Studies on Normal Strength Concrete Cubes Subjected to Elevated Temperatures

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Abstract
Concrete in structures is likely to be exposed to high temperatures during fire. The probability of its exposure to elevated temperatures is high due to natural hazards, accidents and sabotages. Therefore, the performance of concrete during and after exposure to elevated temperature is a subject of great importance and interest to the designer. Popular normal strength grades of concrete produced by Ready Mix Concrete (RMC) India, Mangalore have been used in production of test specimens (150 mm cubes), cured and tested by destructive method for gathering data on strength characteristics. Later, these test samples were subjected to elevated temperatures ranging from 100^{0}C to 800^{0}C, in steps of 100^{0}C with a retention period of 2 hours. After exposure, weight losses and the residual compressive strength retention characteristics are studied. Test results indicated that weight and strength significantly reduces with an increase in temperature. Residual compressive strength prediction equations are proposed for normal strength concretes subjected to elevated temperatures.

Keywords: Elevated Temperatures, Compressive Strength Retention, Concrete Cubes

1. INTRODUCTION

Concrete is the most versatile building material because of its mouldability and high compressive strength. From several decades researchers have been working on improvisation of concrete in all respect, right from its making stage to its long-term performance. The result of which is concrete finds its applications in hostile environments as well.

Fire accidents, sabotages or natural hazards are the situations where the structural concrete may have to withstand elevated temperatures. Concretes near the furnaces or reactors will have to bear elevated temperatures. Even though concrete is the best building material as far as fire resistance is considered, because of its low conductivity and non-combustible nature, even then strength and durability deterioration of concrete is observed when subjected to elevated temperatures.

Some complicated processes of shrinkage, decomposition, expansion, and crystal destruction occur during fire (Min Li et al.)[1]. Concrete undergoes many physical and chemical changes such as colour change, cracking and spalling, coarsening of pore structure, decomposition of C-S-H gel, increase in permeability etc.

1.1. Cracking

With an increase in temperature, cracking is initiated due to thermal incompatibilities between the aggregates and the hardened cement paste, the cement paste would shrink due to the dehydration/decomposition of the hydrates while the aggregates usually expand before disintegration.

When concrete is heated at a rapid rate, a steep thermal gradient may develop between the outer and inner layers of concrete because concrete is a poor conductor, this gradient can also cause cracking. Building up of vapour pressure might be another cause of cracking. Cracking is a visible type of damage to concrete that has significant adverse effects on the mechanical and durability properties of concrete. Y. Xu et al. [2].

In visual observation of concrete samples subjected to elevated temperatures, it was noticed by O. Arioz [3], that the surface cracks became visible when the temperature reached 600°C. The cracks were very pronounced at 800°C and increased extremely when the temperature was increased to 1000°C.

1.2. Spalling

As it relates to concrete at elevated temperatures, spalling may be defined as the flaking off of concrete material from the larger concrete specimen. K.D. Hertz [4] has reported that, for traditional concretes the effect of explosive spalling is mostly seen within the first 20 minutes of a fire. The author also concludes that constructions of traditional concrete with less than 3wt% moisture will not give rise to spalling and that traditional concrete in the range 3–4 wt% moisture has a limited risk of spalling.

V.K.R. Kodur and L Phan [5] observed that the high rate of temperature rise can induce spalling in concrete members. This was mainly due to high temperature gradients that develop within the cross section, which in turn increases the pore pressure generated in the concrete. Y. Xu et al. [2] reported that during exposure to high temperatures, very high pore pressure may be built up as functions of temperature, heating rate and size of specimens. If the pore pressure is much higher than the concrete's tensile strength such a pressure could cause a dramatic type of cracking, generally known as thermal spalling of concrete.

1.3. Colour Changes

The observed colour changes on the surface of concrete subjected to high temperatures by Yuzer et al. [6], may give an idea about the temperature that the concrete was subjected to. He cautions that the results were valid for samples with silica fume and with different cooling regimes.

According to colour image analysis conducted by O. Arioz [3], the intensity of the yellow colour increased with increase in temperature and red colour appeared when the temperature increased to 800°C. Therefore, the results of colour image analysis may also be used to assess the level of temperature to which the concrete was subjected.

1.4. Mechanical Strength

Many researchers have reported strength deterioration with the increase in exposure temperature. The strength degradation is not same under high temperature. It depends on type of aggregates used, the heating and cooling regime, the presence of pozzolanas, fibers etc. The kind of aggregates used for making concrete has a major influence on the performance of concrete at elevated temperature. According to A.H Gustaferro [7] carbonate aggregates perform well at elevated temperatures as compared to siliceous aggregates. Siliceous aggregates begin to expand abruptly at 570^0C and disintegrate.

Y Xu et al. [2] have noted an increase of 110% in the residual compressive strength when the test temperature was 200^0C. Within the temperature range 400^0C - 600^0C the decrease in residual compressive strength is more dramatic with values ranging from 97%- 71% at 400 ^{0}C then dropping to 30% at 600^0C. Within the temperature range 600^0C - 1000^0C the residual compressive strength continues to drop to 9%. According to Min Li et al. [1] the compressive strength of concrete drops with temperature starting from 200^0C. The compressive strength value drops sharply to 21.3% compared to that of specimens unfired after 1000^0C firing. The effect of size of specimens was investigated by Min Li et al. [1] and concluded that larger size specimens perform better and experience lesser strength loss. However very large specimens need to be investigated.

The way the heated concrete is cooled also has an impact on the residual compressive strength. Rapid cooling of hot concrete surface using water induces a thermal shock which causes a bit more deterioration of concrete strength. According to Ivan Janotka et.al [8] the rapid cooling of hot concrete surfaces exposed to 100^0C and 200^0C are for structural quality deterioration equally dangerous as temperature elevations.

Omer Arioz [3] observed a gradual reduction in residual strength up to 600^0C (residual strength 90% for carbonate aggregates and 50% for river gravel) and sharp reduction in relative strength beyond that point. This paper reports the behavior of normal strength concretes when subjected to elevated temperatures ranging from 100^0C to 800^0C, in steps of 100^0C with focus on loss of weight and compressive strength of 150mm cubes.

2. TEST PROCEDURE

The effects of elevated temperatures on various grades of normal concrete are studied in this investigation. The foregoing research makes use of popular grades of normal concrete as designed, produced and supplied by RMC (India), Mangalore. Cube specimens of size 150x150x150mm were cast and 28 days water curried for M20, M25, M30, M35, M40 and M45 Grades of concrete. Table 1 presents the mix design details of all the six grades of concrete used in this study. Siliceous aggregates have been used in all the grades. For every grade a total of 36 number specimens were casted. These were divided in to 12 sets, each set consisting of 3 specimens. Within these 12 sets, 2 sets were tested under destructive testing before exposure, 8 sets for actual exposure testing, and the remaining 2 sets were casted as reserve. Out of the total 216 number of specimens, 180 numbers of specimens have been tested.

Table 1. Details of design mixes for one cubic meter of concrete

		Aggregates						
		Fines		Coarse				
Concrete Grade	OPC* (kg)	CRF** (kg)	Sand (kg)	12mm down (kg)	20mm (kg)	Water (liter)	Water/ Cement	HRWRA*** (kg)
M20	280	342	512	344	746	158	0.56	1.982
M25	310	376	509	289	740	166	0.54	2.196
M30	358	324	502	288	739	156	0.44	2.407
M35	376	311	498	286	735	156	0.41	2.655
M40	422	293	460	286	735	159	0.38	2.938
M45	454	295	434	292	747	170	0.37	3.717

*OPC – Ordinary Portland Cement **CRF – Crushed Rock Fines *** HRWRA- High Range Water Reducing Admixture.

Each set (Consisting of 3 specimens) of all the six grades were exposed to, in an electric oven of size (2.1m x 1.5m x 1.5m) at Building Fire Research Center (BFRC) of NIE college Mysore. These specimens were exposed to elevated temperatures from 100^0C to 800^0C in increments of 100^0C for 2 hours of retention at the designated temperatures. The temperature build up was at the rate of 2^0 C/minute. The time-temperature curve for the electric furnace is shown in figure 1.

In order to evaluate the variation in moisture content all the specimen were weighed before subjecting them to elevated temperatures and also after exposure. To ascertain the residual compressive strength the destructive testing of control specimens for all the grades of concrete was carried out before exposure, further destructive testing of all the exposed specimens to elevated temperatures was later carried out for strength retention assessment.

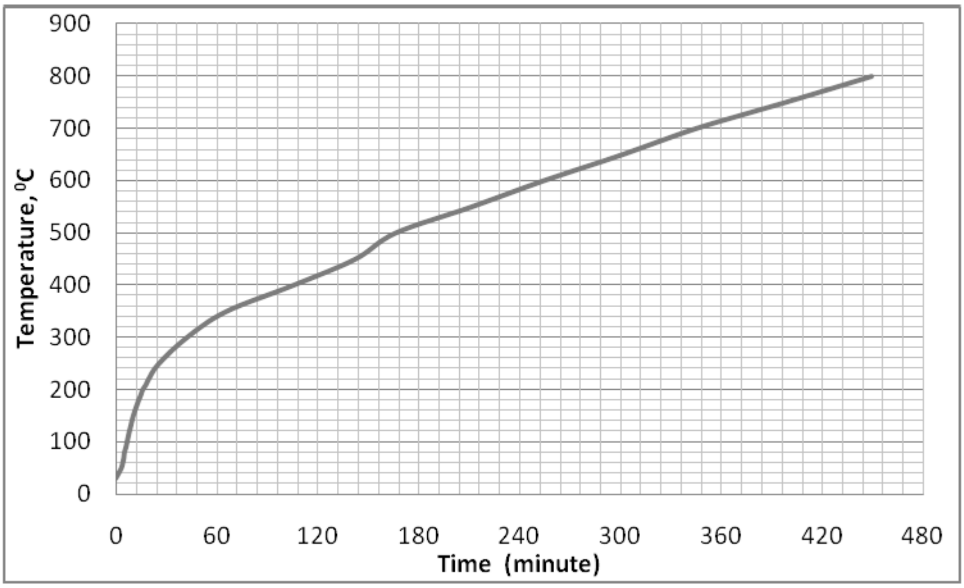


Figure 1. BFRC furnace, Time – Temperature rise curve.

3. RESULTS AND DISCUSSION

3.1. Physical Properties of Specimen

3.1.1. General

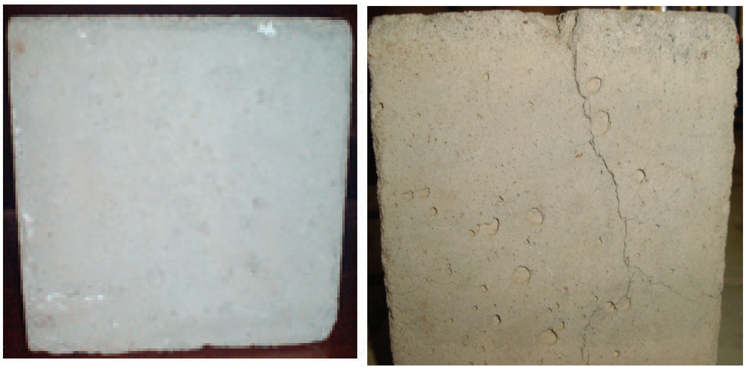
Detailed experimental investigations were carried out on all six grades of concrete specimens. Few physical observations were made before subjecting the specimens for destructive testing to assess the post exposure residual strength, they were colour, surface cracking, amount of spalled surface and presence of surface voids. This will provide some reference for structure in practice. Therefore, the change in colour, and temperature during fire, the retained compressive strength can be inferred primarily. Some complicated processes of shrinkage, decomposition, expansion, and crystal destruction occur at elevated temperatures.

3.1.2. Dimensions of the specimen

Before exposing to elevated temperature, the dimensions of all specimens are found to be within the tolerance limits specified in the relevant IS codes (IS: 516-1959, IS: 5816-1999). The specimens revealed excellent physical appearance without honeycombing or any defect. After exposed to elevated temperature there was no significant distortion of the specimens, observed but for the specimens which all are kept in 500-800 ^{0}C a small amount of deterioration (small smudged edges) of concrete at the edges and corners occurred.

3.1.3. Spalling and surface colour

The change of concrete colour can be attributed to the change in texture and composition, expansion and crystal destruction during a fire. The variation of the colours under rising temperature can be identified under three main categories. Below 300 ^{0}C, the concrete colour doesn't change noticeably. When temperatures are increased up to 400 ^{0}C – 600 ^{0}C concrete colour slightly changed to dust colour or brownish/ yellowish grey. Beyond 600 ^{0}C temperatures, concrete colour observed is straw yellow to pinkish yellow/pinkish red, as observed by Jianzhuang Xiao and H. Falkner [9].



(a) Unexposed (b) Exposed

Figure 2. Specimen surface before and after exposure to 800 ^{o}C

Cracks were appeared on all specimens which are all kept in temperature range of 600 ^{0}C to 800 ^{0}C. Figure 2, shows a typical photograph of the specimen suffering crack, when exposed to 800 ^{0}C. Small cracks were observed in specimens subjected to elevated temperature of 600 ^{0}C and these cracks were more prolonged in the case of specimens subjected to 700^{0}C and 800^{0}C.

Explosive spalling occurred in only 1 specimen of M-40 which was subjected to temperature of 500 ^{0}C. It is observed that the exploded specimen had an initial weight of 8.233 kg which is maximum among all the specimens. Since it has maximum density there may be a formation of moisture clog within that specimen and leading to explosive spalling of the specimen when exposed to elevated temperature.

3.2. Loss of Weight after Exposure to Elevated Temperatures

The weights of the specimens before and after exposure to elevated temperatures were taken for weight loss evaluation. Average percentage loss in weight were determined for various grades of concrete and for different temperatures of exposure. Table 2 shows variation of percentage loss in weight for various grades of concrete when subjected to elevated temperatures. Figure 3 shows variation of average percentage loss in weight with elevated temperatures for various grades of concrete. Also Figure 4 shows bar chart of variation of average percentage loss in weight with elevated temperatures on various grades of concrete. It can be seen from Figs. 3 and 4, that there is a continuous increase in percentage loss in weight of specimen with increase in temperature. Except M25 grade concrete, for all the rest, up to 200^{0}C, the average percentage loss in weight is about 0.5%. It observed that for M35, M40 and M45, there is a steep increase in average percentage loss in weight from 200^{0}C to 400^{0}C and then on there is gentle increase with increase in temperature. However for M20, M25 and M30 there is a gentle increase percentage loss in weight from 200^{0}C to 800^{0}C.

Table 2. Variation of average % loss in weight for various grades of concrete subjected different elevated temperatures.

Temperature exposed to (^{0}C)	Average % Loss in Weight					
	M20	M25	M30	M35	M40	M45
100	0.438	0.910	0.081	0.133	0.054	0.154
200	0.532	1.831	0.313	0.180	0.886	0.621
300	0.993	2.090	1.716	2.272	3.283	2.426
400	2.386	2.961	2.639	4.403	4.040	4.632
500	3.228	3.086	3.778	5.513	4.780	5.037
600	3.877	4.125	4.263	5.911	5.225	5.830
700	4.426	5.428	5.315	6.540	5.473	6.366
800	5.230	5.564	6.067	7.209	6.219	7.261

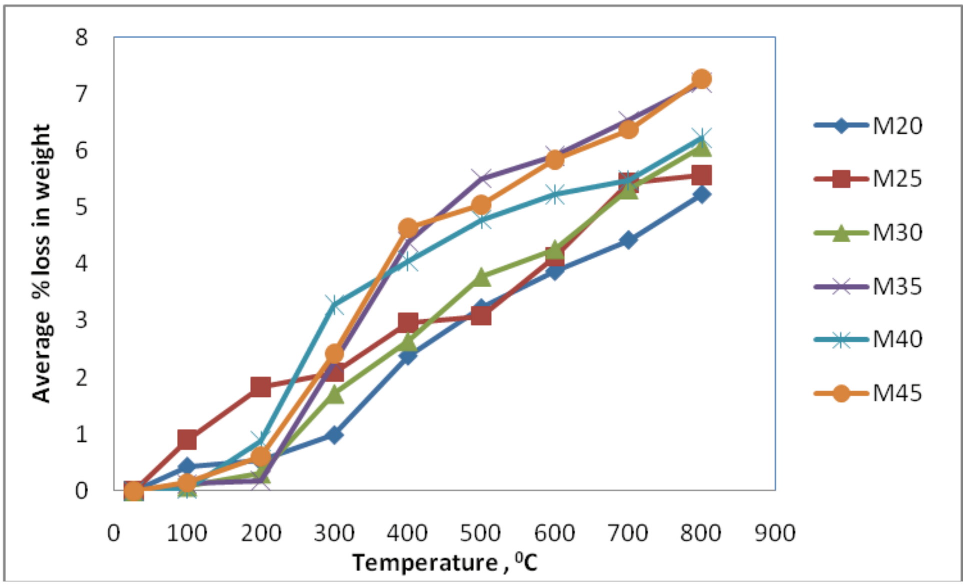


Figure 3. Variation of percentage loss in weight with elevated temperatures for various grades of concrete

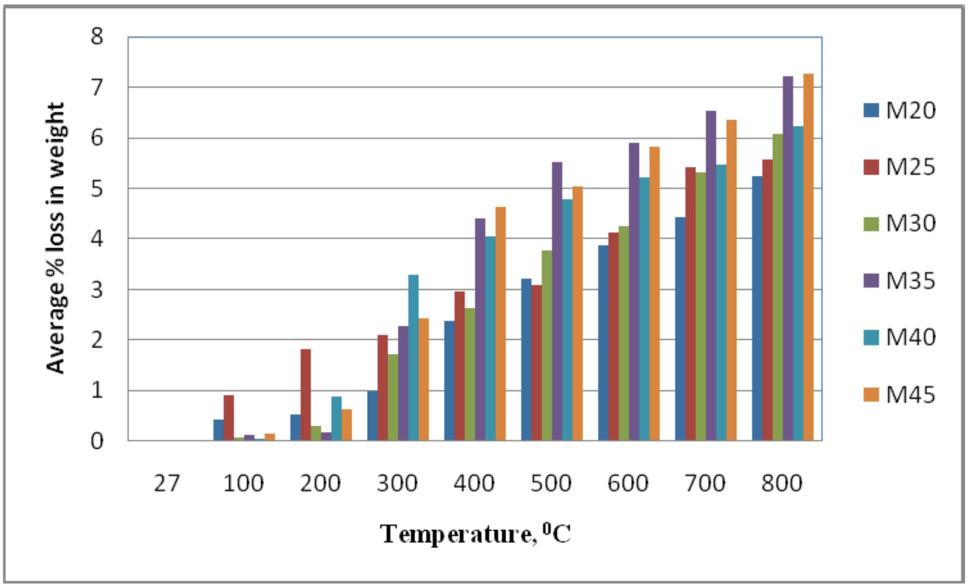


Figure 4. Bar chart showing variation of percentage loss in weight with elevated temperatures for various grades of concrete

From Figure 5, it can be observed that there is no significant loss in weight for all specimens of all grades subjected up to 200^{0}C and afterwards all grades have shown increase in loss of moisture content. Among all grades, M35 grade concrete has shown more decrease in residual weight when compared to other grades. The fallowing observations are drawn concerning to % loss in weight with temperature.

At 100^{0}C and 200^{0}C, no significant % loss in weight is observed for five grades of concrete. Only for M25 at 200^{0}C, the % loss in weight just touches 2%.

At 300^{0}C, on average it is observed that there is 2% loss in weight for all grades of concrete. At 400^{0}C there is a clear cut difference of % loss in weight for M20, M25 and M30 of concrete which is centered around 2% however for M35, M40 and M45 the observed % loss in weight is centered around 4%.

At 500^{0}C and 600^{0}C the same trend is true like that of at 300^{0}C and 400^{0}C as above, the % loss in weight increases to 4% for M20, M25 and M30. The percentage loss in weight increases to 6% for M35, M40 and M45 at 600^{0}C.

At 700^{0}C and 800^{0}C the average % loss in weight for all grades of concrete is observed to be about 6%.

3.3. Residual Compressive Strength

From Table 3. and Figure 6 it is observed that, (i) at 100^{0}C there is an increase in strength of 9%, and 3% increase at 200^{0}C, for M20 grade concrete. No significant loss in strength is observed for remaining grades of concrete up to 200^{0}C, (ii) For all the grades of concrete continuous decrease in % residual strength is observed with the increase in temperatures, (iii) In general there is substantial loss (74%) in strength from 100^{0}C to 800^{0}C for M20, M25 & M30. However for M35, M40 & M45, there is strength loss of strength of 80%. The observed minimum residual strength is 18% for M45 at 800^{0}C.

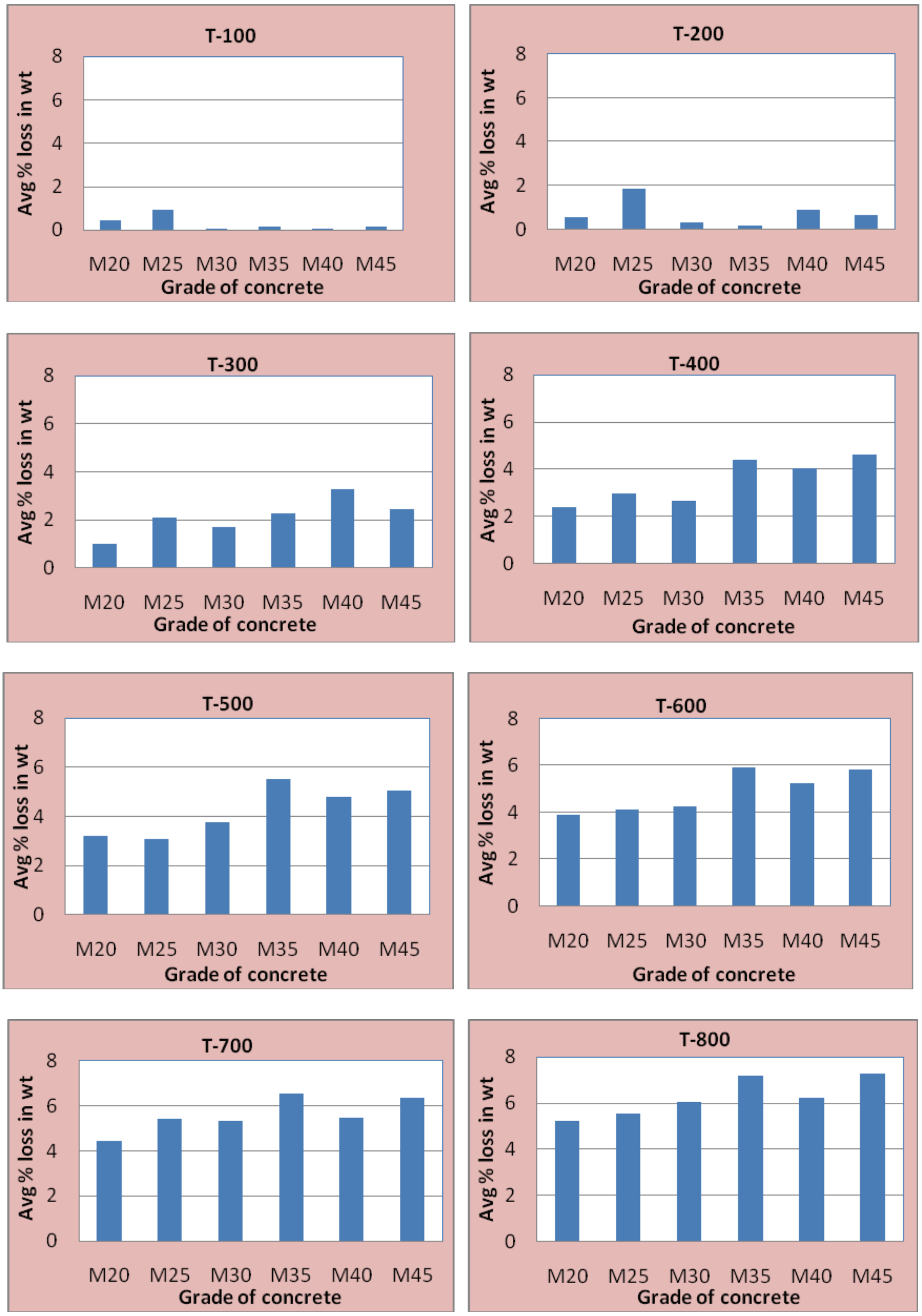


Figure 5. Bar chart showing variation of average % loss in weight for different temperatures of exposure.

Table 3. Summary of residual compressive strength results as factor/ co-efficient for 150mm concrete cubes of various grades subjected to elevated to temperatures.

Temperature exposed to (^{0}C)	Compressive strength as co-efficient or Factor					
	M20	M25	M30	M35	M40	M45
027	1.00	1.00	1.00	1.00	1.00	1.00
100	1.09	0.99	0.98	1.01	0.97	0.89
200	1.03	0.90	0.87	0.99	0.82	0.84
300	0.89	0.84	0.86	0.86	0.78	0.70
400	0.84	0.83	0.80	0.75	0.77	0.70
500	0.82	0.73	0.70	0.63	0.68	0.64
600	0.68	0.58	0.51	0.47	0.44	0.38
700	0.44	0.36	0.37	0.36	0.34	0.33
800	0.26	0.27	0.25	0.21	0.21	0.18

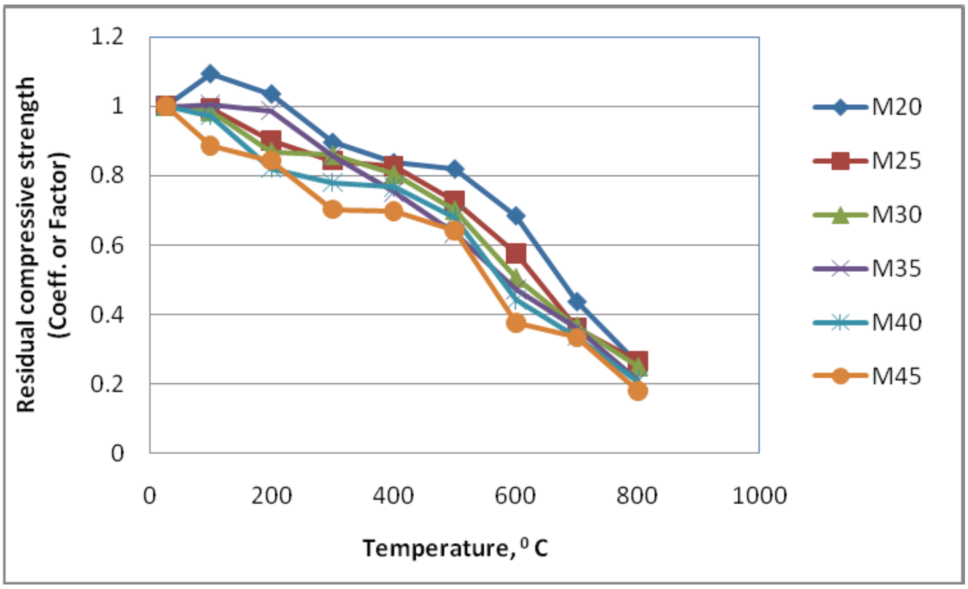


Figure 6. Compressive strength retention behaviour of 150mm concrete cubes subjected to elevated temperatures.

The current results agree well with those published in literature as shown in Figure 7.

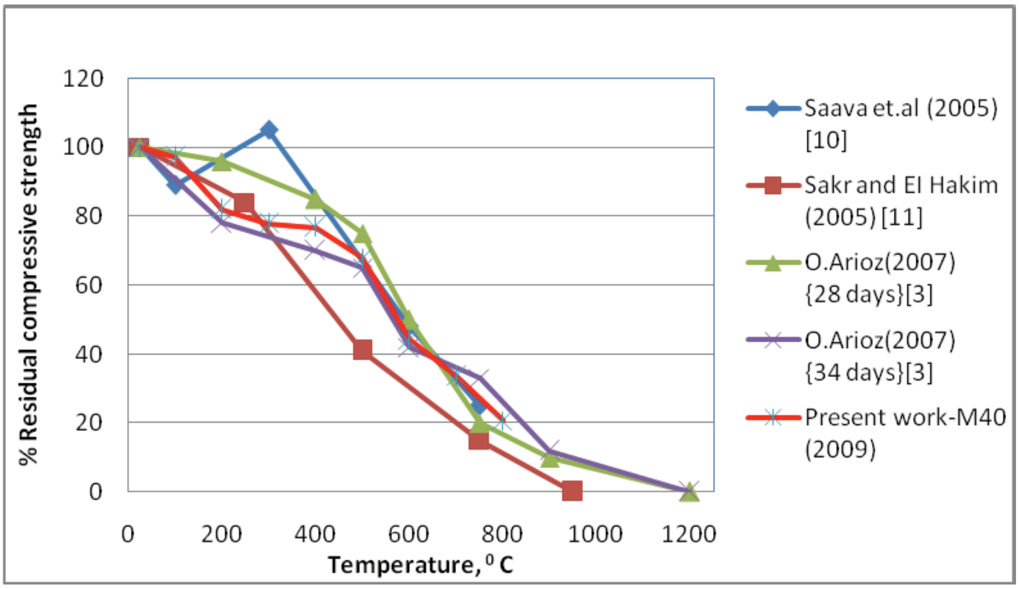


Figure 7. Residual compressive strength of M40 grade concrete exposed to elevated temperature for a retention period of 2hr and air cooled.

From Figure 8, (i) It appears up to 300^0C M35 grade of concrete demarcates the reduction in strength further it is observed that there is a orderly shift towards lower grades of concrete up to 600^0C, (ii) In temperature range of 400^0C to 600^0C decrease in % residual strength is observed with the increase in concrete grade, however in temperature range 700^0C and 800^0C this loss in % residual strength is not significant amongst different grades of concrete.

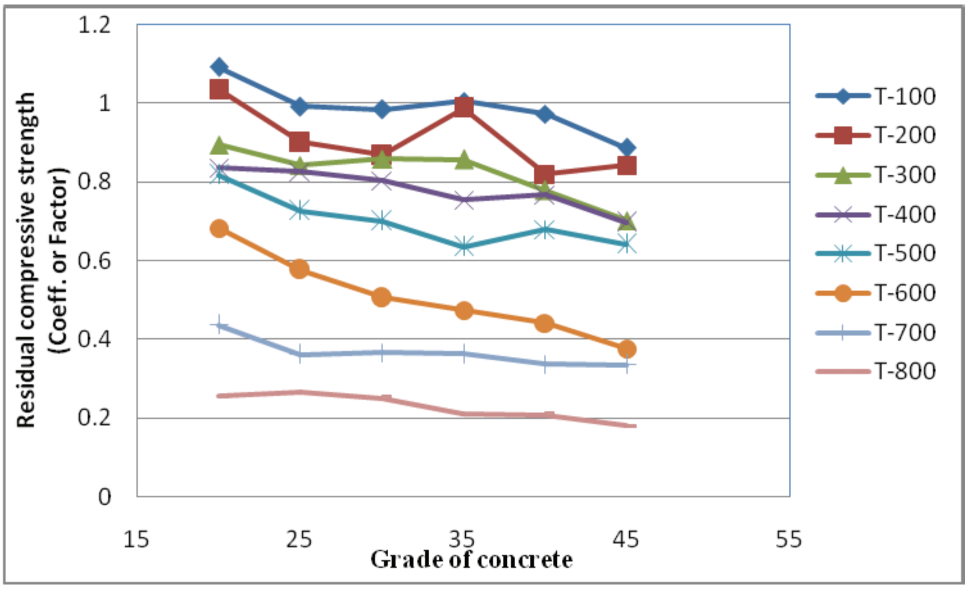


Figure 8. Graphical representation of variation in residual compressive strength with grade of concrete for various temperatures of exposure.

From Figure 9, it is observed that for all the grades of concrete, there is a decreasing trend in % residual strength with the increase in temperatures.

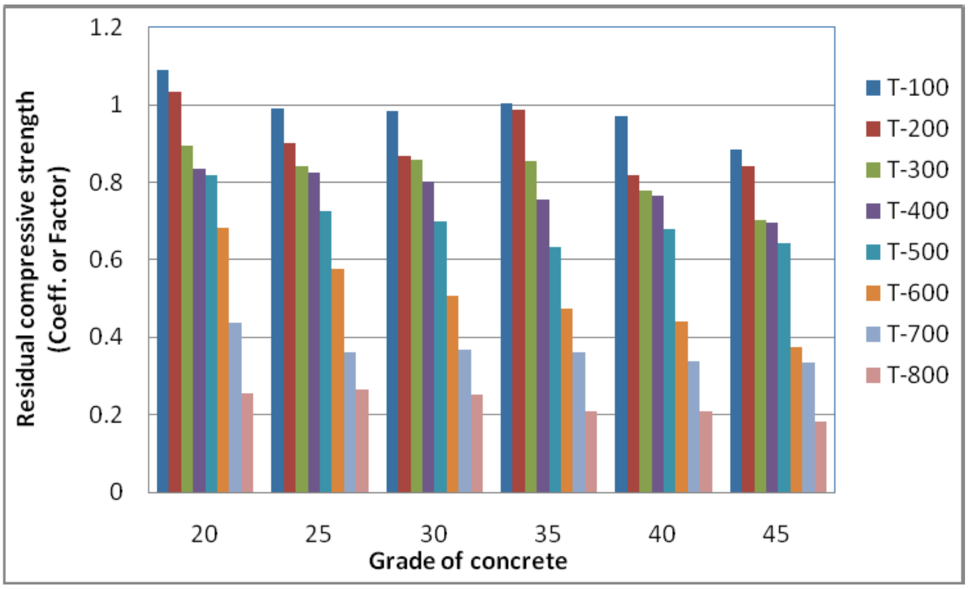


Figure 9. Bar chart representation for variation of residual compressive strength of 150mm cubes subjected to elevated temperatures of different grades.

3.4. Prediction Equations for Residual Compressive Strength Assessment

Data analysis was performed to propose equations for residual compressive strength assessment. The data analysis of all the grades reveled that, there is changeover of behavior from 600 ^{0}C. Therefore equations are proposed for temperature range of 100 to 500 ^{0}C and for the range of 600 to 800 ^{0}C. Figures 10 show the analysis for concrete grades M20, M30, M40 and for data of all grades, for the temperature range of 100 to 500 ^{0}C. Similarly figure 11, shows the analysis for concrete grades M20, M30, M40 and for data of all grades, for the temperature range of 600 to 800 ^{0}C.

In the LHS of the following proposed equations, Coeff. or Factor implies the percentage residual strength after exposure to elevated temperature and read as coefficient or factor, and to be reckoned as coefficient if less than 1 and factor if greater than 1.

Prediction equation proposed up to 500 ^{0}C

The following equation is proposed for residual compressive strength assessment from data of all the grades of concretes investigated. The error in prediction is limited to less than 3%.

$$\text{Coeff. or Factor} = [\,-\,0.0004 \times (\textit{Temp.}\ ^0\text{C}]^2 - 5.76373 \times 10^{-4} \times (\textit{Temp.}\ ^0\text{C}) + 1.028 \qquad (1)$$

Prediction equation proposed for 600 0C to 800 ^{0}C

The following equation is proposed for residual compressive strength assessment from data of all the grades of concretes investigated. The error in prediction is limited to less than 2%.

$$\text{Coeff. or Factor} = [\,-\,0.00055 \times (\textit{Temp.}\ ^0\text{C}]^2 - 18.36111 \times 10^{-4} \times (\textit{Temp.}\ ^0\text{C}) + 1.502 \qquad (2)$$

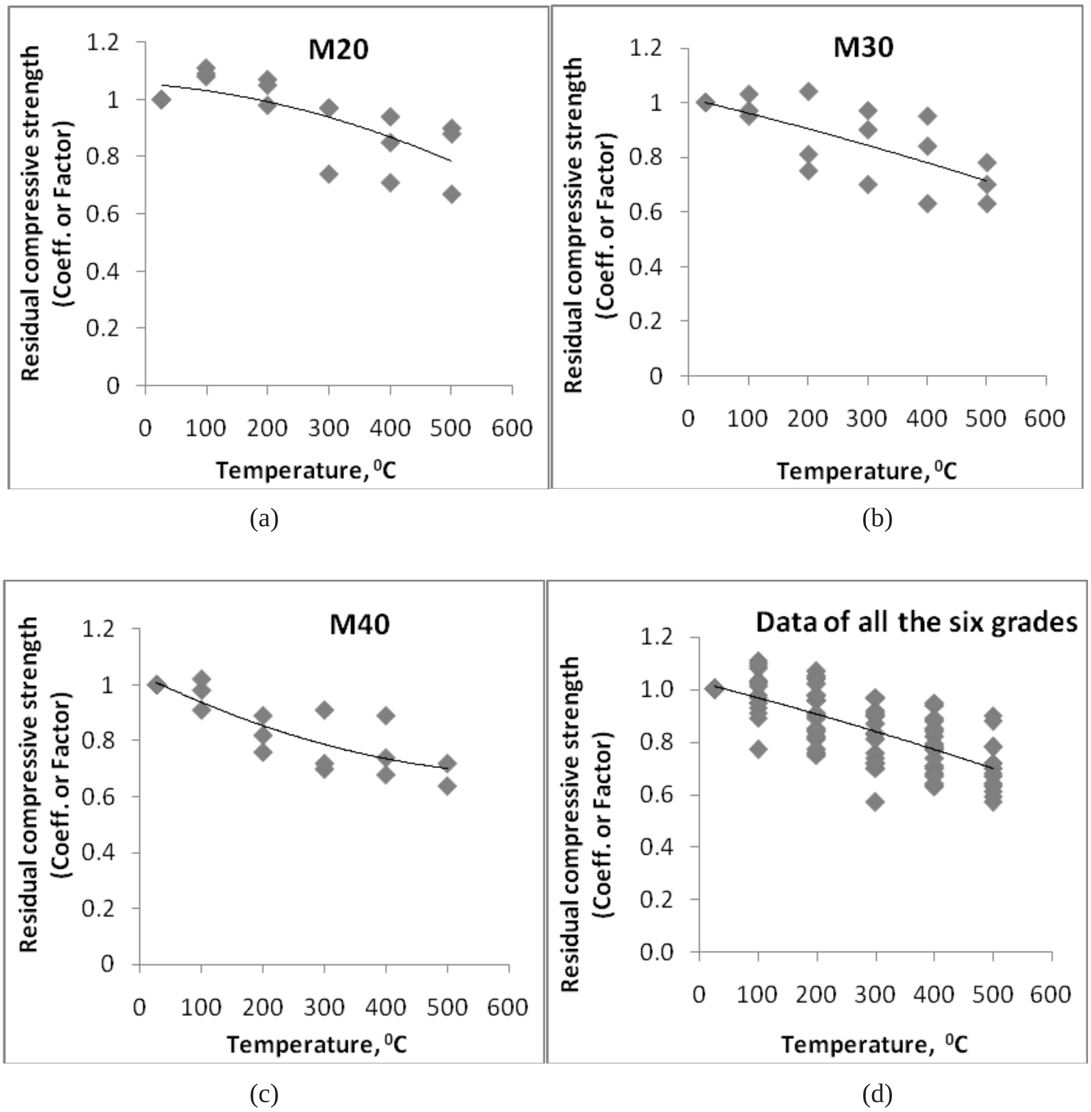
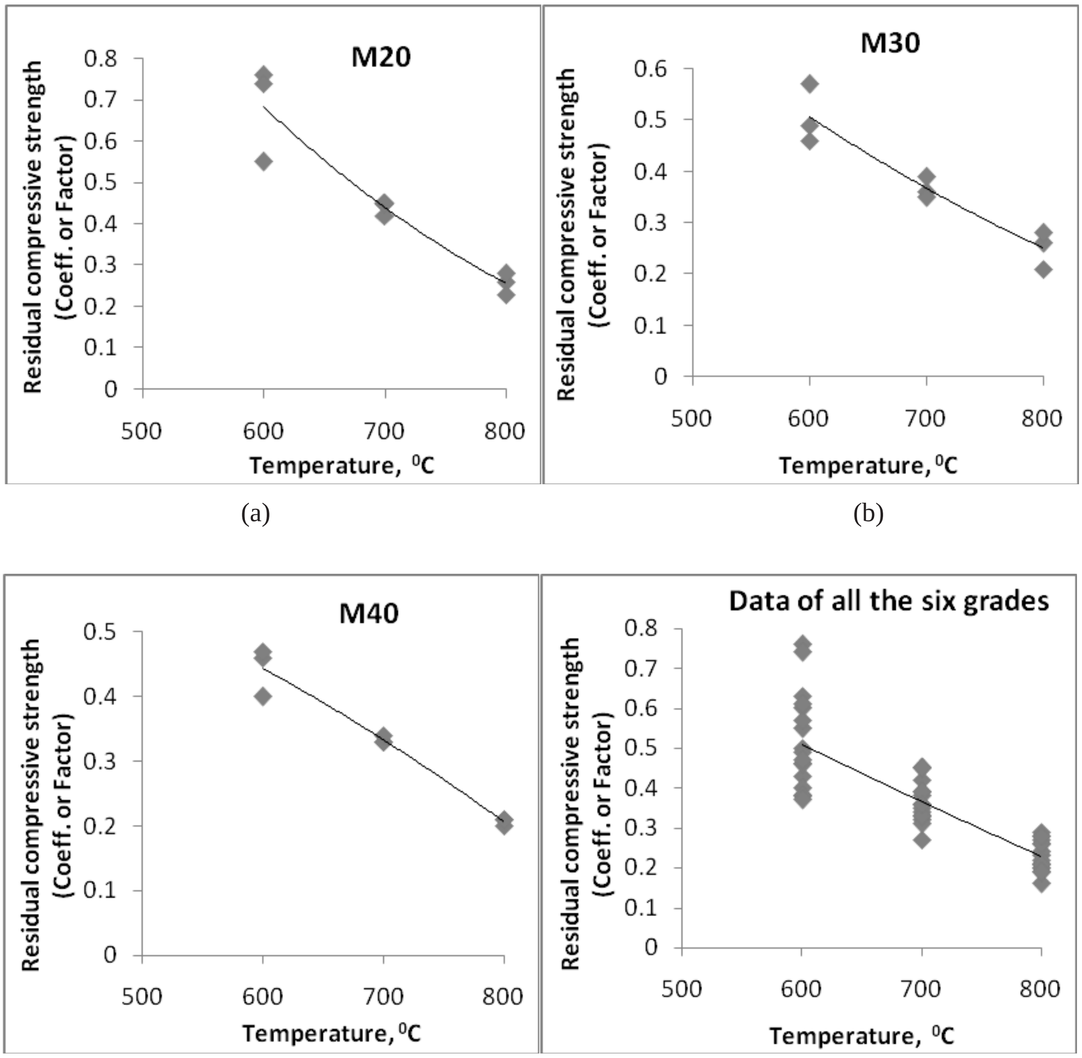


Figure 10. Data analysis of concrete grades M20, M30, M40 and data of all the six grades for temperature up to 500 ^{0}C.



(a) (b)

(c) (d)

Figure 11. Data analysis of concrete grades M20, M30, M40 and data of all the six grades for temperature range 600 ^{0}C to 800 ^{0}C.

4. CONCLUSIONS

(1) As the exposed temperature increases, loss in weight of specimen increases, above 200^{0}C.

(2) With increase in grade of concrete, there is a decrease in loss of weight of specimen after subjecting to elevated temperatures.

(3) In general there is substantial loss (74%) in strength from 100^{0}C to 800^{0}C for M20, M25 & M30. However for M35, M40 & M45, there is strength loss of 80%. The observed minimum residual strength is 18% for M45 at 800^{0}C.

(4) In temperature range 700^{0}C and 800^{0}C the loss in % residual strength is not significant amongst different grades of concrete, in other words the % loss in weight is independent of grade of concrete for these two temperatures.

(5) Residual compressive strength prediction equations are derived for normal strength concretes subjected to elevated temperatures up to 500^0C, and for the range of 600^0C to 800^0C.

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