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THERMAL ENDURANCE OF HIGH STRENGTH FIBER REINFORCED CONCRETE

التحمل الحرارى للخرسانة عالية المقاومة المسلحة بالألياف

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الملخص العربى

تم اجراء استقصاء تجريبى لتحديد الخصائص الحرارية للخرسانة عالية المقاومة والمسلحة بألياف البولى بروبلين بنسب مختلفة. والدراسة تشمل تأثير درجات الحرارة المرتفعة لفترات طويلة على المقاومة والموصلية الحرارية. ومن المعروف أن تقليل نسبة الماء إلى الأسمنت يؤدى إلى تقليل مسامية الخرسانة ورفع المقاومة ويؤدى إلى تغيير البنية الداخلية للخرسانة عالية المقاومة بمقارنتها بالخرسانة عادية المقاومة وبالتالى يؤثر على المعاملات الحرارية. وحيث أن خصائص الركام الكبير الحرارية أكثر تأثيراً على المعاملات الحرارية للخرسانة العادية، فقد تم استخدام الزلط الطبيعى وكسر الحجر الجيرى وسن البازلت والجرانيت فى الخلطات الخرسانية. تم قياس الموصلية الحرارية للخرسانة باستخدام عينات تم تصميمها خصيصاً لهذا الغرض. وقد تم اجراء دراسة مقارنة مع الخرسانة عادية المقاومة لعينات جافة ومبتلة وقد خلصت الدراسة الى ضرورة تحديد هذه المعاملات حسب نوعية الخرسانة المستخدمة فى تطبيقات التحليل والعزل الحرارى.

ABSTRACT

Thermal properties of high strength concrete specimens containig different contents of polypropylene fibers are experimentally investigated. The specimens were subjected to elongated period of high temperature, and thermal conductivity was measured. Reducing the water to cement ratio helps in reducing the concrete porosity and increasing the strength and results in different internal structure for high strength concrete compared with ordinary concrete and therefore influence the thermal parameters. Normally, properties of coarse aggregates tend to govern the overall thermal properties of ordinary concrete. Thus natural gravel, basalt, granite and dolomitic limestone are employed in the experimental program. Thermal conductivity is measured for specially designed specimens. A comparison is carried out with the corresponding results of ordinary concrete for dry and fully saturated samples. The findings indicate some major differences in the thermal features, which should be addressed in thermal analysis and insulation problems.

KEYWORDS: *Fiber reinforced concrete, high strength concrete, polypropylene fibers, thermal endurance, thermal conductivity.*

INTRODUCTION

There is an eminent trend in using fiber reinforced concrete (FRC) in many structural applications because of the advantages of enhancing the ductility especially for members subjected to fatigue or seismic effects [1, 3]. Because of corrosion problems and availability in the local market, polypropylene fibers attracted more people in concrete technology rather than steel fibers [10]. The privileges of fibers become more appealing when used with high strength concrete, which exhibits brittle modes of failure in compression and shear [3]. Definition of high strength

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concrete (HSC) is still arbitrary in the literature [2]. Neville and Brooks [5] gave the view point of yielding compressive strength in the range of 60~100 MPa for HSC.

Many investigators handled the durability problems of HSC such as resistance to sulfate attack [11, 12] but, unfortunately, the thermal problems and fire resistance did not receive the same degree of concern [8, 10, 12]. The fundamental water to cement ratio in the range of 0.26-0.30 is actually required for the hydration process of high strength concrete. With special mix design and concreting the least porosity is achieved [5]. To satisfy workability and compatibility demands, super Plasticizers are utilized. These water-reducing admixtures are produced from ligno-sulfonate or hydroxycarboxylic acids and carbohydrates. Previous studies by the first author and coworkers [7, 8, 10] showed considerable reduction in strength of ordinary concrete with super Plasticizers when subjected to cycles of wetting and drying and to long period of high temperatures. Moreover, HSC is usually produced with relatively high cement content leading to aggrandized CSH gel (calcium silicate hydrate) formation, which is more susceptible to dimensional changes upon application of thermal effects. In addition the influence of fiber inclusion in the concrete mix of HSC, which is added to impose more ductility may be substantial on the thermal characteristics of concrete. However, thermal stability of HSC has not, in general, been completely explored yet. The aim of this study is to shade some light on the behavioral aspects of FRC as related to thermal changes. This has significance in concrete used for cooling towers in nuclear plants, chimneys, and other uses for burners and thermal insulators made of high strength concrete [6, 10].

The sometimes-brittle behavior of high performance concrete under fire conditions may inhibit their structural use. Khalifa et al. [4] demonstrated that spalling may take place under certain thermal and mechanical stresses and that the integrity of the structural element or the structure itself may be jeopardized. Spalling results from two concomitant processes: the so-called thermo mechanical process, associated with thermal dilation/shrinkage gradients that occur within the element when being heated [8], and the thermohydral process that generates high-pressure fields of gas (water vapor and enclosed air) in the porous network. According to Bilodueau et al. [3] the thermal process is controlled among several parameters by permeability. The permeability of high performance concrete, being much lower than that of ordinary concrete and with the pressure built up with temperature, cannot be reduced [8]. Thermal conductivity of concrete is the ability of the materials to conduct the heat .This is defined as "Ratio of the flow of heat to the temperature gradient". It is measured in joules per second per square meter of area of body when the temperature difference is 1° c per meter of thickness of body [9].

Thermal properties of coarse aggregates have a decisive influence on the corresponding features of ordinary concrete [5]. As a matter of fact, this is attributable to the large volume fraction of coarse aggregates and therefore thermal conductivity is affected as such. In this study, samples of HSC are cast using different types of local coarse aggregates such as natural gravel, dolomite limestone, basalt and granite. Thermal endurance at elevated temperatures and thermal conductivity of both dry and wet states are investigated for three fiber contents. A comparison against ordinary and high strength concretes is carried out.

EXPERIMENTAL PROGRAM

Three groups of batches were cast using mix proportions of cement content of 500 Kg/m^3, natural siliceous sand of 550 Kg/m^3, coarse aggregates of 1060 Kg/m^3, and superplasticizers dose of 1.5% of cement weight. These groups were categorized as follows:

- ***Group I:*** ordinary concrete (OC) with water to cement ratio of 0.5 without admixture.
- ***Group II:*** high strength concrete (HSC) with water to cement (W/C) ratio of 0.25 with admixture.
- ***Group III:*** high strength fiber reinforced concrete (HFRC) similar to group II but with polypropylene volumetric fiber content of 0.5%, 1%, 1.5% (HFRC-0.5%, HFRC - 1.0%, HFRC -1.5%). Fibers of 30.0 mm length of random orientation were added.

Samples were mixed using typical type I ordinary Portland cement of fineness corresponding to specific surface area of 275000 mm^2/gm and natural sand of medium size with fineness modulus of 2.35. Four types of coarse aggregates of maximum nominal size of 12mm were used which were designated as G for gravel, B for basalt, D for dolomite and R for granite. Gradation of both the coarse aggregates and the mixed aggregates were found between the well-gradation limits. All aggregates were prepared such that particles be free from dust and fines in order to reduce the unnecessary water demand. Batches with dolomitic crushed lime stones then granite showed, in order, the least degree of workability while natural round smooth gravels then basalt produced the highest level of flow ability. All specimens were mechanically mixed cast on 100 x 100 x 100 mm cubes and thoroughly compacted using an electrical vibrating table. For HSC compaction had been kept continuous until excess water came to the surface. For group III minimum of 5 minutes additional mix time were allowed at the same mixing speed. This additional time was found not to be detrimental to the fibers. Although stiffer slump initially appeared, no more water was added to compensate for workability.

Table (1) summarizes the compressive strength results of the crushing test carried out on 100 mm concrete cubes. The results indicated that reduction of W/C ratio to half of its value allowed obtaining HSC as long as perfect compaction was maintained. Explosive failure was observed for almost all HSC samples except those made with gravel. This was due to the strong interlocking of angular texture of coarse aggregates of dolomite, basalt and granite and then breakage of the aggregate particles. It was observed that fiber inclusion reduced the compressive strength but provided less brittle failure mechanism.

Table (1) Compressive strength of OC, HSC and HFRC, Mpa

Coarse Aggregate	Concrete Group				
	OC	HSC	HFRC-0.5%	HFRC-1.0%	HFRC-1.5%
Gravel	32	75	68	63	58
Basalt	36	83	81	77	76
Dolomite	37	86	85	85	83
Granite	41	95	87	81	74

LONG PERIOD EXPOSURE TO HIGH TEMPERATURES

Apart from the direct exposure to the flaring flames, behavior under elongated period of high temperatures resembles in many aspects exposure to fire. All samples were subjected to different temperatures for 30 hrs. At the early stages, full evaporation of internal humidity took place and slight increase in the compressive strength was recorded as illustrated in Fig. 1. HFRC samples yielded the highest strength gain while OC was the least. With continuous increase in temperature strength declination was noted with maximum rate for HFRC while the reverse happened to OC. It is worth mentioning that existence of fibers had beneficial effect on crack bridging at low levels of temperature. On the other hand, fiber stability commenced to be vitiated at higher temperatures and consequently compressive strength dropped considerably.

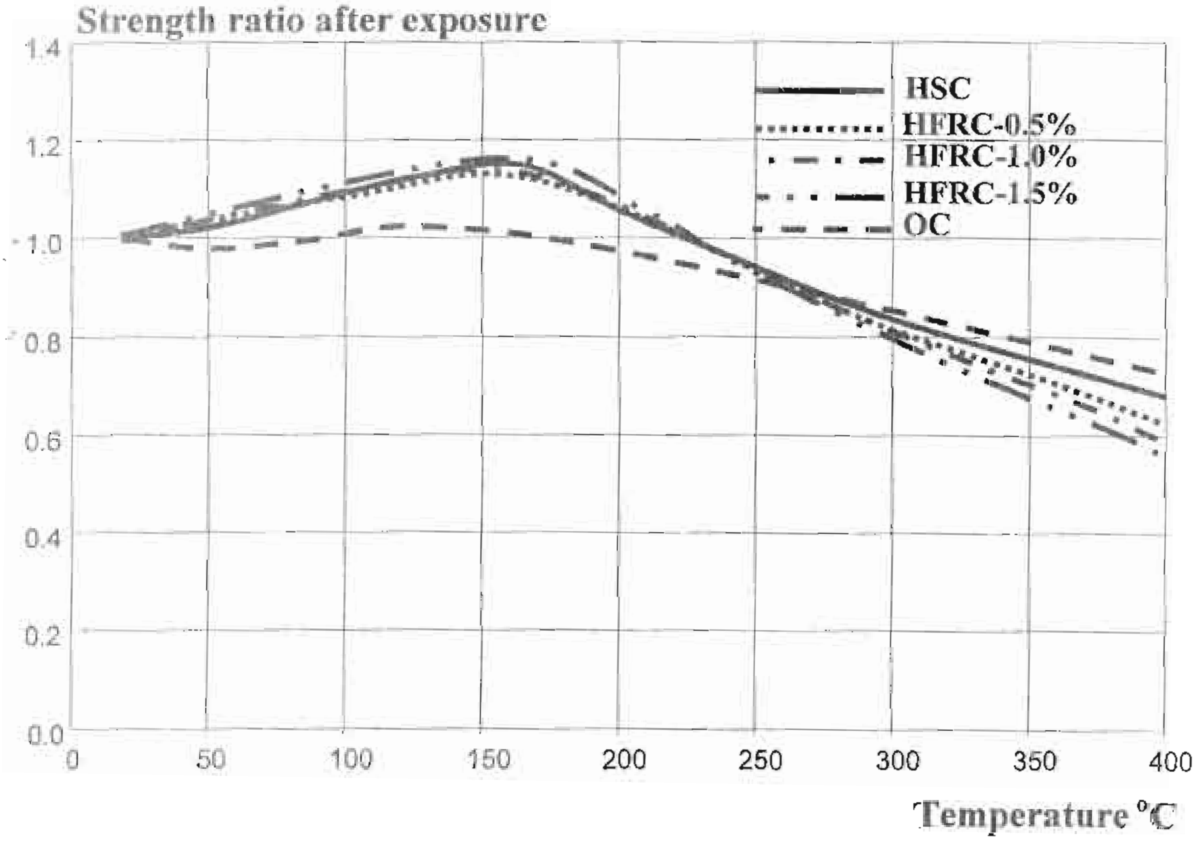


Fig. (1) Effect of elevated temperatures on the strength of OC, HSC, and HFRC

Although the observations so far pertain to concrete cubes cast in the lab, non-massive real structural members of different dimensions are anticipated to exhibit similar trend. In general, concrete strength can be expressed as a function of maturity that describes the temperature-time product as inferred from Fig. (1). This means that concrete subjected to relatively long period of elevated temperature over a particular margin would certainly degrade at higher rate than that exposed for short duration.

Also, the compressive strength is affected by the temperature range, at which the exposure is specified. In other words exposure to very high temperature for a short period may, therefore, be mathematically equivalent to relatively lower temperature for a longer period and mechanically they may both have nearly the same effect on strength. The strength declination takes place when the temperature times the time product (representing cumulative heat) exceeds a threshold limit that may be evaluated to each particular sort of concrete.

THERMAL CONDUCTIVITY

Hollow concrete samples of the three groups were cast to measure the thermal conductivity. The experimental setup is illustrated in Fig. 2 where an electrical coil may be inserted inside each cylinder with special precautions to eliminate energy loss at the ends. When AC current flows in the circuit, a Watt-meter reads the heat, Q, of the system. Having measured the heat, the inner and outer temperatures, φ_i and φ_o, of the hollow cylindrical samples of length L and inner and outer radii r_i and r_o, respectively, at the steady state condition, the thermal conductivity κ can be calculated from the following equations [6, 8, 10]

One-dimensional fin

The differential equation describing the heat flow through one-dimensional fin can be expressed in the following form

$$\kappa A \frac{d^2\varphi}{dx^2} - hP\varphi + hP\varphi_f = 0 \qquad (1)$$

where κ is the thermal conductivity, h is the convection coefficient, A is the cross-sectional area, P is the distance around the fin, φ is the temperature and φ_f is the temperature.

With boundary conditions
i. For specified temperature

$$\varphi(o) = \varphi_o \quad \text{at} \quad x = 0 \qquad (2)$$

where x is the and φ_o is the temperature.
and
ii. For convection heat loss at the free end

$$-\kappa A \frac{d\varphi}{dx} = hA(\varphi_b - \varphi_f) \text{ at } x = h \qquad (3)$$

On the other hand, the heat transfer problem for composite walls may be expressed as follows

Composite walls

The differential equation describing the heat flow through one-dimensional fin can be expressed in the following form

$$\kappa A \frac{d^2\varphi}{dx^2} = 0 \qquad (4)$$

The convection boundary conditions are

$$\kappa A \frac{d\varphi}{dx} = hA(\varphi_b - \varphi_f) \text{ at } x = 0 \qquad (5)$$

and

$$-\kappa A\frac{d\varphi}{dx} = hA(\varphi_b - \varphi_f) \text{ at } x = h \qquad (6)$$

where φ_h is the temperature.
The heat transfer coefficient or thermal resistance represents one of the most important characteristics describing the thermal properties of exterior walls or exposed roofs in buildings.

For the system shown in Fig. 2, the overall heat transfer coefficient U is inversely proportional to the sum of the resistance of heat transfer of the wall in addition to that of its inner, outer sides R_w, R_i and R_o, respectively. This relation is usually expressed in the following form

$$U = \frac{1}{\sum R} \qquad (7)$$

$$R = R_i + R_w + R_o \qquad (8)$$

$$R_o = \frac{t}{K} \qquad (9)$$

where U is the overall heat transfer coefficient, R is the sum of the resistance of heat transfer of the wall, R_i is the resistance of heat transfer of the inner side of wall, R_w is the resistance of heat transfer of the wall, and R_o is the resistance of heat transfer of the outer side of wall.
t is thickness, and K is heat transfer coefficient of the wall.

The values of the heat transfer coefficients of inner and outer sides of the wall are 0.125 and 0.043 m^2 °K/W, respectively (5). Therefore, the heat transfer Q from the outer to inner side of the wall can be expressed as

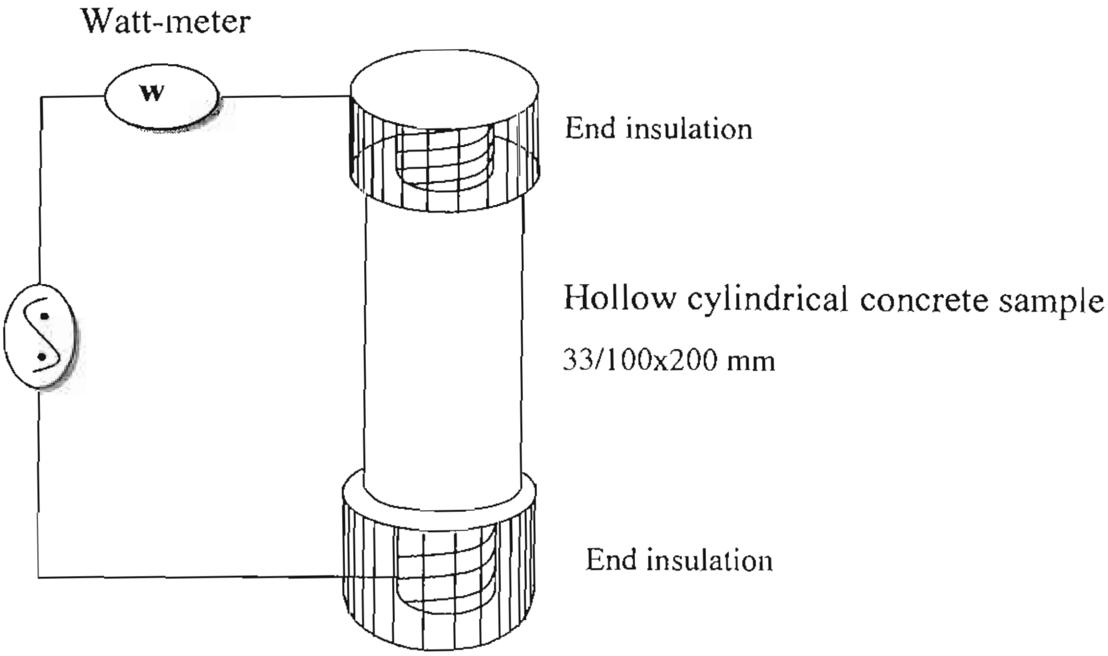
$$Q = UA(\varphi_o - \varphi_i) \qquad (10)$$

where Q is the heat.
The previous equation shows that the heat transfer decreases with the decrease of the overall heat transfer coefficient

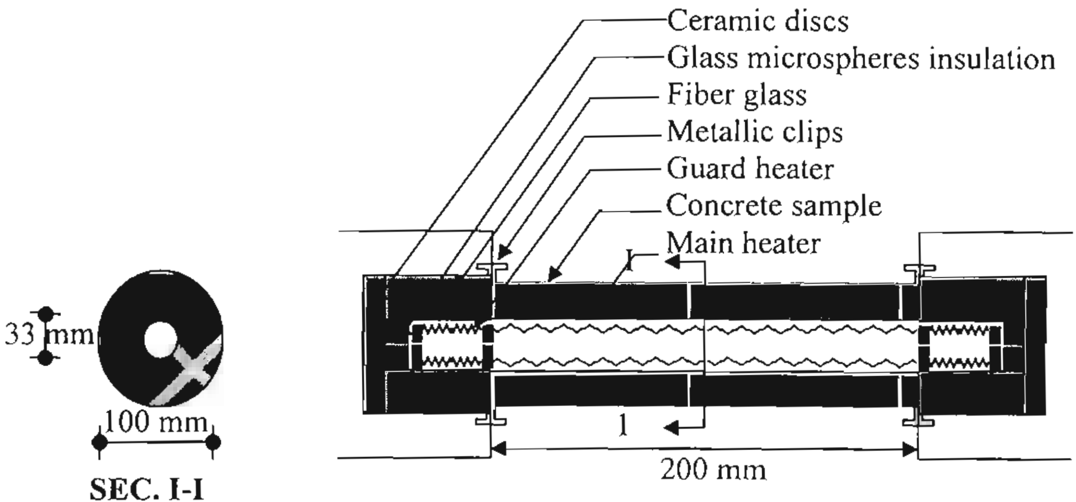
The governing differential equations for the steady-state heat transfer problems are given by simple mathematical manipulation of Fourier equation for heat transfer.
in the following forms:

$$Q = \frac{2\pi KL(\varphi_i - \varphi_o)}{Ln(r_o/r_i)} = 0 \qquad (11)$$

The final expression is utilized in the thermal analysis for evaluating the thermal conductivity of the experimental apparatus.



(a) Perspective Illustration



SEC. I-I
Concrete Specimen

Longitudinal Section

(b) Sectional Description

Fig. (2) Schematic Diagram of Conductivity Measurement Test Set-up.

Table (2) summarizes the test results. The thermal conductivity of HSC was found to be higher than that of HFRC and OC's was the least. This was due to the less porosity and therefore less air voids in HSC. In all cases wet samples showed higher conductivity than the corresponding in the dry state. The conductivity was observed to be highly influenced by the type of aggregates. Granite and gravel aggregates led to the highest conductivity while the opposite occurred to dolomitic limestone. The estimated conductivities were found belong to the usual domain for concrete in the range of 0.8~1.7 Jm /m^{2}S ^{o}C and as expected is higher than the reported values for lightweight concrete cast with expanded calyey aggregates [5].

CONCLUSIONS

Thermal properties of high strength concrete with and without polypropylene fibers differ significantly from ordinary concrete. The type of coarse aggregate and fiber content affect the strength as well as the thermal parameters. Samples exposed to long period of elevated temperature showed a certain strength gain for a certain margin of temperature then degrade drastically that higher rates of heat. Increasing the polypropylene fiber content induces more strength loss at higher temperatures and reduction of thermal conductivity as well. A mutual correlation may be established between the strength change versus the maturity which is the cumulative temperature-time product. Drying and wetting states influence the values of thermal conductivity of concrete.

Table (2) Thermal conductivity of OC, HSC and HFRC, Jm /m^{2}S ^{o}C

	Concrete Group									
	OC		HSC		HFRC-0.5%		HFRC-1.0%		HFRC-1.5%	
	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
Gravel	1.24	1.08	1.25	1.15	1.23	1.12	1.22	1.12	1.21	1.10
Basalt	1.19	1.05	1.25	1.15	1.24	1.13	1.22	1.12	1.21	1.11
Dolomite	1.08	0.93	1.19	1.11	1.17	1.09	1.15	1.08	1.13	1.08
Granite	1.26	1.11	1.31	1.28	1.30	1.21	1.28	1.21	1.28	1.20

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REFERENCES

[1] Abdel-Mohsen, M., " Practical Evaluation of the Flexural Behavior of Fiber Reinforced Concrete Members," M. S., Faculty of Engineering, Tanta University, 2004.

[2] ACI-ASCE Committee 363, State of the Art Report on High Strength Concrete, American Concrete Institute, Detroit, 1984.

[3] Bilodeau, A., Kodur, V. K., and Hoff, G. C. " Optimization of the Type and Amount of Polypropylene Fibers for Preventing the Spalling of Lightweight Concrete Subjected to Hydrocarbon Fire," Cement and Concrete Composites, Vol. 26, 2004, pp. 163-174.

[4] Kalifa, P., Chene, G., and Galle, C., " High-Temperature Behavior of HPC with Polypropylene Fibers from Spalling to Microstructure", Cement and Concrete Research, Vol. 31, 2001, pp. 1487-1499.

[5] Neville, A. M., and Brooks, J. J., "Concrete Technology," Longman, 2nd Edition, 438pp., 1990.

[6] Mehta, P. K. "Concrete Structure, Properties and Materials," Prentice-Hall International, U.K., pp. 449, 1986.

[7] Rehanek, J., "Limit Values of the Heat-Transfer Coefficient of Exterior Walls of Buildings," SSTP-2nd International Conference on Indoor Climate of Building, Bratislava, Solvak, Ed. Petras, D., 1995, pp. 269-289.

[8] Saafi, M., "Effect of Fire on FRP Reinforced Concrete Members," Composite Structures, Vol. 58, 2002, pp. 11-20.

[9] Shetty, M.S., "Concrete Technology" Theory and Practice, S.Chand& Company LTD Fourth Eddition, 358pp., 1993.

[10] Taher, S. F., Abdellah, G. A., Maaty, A., and Bastawisi, A., "Utilization of Ash Residue of Rice Husk Burning as an Additive to Concrete,"1st International Workshop on Environmental Quality and Environmental Engineering in the Middle East Region, Konya, Turky, 1998, pp. 558-573.

[11] Taher, S. F., Kabeel, A. E., Bastawisi, A. E. Abdella, G. A., " Effect of Plasticizers on the Thermal Properties of Concrete," SSTP, International Conference on Indoor Climate of Building, Bratislava, Solvak, Ed. Petras, D., 1998, pp. 275-282.

[12] Taher, S. F., and Khalil, A. A., "Thermal Stability of Very High Strength Concrete," 1st Minia International Conference on Advanced Trends in Engineering, 1999.

[13] Yousry, M. M., "Very High Strength Concrete Using Carbonate Aggregate and Admixture," Ph.D. thesis, Structural Engineering Department, Faculty of Engineering, Mansoura University, 1996.

[14] Yousry, M. M., "Fire Resistance of Very High Strength Concrete," 1st Minia International Conference on Advanced Trends in Engineering, 1999.

NOTATION

The following symbols are used in this paper:

A	The cross-sectional area of the specimen;
h	The convection coefficient.
K	is heat transfer coefficient of the wall.
κ	The thermal conductivity;
L	The length of the hollow cylindrical samples;
P	The distance around the fin
Q	The heat;
R	the sum of the resistance of heat transfer of the wall;
R_i	the resistance of heat transfer of the inner side of wall;
R_o	the resistance of heat transfer of the outer side of wall;
R_w	the resistance of heat transfer of the wall;
r_i	Radius of the inner wall of the specimen;
r_o	Radius of the outer wall of the specimen;
t	is thickness;
U	The overall heat transfer coefficient;
x	Distance;
κ	The thermal conductivity;
φ_b	Temperature at the inner wall of the specimen;
φ_f	Temperature at the outer wall of the specimen;
φ_i	Temperature at the inner wall of the specimen; and
φ_o	Temperature at the outer wall of the specimen;