# Residual Mechanical Properties of Self-Compacting Concrete Exposed to Elevated Temperatures

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## Abstract

This study aims to investigate the residual mechanical properties (compressive strength, modulus of rupture and dynamic modulus of elasticity) of self-compacting concrete (SCC) exposed to elevated temperatures ranging from (100-800 $^{o}$C) as well as studying its fresh and hardened properties at normal temperature. Also it aims to study the influence of high reactivity metakaoline (HRM), as a partial replacement by weight of cement, for improving its mechanical properties after and before exposure to elevated temperatures.

The concrete specimens were subjected to a temperature range of (100, 200, 400, 600 and 800$^{o}$C) with an exposure duration of 2-houres. The test results showed that the performance of SCC containing HRM is higher than that of SCC without HRM , where the residual compressive strength of HRM SCC after an exposure to a temperature level of (800$^{o}$C) was 73.2% while for the normal SCC was 65% from their original strength .At the same exposure temperature (800$^{o}$C) , the loss in modulus of rupture is higher than that of compressive strength , the difference was between (2% - 12.4%). Also the reduction in dynamic modulus of elasticity (Ed) is higher than that of compressive strength and modulus of rupture ,where the residual (Ed) was between (47.3% - 63.5%) after 800$^{o}$C exposure.

# الخواص الميكانيكية المتبقية للخرسانة ذاتية الرص المتعرضة لدرجات الحرارة العالية

## الخلاصة

تهدف هذه الدراسة إلى ايجاد الخواص الميكانيكية المتبقية (مقاومة الانضغاط ، معاير الكسر ومعامل المرونة الديناميكية ) للخرسانة الذاتية الرص المتعرضة إلى درجات حرارة عالية تتراوح بين (100 – 800 ) درجة سيليزية بالاضافة الى دراسة خواصها الطرية والمتصلبة عند درجات الحرارة الاعتيادية. وكذلك تهدف الى دراسة تأثير استخدام الميتاكاوؤلين عالي الفاعلية (كأستبدال جزئي من وزن السمنت) في تحسين خواصها الميكانيكية قبل وبعد تعرضها إلى درجات الحرارة العالية .

تعرضت النماذج الخرسانية إلى درجات حرارة تتراوح بين ( 100 ، 200 ، 400 ، 600 و 800 ) درجة سيليزية ولمدة تعرض مقدارها ساعتين ، أظهرت نتائج الفحوصات أن أداء الخرسانة ذاتية الرص والحاوية على الميتاكاوؤلين عالي الفاعلية اعلى من مثيلاتها من الخرسانة الخالية من الميتاكاوؤلين , حيث أن مقاومة الانضغاط المتبقية للخرسانة الحاوية على الميتاكاوؤلين بعد التعرض لدرجة 800 درجة سيليزية كانت (73,2 %) بينما للخرسانة العادية (65%) من مقاومتها الأصلية. عند نفس درجة حرارة التعرض (800 درجة سيليزية) ، الفقدان في معاير الكسر كان اعلى من الفقدان في مقاومة الانضغاط والفرق كان بين (2% - 12،4 %). كذلك

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النقصان في معامل المرونة الديناميكية أعلى منه في مقاومة الانضغاط ومعاير الكسر حيث ان معامل المرونة المتبقي عند تعرض الخرسانة الى 800 درجة سيليزية كان بين (47،3% - 63،5%).

## 1 - Introduction

Self–compacting concrete (SCC ) is as emerging technology to the construction industry , and has been described as the most revolutionary development in concrete construction for several decades (1). SCC , as the name indicates, is a type of concrete that dose not required external or internal compaction, because it becomes leveled and compacted under its self-weight . SCC can spread and fill every corner of the formwork purely by means of it self-weight, thus eliminating the need of vibration or any type of compacting effort (2,3) .

In most pervious research work and committee reports, efforts were concentrated mainly on the fresh properties and mechanical behavior of this type of concrete, the fire behavior of SCC is not fully understood.

The main aim of this work is to study the residual mechanical properties (compressive strength, flexural strength and dynamic modulus of elasticity) of SCC before and after exposure to elevated temperature up to 800°C, using concrete cube and prism samples, and also the effect of using high reactivity metakaoline (HRM) to enhance its behavior when exposed to high temperatures.

## 2. Experimental Work:-

### 2-1- Material and mix proportioning concrete.

The first step in this work was to design and obtain SCC with mix proportion satisfies the criteria and filling ability , flow ability , pass ability and segregation resistance . Two types of SCC mixes were cast with the same mix proportion (1: 1.55 : 1.77) (cement : fine aggregate : coarse aggregate ) by weight and according to EFNARC(2002)(4) , using ordinary Portland cement (type I ) , which conformed with the requirement of the ASTM C150 standards . Natural siliceous desert sand was used as fine aggregate and crashed river gravel with maximum size of (10mm) was used as coarse aggregate. Both types of aggregate conformed to ASTM C33 requirement .The first type of SCC was obtained by using a superplasticizer which is (Glenium 51) . This superplasticizer conformed to the requirement of type A and F of ASTM C494 standard. The second type of SCC was obtained by using Glenium and metakaoline (HRM) with a fineness of (17000) $cm^2/gm$ . The details of the two SCC mixes are shown in Table (1) .

### 2-2- Tests of fresh SCC

Testing of concrete in its fresh state is of serious importance for the production of SCC which is focused on its ability to flow under its own weight without vibration and the ability to obtain the homogeneity without segregation of aggregate . the slump flow , V- funnel and L – box are used for the assessment of fresh properties of SCC in this study . The tests results of the fresh properties of SCC mixes are shown in Table (2)

### 2-3- Casting ,curing and heating procedure of the test specimens .

In this study the specimens of SCC are divided into two groups (A and B) , each group consists of (18) concrete cubes of (150x150x150)mm for compressive strength test and (18) concrete prisms of (100x100x500)mm for both modulus of rupture and dynamic modulus of elasticity test . The specimens were heated to five temperatures of (100, 200, 400, 600, and 800 $^{o}$C). Three cubes were tested for compressing strength and three prisms for modulus of rupture and modulus of elasticity at each temperature from each group. Also, three specimens were used for each test from each group at room temperature as reference specimens.

After about 24 hours from casting time, the specimens were demoded from their moulds, marked and immersed in tap water to be cured for 28 days .Then the specimens were air- dried in the laboratory environment for 3 days to attain specimens of drying condition which is similar to that in the site . After curing, the specimens for each mix were subjected to different levels of elevated temperature.

The specimens were slowly heating in this research to reach to the worst situation may the concrete exposed to it ,because the concrete specimens slowly heating suffered a further reduction in their compressive strength compared with concrete quickly heating as mentioned by Mohamedbhai(5) ,who study the affect of rates of heating on the residual strength of concrete . The author found that, this variable has a very significant affect on residual strength of concrete heated to lower temperature (below 600 $^{o}$C ),also residual compressive strength of concrete quickly heating was greater than that of concrete slowly heating , this can be seen from Fig.(1).

Using an electrical furnace, the specimens were heated slowly at a constant rate of about 2$^{o}$C/min to avoid steep thermal gradient (5,6) . Once the required temperature was attained, the specimens were thermally saturated for two hours at that temperature to attain a steady state of thermal equilibrium . Then the furnace was switched off and the specimens were kept inside the furnace to cool down. After that they were removed and tested the day after heating.

### 2-4- Performed standards:

To study the effect of elevated temperature on the SCC, the following testes were performed on the specimens before and after heat exposure

a . **Compressive strength**:-The test was carried out according to **BS 1881:part 116**(7)

b . **Modulus of rupture**:-According to **ASTM C78-84(8).**

c . **Dynamic modulus of elasticity**: According to **ASTM C215-85(9)**.

## 3 – Results and discussions

### 3-1- Concrete compressive strength

The residual compressive strength for two types of SCC exposed to different temperature is shown in Fig.(2) . While Fig.(3) shows the effect of temperature exposure on the percentage residual compressive strength (the ratio of the maximum compressive strength at a specified temperature to the maximum compressive strength at room temperature)

From Figure(2)and Figure(3) it con be noticed that :-

Concrete compressive strength for two group (A and B) suffers a noticeable deteriorations when exposed to high temperature . This is an expected result since exposing to elevated temperature makes a lot of physical and chemical changes in concrete, such as loss of moisture, thermal movements between cement paste and aggregate , and dehydration of calcium silicate hydrated in the cement paste (10,11) . These changes lead to the initiation of thermal microcracks and growth of the cracks that are formed previously either in the earlier stages of heating or cracks that exist before heating (during shrinkage cracks), and consequently lead to deterioration of concrete strength.

Initially, as the temperature increase to 100°C, the SCC specimens group(B) with (HRM) suffered about 2.2% decrease in compressive strength . It is believed that absorbed water in concrete softens the cement gel or attenuates the surface forces between gel particles (van der walls forces), thus reducing the strength in lower elevated temperature (10) . Also, the reduction in compressive strength at lower temperatures may be attributed to the triaxial state of stress apparently existing when the paste pores are filled with water (12 ,13)

At the same temperature (100°C) the SCC specimens group (A) without (HRM) exhibited a slight increase in their compressive strength 1% above the room temperature strength . The increase in strength associated with the increase in temperature is attributed to the general stiffening of the cement gel , or the increase in surface forces between gel particles due to the removal of adsorbed moisture(10,13,14) . The temperature at which adsorbed water is removed and the strength begins to increase depends on the porosity of concrete. Therefore , the adsorbed moisture in group (A) specimens escaped before that of group(B) resulting in an early increase in the compressive strength since the SCC group(B) which containing HRM is denser than that of group(A) .

With further increase in exposure temperature (200°C), group (A)of concrete specimens suffered about 19.2% decrease in their compressive strength. While SCC group (B) showed some strength recovery , the residual compressive strength was 98.9%.

At exposure temperature of 400°C, group (B)of concrete specimens showed increase in strength recovery reach to 105.2% above that at room temperature strength . This increase in the compressive strength is attributed to the fact that the specimens of group (B) is denser than group (A) and have little porosity , so the adsorbed moisture could not escape until after 200°C.Thus the recovery of strength was delay and occurred between 200 and 400°C . While group(A) exhibit a slight increase in strength and the residual compressive strength was 83.3% .

In addition, the change of color to pink in all heated specimens was shown at 400°C. This is attributed to the hydration of iron oxide compounds which is stated to be responsible for the color change (15) .

At exposure temperature of 600°C, the two groups of SCC (A and B)exhibit a loss of compressive strength .The decrease was 24% for group (A) and 17.6% for group(B) compared with their original strength .This is due to the dehydration of the cement paste due to the decomposition of calcium hydroxide, in addition to the weakness of bond between the aggregate and the cement paste, thus gradually reducing the concrete strength(13). The formation of surface hair – crack was also observed in SCC specimens group(A) while specimens of group(B) did not reveal any obvious cracks during this period . The reason for this cracking is the expansive and hence disruptive rehydration of dissociated $Ca(OH)_2$ , which is accompanied by volume increase(15) .

Finally at exposure temperature of 800°C, the decrease in strength for the two group of SCC (A and B) was 35% and 26.8% respectively, compared with their strength at room temperature. This reduction can be attributed to dehydration progressed and due to the decomposition of the calcium silicate hydrate at that temperature (16). Visual examination of the heated concrete specimens at 800°C revealed some fine cracks at the surface of SCC specimens containing HRM.

It is clear from the test results that the two types of SCC exhibit good fire resistance compared with conventional concrete and the loss in their strength resulting from exposure to high temperature was less than that referred to by many investigators (17,18,19,20) ,for example Hassan ,S.A., found that the residual compressive strength after exposure to temperature level (800) °C for (NSC)and (HSC) were (39.5)% and (19.5)% respectively ,while Habeeb ,G.M., found that the residual compressive strength for (NSC)was (28.8)% at exposure temperature of 800 °C . It is also found that the reduction in compressive strength of SCC specimens group(B) which contain 10% HRM as a partial replacement from the weight of cement was smaller compared to that of group(A) (without HRM) . This is due to the fact that HRM is a pozzolanic material that can react with lime liberated from the hydration of ordinary Portland cement (OPC) and produce alumina gel , such as hydrated calcium alumino – silicate , $2CaO . Al_2 O_3 . SiO_2$ . aq and $4CaO. Al_2O_3$ . aq which have good refractoriness .This reaction improves the microstructure of cement pastes and increase heat resistance of cement paste(15,21). Also the content of $Ca(OH)_2$ percent in the hydrated cement paste plays an important role in the deterioration of concrete strength .Hence , the decreasing amount of disruption of the concrete containing (HRM) after heating , reflects the decreasing amount of $Ca(OH)_2$ percent in the hydrated cement pastes prior heating , due to pozzolanic reactions(15) .

$$2(Al_2O_3.2siO_2)+7Ca(OH)_2 \rightarrow 3CaO.2SiO_2.aq+2(2CaO.Al_2O_3.SiO_2.aq) \ldots\ldots\ldots 1$$

## 3-2- Modulus of rupture(flexural strength)

The test results of modulus of rupture for two types of SCC (A and B) at different temperature are plotted in Fig. (4) and Fig. (5) . At room temperature , the modulus of rupture of SCC (B) is higher than that of SCC (A) about (5.2)% . This is due to the usage of HRM which leads to better binding strength at the interface transition zone (ITZ) than those without HRM (3) .

Initially , as the exposure temperature increase to 100°C , the specimens of SCC (A and B) showed a slight reduction in their modulus of rupture with increasing temperature , the reduction were 8.5% and 3.6% , respectively .

At exposure temperature of 200°C , SCC specimens group(B) suffered a further reduction in their modulus of rupture and reach to about 10% of the room temperature strength .The reduction in modulus of rupture of SCC when exposed to temperature ranging from less than 100°C to around 200°C can be explained by the fact that during initial heating , the evaporable water present in the concrete vaporized 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 flexural strength.

At the same exposure temperature (200°C), SCC specimens group(A) recovered some of their modulus of rupture loss to reach about 96.2% of the room temperature value ,Fig.(2) .It is believed that when most of the water has evaporated at higher temperatures , the effect of both the triaxial tension and the Van der walls internal forces which exist in moist concrete , disappear resulting in an apparent increase in strength as indicated by the strength recovery phase . This was also confirmed by akhtaruzzaman(22) .

At exposure temperature of 400°C, the SCC specimens group(B) showed some strength recovery and reach to about 97% of the room temperature strength . This increase in modulus of rupture is attributed to the fact that the specimens of SCC group(B) with HRM were denser and have lower porosity compared with specimens of group(A) and the a adsorbed moisture could not escape until after 200°C , thus the recovery of strength was delayed . While at the same exposure temperature 400°C specimens of SCC group (A) suffered a further reduction in their flexural strength, Fig. (5).

At exposure temperature of 600°C,all SCC specimens suffered a further decrease in their flexural strength .The reduction was about 26% and 20% for group A and B ,respectively compared with their control specimens .

At exposure temperature of 800°C, all types of SCC specimens (A and B) suffered a significant decrease in their flexural strength, The mixes had 52.6% and 71.2% of their initial flexural strength for group (A and B) , respectively .

### 3-3- Dynamic Modulus of Elasticity:-

The value of dynamic modulus of elasticity (Ed) gained from testing two types of SCC (A and B) exposed to different temperature are shown graphically in Fig.(6) and Fig. (7). It is noticed that , at room temperature , the modulus of elasticity of mix (B) which contain HRM are higher than those of mix (A) without HRM . this behavior refers to the pozzolanic activity of HRM .

Previously some researchers (15,17,20) found that (Ed) of concrete decrease as temperature increases. The test results of this study completely confirm this result. The modulus of elasticity of both group (A and B) SCC decreased as exposure temperature increase by a mount depending on temperature level.

It is observed that all SCC specimens (A and B) heated at temperature range of 100 to 400°C exhibit a slight reduction in their (Ed) ranging from (4.7% to 27.2%) and from (2.2% to 16.3%) for group (A and B), respectively. Exposure to higher temperature resulted in many changes in the structure of concrete , which cause much deterioration in concrete properties . Where , during the drying process , which occurs simultaneously with temperature increase , the dynamic modulus of elasticity is reduced .This occurs because any movement in moisture results in some bond rupture , increasing porosity and causing decrease of concrete stiffness(17) .

At exposure temperature of 600°C, as the dehydration progressed and the bond between materials was gradually lost , all SCC specimens suffered a farther decrease in their (Ed) , the losses were about 33.8% and 21.9% for group A and B , respectively as compared with their control specimens .

After exposure to 800°C, the modulus of elasticity deteriorated significantly, where a percentage loss in (Ed) were about 52.7% for group (A) and 36.5% for group (B).This is due to the fact that, as temperature increases , the stiffness decreases due to the breakage of bond in the microstructure of cement paste as well as the short time creep at incensing temperature(17) .

In general , SCC group(B) (containing HRM) showed a lesser degree of dynamic modulus of elasticity loss than group(A) , which indicates that , such SCC are less sensitive to high temperature from the point of view of modulus of elasticity .

## 4 – Conclusions

1 – In general, SCCs are less sensitive to elevated temperature than conventional concrete.

2 – The mechanical properties of two types of SCC (with and without HRM), decrease after exposure to elevated temperature by a mount depending on the exposure temperature and the existing of HRM.

3 – The loss in mechanical properties resulting from exposure to elevated temperature in SCC (containing10% HRM as a partial replacement by weight of cement) was relatively smaller than that in SCC (without HRM). The difference in compressive strength was a bout (6.4% - 21.9%) and in modulus of rupture was(4.9%- 18.6%).

4 – The compressive strength temperature correlation of the SCC (without HRM) has two peak at (100°C and 400°C), and reach its maximum value at (100°C) which is higher than its original value by (1%) , while the compressive strength-temperature correlation of SCC (with HRM) has one peak only at (400°C) and the maximum value compressive strength is higher than its original value by (5.2%) .

5 – For two types of SCC, the behavior of heated SCC under both the modulus of rupture and compressive strength were very much a like at (600°C and 800°C), while it is differ from the temperature of (100 to 400°C). At 800°C the loss in modulus of rupture is high than that of compressive strength and the difference was between (2% - 12.4%).

6 – The reduction in dynamic modulus of elasticity was higher than that in compressive and modulus of rupture and dropped more rapidly than them.

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**Table (1):- Details of self-compacting concrete mixes**

| Mix Symbol | W/P* ratio | Water L/m$^3$ | Cement kg/m$^3$ | HRM kg/m$^3$ | Sand kg/m$^3$ | Gravel kg/m$^3$ | Sp** L/m$^3$ |
|---|---|---|---|---|---|---|---|
| A | 0.35 | 170 | 500 | 0 | 775 | 885 | 5.2 |
| B | 0.36 | 170 | 450 | 50 | 775 | 885 | 9 |

* W/P : water / powder : water / (cement + HRM)

** Sp : superplasticizer

**Table (2):- Fresh properties of SCC mixes**

| Mix symbol | Slump flow (mm) | T500 mm (sec) | V – Funnel | | L - box |
|---|---|---|---|---|---|
| | | | TV(sec) | TV5(sec) | Blocking Ratio |
| A | 745 | 3.5 | 6 | 8.5 | 0.94 |
| B | 720 | 4.5 | 8 | 10 | 0.9 |

Table (3) :- Compressive strength of SCC mixes before and after exposure to different temperatures

| Exposure Temperature($^o$C) | Group Mix (A) | | Mix(B) | |
|---|---|---|---|---|
| | Compressive Strength | | Compressive Strength | |
| | After exposure to T ($^o$C) (MPa) | Residual (%) | After exposure to T ($^o$C) (MPa) | Residual (%) |
| 28+2 | 64.0* | 100.0 | 71.0* | 100.0 |
| 100 | 64.6 | 101.0 | 69.5 | 97.8 |
| 200 | 52.4 | 81.8 | 70.2 | 98.9 |
| 400 | 53.3 | 83.3 | 74.7 | 105.2 |
| 600 | 48.7 | 76.0 | 58.5 | 82.4 |
| 800 | 41.6 | 65.0 | 52.0 | 73.2 |

* Tested at room temperature after 28 days moist-curing and 3 days air-drying (as control specimens).

Table (4) :-Modulus of rupture of SCC mixes before and after exposure to different temperatures.

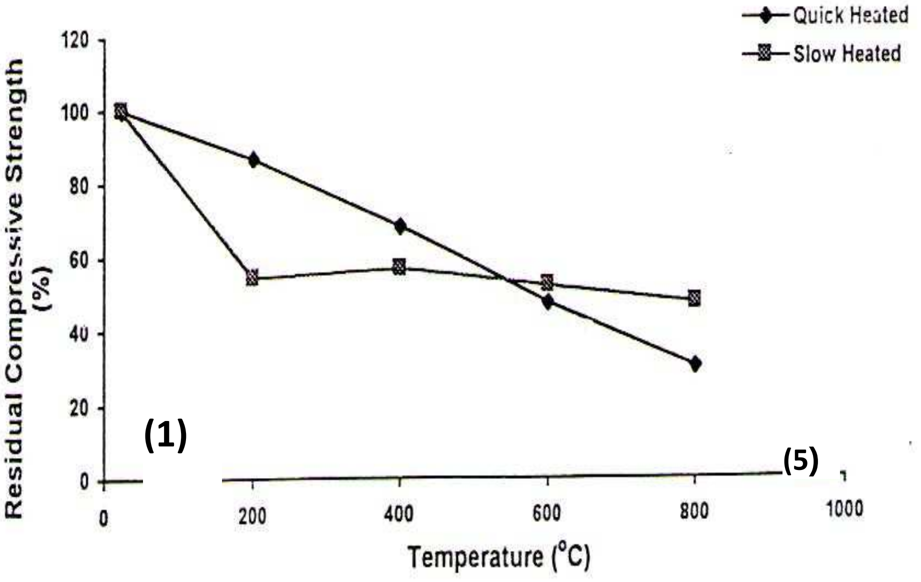
| Exposure Temperature($^o$C) | Mix (A) | | Mix(B) | |
|---|---|---|---|---|
| | Modulus of rupture | | Modulus of rupture | |
| | After exposure to T ($^o$C) (MPa) | Residual (%) | After exposure to T ($^o$C) (MPa) | Residual (%) |
| 28+2 | 7.90* | 100.0 | 8.30* | 100 |
| 100 | 7.23 | 91.5 | 8.00 | 96.4 |
| 200 | 7.60 | 96.2 | 7.47 | 90.0 |
| 400 | 6.77 | 85.7 | 8.05 | 97.0 |
| 600 | 5.85 | 74.0 | 6.64 | 80.0 |
| 800 | 4.16 | 52.6 | 5.91 | 71.2 |

* Tested at room temperature after 28 days moist-curing and 3 days air-drying (as control specimens) .

Table (5):- Dynamic modulus of elasticity of SCC mixes before and after exposure to different temperatures.

| Exposure Temperature($^o$C) | Mix (A) | | Mix(B) | |
|---|---|---|---|---|
| | Dynamic Modulus of elasticity | | Dynamic Modulus of elasticity | |
| | After exposure to T ($^o$C) (GPa) | Residual (%) | After exposure to T ($^o$C) (GPa) | Residual (%) |
| 28+2 | 42.3* | 100.0 | 44.8* | 100.0 |
| 100 | 40.3 | 95.3 | 43.8 | 97.8 |
| 200 | 37.1 | 87.7 | 42.0 | 93.8 |
| 400 | 30.8 | 72.8 | 37.5 | 83.7 |
| 600 | 28.0 | 66.2 | 35.0 | 78.1 |
| 800 | 20.0 | 47.3 | 28.4 | 63.5 |

* Tested at room temperature after 28 days moist-curing and 3 days air-drying (as control specimens)



**Figure(1)** Effect of rate of heating on residual compressive strength of slowly cooled concrete [26]

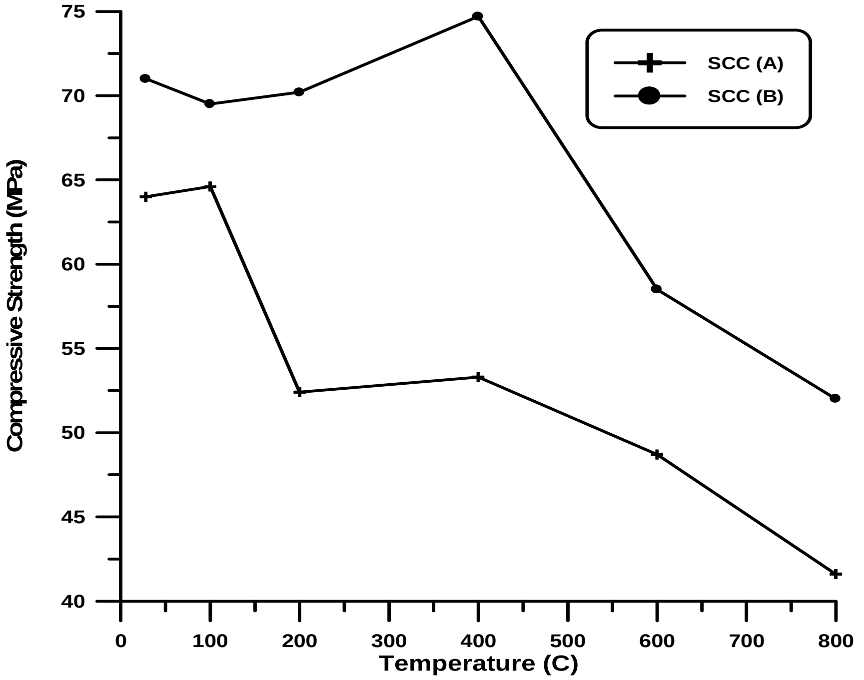


Figure (2) The Effect of elevated temperature on the compressive strength of SCC

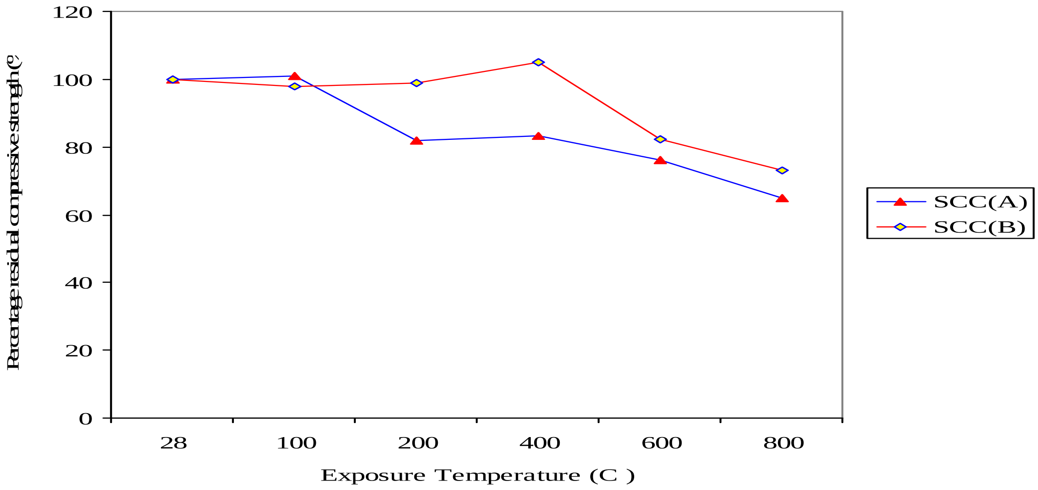


Figure (3) Residual compressive strength for two types of SCC exposed to different elevated temperature

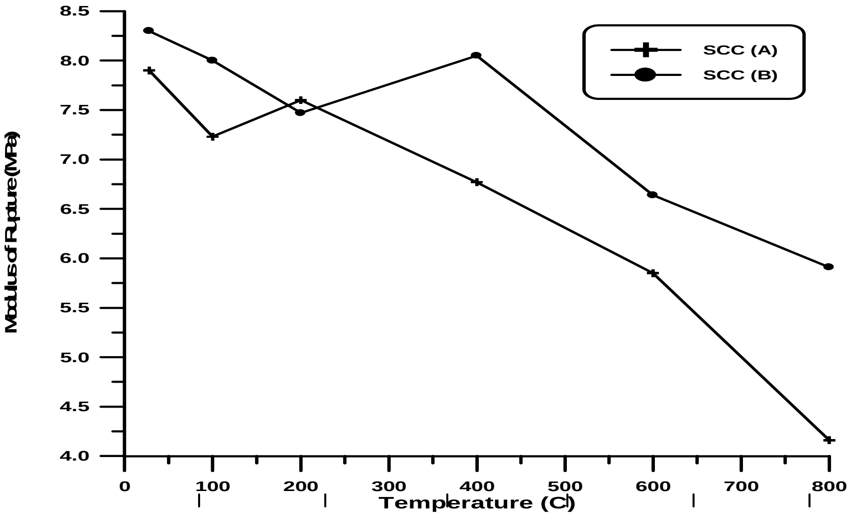


Figure (4)Effect of elevated temperature on the modulus of rupture of SCC

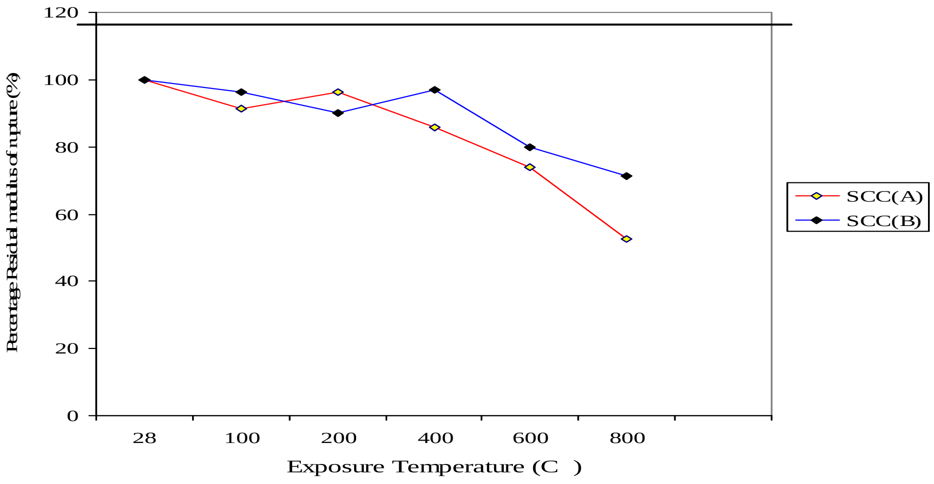


Figure (5) Residual modulus of rupture for two types of SCC exposed to different elevated temperature

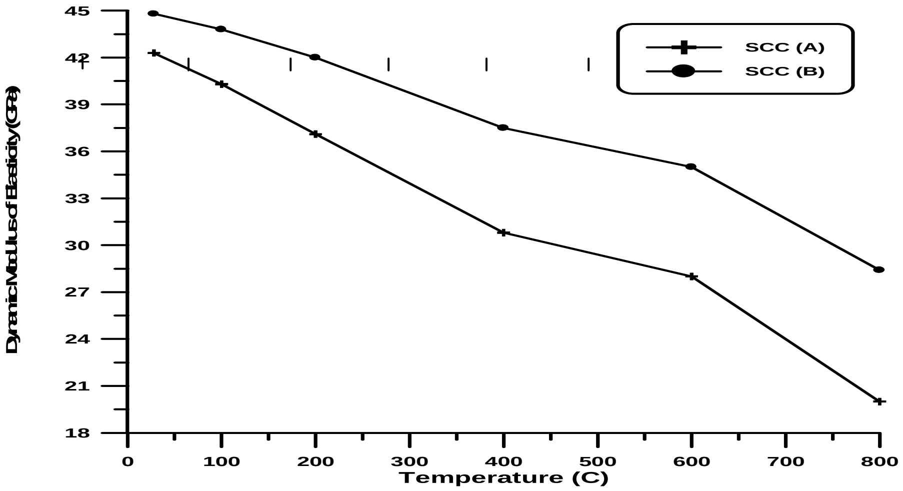


Figure (6) Effect of elevated temperature on the dynamic modulus of elasticity

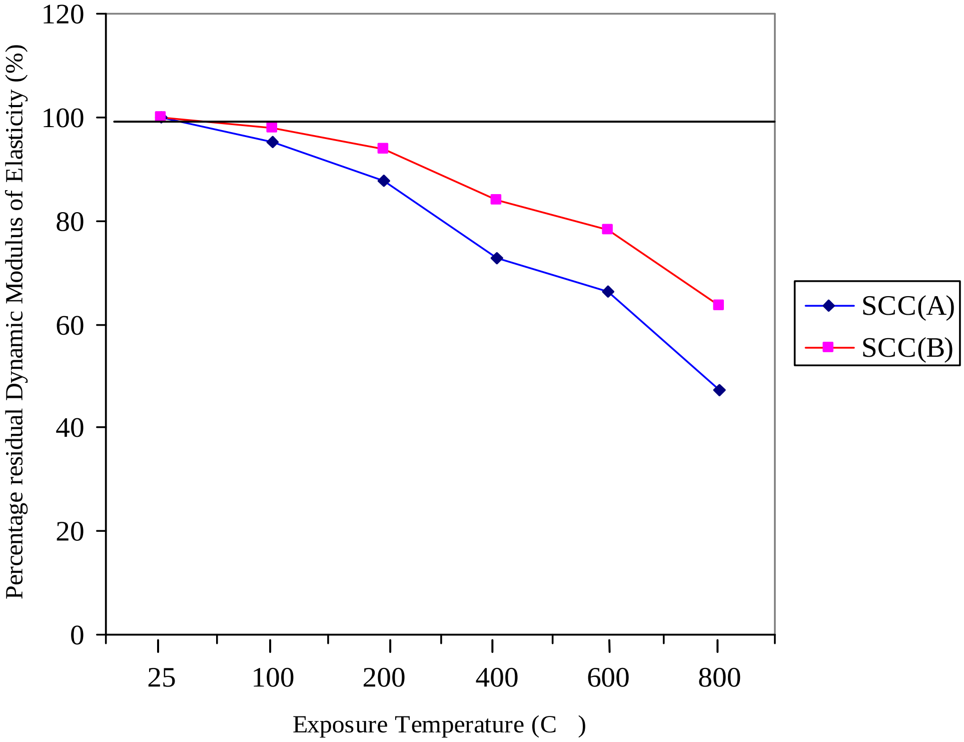


**Figure (7) Residual dynamic modulus of elasticity for two types of SCC exposed to different elevated temperature**