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Effect of Heating on the Behaviour of Direct Shear Transfer in Self-Compacting Concrete

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Abstract: ***This laboratory research is concerned with the shear transfer behavior of self-compacted concrete SCC push-off specimens being exposed to high temperatures for one time or more. Two types of casting water are used, namely, tap water (drinkable) and raw water (undrinkable) which is brought from local wells, a situation which is currently under use in Iraq especially in large engineering facilities far from cities. Effect of heat exposure is also studied due to well-known unstable circumstances that Iraq faces. Twenty-four specimens are cast and some of them are exposed to different levels of heating. Later on after heating in an electrical furnace, specimens are cooled down by two ways, gradually, by leaving them to air for one day, and the fast way by gently putting in water. Testing of specimens is carried out by loading each one, using compression machine until failure. It is observed that using raw water in casting SCC (no heatexposure) leads to decrease in shear transfer strength and in vertical slip in addition to the decrement in compressive strength and tensile strengthin comparison with using potable water. It is also observed that heating and then rapid cooling cause tangible shear transfer strength,slip, compressive strength and tensile strength decrease especially when raw water is used for concrete casting.***

Keywords: direct shear, self-compacted concrete, push-off tests, heating, cyclic heating, way of cooling,type of water.

Notations

Ag	Gross section area in direct shear (the shear plane)
D	Vertical slip of the upper flange
$f'c$	Cylinder compressive strength (of plain concrete)
f_t	Tensile strength of concrete (indirect splitting test)
f_y	Yield strength of reinforcement steel bars
f_u	Ultimate strength of reinforcement steel bars
f_v	Shear stress in the shear plane
P	Shear force in the shear plane
SCC	Self-compacted concrete
SP	Super plasticizer
VC	Vibrated concrete
%↓	decrement percentage

1. Introduction

Although shear transfer strength is one of the most important characteristics of reinforced concrete structural members, the studies concerning shear transfer strength in SCCexposed to high temperature still are very limited. **Bryan Barragán et al. (2006)** used push-off specimens to analyze the shear behavior of normal- and high-strength steel fiber-reinforced concrete. The authors calculated the toughness-based parameters, for possible use in design. They concluded that important improvements in the ductility of concrete in shear failure and some increase in the shear strength are accomplished through the incorporation of steel fibers in normal- and high-strength concretes. **Anagnostopoulos et al. (2009)** studied the mechanical characteristics of different strength classes of SCC with different filler materials when exposed to elevated temperatures. One of their conclusions was that the SCC spall more compared to VC due to lower permeability and higher moisture content. **Hanaa Fares et al.(2009)**discussed the negative effect of heating exposure through a heat rate of 1 °C/min up to desired target temperatures of 150, 300, 450 and 600°Con the compressive strength, flexural strength, bulk modulus of elasticity, porosity and permeability in SCC. **Jin Tao et al.(2010)**investigated the passive effects of elevated temperatures up to 800°C on the compressive strength of normal strength SCC and high strength SCC. The authors found that grade of concrete has an effect on the strength loss of concrete, especially in the temperature range below 400°C. They also found that normal strength SCC has a less compressive strength than high strength SCC after heat exposure. **Pedro and Estefania(2010)** investigated the shear behavior in push-off specimens along the shear plane by means of crack opening and shear displacement versus shear load process. They observed that the failure occurrence is better controlled by the presence of fibers in addition to the fact that the shear failure was more ductile. **Anand and Arulraj(2014)**found from testing SCC beams of different grades that the loss of strength of lower grade SCC beams is less than that of the SCC beams of higher grades. They also found that the drop in compressive, tensile and flexural strength of the tested beams relies on type of heating and cooling conditions.

2. Materials and SCC Mix Proportions

2.1 Water

Two types of water are used in experimental work. The first one is potable water and the second is raw water brought from a local well. The raw water of the local well is approximately similar to that of tap water in terms of transparency and odour, see Table 1. It is clear from the chemical analysis the following indicators:

- Turbidity value is about six times more than permitted for drinking water.
- Total dissolved solids T.D.S. is six times more than permitted in drinking water.

Table 1.*Analysis of the used raw water*

Parameter Mg/l	*Water Type*		*Max. Permissible*
	Raw	Clean	
Turbidity NTU (Nephelometric Turbidity Unit)	30	-	5
pH (power of Hydrogen)	6.9	-	6.5-8.5
E.C. (Ms/cm) (Electrical Conductivity)	11457	-	/
T.D.S (Total Dissolved Solids)	6274	-	1000
Recommendation	Not for drink		

2.2 Cement

Iraqi national ordinary Portland cement produced in Tasloja according to the Iraqi standard specification **IQS No.5(1984)** is used throughout the research work. It is stored in a semi-dry place (Laboratory conditions) to avoid exposure to atmospheric conditions.The analyses of physical properties and chemical compositionsare shown in Table 2and Table 3 respectively.

Table 2: Physical properties of cement

Physical properties	Test results	Standard Specifications IQS 5/1984
Specific surface area (Blaine method), m^2/kg	495	≥230
Setting time (Vicate apparatus), Initial setting, h:min Final setting, h:min	 2:55 4:35	 ≥00:45 ≤10:00
Compressive strength, MPa 3 days 7days	 33.5 38.6	 ≥15 ≥23
Soundness (Autoclave) method, %	0.3	≤0.8

Table 3: Chemical compositions and main compounds of cement

Oxides composition	*Content %*	*Standard Specifications IQS 5/1984*
CaO	63.06	-
SiO_2	22.	-
Al_2O_3	6.25	-
Fe_2O_3	3.13	-
MgO	2.95	<5
SO_3	3.03	<2.8
L.O.I. loss onignition	3.33	<4
Insoluble residue	1.21	<1.5
Lime Saturation Factor L.S.F	0.88	0.66-1.02
Mineralogical Composition (Bogue's equations)		
C_3S	47.04	-
C_2S	28.11	-
C_3A	10.98	-
C_4AF	6.98	-

2.3 Fine Aggregates

Natural river aggregates are used. Characteristics are shown in Table 4. The sieve analysis of sand used throughout this work lies within the range defined by **ASTM C33-03 (2002)**, see figure 1.

Table 4: Chemical and physical tests results for sand

Properties	*Test results %*
Absorption	0.81
Specific gravity	2.32
Sulfate content (SO_3)	0.28

2.4 Coarse aggregates

Natural river gravel with a maximum aggregate size of 6mm is used. The grading obtained from the results of sieve analysis for the aggregate lies within the range defined by **ASTM C33-03 (2002)**, see figure 2.Chemical and physical properties for gravelareshown in Table 5.

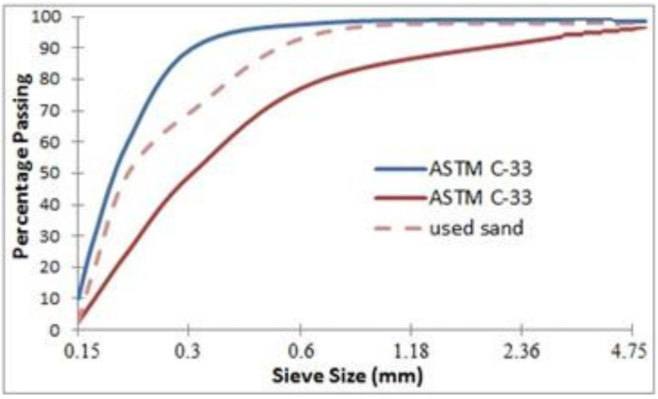

Figure 1: Grading of fineaggregate

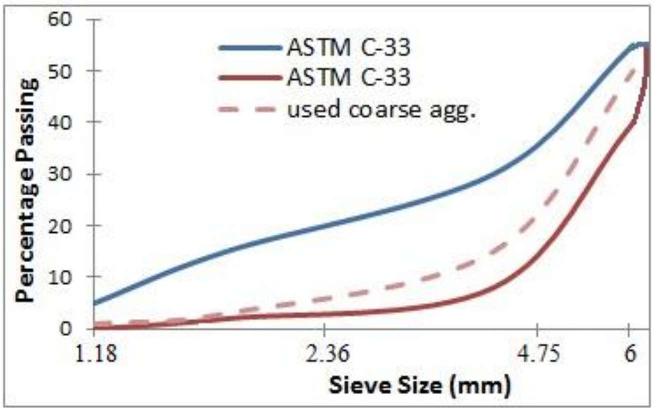

Figure 2: Grading of coarseaggregate

Table 5: Chemical and physical test results for gravel

Properties	*Test results %*
Absorption	0.61
Specific gravity	2.24
Sulfate content SO_3	0.06
Dry loose-unit weight kg/m^3	1496
Material finer than 75 μm	1.52

2.5 Reinforcing steel bars

Deformed steel bars of 4 and 6mm diameter are used. Table 6 shows the properties of these reinforcing bars.

Table 6: Properties of reinforcing steel bars

Nominal Diameter (mm)	Measured Diameter(mm)	Cross-section Area (mm^2)	f_y (MPa)	f_u (MPa)
4	4	12.566	557	835
6	5.840	26.786	672	765

2.6 Super Plasticizer

FlocreteSP42 is used in this work research to enable the water content of the concrete to perform more effectively, **FlattR. J. (2004)**. This effect is used to improve workability and to increase ultimate strength by the very high levels of water reduction in the concrete, (http://uct-dcp.com/index.php/products/rmc-precast-concrete).

2.7 Metakaolin

Metakaolin is usedbecause it is a highly pozzolanic and"reactive" material that improves most mechanical anddurability properties of concrete. Metakaolin reacts with the calcium hydroxide byproducts produced throughout cement hydration, **Ding, J. and Li, Z. (2002)**. Specific weight is 2.62 and the surface area is 19,000 cm^2/g, see Table 7.

Table 7: Properties of Metakaolin

Oxide	*% weight*	*ASTM C618-03*
SiO2	51.34	Not less than 70%
Al2O3	33.4	
Fe2O3	2.3	
Ca3O	-	-
MgO	0.17	-
SO3	0.15	Not more than 4%
L.O.I	7.8	Not more than 10

2.8 Concrete Mix Proportions

Aim of this study is not to get a job-mix formula but to study shear strength behavior in SCC casted with tap and raw water under different levels of heat. A specific mix is obtained after some trails, **Khayat(1999)**. The amounts used in every casting campaign (i.e. every four specimens in addition to 150mm x 150mmcubes and150mm x 300mmcylindersin order to measure $f'c$ and f_t of SCC mix before and after heating) are 950 kg/m^3cement, 1400kg/m^3fine aggregate, 1640kg/m^3 coarse aggregate, 170kg/m^3Metakaolin, 413 liter/m^3 water and 32.5 liter/m^3 SP. L-box, V-funnel and slump flow tests are conducted to insure mix abilities of filling and passing in addition to segregation resistance, see Plate 1and Table 8, **ASTM C1611&C1621 (2009)**.

Plate 1: Rheological parameters of the SCC

Table 8: SCC rheological parameters

Test	Results
Slump flow	700 mm
T_{50cm} Slump flow	4 sec.
V-Funnel	10 sec.
L-Box	26 mm (H_2/H_1)

3. Experimental Work

Twenty-four specimens divided into two groups of push-off specimens are cast in order to cover all conditions and parameters that are intended to be studied in this work, care for Table 9. All specimens having same dimensions which are 300mm x 140mm x 50mmcast in four.

Table 9: Specimens details

Group	*No. of Specimens*	*Water Type*	*Heating (^{o}C)*	*Specimen designation*	*Description*
A	4	Potable (tap)	-	A01&A02	tested without heating (reference)
			400	A400R	heating to 400^{o}C, rapid cooling
			400	A400G	heating to 400^{o}C, gradual cooling
	4		700	A700R	heating to 700^{o}C, rapid cooling
			700	A700G	heating to 700^{o}C, gradual cooling
			1000	A1000R	heating to 1000^{o}C, rapid cooling
			1000	A1000G	heating to 1000^{o}C, gradual cooling
	4		400+800	ACG-II	heating to 400^{o}C&800^{o}C, gradual cooling after each heating
			400+800	ACR-II	heating to 400^{o}C&800^{o}C, rapid cooling after each heating
			400+800+1000	ACG-III	heating to 400^{o}C, 800^{o}C&1000^{o}C, gradual cooling after each heating
			400+800+1000	ACR-III	heating to 400^{o}C, 800^{o}C&1000^{o}C, rapid cooling after each heating
B	4	Raw (well)	-	B01&B02	tested without heating (reference)
			400	B400R	heating to 400^{o}C, rapid cooling
			400	B400G	heating to 400^{o}C, gradual cooling
	4		700	B700R	heating to 700^{o}C, rapid cooling
			700	B700G	heating to 700^{o}C, gradual cooling
			1000	B1000R	heating to 1000^{o}C, rapid cooling
			1000	B1000G	heating to 1000^{o}C, gradual cooling
	4		400+800	BCG-II	heating to 400^{o}C&800^{o}C, gradual cooling after each heating
			400+800	BCR-II	heating to 400^{o}C&800^{o}C, rapid cooling after each heating
			400+800+1000	BCG-III	heating to 400^{o}C, 800^{o}C&1000^{o}C, gradual cooling after each heating
			400+800+1000	BCR-III	heating to 400^{o}C, 800^{o}C&1000^{o}C, rapid cooling after each heating

Steel forms fabricated especially for this work, see Plate 2andfigure 3. Reinforcing bars to prevent failure except direct shear transfer are provided. They are cut to the desired lengths, and 90-degree hooks are formed at each 6mm diameter deformed bar. Stirrups made from 4mm diameter deformed bars are provided, with a 6mm concrete cover.

Plate 2: Steel form with reinforcement

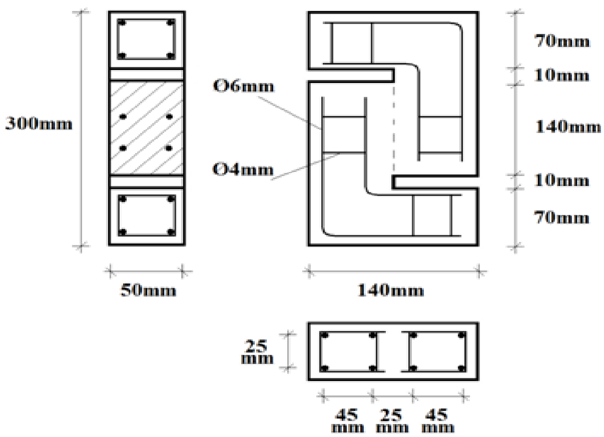

Figure 3: Push-off Specimen

Twenty specimens are heated slowly at a constant rate of 3^{o}C/min to avoid sudden rise in heat. Electrical high temperature furnace is used in this study in providing heat for specimens, see Plate 3. Heating time is kept 2 hours after reaching the required temperature for one time heating and 1 hour at each time when cycling heating. Later on after heating, specimens are cooled down by two ways, gradually, by leaving them in the air for one day, and the fast way by gently putting them in water. This is to reflect the case of fire extinguish process on integrity of concrete, see Plate 4 that shows the effect of sudden cooling on spalling phenomenon in concrete.

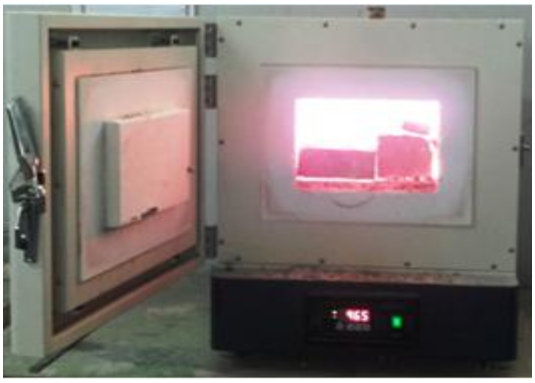

Plate 3: Used Electrical Furnace

Plate 4: Effect of rapid cooling

Load is applied on each specimen through one concentrated point on top of the specimen and all of them are tested till total failure. Small increments of load are applied to the specimen and slip is measured at each load increment. First cracking load and ultimate load are observed. Specimen own dead load is neglected here because dead load effects are negligible in comparison with the effects of concentrated failure loads. Testing of specimens is carried out by loading each specimen, using compression machine as shown in Plate 5.The maximum shear transfer stress f_v is obtained by dividing the applied shear transfer load P by the area of the shear transfer plane Ag (i.e. 140mm x 50mm = 7000 mm^2), **Wong et. Al. (2007)**.

Plate 5: ELE compression testing machines

It is worth to mention that heat cycling, refers to the process of heating – cooling – heating – cooling and the like. This type of cycles may have an actual ground in real life and the probability of fire is a great event, and happening once (or twice or even more) again in the same place in another time. Here, the four specimens from each group are heated to 400^{o}C, and after that, cooled then heated again to 800^{o}C and finally cooled, while two of them are heated additionally to 1000^{o}C then also cooled.

4. Effect of Heating

According to **ACI237R-07 (2007)** SCC is a brittle composite material that consists of binder (cement) paste in addition to sand and gravel. It is well-known that pastes of cement, sand and gravel have different thermal expansion coefficients. At a lower elevated temperature, the expansion due to heat of the paste of cement is a little greater than that of the sand and gravel. So, in the concrete matrix, the paste of cement is under hydrostatic compression, while the sand and gravel are under biaxial compression and tension. As the temperature further increases, the thermal strain of the paste of cement changes to negative (shrinking) due to chemical changes, while the aggregate continues to expand. The concrete corresponding stresses are that, the sand and gravel are under hydrostatic compression and the cement paste is under biaxial compression and tension. Also, the development of micro-cracks increases beyond 300°C and firstly occurs around calcium hydroxide $Ca(OH)_2$ crystals, and partial volatilization of calcium silicate hydrate gel commenced at about 500°C. The pore size and porosity of the hydrate matrix will increase, and the mechanical properties (compressive strength and modulus of rupture) of the hydrates will be weakened, **Piasta and Rudzinski(1984).**

For specimens of group A, see Plate 6, direct shear stress $f_v$is affected negatively by the heat as shown by the results of Table 10.

Plate 6: Specimens of Group A

Table 10: Results of group A

Specimen	Before heating	After heating except specimens A01&A02							
	$f'c$ (MPa)	$f'c$ (MPa)	%↓ $f'c$	f_t (MPa)	%↓ f_t	Δ (mm)	%↓ Δ	f_v (MPa)	%↓ f_v
A01&A02 (ref.)	41.9	41.9	-	4.3	-	0.084	-	6.28	-
A400G		38.4	8.3%	3.37	21.6%	0.075	10.7%	5.48	12.7%
A400R		37.3	10.9%	3.27	23.9%	0.073	13.1%	5.17	17.7%
A700G	40.8	21.85	46.4%	1.68	60.9%	0.051	39.3%	2.57	59.1%
A700R		19.53	52.1%	1.46	65.8%	0.047	45.2%	2.24	64.3%
A1000G		-	-	-	-	-	-	-	-
A1000R		-	-	-	-	-	-	-	-
ACG-II	40.76	14.57	65.2%	1.02	76.2%	0.040	52.4%	2.02	67.8%
ACR-II		11.08	73.5%	0.79	81.6%	0.036	57.1%	1.64	73.9%
ACG-III		-	-	-	-	-	-	-	-
ACR-III		-	-	-	-	-	-	-	-

It can be observed the following:

- Two hours of 400°C heat causes f_v decrease about (12.7% & 17.7%) for gradual and rapid cooling respectively, i.e. rapid cooling leads to f_v decrease about (5%).
- Two hours of 700°C heat causes f_v decrease about (59% &63%) for gradual and rapid cooling respectively, i.e. rapid cooling leads to f_v decrease about (4%).
- Heat cycling for one hour at each time to 400°C and then to 800°C causes f_v decrease about (67.8% &73.8%), i.e. rapid cooling leads to f_v decrease about (6%).

Plate 7 and Table 11 show the effect of heating on $f_v$in specimens of group B.

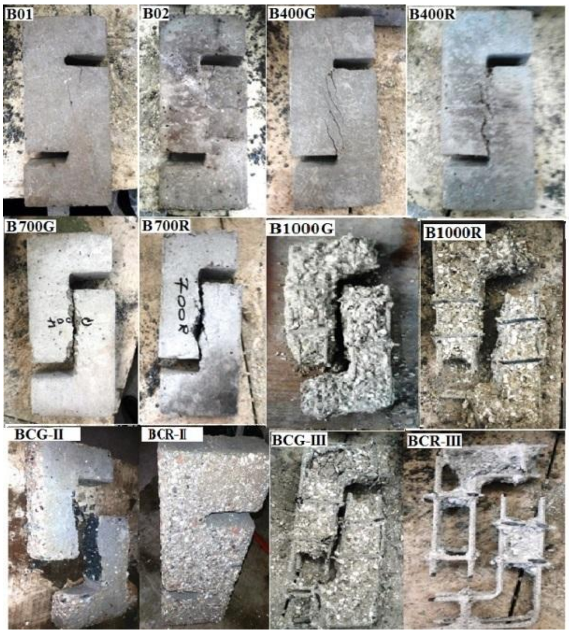

Plate 7: *Specimens of Group B*

Table 11: Results of group B

Specimen	Before heating	After heating except specimens B01&B02							
	$f'c$ (MPa)	$f'c$ (MPa)	%↓ f'c	f_t (MPa)	%↓ f_t	Δ (mm)	%↓ Δ	f_v (MPa)	%↓ f_v
B01&B02 (ref.)	36.94	36.94	-	4.03	-	0.064	-	5.36	-
B400G		33.40	9.6%	3.1	23.2%	0.056	12.5%	4.61	14%
B400R		30.28	18%	3	25.5%	0.054	15.6%	4.32	19.4%
B700G	36.07	18.07	50%	1.46	63.8%	0.036	43.7%	2.01	62.5%
B700R		16.92	53.1%	1.3	67.7%	0.033	48.4%	1.7	68.3%
B1000G		-	-	-	-	-	-	-	-
B1000R		-	-	-	-	-	-	-	-
BCG-II	37.03	10.48	71.7%	0.88	78.2%	0.027	57.8%	1.41	73.7%
BCR-II		8.97	75.8%	0.63	84.4%	0.025	62%	1.1	80.5%
BCG-III		-	-	-	-	-	-	-	-
BCR-III		-	-	-	-	-	-	-	-

From which it is clear that:

- Two hours of 400°C heat causes f_v decrease about (14% &19.4%) for gradual and rapid cooling respectively, i.e. rapid cooling leads to f_v decrease about (5.4%).
- Two hours of 700°C heat causes f_v decrease about (62.5% &68.3%) for gradual and rapid cooling respectively, i.e. rapid cooling leads to f_v about (5.8%).
- Heat cycling for one hour at each time to 400°C and then to 800°C causes f_v decrease about (73.7% &80.5%), i.e. rapid cooling leads to f_v decrease about (6.8%).

It is observed that heating and then rapid cooling cause tangible shear transfer strength especially when raw water is used for concrete casting, see figure 4.

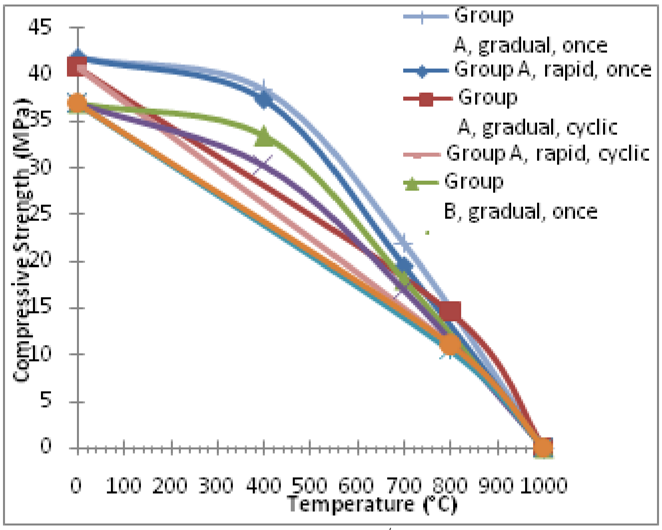

Figure 4: Effect of heating on f'c for specimens of Group A and Group B

The decrement of D is relatively small. In all heating cases, it is noticeable that the f_v-D behaviour of the specimens subjected to heat is similar to that of theones did notsubjected to heat but with sudden and lower values as shown in figure 5for group A and group B respectively. It is also noticeable that the behavior of $f'c$ and f_v are more similar than f_t.

5. Behavior of Shear Transfer Tests Specimens

In all cases, cracks along or parallel the shear plane took place at lower loads, these cracks are gone together with few and short diagonal tension cracks, with further loading, these cracks spread to form continuous cracks along the shear plane.The cracks were formed at an angle of about (18-21) degree to the shear plane, they were about (25-35) mm long and the width of cracked region was (10-25) mm. In addition, a small amount of concrete compression spalling occurred near to the shear plane crack in most specimens.

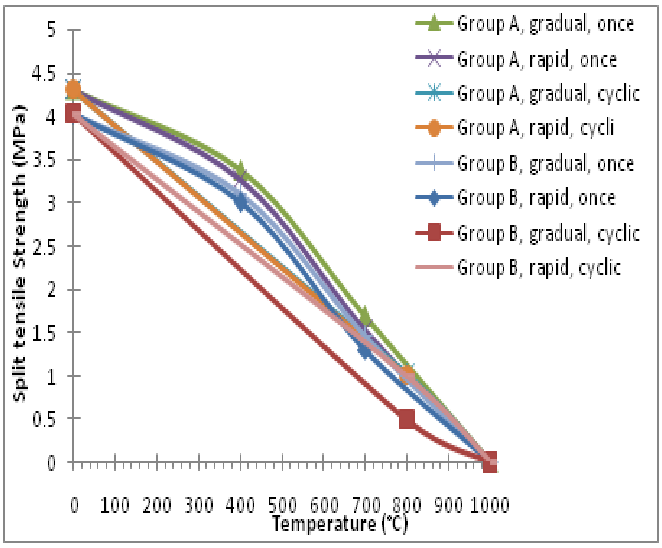

Figure 5: Effect of heating on f_t for specimens of Group A and Group B

It could be said, the existence of some thermal cracks parallel and across the shear plane due to heating process, led to form some longitudinal shear cracks along the shear plane after loading instead of one continuous crack. It was obvious that the specimens subjected to heat (specially that cooled down rapidly) spall more compared to specimens did not subjected to heat.

In general, it is noticed that specimens subjected to high level of heat showed brittle failure with no warning before failure, while specimens that did not exposed to heat started first several small diagonal cracks that later were joined together, so the specimens failed in less brittle manner. In more details, specimens subjected to heat exhibited the formation of the first diagonal tension crack at about (92%) while the specimens did not subjected to heat at about (73%) of the ultimate shear strength. These cracks are discrete with short length, spaced closely and have passed over the surface of the aggregateat the direct shear plane of the specimen.

6. Conclusions

From the results of this study, decisive decisions could be made concerning the SCC structures like the possibility of repairing orloads re-evaluating or even removing after heat exposure. The conclusions are:

1) Experimental results obtained, when tap water is used, show that rate of decrease instrength properties is proportional to the temperature rise. Heating to 400^{o}Chas decreased $f'c$ by 11%, f_t by 24%, D by 13% and f_v by 18% while heating to 700^{o}C has decreased $f'c$ by 52%, f_t by 66%, D by 45% and f_v by 64%. It is observed that there is a direct correlation between $f'c$ and f_v with temperature. In addition, subjecting SCC to high level of heat showed brittle failure with no warning before failure. Finally, it is worth to mention that heating to 1000^{o}C led to specimens crush.
2) Laboratory results reveal that cyclic heating may cause the SCC to become malfunctioned. The strength properties have decreased in a noticeable way. It is observed that the majority drop in strength properties takes place in the first heating process more than the second one. Cyclic heating has decreased $f'c$by 76%, f_t by 84%, D by 62% and f_v by 80%. It is also observed that cyclic heating to 400^{o}C, then to 800^{o}C and finally to1000^{o}C led to specimens crush.
3) In using raw water, the effect of temperature is noticed to be greater in decreasing the strength properties of SCC. Replacing tap water with raw one and heating to 400^{o}Chas made additional decrement in $f'c$ by 11% and heating to 700^{o}C has increased the decrement in f_t by 3% while cyclic heating to 400^{o}Cthen to 800^{o}Chas additionally decreased D by 3%and f_v by 6%.
4) In general, the rapid cooling leads to an additional decrease in strength properties than the gradual cooling. Laboratory results show a decrease of 8% in $f'c$, 6% in f_t,5% in D and 7% in f_v after cyclic heating and cooling at 400 and then to 800^{o}C.

7. Acknowledgment

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