

Effect of High Temperatures on Shear Transfer Strength of Concrete

Lect. Sallal Rashid Al-Owaisy

Civil Engineering Department, College of Engineering
Al-Mustansiriya University, Baghdad, Iraq

Abstract

The effect of exposure to elevated temperatures up to (500 °C) on shear transfer strength of concrete was investigated experimentally in this study using push-off specimens. Three groups of specimens were used, each of four specimens. One specimen from each group was heated to (150 °C), the second specimen was heated to (350 °C) and the third specimen was heated to (500 °C), while one specimen from each group was tested without heating as a reference specimen. The three groups of specimens differed from each others by the amount of shear reinforcement crossing the shear plane.

The test results of this study showed that shear transfer strength decreased by about (18% to 42%) and that the higher shear reinforcement specimens retained higher strength values than those of lower shear reinforcement ones after exposure to all the studied temperatures. Also, a comparison was made between the post heat exposure behavior of shear transfer strength and the compressive and tensile strengths of concrete. It was observed that the behavior of shear transfer strength of concrete after high temperature exposure can be closely related to compressive strength than splitting tensile strength.

الخلاصة

تم في هذا البحث دراسة تأثير التعرض للحرارة العالية لحد (٥٠٠ °س) على مقاومة انتقال القص للخرسانة عملياً باستخدام نماذج خاصة. تقسم هذه النماذج إلى ثلاثة مجاميع تتكون كل منها من أربعة نماذج. تم تعريض نموذج من كل مجموعة إلى (١٥٠ °س) والثاني إلى (٣٥٠ °س) والنموذج الثالث تم تعريضه إلى (٥٠٠ °س)، بينما لم يتم حرق النموذج الرابع وتم فحصه كنموذج مرجعي. تختلف المجاميع الثلاثة عن بعضها بكمية حديد القص الذي يقطع مستوى القص.

نتائج هذه الدراسة تبين أن مقدار النقص الحاصل بمقاومة انتقال القص يتراوح تقريباً بين (١٨ و ٤٢%) وأن مقاومة انتقال القص وبعد التعرض لكل درجات الحرارة المدروسة، بقيت أعلى للنماذج ذات كمية تسليح القص الأكبر منها لذات كمية تسليح القص الأقل. كما تم في هذا البحث مقارنة تصرف مقاومة انتقال القص بعد التعرض إلى درجات الحرارة العالية مع تصرف مقاومة الانضغاط والشد للخرسانة وتبين أن تصرف مقاومة انتقال القص أقرب لتصرف مقاومة انضغاط الخرسانة منها لمقاومة شد الخرسانة.

1. Introduction

Shear transfer strength is an essential property in structures where shear transfer occurs at a definable plane, such as in: precast concrete connections, interface between different concretes or concretes cast at different times, and at the junction of (brackets) with a column. If such structures are exposed to elevated temperatures as in fires, structural behavior and strength could be damaged. Thus compression, flexural, shear and torsional strength, and also shear transfer strength of concrete could deteriorate due to the deterioration of material properties. A considerable amount of information on concrete material properties, strength and structural behavior of reinforced concrete members after high temperature is available. Although shear transfer strength is one of the major characteristics in many reinforced concrete structural members, the information concerning shear transfer strength after high temperature exposure still very limited.

2. Experimental Program

In this study, the influence of elevated temperatures on shear transfer strength was studied using push-off specimens with dimensions of (400 x 200 x 100 mm) (height x width x thickness), with shear plane length of (200 mm) as shown in **Fig.(1)**. Three groups of push-off specimens were fabricated, each of four specimens. Group A specimens were unreinforced with shear reinforcement across the shear plane, while group B and C specimens were reinforced with one and two (10 mm) diameter closed stirrups respectively. Additional reinforcement was provided away from shear plane to prevent failure other than along the shear plane ^[1]. The specimens were heated to three levels of temperatures of (150, 350 and 500 °C) (302, 662 and 932 F). One specimen from each group was heated to each particular temperature, and one specimen from each group was tested as a reference specimen (not heated). **Table (1)** summarizes push-off specimen's properties.

A single concrete mix of (1:1.5:3) (cement: fine aggregate: coarse aggregate) in proportion by weight with water/cement ratio of 0.5 was used. In this mix, the cement was Ordinary Portland cement which was manufactured in Kubbaisa factory according to Iraqi standards (IQS 5:1984). The fine aggregate was local sand from Rahhalia (Anbar region), while the coarse aggregate was local rounded river gravel from Alnibaaey region with maximum size of aggregate of (19 mm).

Twenty four hours after pouring, the specimens were stripped out from moulds and cured in water containers for twenty one days. Then, the specimens were removed from the water containers and were stored in the laboratory environment for seven days. The heating process was carried out at age of twenty eight days using an electrical furnace. The specimens were heated slowly at a constant rate of (2 °C/min) to avoid steep thermal gradient ^[2]. Once the required temperature was attained, the specimens were saturated thermally at that level for one hour. The specimens were then air cooled until testing time after about (20 to 24 hours). The specimens were concentrically loaded using a hydraulic testing machine as shown in **Fig.(2)**.

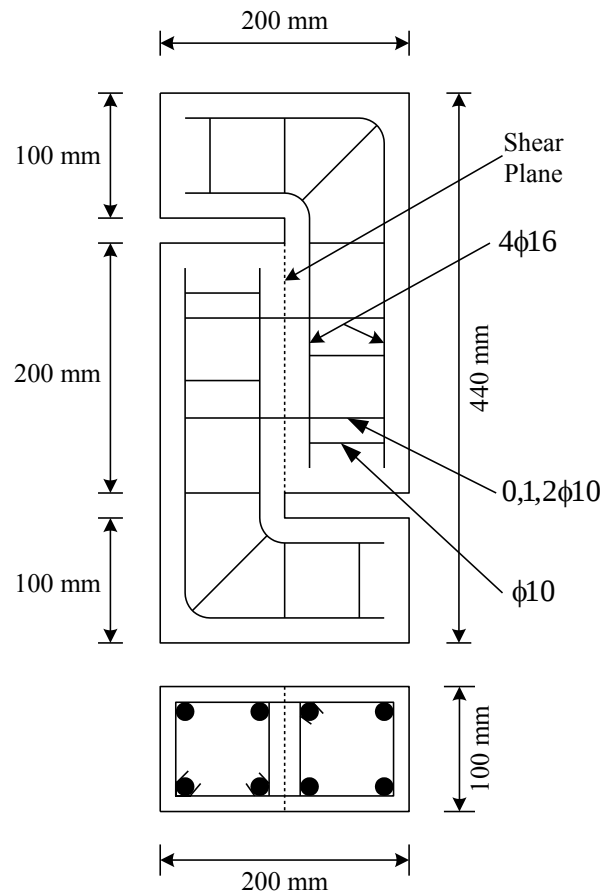


Figure (1) Push-off specimen's dimensions and reinforcement

Table (1) Push-off specimen properties

Specimen No.	No. of stirrups legs	ρf_y (MPa)	f_{cu} (MPa)	Temperature ($^{\circ}\text{C}$)	Shear Transfer Strength (MPa)
A0 A1 A2 A3	0	0	28.2	Room 150 350 500	5.78 4.72 4.7 3.62
B0 B1 B2 B3	2	3.66	29.0	Room 150 350 500	9.18 6.63 6.5 5.92
C0 C2 C3 C3	4	7.32	29.3	Room 150 350 500	11.83 8.75 8.5 6.88

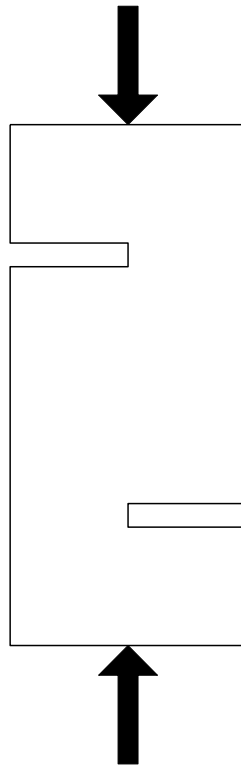


Figure (2) Loading of push-off specimens

3. Results and Discussion

3.1 Push-off Specimens Behavior

The general behavior of all reinforced specimens was the same. On the other hand, the behavior of all unreinforced specimen was also the same. For unreinforced specimens, cracks parallel or along the shear plan formed at lower loads, these cracks were accompanied with few and short diagonal tension cracks in some specimens, as load increased these cracks propagated to form continuous cracks along the shear plane as shown in **Fig.(3-a)**. The reinforced specimen's behavior differed than unreinforced ones. Where the first crack formed at higher loads, as load increased, several diagonal cracks formed adjacent to and across the shear plane.

Then after, these cracks propagated parallel to the shear plane as shown in **Fig.(3-b)**. Also, a small amount of concrete compression spalling occurred adjacent to the shear plane crack in most cases.

The presence of several thermal cracks parallel and across the shear plan due to heating process, led to form several longitudinal shear cracks along the shear plane after loading instead of one continuous crack and to additional concrete compression spalling adjacent to shear plane.

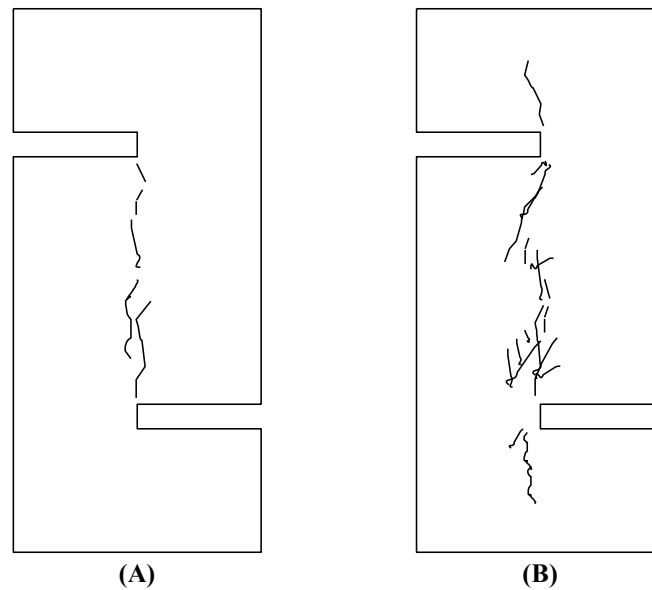


Figure (3) Cracking of push-off specimens
(a) Without Shear Reinforcement; (b) With Shear Reinforcement

3.2 Ultimate Strength

The ultimate shear transfer strength is defined as the maximum shear that the test specimens can carry during the test. The shear transfer through the shear plane can be expressed as the ultimate force carried by the specimens divided by the area of the shear plane [3, 4].

$v_u = \text{ultimate shear force} / \text{area of shear plane}$

In this research, the shear force equals the applied load and the shear plane area equals (200 x 100 mm). **Table (1)** shows the values of ultimate shear transfer strength of all specimens with other test data.

3.3 Effect of Elevated Temperatures

Figures (4, through 7) show the effect of exposure to elevated temperatures on shear transfer strength of the tested push-off specimens. The exposure to temperatures of (150, 350 and 500 °C) (302, 662 and 932 F) affected the shear transfer strength noticeably. Shear strength of push-off specimens decreased with percentages ranging between (18.3 to 41.8%) for all heated specimens. **Figures (4)** shows the residual shear transfer strength-temperature relationship for the three groups of specimens, while **Fig.(5)** shows the relationship between the percentage residual shear transfer strength and exposed temperatures. As it is noticeable in **Fig.(4)** and **(5)**, the push-off specimens suffer loss in strength when exposed to high temperatures, the amount of this strength loss depends on the level of temperature to which the specimens were exposed.

For group A specimens, the shear transfer strength decreased from (5.78 MPa) before heating to (3.62 MPa) after exposure to (500 °C). The shear transfer strength of group B specimens was (6.63, 6.5 and 5.92 MPa) after exposure to (150, 350 and 500 °C), with a

percentage decrease of (27.8, 29.2 and 35.6 %) respectively. Similar behavior for group C specimens was also observed as shown in Figs.(4) and (5).

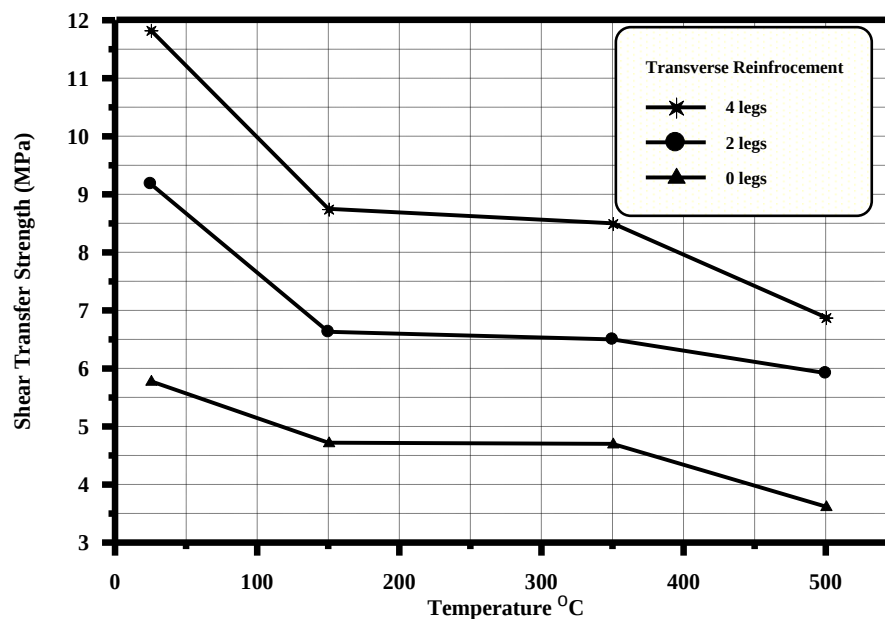


Figure (4) Shear transfer strength-temperature relationship for push-off specimens with different shear reinforcements

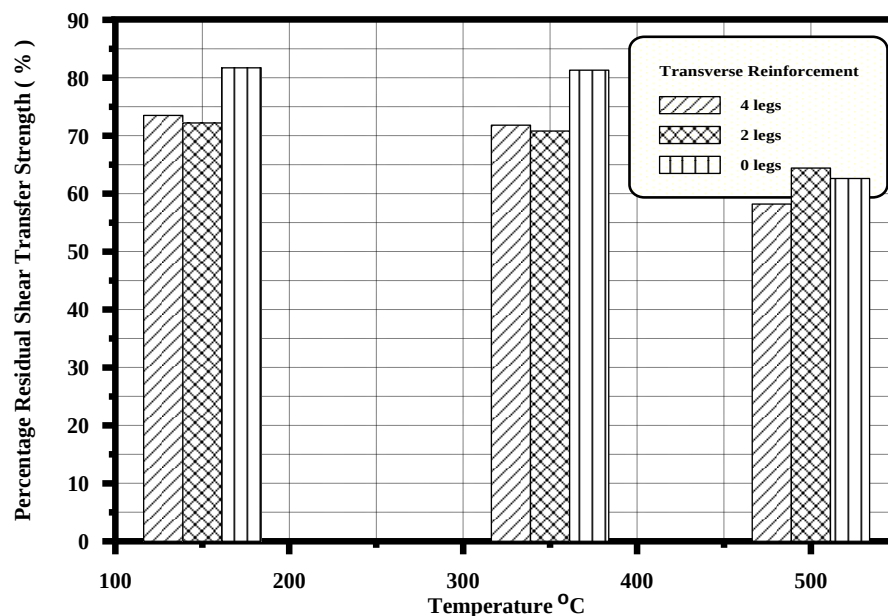


Figure (5) Percentage residual shear transfer strength-temperature relationship for push-off specimens with different shear reinforcements

This deterioration in strength can be attributed to the several physical and chemical changes which take place in concrete after exposure to high temperatures. Such as, the loss of free moisture which is not used in the hydration process^[5]. Also, the expansion of aggregates and shrinkage of cement paste causes different thermal movements and lead to bond deterioration between aggregate particles and surrounding cement paste^[6]. The loss of chemically combined water from hydrated cement paste (dehydration of calcium silicate) at about (400 °C), is also disruptive^[2,5,7], where the volume changes resulting from this process lead to further cracking and more deterioration.

It is observed from **Fig.(4)**, that three different stages of shear transfer strength behavior can be observed when exposed to temperatures of (150, 350 and 500 °C). First, shear transfer strength decreased at (150 °C) composing a decline line between room temperature and (150 °C). Then the strength loss stabilized between (150 and 350 °C) forming a horizontal line. Finally, further decrease in strength occurred after exposure to (500 °C) to form a second decline line between (350 and 500 °C).

3.4 Effect of Shear Reinforcement

The presence effect of transverse reinforcement on shear transfer strength before heating (at room temperature) is shown in **Fig.(6)**. As shown in the figure, the shear transfer strength for group A reference specimens was (5.78 MPa), this value increased by about (59%) when two legs of (10 mm) diameter bars (one closed stirrup) were used to reach (9.18 MPa). When two closed stirrups (4 legs) were used, the value of shear transfer strength jumped to (11.83 MPa) with a percentage increase in strength of about (105 %). This result is attributed to the interlocking action of transverse reinforcement crossing the shear plane at a right angle, which restrict the shear cracks and increase the shear capacity. The high percentages of increase in strength is related to the high values of reinforcement parameter ($\rho_f y$) which was (3.33 MPa) for two legs and (7.32 MPa) for four legs.

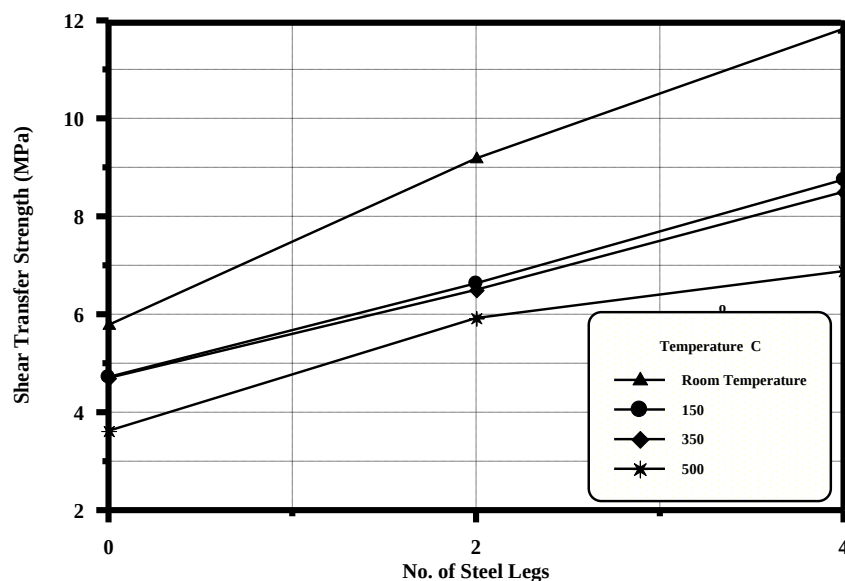


Figure (6) Effect of shear reinforcement (no. of stirrups legs) on shear transfer strength at different temperatures

After exposure to elevated temperatures, similar behavior can be observed. Where for all exposure temperatures, the shear transfer strength of higher amount shear reinforcement specimens still higher than the values of lower shear reinforcement as shown in **Figs.(4) and (6)**.

Figure (5) shows that the percentage residual strengths of push-off specimens without reinforcement were higher than those of reinforced specimens after exposure to (150 and 350 °C). This result can be attributed to the additional thermal movement which resulted from the presence of steel, where instead of one thermal movement (between cement paste and aggregate), a third component contributed, this contribution resulted in further cracking across the shear plane at the concrete-steel interface due to bond deterioration between steel bars and surrounding concrete. As mentioned previously, the dehydration of calcium silicate beyond (400 °C) is disruptive and causes further cracking and more deterioration in concrete, this may explain why the presence of steel was less effective after exposure to (500 °C).

From the observation of **Fig.(7)**, it can be noticed that the percentage increase in shear transfer strength due to the presence of shear reinforcement, decreased as temperature increased except at (500 °C). Where the percentage increase in strength when two legs of stirrups were used was (58.5%) before heating, while after heating to (150 and 350 °C), the percentages increase in strength were (40.5 and 38.3%) respectively. Similar sequence was recorded for group C specimens (4 legs stirrups) as shown in **Fig.(7)**.

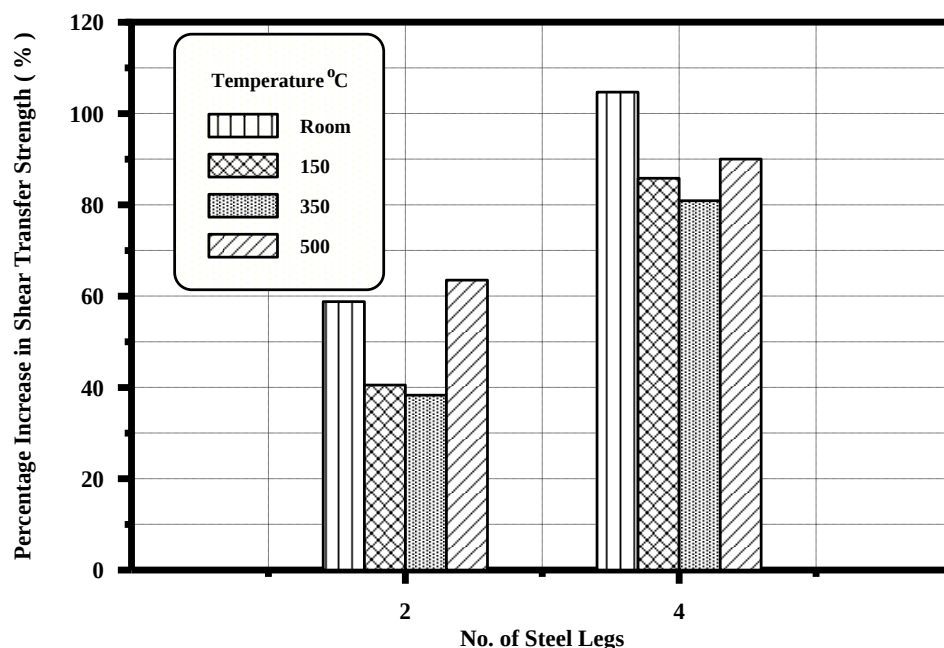


Figure (7) Relationship between percentage increase in shear transfer strength and number of shear stirrups legs at different temperatures

3.5 Comparison of Residual Shear Transfer Strength, Compressive Strength and Splitting Tensile Strength of Concrete

Depending on previous studies ^[8,9,10,11], the relationship between percentage residual compressive strength and temperature for many types of specimens (cubes 150mm, cubes 100mm, cylinders 150x300mm and cylinders 100x200mm) are shown in **Fig.(8)**, together with the residual shear transfer strength-temperature curves of this study. This comparison was made to study the effect of concrete compressive strength on shear transfer strength after exposure to elevated temperatures. Similarly, **Fig.(9)** shows a comparison of percentage residual tensile strength with percentage residual shear transfer strength after exposure to high temperatures.

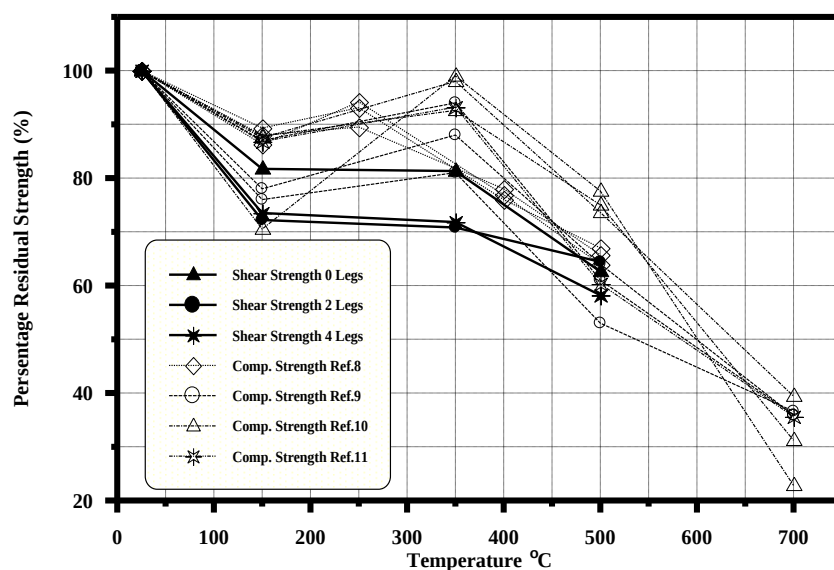


Figure (8) Comparison of percentage residual shear transfer strength with percentage residual compressive strength (obtained from previous studies)

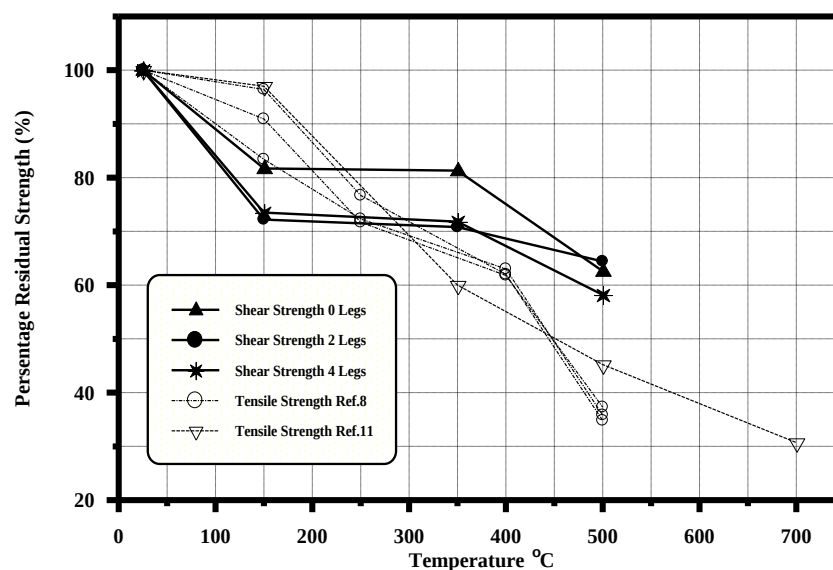


Figure (9) Comparison of percentage residual shear transfer strength with percentage residual splitting tensile strength (obtained from previous studies)

Form the observation of **Figures (8) and (9)**, two points need to be discussed. First, the shape of strength-temperature curves. And second, the amount of residual strength at each temperature. It is noticeable that the percentage residual compressive strength-temperature curves displayed three different behaviors. First, a decline line between room temperature and (150 °C) is noticed, which reflects the strength loss occurring at (150 °C). Then a stage of stabilized strength or strength recovery occurred from (150 °C) to (350 °C). Followed by the third step, where at higher temperatures, the specimens suffered higher percentage loss in strength. Abrams ^[12], found that the unstressed specimens behaved according to the mentioned three stages but the behavior of the residual unstressed specimens which had been cooled for 7 days before testing was different, where it was consisting of two stages only: (1) an initial stage of minor strength gain or loss (25 °C to 200 °C), (2) a stage above (200 °C) in which the strength decreases with temperature increase. This difference can be attributed to the different procedures and periods of cooling. Where cooling in air for longer periods (7 days or 1 month) after heating causes further reduction in strength than cooling for one day ^[12,13,14].

The behavior patterns of shear transfer strength-temperature curves were similar to that of compressive strength, but no similar strength recovery at (350 °C) was observed. Instead there was a stabilized strength between (150 and 350 °C), this means that neither increase nor significant decrease occurred in shear transfer strength at (350 °C).

In the case of splitting tensile strength there were no such distinguishable three stages of behavior, instead there was a continuous decrease in strength as temperature increased. Another notice is that shear transfer strength and compressive strength retained nearly similar percentage residual strengths at (150 °C and 500 °C). The percentage residual shear transfer strength and compressive strength at (150 °C) were in the range of (72.2 to 81.7%) and (70.5 to 89.3%) respectively. Similarly, the percentage residual shear transfer strength and compressive strength at (500 °C) were in the range of (58.2 to 64.4%) and (53 to 77.6%) respectively. While compressive strength retained higher percentage residuals at (350 °C). On the other hand, splitting tensile strength retained lower percentage residual strengths than both shear transfer strength and compressive strength after exposure to (350 °C and 500 °C), and retained higher percentages at (150 °C) in most cases. The percentage residual tensile strength was in the range of (83.4 to 97 %) at (150 °C), about (60%) at (350 °C) and in the range of (34.8 to 45.2 %) at (500 °C). This leads to the conclusion that the behavior of shear transfer strength after high temperature exposure is much closer to that of compressive strength than of splitting tensile strength.

4. Conclusions

1. Shear transfer strength was affected significantly after exposure to elevated temperatures, where the percentage loss in strength ranged from (18.3 to 41.8 %) after exposure to temperatures from (150 to 500 °C).
2. After exposure to (150 °C and 350 °C), the push-off specimens suffered similar amounts of strength loss, where the percentage residual shear transfer strength were in the range of (72.2 to 81.7 %) and (70.8 to 81.3 %) after exposure to (150 °C) and (350 °C) respectively. While further loss in strength occurred at (500 °C).
3. The shear transfer strength of higher amount shear reinforcement specimens was higher than those of lower shear reinforcement ones, both before heating and after exposure to each particular temperature.
4. The behavior of shear transfer strength after exposure to temperatures up to (500 °C), was much closer to the behavior of compressive strength than of splitting tensile strength.

5. References

1. Mattock, A. H., and Hawkins, N. M., *"Shear Transfer in Reinforced Concrete-Recent Research"*, PCI Journal, Vol. 17, No. 2, March-April 1972, pp. 55-75.
2. Moreley, P. D., and Royels, R., *"Response of the Bond in Reinforced Concrete to High Temperature"*, Magazine of Concrete Research, Vol. 38, No. 123, June 1983, pp. 67-75.
3. Hofbeck, J. A., Ibrahim, I. O., and Mattock, A. H., *"Shear Transfer in Reinforced Concrete"*, ACI Journal, Proceedings Vol. 66, No. 2, Feb. 1969, pp. 119-128.
4. Mattock, A. H., Li, W. K., and Wang, T. C., *"Shear Transfer in Light Weight Concrete"*, PCI Journal, Vol. 21, No. 1, Jan.-Feb. 1976, pp. 20-39.
5. Lankard, D. R., Birkimer, D. L., Fondriest, F. F., and Snyder, M. J., *"Effect of Moisture Content on the Structural Properties of Portland Cement Concrete Exposed to Temperatures up to 500F"*, ACI Special Publication SP-25, Temperature and Concrete, Detroit, Michigan, USA, 1971, pp. 59-102.
6. Zoldners, N. G., *"Thermal Properties of Concrete under Sustained Elevated Temperatures"*, ACI Special Publication SP-25, Temperature and Concrete, Detroit, Michigan, USA, 1971, pp. 1-31.
7. Neville, A. M., *"Properties of Concrete"*, Fourth and Final Edition, John Wiley and Sons, New-York, 1994, pp. 359-411.
8. Al-Owaisy, S. R., *"Effect of Elevated Temperatures on Bond in Reinforced Concrete"*, M.Sc. Thesis, College of Engineering, University of Al-Mustansiriya, Baghdad, Iraq, Feb.2001, 107 pp.
9. Al-Owaisy, S. R., *"Post Heat Exposure Behavior of Bond Strength and Concrete Compressive Strength"*, Iraqi Journal for Civil Engineering, March 2004, pp. 135-149.

10. Al-Owaisy, S. R., and Al-Chalabi, N. N., "***Nondestructive Tests on Concrete Exposed to Temperatures up to 700 °C***", Journal of Engineering and Development, Vol. 8, No. 1, April 2004, pp. 29-39.
11. Al-Owaisy, S. R., "***Post Heat Exposure Properties of Steel Fiber Reinforced Concrete***", Journal of Engineering and Development, Vol. 10, No. 2, June 2006, pp. 194-207.
12. Abrams, M. S., "***Compressive Strength of Concrete at Temperatures to 1600 F***", ACI Special Publication SP-25, Temperature and Concrete, Detroit, Michigan, USA, 1971, pp.33-58.
13. Zoldners, N. G., "***Effect of High Temperatures on Concrete Incorporating Different Aggregates***", Proceedings, ASTM, Vol. 60, 1960, pp. 1087-1108.
14. Habeeb, G. M., "***Residual Mechanical Properties of High Strength Concrete Subjected to Elevated Temperatures***", Ph.D. Thesis, College of Engineering, Department of Civil Engineering, Al-Mustansiriya University, Baghdad, Iraq, November, 2000, 164 pp.