | - |
| | 28-D | 49 | - |
| Strength Activity Index with PC (%) | | - | 114 |

A natural sand passing 4 mm sieve was used. Sikament FF-N superplasticizer was used to adjust the flow of the mixtures (if necessary) in the ranges recommended by the manufacturer.

**Mix Proportions**

In addition to control mortar mixtures containing no SF, 5 and 10% by weight of cement was replaced by SF. The W/B ratios of the mixtures were 0.4, 0.5 and 0.7. The flow of the mixtures having 0.4 and 0.5 W/B ratios were kept constant at 110±5% using a superplasticizer in the range of 0.8 to 3% by binder weight (if necessary). The cement/aggregate ratio was 1 : 2.75 in all of the mixtures.

**Testing Procedure**

40×40×160 mm mortar specimens were cured in water for 7, 28 and 90 days, then air dried in the laboratory for 7 days before exposing to high temperature. An electric heater was used and heat was applied at a rate of 5-7$^{o}$C/min. Specimens were heated for 24 hours at 300 and 600$^{o}$C then heater was turned off and specimens continuously cooled to air temperature. The flexural and compressive strength of the specimens were determined.

## Test Results and Discussions

Test results are summarized in Table 2 and Table 3. The compressive strength of SF incorporated specimens cured and tested in 20 $^{o}$C is superior to that of control specimens at all ages. The effect is more pronounced in 10% SF bearing mixes. These results are in good agreement with the previous studies (Khayat and Aïtcin, 1992 Papadakis, 1999). Flexural strength test results are somewhat contradictory. SF addition decreases flexural strength of control mixtures, particularly in mixes having lower W/B ratios. The sensitivity of test results to the local flaws around midspan seems to be responsible for low flexural strength of SF bearing mixtures. At elevated temperatures, with a few exceptions, 5% SF incorporation improves the residual flexural strength.

Table 2. Compressive Strength Test Results

| | SF Content (%) | Compressive Strength (MPa) 20°C cured for | | | 300°C cured for | | | 600°C cured for | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 7D | 28D | 90D | 7D | 28D | 90D | 7D | 28D | 90D |
| W/B=0.4 | 0 | 57.6 | 62.8 | 63.6 | 72.2 | 74.2 | 75.1 | 32.7 | 45.2 | 51.5 |
| | 5 | 64.5 | 64.3 | 67.7 | 78.8 | 80.3 | 81.1 | 50.8 | 54.1 | 59.0 |
| | 10 | 58.8 | 67.4 | 68.6 | 72.8 | 76.1 | 78.1 | 42.9 | 50.2 | 53.6 |
| W/B=0.5 | 0 | 50.9 | 56.4 | 56.7 | 49.4 | 55.9 | 58.6 | 23.8 | 32.7 | 35.6 |
| | 5 | 52.5 | 59.9 | 60.4 | 53.4 | 63.5 | 65.5 | 39.8 | 37.7 | 40.4 |
| | 10 | 62.8 | 66.0 | 67.1 | 64.7 | 67.3 | 68.5 | 43.1 | 43.0 | 45.4 |
| W/B=0.7 | 0 | 19.5 | 25.0 | 26.8 | 18.5 | 27.6 | 30.3 | 11.9 | 15.6 | 20.3 |
| | 5 | 20.9 | 30.7 | 32.7 | 20.8 | 35.1 | 35.9 | 14.0 | 18.1 | 20.1 |
| | 10 | 23.2 | 31.5 | 33.1 | 28.3 | 36.4 | 37.4 | 14.4 | 18.7 | 20.7 |

Table 3. Flexural Strength Test Results

| | SF Content (%) | Flexural Strength (MPa) 20°C cured for | | | 300°C cured for | | | 600°C cured for | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 7D | 28D | 90D | 7D | 28D | 90D | 7D | 28D | 90D |
| W/B=0.4 | 0 | 9.6 | 9.8 | 10.8 | 8.4 | 8.5 | 9.1 | 3.4 | 5.0 | 5.5 |
| | 5 | 8.2 | 8.4 | 8.4 | 8.7 | 9.1 | 10.2 | 4.6 | 5.7 | 6.2 |
| | 10 | 7.9 | 8.2 | 9.7 | 7.4 | 8.0 | 6.2 | 3.8 | 5.6 | 5.8 |
| W/B=0.5 | 0 | 8.9 | 8.9 | 9.0 | 8.2 | 8.3 | 9.2 | 2.8 | 4.1 | 5.2 |
| | 5 | 8.6 | 8.4 | 8.5 | 8.9 | 9.2 | 9.5 | 5.7 | 5.9 | 5.9 |
| | 10 | 8.0 | 8.2 | 8.3 | 9.9 | 10.0 | 7.7 | 4.9 | 5.4 | 5.8 |
| W/B=0.7 | 0 | 6.0 | 6.3 | 6.6 | 4.0 | 5.1 | 6.3 | 1.5 | 2.2 | 2.8 |
| | 5 | 4.7 | 4.9 | 5.1 | 4.1 | 4.8 | 5.2 | 2.1 | 2.4 | 2.7 |
| | 10 | 5.7 | 5.8 | 5.9 | 5.0 | 5.4 | 5.4 | 1.8 | 2.0 | 2.6 |

Test results reveal that long term curing beyond 28 days causes a negligible increase in compressive strength of either SF or non SF mixtures exposed to 20 °C and 300 °C. However, it increases the residual compressive strength of specimens heated at 600 °C by about 10%.

Upon exposure to 300°C, the compressive strength of nearly all mortar specimens increases significantly compared to the corresponding specimen tested at 20°C (Fig.1). The effect is more pronounced in mixtures having W/B ratio of 0.4. It seems that SF addition does not provide any considerable additional benefit or damage to the relative compressive strength.

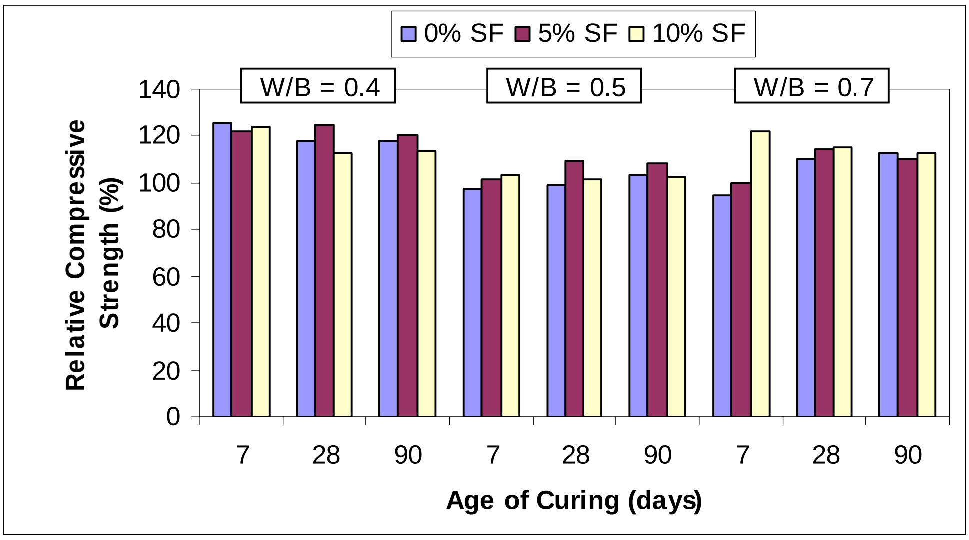

Fig.1 The ratio of the compressive strength of specimens exposed to 300°C to that of corresponding control specimens cured and tested at 20°C

24-hour exposure to 600°C resulted in a great decrease in both compressive and flexural strengths of control and SF bearing mixtures. However, the residual strength of SF incorporated specimens is higher than that of corresponding control specimens. Moreover, 7-day moist cured specimens show greater loss on strength than 28 and 90-day cured ones. From flexural strength point of view, the optimum SF content for mixtures having W/B ratios of 0.4 and 0.5 seems to be 5%. Further, SF addition causes a slight reduction in flexural strength irrespective of the exposure temperature.

The relative compressive strength of specimens exposed to 600°C is shown in Fig. 2. Substitution of 5% of cement with SF improves the relative compressive strength, particularly at low W/B ratios. Further increase in SF content causes a negligible increase or even a considerable decrease in relative strength. Besides, finely distributed surface micro cracks were observed in 10% SF bearing mixtures having W/B ratio of 0.4. These facts are, perhaps, due to the build up of higher pore pressure by water vapor.

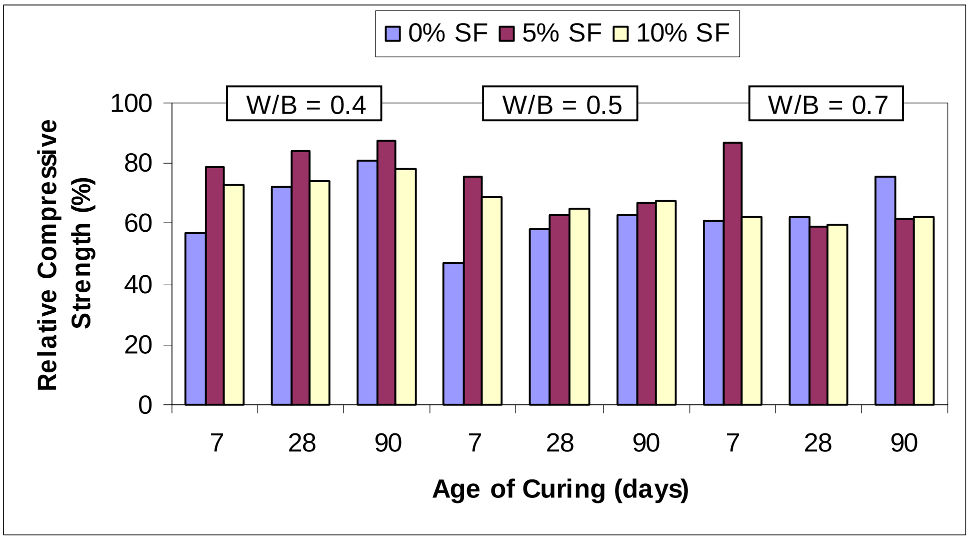

Fig.2 The ratio of the compressive strength of specimens exposed to 600°C to that of corresponding control specimens cured and tested at 20 °C

The relative flexural strengths of specimens exposed to 300 and 600°C to that of corresponding control specimens cured and tested at 20°C are shown in Fig. 3 and Fig..4, respectively. It can be revealed that irrespective of the W/B ratio of the mixture and the level of the applied temperature, the optimum SF replacement level to provide higher relative flexural strength is 5%. Moreover, compared to the relative compressive strength (Fig. 1 and 2) relative flexural strength (Fig. 3 and 4) suffers more in mixtures having 0,7 W/B ratio.

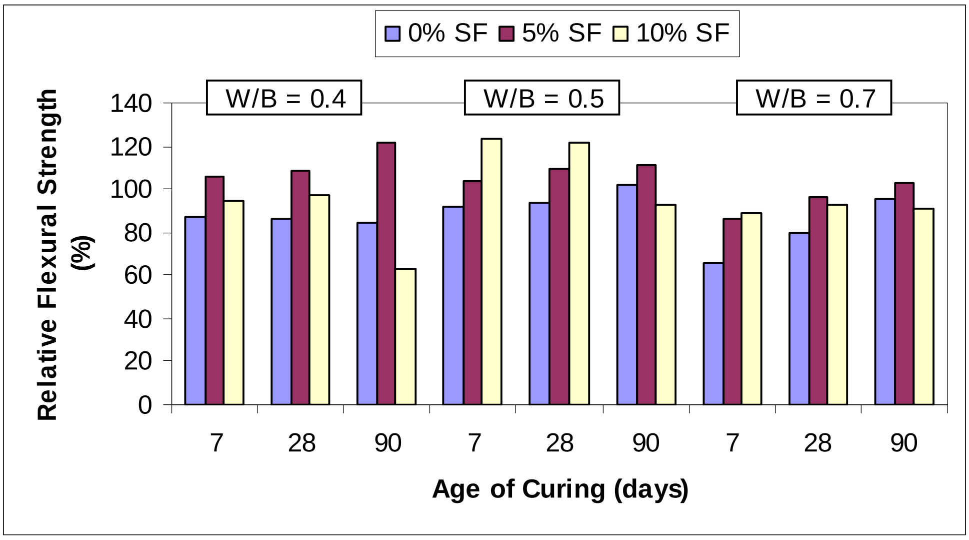

Fig.3 The ratio of the flexural strength of specimens exposed to 300 °C to that of corresponding control specimens cured and tested at 20 °C

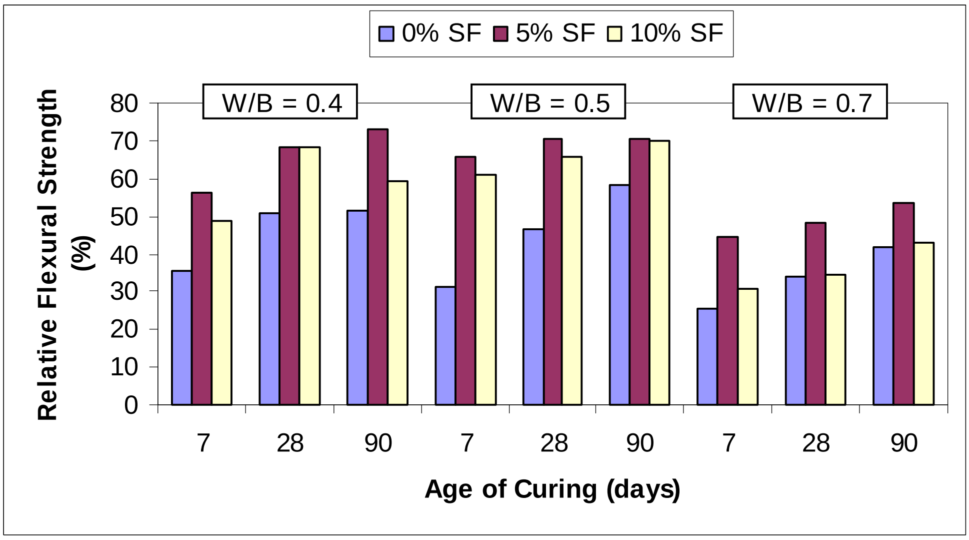

Fig.4 The ratio of the flexural strength of specimens exposed to 600 °C to that of corresponding control specimens cured and tested at 20 °C

As shown in Table 4, the compressive strength/flexural strength ratio of specimens exposed to 20 °C increases even up to 50% by 5% SF addition. This indicates that SF incorporation improves the compressive strength of the mortar more than its flexural strength. This may be due to lower grain refinement effect of SF as a result of absence of coarse aggregate particles in the mortar mixture. It is known that flexural strength is more sensitive to the characteristics of transition zone than compressive strength.

Besides, exposure to elevated temperatures further increases the compressive/flexural strength ratio. The effect is more pronounced in control mixtures containing no SF. It seems that at high temperatures, flexural strength is more suffered than compressive strength.

Table 4. Compressive Strength/Flexural Strength Ratios

| | SF Content (%) | Compressive Strength/Flexural Strength Ratios | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 20°C cured for | | | 300°C cured for | | | 600°C cured for | | |
| | | 7D | 28D | 90D | 7D | 28D | 90D | 7D | 28D | 90D |
| W/B=0.4 | 0 | 6.0 | 6.4 | 5.9 | 8.6 | 8.7 | 8.3 | 9.6 | 9.0 | 9.4 |
| | 5 | 7.9 | 7.7 | 8.1 | 9.1 | 8.8 | 8.0 | 11.0 | 9.5 | 9.5 |
| | 10 | 7.4 | 8.2 | 7.1 | 9.8 | 9.5 | 12.6 | 11.3 | 9.0 | 9.2 |
| W/B=0.5 | 0 | 5.7 | 6.3 | 6.3 | 6.0 | 6.7 | 6.4 | 8.5 | 8.0 | 6.8 |
| | 5 | 6.1 | 7.1 | 7.1 | 6.0 | 6.9 | 6.9 | 7.0 | 6.4 | 6.8 |
| | 10 | 7.9 | 8.0 | 8.1 | 6.5 | 6.7 | 8.9 | 8.8 | 8.0 | 7.8 |
| W/B=0.7 | 0 | 3.3 | 4.0 | 4.1 | 4.6 | 5.4 | 4.8 | 7.9 | 7.1 | 7.3 |
| | 5 | 4.4 | 6.3 | 6.4 | 5.1 | 7.3 | 6.9 | 6.7 | 7.5 | 7.4 |
| | 10 | 4.1 | 5.4 | 5.6 | 5.7 | 6.7 | 6.9 | 8.0 | 9.4 | 8.0 |

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## Conclusions

- Before exposure to high temperature, SF incorporated mixtures show higher compressive strength than control mixtures. The effect increases by increasing SF content. However, SF addition causes somewhat reduction in flexural strength.
- Upon exposure to 300°C the compressive strength of nearly all specimens increases compared with corresponding specimens tested at 20°C. the increment is superior for specimens containing SF.
- The flexural strength test results of specimens subjected to 300°C are inconsistent. At low W/B ratio mixtures 5% SF addition improves the flexural strength. However, beyond 5% inclusion it may reduce the flexural strength.
- Both control and SF specimens show a dramatic decrease in compressive strength upon exposure to 600°C. However, SF incorporated specimens have a higher residual compressive strength than control specimens. Irrespective of the W/B ratio, SF addition beyond 5% reduces the flexural strength upon exposure to 600°C.
- Incorporation of SF and increasing exposure temperature increases the compressive/flexural strength ratio. The grain refinement effect of SF seems to be less than its pore refinement effect. Besides, at elevated temperatures, aggregate-cement paste transition zone seems to be more suffered than the matrix itself.

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