JKAU: Eng. Sci., **Vol. 2**, pp. 119-131 (1410 A.H. / 1990 A.D.)

Behaviour of Foamed Slag Concrete at High Temperatures

ALI A. AKHTARUZZAMAN
Civil Engineering Department, Faculty of Engineering,
King Abdulaziz University, Jeddah, Saudi Arabia.

ABSTRACT. Lightweight beams (50 × 75 × 850mm) using foamed slag aggregate, were tested in flexure at steady state temperatures up to 600°C. The properties investigated were thermal movement, ultimate strength, flexural rigidity and weight loss. The results were compared with those of identically dimensioned specimens made from concrete using sintered pulverized fuel ash (pfa) aggregate and gravel aggregate. Foamed slag concrete exhibited characteristics somewhat similar to those of sintered pfa concrete, and performed better than gravel aggregate concrete.

Introduction

Foamed slag concrete is an important structural lightweight concrete which is being increasingly used in construction industry. However, its properities under various exposure conditions, especially under high temperatures, have not been fully investigated. An investigation was, therefore, carried out to study the flexural behaviour of foamed slag concrete exposed to high temperatures. The investigation formed part of a comprehensive research programme to ascertain the properties of different types of concrete under elevated temperatures. The materials previously investigated under this programme included sintered pfa concrete[1] and gravel aggregate concrete[2,3]. This paper compares the properties of foamed slag concrete with those of sintered pfa concrete and gravel aggregate concrete. The results provide important information on the behaviour of foamed slag concrete and also supplement the available data[4-7] on lightweight aggregate concrete behaviour under high temperatures.

Research Significance

The results presented in this paper will be useful in assessing the performance of foamed slag concrete structural members exposed to high temperatures.

Concrete Mix and Text Specimens

Foamed slag coarse aggregate with nominal 10mm diameter together with foamed slag fines was used. The aggregates had an apparent specific gravity of 2.59 and its 24-hour water absorption capacity was 19.2 percent by weight. The cement was ordinary portland (Type I) cement. The mix proportions used were 1: 0.84: 0.84 by weight with water-cement ratio of 0.54. The mix had a compacting factor of 0.84 and a Vebe time of around eight seconds. The nominal concrete strength, using 100mm cubes, was 40 MPa at 28 days and 45 MPa at one year. The average density of concrete was 2010 kg per cubic meter at demoulding and 1890 kg per cubic meter before testing. The loss of moisture prior to testing was on the average about 34 percent of the total water used in the mix.

The specimens were 850mm long plain concrete beams with a 50 × 75mm cross-section. The specimens were cast in partitioned timber moulds in batches of six beams. One of the beams had nine thermocouples embedded in it. Twelve 100mm cube control specimens were also cast with each batch. All the specimens including the control specimens were demoulded 24 hours after casting and were kept covered under moist hessian wrapped with polyethylene sheets for further six days. The specimens were then stored at 20° and 50 percent relative humidity until they reached hygral equilibrium with the ambience when they were tested. The specimen age at testing was 350 days or more.

Experimental Set-up

A purpose-built furnace[8] shown in Fig. 1 was used in the testing programme. It essentially consisted of a 200 × 275 × 925mm heating chamber designed to accommodate a 50 × 75 × 850mm beam specimen. The furnace was heated electrically by heating elements attached to its four vertical sides. A thermocouple located centrally in the furnace chamber was connected to a recorder and a controller which could be set to temperatures up to 1000°C. The heating rate used in the tests is shown in Fig. 2.

The furnace had an integral loading system capable of applying a two-point load to a test specimen over a 690mm span. The load was applied by an electrically operated screw jack mounted below the furnace with its piston pressing downward against a pair of steel cross beams. The cross beams were attached to two pairs of nimonic steel tie rods passing through holes in the furnace base as shown in Fig. 1. Inside the furnace, the tie rods linked up with a loading saddle resting to top of the test specimen. A load cell attached to the piston head of the jack monitored the applied load.

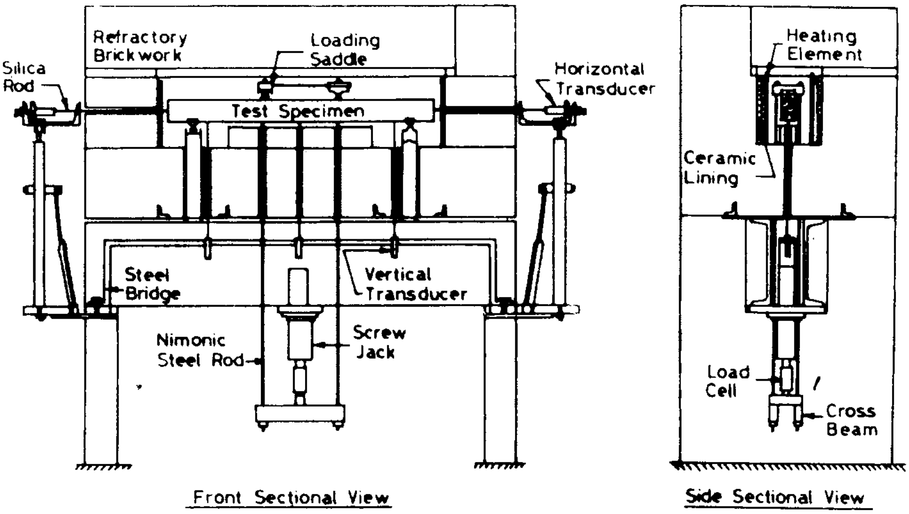

FIG. 1. Details of the furnace used.

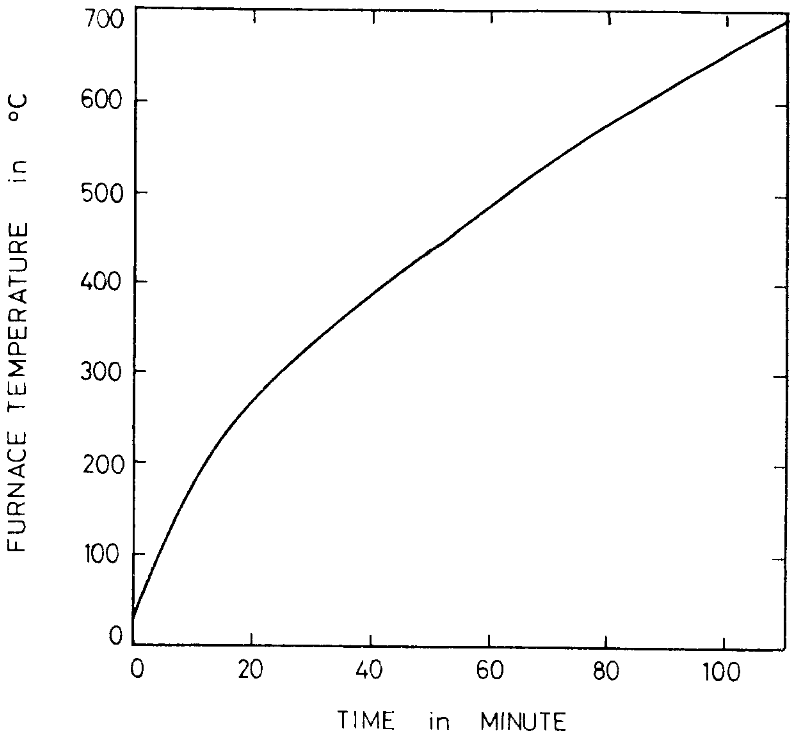

FIG. 2. Heating rate of the furnace.

The displacements of the two ends of the test specimen and of three points along the span length were measured by linear displacement transducers mounted on a steel bridge outside the furnace. Fused quartz silica rods in contact with the test specimen and passing through openings in the furnace were used to transmit the specimen displacements to the individual transducers as shown in Fig. 1. The transducers monitoring the horizontal movements were connected to a multi-pen millivolt recorder which also recorded the furnace temperature and the load-cell output. The signals from the three transducers monitoring the vertical displacements were fed to the recorder through an integrated operational amplifier system[9] which combined the signals to give the deflection at the midspan of the test specimen with respect to two points close to the supports.

Procedure

The test specimen was carefully placed on the supports inside the furnace chamber and was load cycled three times to a maximum load corresponding to a third of its ultimate load at room temperature. The initial slope of the load-deflection curve at room temperature was obtained from the final loading cycle. The furnace was then switched on. When the furnace temperature reached the desired level, it was maintained constant for ninety minutes to let the specimen attain a state of thermal equilibrium. The specimen was then loaded to failure. The vertical displacements and the longitudinal movements of the specimen were monitored continuously throughout the heating and the loading stages. The applied load was also recorded. The specimen was finally removed from the furnace and weighed.

Results and Discussions

Figure 3 shows the variation of mean concrete temperature with the furnace temperature during heating. The mean temperature refers to the average temperature of the specimen as determined by heating tests on the beams with embedded thermocouples. The average temperatures attained by the specimens at the end of the heat soaking periods are also shown in the figure. It was observed that ninety minutes of heat soaking at constant temperature level was adequate to ensure a steady state of internal temperature distribution.

The various properties of the foamed slag concrete have been plotted against mean concrete temperature and are compared below with those of sintered pfa concrete[1] and gravel aggregate concrete[2,3].

Thermal Movement

Figure 4 shows thermal movement versus mean concrete temperature plot during heating. The thermal movement defined as the average change in length of the specimen per unit length due to thermal expansion and shrinkage, varied throughout the heating phase. The behaviour of foamed slag concrete was similar to that of sintered pfa concrete. The former, however, exhibited progressively larger thermal movements than the latter. In comparison with gravel aggregate concrete, foamed slag concrete had appreciably smaller thermal movements for the entire temperature range investigated.

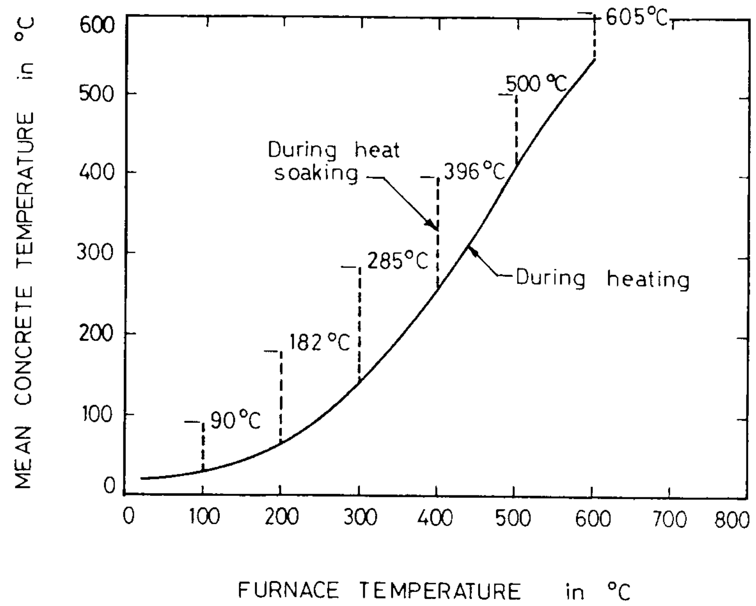

Fig. 3. Relation between furnace temperature and mean concrete temperature.

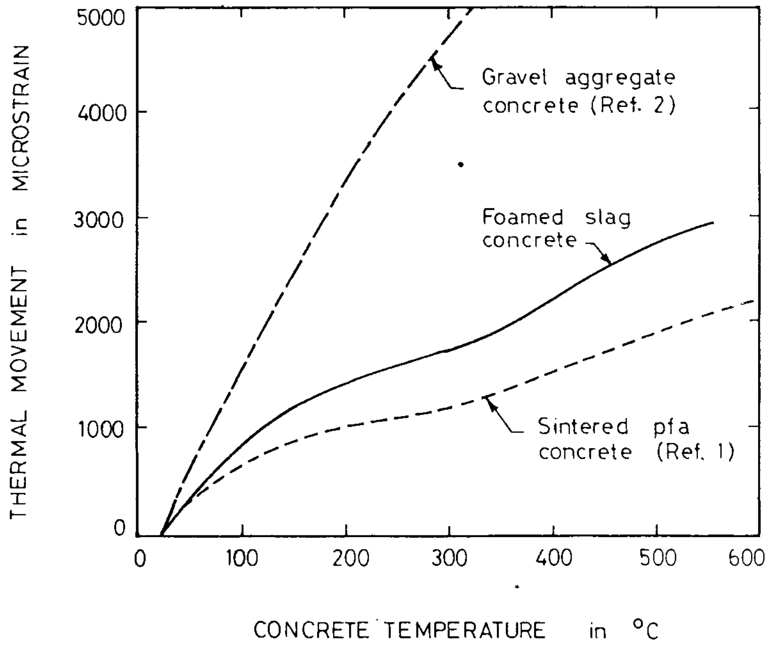

Fig. 4. Relation between thermal movement and temperature during heating.

Although the rate of longitudinal movement of foamed slag concrete varied throughout the heating phase, the plot in Fig. 4 may be assumed to consist of several linear segments. The average coefficient of thermal movement obtained on this basis and the respective temperature ranges are shown in Table 1.

TABLE 1. Effect of mean concrete temperature on the coefficient of thermal movement of foamed slag concrete.

Temperature Range	Coefficient of Thermal Movement (10^{-6} per °C)
20 - 65°C	11.1
65 - 100°C	10.0
100 - 140°C	7.5
140 - 190°C	4.0
190 - 330°C	3.6
330 - 480°C	5.3
480 - 545°C	3.9

Figure 5 shows the relationship between the thermal movement and the time during heat soaking at constant furnace temperatures. The thermal movements stabilized at the end of the heat soaking periods of ninety minutes when the internal temperature distributions had also attained steady state.

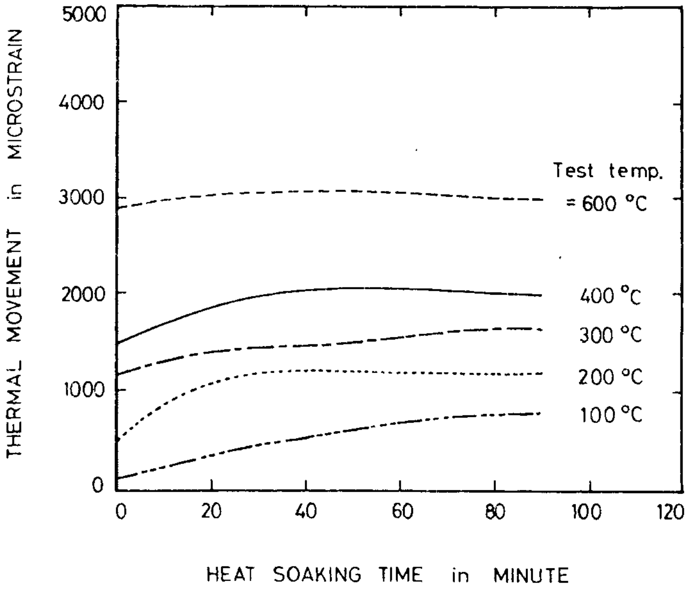

FIG. 5. Relation between thermal movement and time during heat soaking.

Weight Loss

Figure 6 shows the loss of weight suffered by the specimens when tested at various temperatures. The loss of weight has been expressed as a percent of the total water content used in the mix. The figure shows that the maximum loss in weight occurred in two main stages. In the first stage, the loss was mainly due to evaporation of water from the pores and capillaries in the concrete. Some gel water was also lost. This stage lasted from 90°C to 285°C for foamed slag concrete, and from 88°C to 180°C for sintered pfa concrete. The variation in the temperature range was possibly due to a difference in the pore structures of the two types of concrete. The sintered pfa concrete with a water-cement ratio of 1.05 is deemed to have more and larger pores than the foamed slag concrete having a water-cement ratio of 0.54, and its evaporable water could be lost early. For the same reason, the sintered pfa concrete specimens lost more water, about 45 percent, during storage compared to about 34 percent of the foamed slag concrete specimens, although the latter were stored for a longer period, 350 days compared to 240 days for the former.

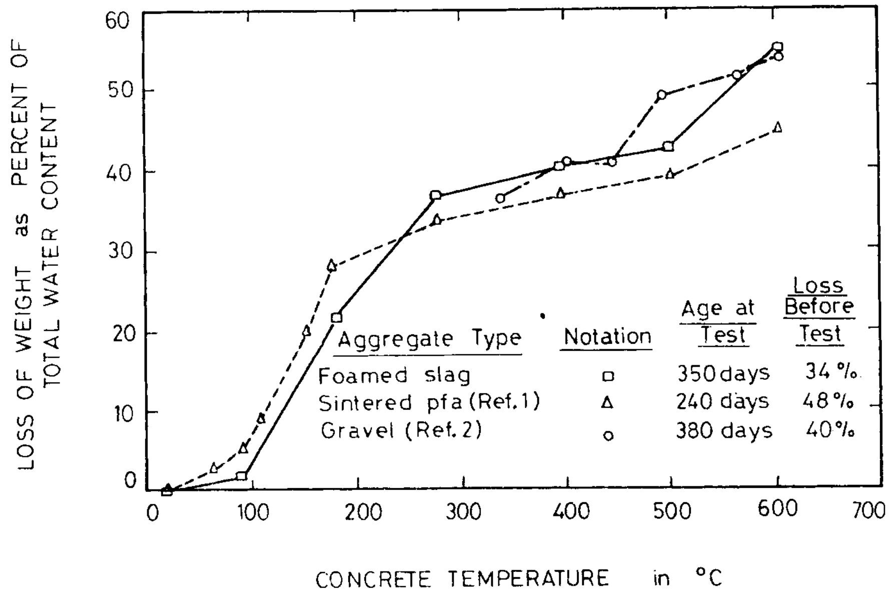

FIG. 6. Loss of weight versus concrete temperature.

The second stage of pronounced weight loss occurred from 500°C to 600°C for both types of concrete. The loss during this stage was due to some endothermic reactions occurring in the paste like dissociation of cement hydrates and due to evaporation of a small amount of moisture still held within the aggregates.

Flexural Strength

Figure 7 shows the relationship between flexural strength and mean concrete temperature. The flexural strength is expressed as a percent of the flexural strength at room temperature. The results of the sintered pfa concrete and the gravel aggregate concrete specimens are also included. The flexural strength of foamed slag concrete decreased to a minimum of around 39 percent of its room temperature value at 180°C, whereas sintered pfa concrete reached its minimum at 88°C. This was followed by a strength recovery phase when the flexural strength increased steadily to reach about 66 percent of the room temperature value at 395°C. Sintered pfa concrete also had a similar mode of strength recovery. The extent of strength recovery, however, was much smaller for foamed slag concrete. Gravel aggregate concrete did not have any strength recovery. Instead, it suffered a sharp decline in strength beyond 400°C.

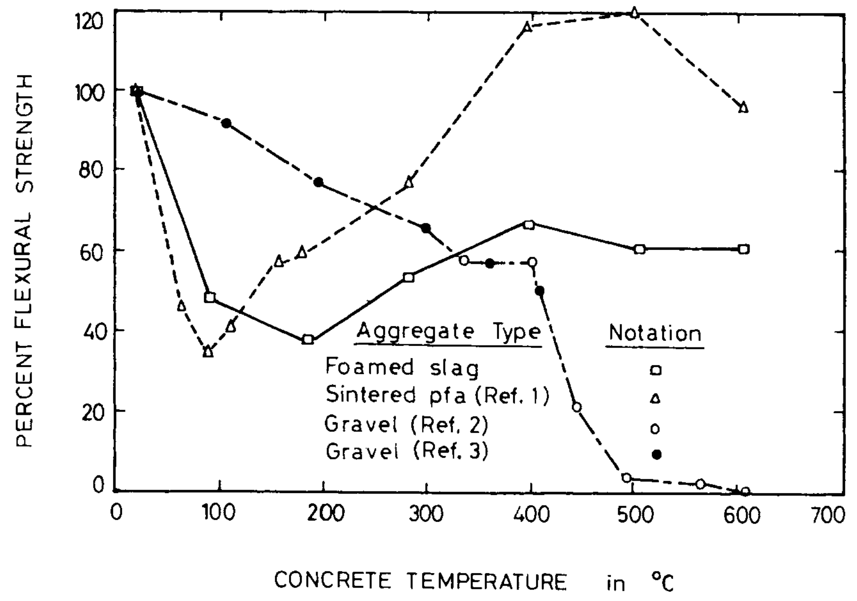

FIG .7. Effect of temperature on flexural strength.

The rest results point to a condition of interdependence between the flexural strength of concrete and the amount and state of evaporable water in the specimen during a test. It is postulated that during initial heating at temperatures ranging from less than 100°C to around 200°C, the evaporable water present in the concrete vapourizes causing triaxial tension within the concrete. When a flexural load is applied the tensile stresses due to the applied load become additive to the triaxial tension resulting in a drop in strength. Thereafter, as moisture continues to be lost at higher temperatures, the concrete appears to stabilize. When most of the water has evaporated, the effect of both the triaxial tensions and the Van der Waals internal forces which exist in moist concrete, disappear resulting in an apparent increase in strength as indicated by the strength recovery phase. This phase does not appear in the case of gravel aggregate concrete due to increased thermal incompatibilities between the gravel aggregate and the surrounding paste at higher temperatures as well as due to the phase transformation suffered by the silica in the gravel.

Weight Loss Versus Flexural Strength

Figures 6 and 7 have been combined in Fig. 8 to illustrate further the influence of the weight lost during heating on the flexural strength of concrete. It shows that the large initial reduction in strength occurred with a correspondingly small percentage of weight loss during a test. Thereafter, the strength recovery phase followed. For both types of lightweight concrete, this phase lasted until 40 percent of the total water content was lost. This occurred at about 400°C for foamed slag concrete when the strength was about 66 percent of its room temperature strength and at 500°C for sintered pfa concrete when the strength was about 120 percent.

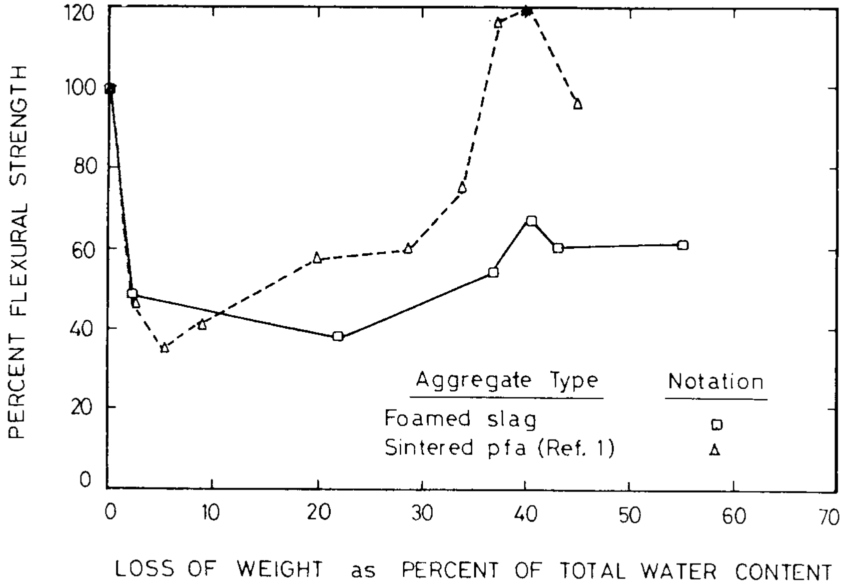

FIG. 8. Effect of weight loss on flexural strength.

Flexural Rigidity

Figure 9 shows the load-deflection characteristics of the foamed slag concrete beams tested at various temperatures. The initial deflections at the start of loading have been subtracted to have a common origin for the curves. The flexural rigidity defined by the initial slope of the load-deflection curves has been plotted against mean concrete temperature in Fig. 10. At 90°C, the flexural rigidity was about 58 percent of its room temperature value. It then increased steadily to about 80 percent at around 400°C. Then it reduced slightly. The results of the sintered pfa concrete included in the figure show similar features. The foamed slag concrete beams, however, retained a higher percentage of the initial flexural rigidity at room temperature in the entire temperature range investigated.

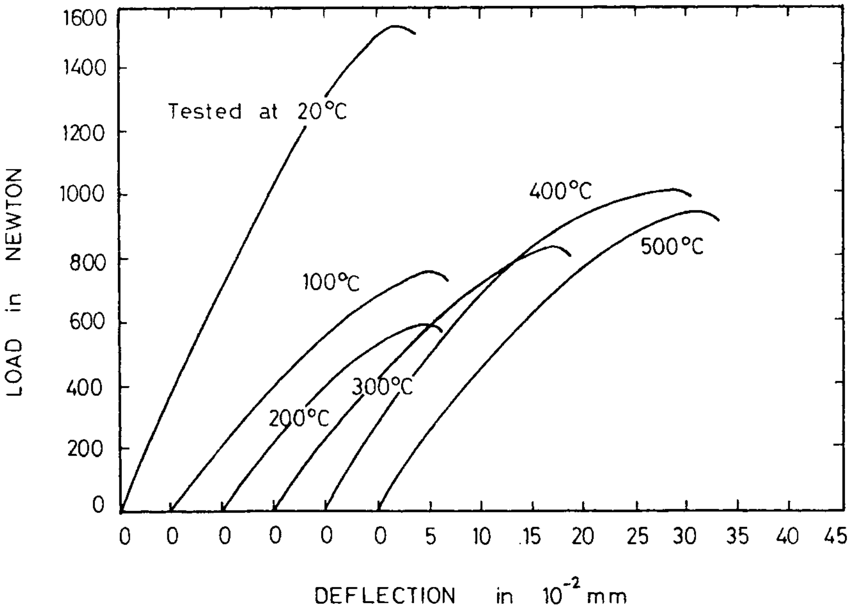

FIG. 9. Load-deflection characteristics.

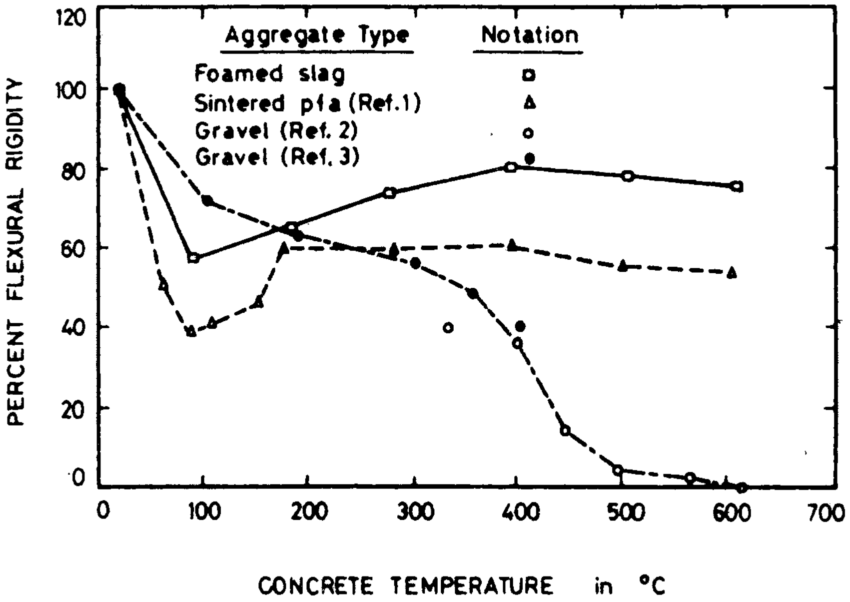

FIG. 10. Relation between flexural rigidity and temperature.

The gravel aggregate concrete specimens exhibited a different trend with the flexural rigidity decreasing continuously at a varying rate, to reach zero percent at around 600°C. The difference in behaviour between the lightweight concrete and the gravel aggregate concrete is possibly due to the larger thermal incompatibilities among the constituents of the latter.

Conclusion

The following conclusions can be drawn from this investigation:

1. The behaviour of foamed slag concrete at high temperatures is similar to that of sintered pfa concrete, but differs from that of gravel aggregate concrete. The thermal and physical properties of both types of lightweight concrete are influenced by movement of moisture during heating.
2. There are two distinct stages during heating when weight loss occurs at its maximum rate. The first stage lasts from 90°C to 285°C for foamed slag concrete and is longer than that for sintered pfa concrete. The second stage starts at 500°C.
3. Foamed slag concrete suffers an initial loss of flexural strength during the first stage of heating. It then stabilizes and regains some strength as in the case of sintered pfa concrete. Gravel aggregate concrete, however, does not have any strength recovery.
4. Flexural rigidity of foamed slag concrete beams is also influenced by temperature and moisture loss. The variation is similar to that of sintered pfa concrete. Foamed slag concrete, however, always retains a larger percentage of its flexural rigidity compared to sintered pfa concrete beams. Gravel aggregate concrete beams are not reported to exhibit any recovery of flexural rigidity.
5. Foamed slag concrete has larger thermal movements than sintered pfa concrete but much smaller than those of gravel aggregate concrete.

Acknowledgement

The work described here was carried out at Imperial College of Science and Technology, London, in collaboration with the Fire Research Station, Boreham Wood, England.

References

[1] **Labani, J.M.**, *The Short-term Structural Behaviour of Lightweight Aggregate Concrete at Elevated Temperatures,* Thesis submitted to the University of London for the degree of Ph.D., 556 p. (1977).

[2] **Akhtaruzzaman, A.A.**, *An Investigation into the Structural Behaviour of Concrete under Transient and Steady States of Temperature,* Final Research Report submitted to the Fire Research Station, Boreham Wood, England, 286 p. Nov. (1973).

[3] **Sullivan, P.J.E.**, The Effects of Temperature on Concrete, *in:* **Lydon, F.D. (ed.)**, *Developments in Concrete Technology – I,* Applied Science Publishers Ltd., England, pp. 1-49 (1982).

[4] **Harmathy, T.Z.** and **Brendt, J.**, Hydrated Portland Cement and Lightweight Concrete at Elevated Temperatures, *ACI Journal,* **63:** 93-106 (1966).

[5] **Zoldners, N.G.** and **Wilson, H.S.**, Effect of Sustained and Cyclic Temperature Exposures on Lightweight Concrete, *in: Behaviour of Concrete under Temperature Extremes, ACI Special Pub.* **SP-39:** 149-163 (1943).

[6] **Harada, T., Takeda, J., Yamane, S.** and **Furamura, S.**, *Strength, Elasticity and Thermal Properties of Concrete Subjected to Elevated Temperatures, ACI Seminar on "Concrete for Nuclear Reactors", Berlin 1970,* also *ACI Special Publication* **SP 34:** 377-390 (1972).

[7] **Sullivan, P.J.E.** and **Labani, J.M.**, Flexural Behaviour of Plain and Reinforced Lightweight Aggregate Concrete Beams up to 600°C, *Cement and Concrete Research, New York,* **4**(2): 231-237 (1974).

[8] **Dougill, J.W.** and **Sullivan, P.J.E.**, A Furnace and Loading Rig for Testing Small Concrete Beams at High Temperatures, *Magazine of Concrete Research, London,* **25**(82): 47-52 (1973).

[9] **Akhtaruzzaman, A.A.** and **Sullivan, P.J.E.**, Deflection Measuring System Uses Transducers and an Operational Amplifier, *Electronic Engineering, London,* **43**(9): 55-57 (1971).

سلوك خرسانة الخبث الرغاوية عند درجات الحرارة المرتفعة

علي أمجد أختر الزمان
قسم الهندسة المدنية ، كلية الهندسة ، جامعة الملك عبد العزيز
جدة ، المملكة العربية السعودية

تحتوى هذه الدراسة على اختبارات لعتبات الخرسانة الخفيفة (٥٠ × ٧٥ × ٨٥٠ مم) التي استعمل فيها ركام خبث المعادن الرغوي وهى في درجات حرارة عالية ثابتة لا تتجاوز ٦٠٠°م . وقد اختبرت هذه العتبات لمعرفة الخواص التالية : التمدد الحراري والمقاومة القصوى ، وجساءة الانحناء ونقصان الوزن .

ثم قورنت نتائج هذه التجارب بتجارب أخرى أجريت على عينات مماثلة من حيث الأبعاد ، ولكنها من خرسانة استعمل فيها ركام مصنوع من رماد الوقود المحروق المتلبد المسحوق ، وأخرى من خرسانة استعمل فيها الركام الحصبائي . فتبين أن لخرسانة خبث المعادن الرغاوية خواصّ مشابهة نوعاً ما لخواص خرسانة بقايا الوقود المحروق المسحوق ، وأن خواصها أفضل من خواص الخرسانة العادية .