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Evaluation of Fire Endurance of Concrete Slabs Reinforced with Fiber-Reinforced Polymer Bars

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Abstract: One of the major safety requirements in the design of buildings is the provision of appropriate fire endurance of structural members. To assess and develop information on the fire endurance of fiber-reinforced polymer (FRP) reinforced concrete structural members, a numerical model was applied to the analysis of FRP-reinforced concrete slabs. The computer program was validated against data obtained from fire endurance tests on concrete slabs reinforced with steel or FRP bars. Parametric studies were carried out to investigate the effect of a range of parameters on the fire performance of FRP-reinforced concrete slabs. Results of the parametric studies show that FRP-reinforced concrete slabs have lower fire resistance than slabs reinforced with conventional reinforcing steel when fire endurance is defined in terms of the critical temperature of the reinforcement. In this context the main factors that influence the fire resistance of FRP-reinforced concrete slabs are: the concrete cover thickness, type of reinforcement, and the type of aggregate in the concrete. A higher fire resistance for FRP-reinforced concrete slabs can be obtained through greater concrete cover thickness and through the use of carbonate aggregate concrete. Based on the parametric studies, a series of simple design charts is presented that can be used to evaluate the fire endurance of FRP-reinforced concrete slabs.

CE Database Subject Headings*: Concrete slabs, Fiber reinforced plastics, Fire resistance, Fire protection, Heat transfer, Numerical analysis.*

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INTRODUCTION

In recent years, there has been significant increase in interest in the use of fiber-reinforced polymers (FRP) in civil engineering applications. This is due, in part, to various advantages, such as high strength and resistance to electrochemical corrosion, which FRP offer over conventional materials such as concrete and steel (Bakis et al., 2002). Furthermore, the costs associated with the use of FRP reinforcement in construction have decreased during the past few years, making FRP more competitive in civil engineering applications.

FRP can be used as an internal tensile reinforcement in the form of bars or grids, or as external reinforcement in various forms, such as wrapping and plating. As external reinforcement, FRP sheets can be wrapped circumferentially around columns, to increase their strength and ductility, or bonded to the tension face of beams or slabs to increase their flexural capacity. Internal FRP reinforcing bars, used as an alternative to conventional steel reinforcement, can be incorporated as continuous internal tensile reinforcement for concrete.

While the use of FRP in structural engineering applications is, at present, limited mainly to bridge structures, there is an enormous potential for its use in multi-storey buildings, parking garages and industrial structures (Burn and Martin, 1991). When used in buildings, FRP-reinforced structural members must be designed to satisfy appropriate fire resistance requirements in addition to structural requirements specified in building codes. At present very little information is available on the performance of FRP-reinforced structural members in fire, and this is one of the primary impediments to using FRP in buildings (Kodur, 1999).

The National Research Council of Canada (NRCC), in conjunction with Public Works and Government Services Canada (PWGSC), has initiated a research project to develop information on the fire resistance of concrete slabs reinforced with FRP bars. As part of this project, a detailed literature review has been carried out to study the fire behaviour of FRP materials and FRP-reinforced concrete (RC) members; experimental fire tests on FRP-RC slabs have been conducted to quantify the influence of various factors on the fire resistance of these members; and numerical parametric studies have been performed.

This paper discusses the various factors that differentiate the performance of FRP-reinforced concrete slabs at elevated temperatures, as compared with slabs incorporating traditional reinforcing steel. A numerical model for evaluating the fire resistance of FRP-reinforced concrete slabs, based on a purely thermal analysis, is presented and validated against test data, and the application of the numerical procedure for modelling the fire behaviour of FRP-RC slabs is illustrated through parametric studies. Results from the parametric studies are presented to show the influence of various factors on the predicted fire performance of FRP-RC slabs. Based on the numerical studies, preliminary guidance is offered for the fire design of FRP-RC slabs. Finally, a discussion of a number of critical unresolved issues with regard to the fire endurance of FRP-RC members is presented.

FIRE RESISTANCE OF FRP-REINFORCED CONCRETE

While the commonly-used fire protection techniques for concrete and steel members can also be adapted to achieve the required fire ratings of FRP structural members, there are significant differences associated with FRP as compared with steel reinforcement (Kodur and Baingo, 1998; Kodur, 1999). FRP materials are extremely susceptible to elevated temperatures, and severe degradation of mechanical and bond properties have been observed for relatively mild increases in temperature (Bisby et al, 2002). In conventionally-reinforced and prestressed concrete structural members, the required fire resistance is generally obtained through the provision of minimum member dimensions and a minimum thickness of the concrete cover to the reinforcement. The minimum concrete cover requirements are generally sufficient to ensure that the temperature in the reinforcement does not reach its critical temperature for the required duration of fire exposure. The critical temperature for tensile reinforcement has historically been defined as the temperature at which it loses much of its strength (50% loss of room temperature yield strength) and can no longer support the applied load. For reinforcing steel, the critical temperature is 593°C, while for prestressing steel it is 426°C (Lie, 1992). For RC slabs, the provision of minimum member dimensions (minimum slab thickness) maintains the temperatures at the unexposed surface within allowable limits for the required fire endurance.

In the case of steel reinforcement, the concrete cover thickness requirements for corrosion control serve, to a certain extent, to fulfil the requirements for fire resistance. Unlike steel-RC structural members, for FRP-RC members there is no special concrete cover thickness provision required for corrosion control. Furthermore, because FRP-RC members can be thinner than steel reinforced members, the provision of minimum concrete cover for FRP reinforcement is necessary to satisfy fire resistance requirements which may be very different from the requirements for steel reinforcement, and which may not be practical or economical (Kodur, 1999). In addition, detailed literature reviews (Bisby et al., 2002; Kodur and Baingo, 1998) have revealed that the critical temperature of FRP is, in general, much lower than that of steel, and that the general impact of elevated temperatures on the behaviour of FRP composites is rapid and severe degradation of both mechanical and bond properties.

Under current fire design guidelines (ASTM, 2001), FRP-RC slabs must be treated in a similar manner as conventionally reinforced slabs, and their fire resistance is defined in terms of reaching temperature dependent failure criteria. The following failure criteria, which are currently used for conventionally reinforced slabs under exposure to fire (Lie, 1992), can be used:

1. A single point thermocouple reading under an insulated pad on the unexposed face of the slab rises 180°C above ambient temperature.
2. The average temperature of five thermocouple readings (nine for a full-scale slab) under an insulated pad on the unexposed face of the slab rises 140°C above ambient temperature.
3. There is passage of flame (or gas sufficiently hot to ignite cotton waste) through the slab, or if the assembly fails (collapses) under its own weight.
4. The temperature at the level of the internal tensile reinforcement exceeds the critical temperature of the reinforcement.

Failure criterion 4, based on the critical temperature of the reinforcement, is potentially problematic for FRP reinforcement, for reasons that are discussed in detail later. Nonetheless, with the above four failure criteria in mind, existing heat-transfer models for RC slabs can be used to evaluate the fire endurance of FRP-reinforced slabs under the methodology currently used in CAN/ULC-S101 (CAN/ULC, 1989) or ASTM-E119 (ASTM, 2001).

NUMERICAL MODEL

To assess the fire resistance of FRP-RC slabs, a previously developed simplified numerical model was applied for evaluating the fire resistance of concrete slabs (Kodur and Baingo, 1998). The model selected for the analysis was originally developed by Lie (1992) for conventionally-RC slabs. This simple model has been used previously to carry out detailed numerical studies on the behaviour of conventional concrete slabs reinforced with steel, and has yielded adequate overall agreement with test data. For the present studies, the existing model was used to examine the effect of the FRP reinforcement's critical temperature as compared with steel. While more sophisticated models for heat transfer within a concrete slab exist in the literature (Hurst and Ahmed, 1998), the greater computational effort required for such models is not required for the current study.

In the model, the transient heating of a concrete slab during fire is represented as a one-dimensional heat transfer problem. The model calculates only the temperatures across the cross-section of the slab and has not yet been extended to predict the mechanical behaviour of fire-exposed FRP-RC slabs, as this requires more detailed information on the variation in mechanical and bond properties of FRP reinforcement with temperature. For the calculation of temperatures, only the properties of concrete are considered, and the reinforcement is assumed to have no influence on the temperature propagation. This assumption can be justified on the basis that the volume of reinforcement is small in comparison with the volume of concrete. Variations in the thermal properties of concrete with temperature are taken into account using the mathematical relationships provided by Lie (1992), and moisture is taken into account by assuming that moisture begins to evaporate from an element when its temperature reaches 100˚C, and the temperature of the element remains 100˚C until all of the moisture has evaporated. The model accounts for the strength degradation of the reinforcement with increasing temperature by considering a failure criterion defined in terms of the critical temperature of the reinforcement.

Analysis Procedure

The numerical model uses an explicit finite difference approach to calculate temperatures in the slab, based on a one-dimensional heat transfer model where the member is exposed to a standard fire from below. For the purposes of calculation, the slab is divided into a number of elementary layers, as shown schematically in Figure 1. The thickness of all layers is Δx, with the exception of the boundary layers which are $1/2\Delta x$ thick, and each layer is represented by a unique point, P_m. Only a thermal analysis is carried out during the modelling, since the failure is assumed to be governed by temperature criteria as listed previously.

The temperature in each layer is assumed to be uniform and equal to that of the representative point, P_m. Initially, at time $t = 0$, the slab is assumed to be at room temperature (20°C). The temperature in the various layers of the slab is then calculated for time $t = \Delta t$ using finite difference heat transfer equations derived on the basis of an elemental energy balance. Full details of the numerical procedure, including the derivation of the finite difference equations, have been presented previously by Kodur and Baingo (1998). The temperatures determined for $t = \Delta t$ are used as the initial temperatures for the calculation of the temperatures at time $t = 2\Delta t$, and the process is repeated until one of the failure criteria is reached. The boundary condition on the fire-exposed side of the slab is treated by assuming that heat is transferred by radiation only, an assumption that has been used successfully in the past (Lie, 1992). On the unexposed side of the slab, heat transfer is assumed to occur through a combination of radiation and free convection, again using the procedures suggested by Lie, 1992. Complete details of the numerical model are given by Kodur and Baingo (1998).

For the purposes of modeling, the failure of the slab is assumed to occur either when the temperature in the reinforcement reaches the critical temperature or when the unexposed surface temperature exceeds the limiting criterion as specified in the appropriate standard, such as CAN/ULC-S101 (CAN/ULC, 1989) or ASTM-E119 (ASTM, 2001).

Material Properties

Only the thermal properties of concrete – thermal conductivity, specific heat, and density – are required as a function of temperature for the analysis. These properties are built into the program for four commonly used types of concrete, namely siliceous, carbonate, shale and pure quartz aggregate concretes, using relationships presented previously by Lie (1992). The mechanical properties of the materials, such as the stress-strain relationships at elevated temperature, are not considered, since no structural analysis has been conducted at this time. However, the critical temperature for the reinforcement must be specified.

In the analyses presented herein, critical temperatures of 250°C and 325°C have been assumed for carbon FRP and glass FRP bars, respectively, based on the results of tensile tests of FRP bars at high temperature performed recently by Wang et al. (2003). These critical temperatures are those at which the carbon and glass FRP rebars used in the test program described herein lose 50% of their ultimate tensile strength. The reader should note that these critical temperatures are representative values for two specific FRP rebar products, and they do not account for the potentially disastrous effects of bond degradation at high temperature. The critical temperature for conventional non-prestressed steel rebar is currently taken as 593°C in North-America.

EXPERIMENTAL STUDIES ON FRP-RC SLABS

A series of fire resistance tests were conducted on steel-reinforced and FRP-RC slabs to examine the fire endurance behaviour of these members and to provide test data which could be used to validate the numerical model. The following sections provide an overview of the test program and the data it yielded.

Test Program

A total of 10 RC slabs were tested, in an unloaded condition, under exposure to the ASTM-E119 standard fire. Figure 2 gives the slab dimensions and reinforcement details for a typical RC slab tested in this study. A summary of the test parameters for the other slabs tested to date is presented in Table 1. The cover to the tensile reinforcement was varied among the slabs (25.4 mm or 38.1 mm), as was the reinforcement type (steel, carbon FRP, or glass FRP), the aggregate type (carbonate or siliceous), the overall slab thickness (152 mm or 203 mm), and the presence of a supplemental intumescent fire protection coating (on two slabs only). The slabs with fire protection behaved very poorly under fire exposure and are omitted from the present discussion.

All slabs were cast using normal Portland cement concrete. Two types of coarse aggregate were used, namely siliceous and carbonate. The 28-day compressive strengths of the siliceous and carbonate aggregate concretes were 46 MPa and 49 MPa respectively. Three different types of tensile reinforcement were used in the construction of the 10 slabs. One slab was made using conventional reinforcing steel. 15 mm diameter bars were used in the longitudinal direction, with 10 mm diameter bars in the transverse direction. Six slabs were fabricated with 12.7 mm diameter glass FRP bars in both directions, supplied by Pultrall Inc., and the remaining three slabs were fabricated using 9.5 mm diameter carbon FRP bars, also in both directions and supplied by Pultrall. The spacing of the reinforcement was varied in the slabs, as presented in Table 1. The design of reinforcement in the slabs was performed according to CSA-A23.3: Design of Concrete Structures (CSA, 1994) and/or CSA-S806: Design and Construction of Building Components with Fibre Reinforced Polymers (CSA, 2002), for the steel and FRP reinforced slabs respectively.

Test Apparatus

The fire tests were carried out by exposing the slabs to heat in a furnace designed specifically for fire testing intermediate-scale floor and slab assemblies. The slabs were exposed to heat from below in such a way that the average temperature of the furnace followed, as closely as possible, the ASTM-E119 (ASTM, 2001) standard time-temperature curve. Tests were continued for 4 hours or until one of the failure criteria outlined above was reached. The furnace temperature was controlled during tests by taking the average temperature of four shielded thermocouples located 150 mm below the exposed surface of the concrete slabs.

Instrumentation

Instrumentation for temperature measurement in each slab consisted of twenty-two chromel-alumel thermocouples placed at various locations within the slab and on the unexposed face. The typical number and location of thermocouples in the concrete and on the reinforcement is shown in Figure 3. In addition to the thermocouple sensors installed within the concrete slabs, five thermocouples were installed on the unexposed face of the slabs. Temperatures in the furnace (4 thermocouples), in the slabs (17 thermocouples), and on the unexposed face of the slabs (5 thermocouples) were recorded at one-minute intervals throughout the fire exposure.

Overview of Test Results

The average temperature increase at the unexposed face remained less than 140°C for the full fire exposure for all slabs tested. Thus, failure by the average unexposed face temperature criterion did not occur for any of the slabs. Additionally, the average unexposed surface temperatures were less for slabs with a greater overall thickness (slabs 6 and 7), as should be expected. With regard to the individual unexposed face thermocouple readings, examination of the test data indicated that the largest local temperature increase (taken from any of the five thermocouples on the unexposed face of a particular slab) was 158°C.

Qualitative observations for all slab tests were taken periodically on top of the slab (unexposed surface) and through small view ports in the furnace walls. All slabs behaved well under exposure to fire, and the most interesting observations were generally made after the tests were completed. Very little spalling was observed for any of the slabs for the full 4 hours of fire exposure, and no increase in spalling was observed for slabs reinforced with FRP. Slabs reinforced with FRP emitted a strong smell of burning plastic after about 50 minutes of exposure, which was likely the result of combustion of the FRP polymer resin matrix of the bars at specific locations. The smell persisted until the end of the tests. Based on the experimental studies, a number of significant conclusions were drawn:

- The qualitative fire and heat transfer behaviour of FRP-RC slabs appeared similar to slabs reinforced with steel bars.
- The reinforcement type did not significantly affect the temperatures recorded in the concrete for any of the slabs, except for a very mild heat-sink effect observed near the reinforcement in steel reinforced slabs.
- Overall slab thickness did not have a significant effect on the temperatures in the concrete, although the temperatures in the reinforcement were slightly lower for the thicker slab.
- Concrete cover thickness had a significant influence on the fire endurance of the FRP-RC slabs when fire endurance is defined in terms of the critical temperature of the reinforcement. Slabs with a greater cover thickness performed better in fire.
- Aggregate type had a moderate role in determining the fire resistance of FRP-RC slabs. Slabs with carbonate aggregate performed slightly better in fire.
- Overall, heat transfer in FRP-RC slabs during fire appeared similar to that observed in steel-reinforced slabs. However, the fire resistance of FRP reinforced slabs was lower due to the lower critical temperature of the FRP reinforcement.

MODEL VALIDATION

The model was evaluated by comparing the predictions of the computer program with test data from the fire tests described above. Figures 4, 5, and 6 provide validation comparisons for 150 mm thick concrete slabs incorporating glass FRP (GFRP), carbon FRP (CFRP), and conventional reinforcing steel at various locations in the concrete during exposure to fire. These three slabs were randomly selected from the 10 fire tests for the purposes of illustration.

The temperatures predicted by the model, at known locations in the slabs, are compared with measured temperatures for slabs 5, 3, and 4 in Figures 4, 5, and 6 respectively. Also included in these figures are horizontal lines showing the critical temperatures, T_{cr}, for the respective reinforcing materials. Generally, there is good agreement between the predicted and measured temperatures for all three slabs throughout the heating curve. However, in the CFRP and GFRP-reinforced slabs there are some discrepancies in the experimental data close to the rebar locations in the lower range of temperatures. This was likely due to the thermal degradation of the FRP polymer matrix which was not accounted for in the model or to a mild heat sink behaviour associated with the steel reinforcement. Figure 7 gives a comparison of predicted and recorded temperatures at the level of the reinforcement for slabs 3, 4, and 5. The agreement between the model predictions and experimental data is satisfactory, and confirms the assumption that the type of reinforcing material used does not noticeably influence heat transfer within the slabs. Additional validation comparisons were made and gave credence to the model, although these have not been included here. Thus, the model can be used to approximately predict the temperatures within a steel or FRP-RC slab during exposure to the standard fire. Furthermore, the model generally over-predicts the temperatures in the slab, a conservative result.

Table 2 provides an overall summary of the validation studies, based on the ability of the numerical model to predict the fire endurance of 8 of the slabs tested in the experimental study. Figure 2 and Table 1 provide additional details of the characteristics of the slabs analysed. It is evident that the fire resistance predictions from the model are conservative for all slabs analysed, with fire endurance predictions being conservative by between 18% and 36% (based solely on exceeding the assumed critical temperature of 250°C for CFRP at the level of the tensile reinforcement). The slabs used in the validation studies cover a range of thicknesses, aggregate types, reinforcement types, and cover thicknesses. Thus, the numerical model is capable of predicting the fire endurance of FRP-RC slabs with reasonable accuracy, assuming fire endurance can indeed be defined in terms of thermal criteria alone, and the model results in conservative fire endurance predictions in this context.

NUMERICAL STUDIES

A set of numerical studies was carried out using the model to investigate the effect of various parameters on the fire resistance of FRP-RC slabs. The slabs were exposed to standard fire conditions for 4 hours, and the temperatures across the cross-section of the slabs were traced. Data from the numerical studies were analyzed to predict the failure of the slabs based on the thermal failure criteria outlined previously. In all of the slabs studied, failure was attained when the internal tensile reinforcement reached its critical temperature. The goal of the parametric studies was to identify the governing factors in the development of fire resistance design guidelines for FRP-RC slabs.

Unless otherwise stated, the slabs used for the parametric studies consisted of 150 mm thick carbonate aggregate slabs reinforced with CFRP reinforcement (with an *assumed* critical temperature of 250°C). The initial volumetric moisture content of the concrete at room temperature has been assumed as 5%, which is at the conservative end of the likely moisture content range for concrete structures in service. Table 3 provides an overview of the various slabs which were analyzed for the parametric studies.

Effect of Slab Thickness

The effect of the overall slab thickness on the fire resistance of an FRP-reinforced carbonate-aggregate concrete slab is given in Figure 8 for three concrete cover thicknesses (Group A slabs in Table 3). For slab thicknesses above 100 mm, the predicted fire resistance remains essentially constant. This is due to the fact that the reinforcement is close to the fire-exposed face of the slab, and so the overall thickness does not significantly affect the heat transfer in the critical cover region between the reinforcement and the fire. For thinner slabs (less than 80 mm thick) the fire resistance decreases with decreasing slab thickness (all other factors being equal). This can be attributed to the larger thermal mass of thicker slabs, which allows them to absorb more thermal energy for an equivalent overall rise in temperature.

Hence, for the case of fire resistance defined in terms of exceeding the critical temperature of the reinforcement, for slab thicknesses that would be used in practice, the overall slab thickness does not appear to be a significant parameter. However, if fire resistance is controlled by the unexposed face temperature limits, as is often the case for steel-RC slabs, then slab thickness could indeed be a key parameter in controlling fire resistance.

Effect of Concrete Cover Thickness

The effect of concrete cover thickness on the fire resistance of a 150 mm thick FRP-RC slab is shown in Figure 9 for Group B slabs (refer to Table 3). It is evident that the thickness of the concrete cover to the reinforcement has a pronounced effect on the fire resistance of the slabs. This can be attributed to the fact that failure of the slabs is assumed to be governed by the critical temperature of the reinforcement. Larger concrete cover thickness delays the transmission of heat to the reinforcement, thereby enhancing fire resistance. For instance, the fire resistance of slab B1, assuming a reinforcement critical temperature of 250ºC, is 22 minutes with

20 mm cover, whereas it is 51 minutes with 40 mm cover.

Also evident in Figure 9 is the idea that much larger concrete cover thicknesses are required to achieve satisfactory fire resistances for FRP-RC slabs as compared with steel-reinforced slabs. For instance, for a 1-hour fire resistance rating for slab B1 (with GFRP rebar), the model predicts that a concrete cover thickness of 45 mm is required. This is significantly greater than the concrete cover thickness that would be required for a 1-hour fire resistance rating if the same slab was reinforced with conventional reinforcing steel. Hence, concrete cover thickness appears to be a primary variable in the development of fire resistance design aids for FRP-RC slabs.

Effect of Aggregate Type

Results from parametric studies on Group B slabs can also be used to illustrate the effect of aggregate type on the fire resistance of FRP-RC slabs (Figure 9). It can be seen that the use of siliceous aggregate concrete generally results in lower fire resistances, while use of expanded shale aggregate generally results in higher fire resistances and carbonate aggregate concrete displays an intermediate fire resistance. For instance, examining slabs B1, B2, and B3; if a cover of 50 mm is assumed, the fire resistances for the siliceous, carbonate, and expanded shale aggregate slabs are 65 minutes, 72 minutes, and 85 minutes respectively.

The lower temperature rise in the carbonate aggregate slab, as compared with the siliceous aggregate slab, is mainly caused by the higher heat capacity of carbonate aggregate concrete, which increases to a value of about 10 times that of siliceous aggregate concrete at about 700°C. This is due to an endothermic reaction caused by the dislocation of dolomite present in carbonate aggregates. Thus, aggregate type has a moderate influence to be considered in the fire resistance of RC slabs.

Effect of Reinforcement Type

To investigate the effect of reinforcement type (essentially the effect of critical temperature) on the fire resistance of concrete slabs, numerical studies were carried out on slabs reinforced with different types of rebars. Figure 10 shows the effect of the critical temperature of the reinforcement on the fire resistance of a 150 mm thick RC slab for three different concrete cover depths (Group C slabs). Recalling that the critical temperatures for carbon FRP, glass FRP, and conventional reinforcing steel have been defined as 250°C, 325°C, and 593°C respectively, the critical temperature of the reinforcement is seen to be a primary factor in the fire resistance of an FRP-RC slab, as expected. For a concrete slab with 20 mm concrete cover to the reinforcement, the fire resistance is predicted to be about 25 minutes with CFRP bars, 32 minutes with GFRP bars, and 110 minutes with conventional reinforcing steel. Furthermore, the rate of temperature increase in the slabs is more rapid at temperatures below about 350°C, and above 350°C the rate temperature increase begins to level off. For typical concrete slabs with glass or carbon FRP reinforcing bars, fire resistances of 25% to 40% of those obtained using conventional steel reinforcement can be expected. Thus, reinforcement type (critical temperature) has a major influence on the fire resistance of concrete slabs as defined herein.

Effect of Moisture Content

To investigate the effect of the moisture content of the concrete on the fire resistance of concrete slabs, numerical studies were carried out on Group D slabs. Figure 11 shows the relationship between the initial volumetric moisture content of the concrete and the fire resistance for a 150 mm thick FRP-RC slab for three different cover thicknesses.

Fire resistance increases with an increase in the moisture content of the concrete in the slabs. The beneficial effect of increased moisture content on the fire resistance of concrete slabs can be explained by considering the fact that moist concrete requires more thermal energy to raise its temperature than an equivalent slab with lower moisture content, subsequently increasing the fire resistance of the slab. The reason for this is twofold. First, moist concrete has a slightly higher heat capacity than dry concrete by virtue of the pore space that is occupied by water. Second, moisture in the concrete evaporates at temperatures close to 100°C, which consumes thermal energy due to the latent heat of vaporization of water (which is accounted for in the model). The result is that the temperature in the concrete remains close to 100°C until all of the moisture has evaporated, increasing the fire resistance of slabs with a higher moisture content. Thus, for typical slabs, with concrete moisture content in the range of 5 to 10%, the effect of moisture content on fire resistance is marginal.

PRELIMINARY DESIGN GUIDANCE

Using the results of the parametric studies presented above, and assuming that fire resistance can be defined in terms of the critical temperature of the reinforcement, a series of design charts were developed for determining the fire resistance of FRP-RC slabs. These charts give the required cover to the FRP reinforcement for a particular slab thickness, critical temperature of reinforcement (T_{cr}), aggregate type, and fire resistance. An example of these design charts is shown in Figure 12 for a 120 mm thick carbonate aggregate concrete slab. Versions of such charts have been incorporated into CSA-S806 (CSA, 2002).

Examining the chart presented in Figure 12, the user can determine the required concrete cover to the FRP reinforcement for a desired fire resistance rating and *known* reinforcement critical temperature. For instance, for a 120 mm thick carbonate aggregate FRP-RC slab with a desired 1-hour fire resistance rating, a CFRP bar or grid with a critical temperature of 250°C would require a concrete cover of about 50 mm. The same slab with GFRP reinforcement, with a slightly higher critical temperature of 325°C, would require a cover of about 40 mm, and a slab with conventional steel reinforcement would require a concrete cover of only about 15 mm to achieve the same level of fire resistance. Thus, it appears that substantially larger concrete cover thicknesses are required for FRP-RC slabs to achieve the same level of fire resistance as for steel-reinforced slabs.

UNRESOLVED ISSUES

It is critically important to remain cognizant of the fact that failure of the FRP-RC slabs in fire has been defined in the current discussion in terms of exceeding the critical temperature of the reinforcement, and experimental data confirming this assumed failure criterion do not currently exist. The assumption of member failure coincident with reaching the reinforcement critical temperature has been used in this initial study because of the ways in which fire endurance is *currently* defined for conventionally-RC slabs in North America (i.e. in terms of purely thermal criteria). However, there are a number of issues that warrant discussion with respect to the potential differences in behaviour between steel and FRP-RC slabs in actual building fires, where the service loads on the slabs should also be considered.

First, the critical temperatures of 250°C for CFRP and 325°C for GFRP have been assumed herein based on tests of specific carbon and glass FRP reinforcing bars at elevated temperature. Different FRP reinforcing products can be expected to behave differently, and hence detailed information on critical temperatures is required for any specific FRP reinforcing product being contemplated for use.

Second, the current discussion makes no attempt to address degradation of the bond between FRP reinforcement and concrete at high temperature. The critical temperatures used in the preceding discussions were based on tensile test data at high temperature and thus depend largely on the properties of the fibres. When used as reinforcement for concrete, the bond between the FRP rebars and the concrete, which is critical for overall member strength, depends not on the fibres but primarily on the properties of the polymer matrix. The polymer matrix can be expected to deteriorate very rapidly under exposure to high temperature, and it is thus possible that the bond between the FRP and the concrete could be lost at temperatures well below the critical temperatures quoted above (Katz et al., 1999). Current fire design guidelines do not appear to be concerned with the effects of bond degradation. However, it is possible that thermally-induced bond degradation of FRP reinforcement could lead to premature failure of loaded FRP-RC slabs during fire, and so full-scale fire tests on *loaded* FRP-RC slabs are badly needed.

It is also important in the context of the current discussion to highlight a fundamental design difference between FRP and steel-RC slabs. Properly designed steel-reinforced slabs at room temperature generally fail by crushing of the compression concrete after yielding of the tensile reinforcement, such that a 50% reduction in the yield strength of the steel results in a similar reduction in the flexural capacity of the slab (hence the critical temperature of the reinforcement is based on a 50% strength loss criterion). In the design of FRP-reinforced slabs serviceability criteria often govern, and these members are likely to fail by concrete crushing with no yielding of the tensile reinforcement. The strains in the FRP reinforcement at failure may thus be significantly less than ultimate. Hence, definition of the critical temperature of FRP reinforcement in terms of a 50% strength reduction may not correspond to a similar reduction in the flexural capacity of the slab.

The preceding discussion highlights the need for a re-evaluation of the purely thermal failure criteria currently used for assigning fire resistances to FRP-RC slabs. The use of FRP reinforcement for concrete is, of course, relatively new, and the fire testing guidelines have yet to catch up with the new technology.

CONCLUSIONS

Based on the results of the experimental program and numerical studies presented in this paper, the following conclusions can be drawn:

1. The qualitative fire performance and heat transfer behaviour of FRP-RC slabs appears similar to slabs reinforced with steel bars.
2. The reinforcement type has a significant effect on the predicted fire resistance of RC slabs, with FRP-RC slabs having much lower fire resistance as compared to those reinforced with steel. This conclusion is based on the assumed critical temperatures for FRP rebars as compared with conventional steel reinforcement, and does not account for thermally-induced bond degradation, which may be severe at temperatures well below the critical temperature of the FRP reinforcement.
3. Slab thickness does not have a significant effect on the fire resistance of the concrete slabs.
4. Concrete cover thickness has a significant influence on the fire resistance of RC slabs. Slabs with a greater cover thickness provide higher fire resistance.
5. Aggregate type has a moderate influence on the fire resistance of FRP-RC slabs. Concrete slabs with carbonate aggregate display about 10% greater fire resistance as compared with siliceous aggregate concrete slabs.
6. Higher fire resistance for FRP-RC slabs can be obtained by using larger concrete cover thickness and through the use of carbonate aggregate concrete.
7. Fire design and testing guidelines in North America do not currently consider the effects two important factors on the fire endurance of RC slabs, namely applied load and reinforcement

bond degradation. Full scale tests on loaded FRP-RC slabs are required to determine if bond degradation, which can be expected to be severe at only mildly increased temperatures, might cause premature structural failure during fire.

APPENDIX I. ACKNOWLEDGEMENTS

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APPENDIX II. REFERENCES

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Table 1: Test parameters for FRP-RC slabs

Slab no. (1)	Thickness (mm) (2)	Rebar type[1] (3)	f'_c (MPa) (4)	Agg. type[2] (5)	Conc. cover thickness (mm) (6)	Rebar [diam./spacing] (mm) Slab length (7)	Rebar [diam./spacing] (mm) Slab width (8)	Test parameter (9)
Slab 2	152	G	40	CA	25.4	12.7/135	9.5/135	FRP type
Slab 3	152	C	40	CA	25.4	9.5/300	9.5/300	FRP type
Slab 4	152	S	40	CA	25.4	15/300	10/300	Baseline
Slab 5	152	G	40	SA	25.4	12.7/135	9.5/135	Agg. type
Slab 6	203	G	40	CA	25.4	12.7/135	9.5/135	Thickness
Slab 7	203	G	40	CA	38.1	12.7/135	9.5/135	Cover
Slab 8	152	G	40	CA	25.4	12.7/135	9.5/135	Protection
Slab 10	152	G	40	SA	25.4	12.7/135	9.5/135	Additional
Slab 11	152	C	40	CA	25.4	9.5/300	9.5/300	Protection
Slab 12	152	C	40	CA	25.4	9.5/300	9.5/300	Additional

[1] S – Steel reinforcement, G – Glass FRP reinforcement, C – Carbon FRP reinforcement

[2] SA – Siliceous aggregate, CA – Carbonate aggregate

Table 2: Summary of results from model validation

Slab no. (1)	Thickness (mm) (2)	Rebar type[1] (3)	Agg. type[2] (5)	Conc. cover thickness (mm) (6)	Test fire endurance (min) (7)	Model fire endurance (min) (8)	% Difference (test vs. model) (9)
Slab 2	152	G	CA	25.4	36	28	22
Slab 3	152	C	CA	25.4	42	28	33
Slab 4	152	S	CA	25.4	44	28	36
Slab 5	152	G	SA	25.4	35	26	26
Slab 6	203	G	CA	25.4	43	28	35
Slab 7	203	G	CA	38.1	64	45	30
Slab 10	152	G	SA	25.4	40	26	35
Slab 12	152	C	CA	25.4	34	28	18

[1] S – Steel reinforcement, G – Glass FRP reinforcement, C – Carbon FRP reinforcement

[2] SA – Siliceous aggregate, CA – Carbonate aggregate

Table 3: Characteristics of reinforced concrete slabs used in parametric studies

Group (1)	Slab (2)	Thickness (mm) (3)	Rebar type[1] (4)	Cover (mm) (5)	Rebar T_{cr} (ºC) (6)	Aggregate type[3] (7)	Moisture content (% by Vol.) (8)	Fig. (9)
A	A1	0 to 200	C	20	250[2]	CA	5	Fig. 8
	A2	0 to 200	C	40	250	CA	5	
	A3	0 to 200	C	60	250	CA	5	
B	B1	150	C	0 to 70	250	CA	5	Fig. 9
	B2	150	C	0 to 70	250	SA	5	
	B3	150	C	0 to 70	250	EA	5	
C	C1	150	N/A	20	50 to 600	CA	5	Fig. 10
	C2	150	N/A	40	50 to 600	CA	5	
	C3	150	N/A	60	50 to 600	CA	5	
D	D1	150	C	20	250	CA	0 to 20	Fig. 11
	D2	150	C	40	250	CA	0 to 20	
	D3	150	C	60	250	CA	0 to 20	

[1] C – Carbon FRP (for illustrative purposes)

[2] a reinforcement critical temperature of 250°C has been assumed for CFRP rebars

[3] SA – Siliceous aggregate, CA – Carbonate aggregate, EA – Expanded shale aggregate

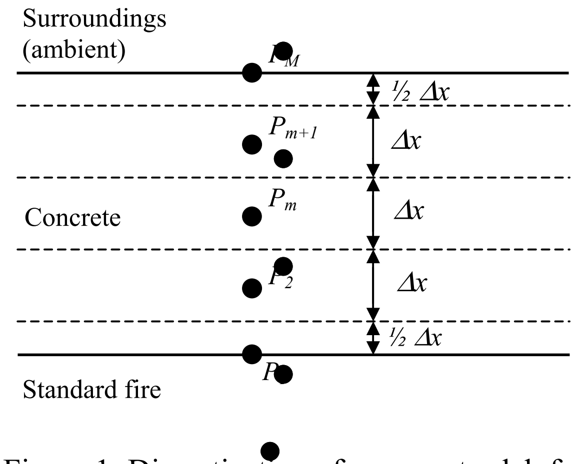

Figure 1: Discretization of a concrete slab for the heat transfer analysis

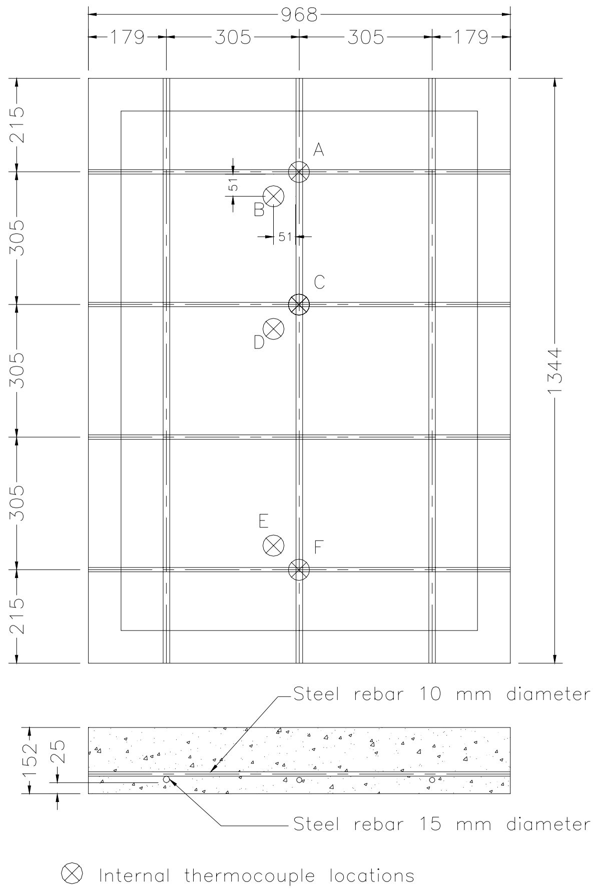

Figure 2: Slab dimensions and reinforcement details for a typical test slab (refer to Table 1)

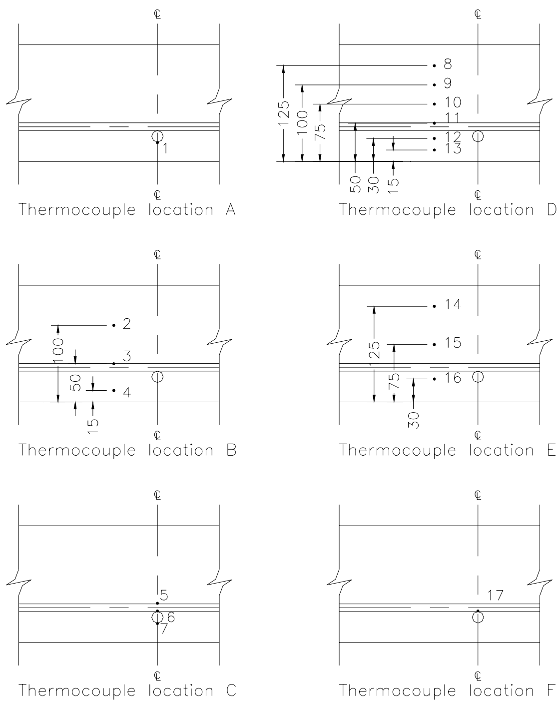

Figure 3: Thermocouple location for a typical test slab (refer to Table 1)

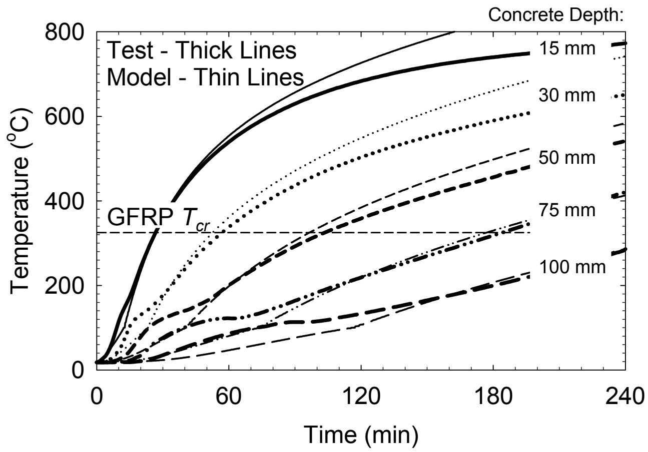

Figure 4: Measured and predicted temperatures in GFRP-reinforced concrete slab 5

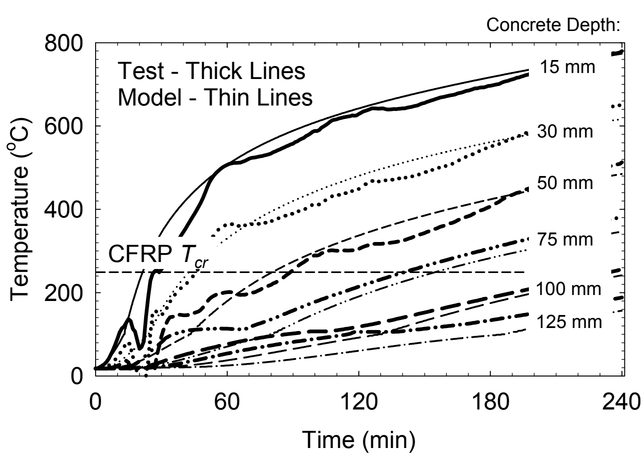

Figure 5: Measured and predicted temperatures in CFRP-reinforced concrete slab 3

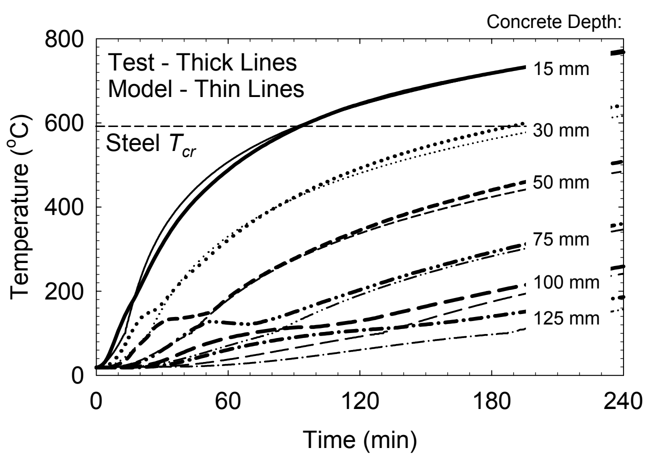

Figure 6: Measured and predicted temperatures in steel-reinforced concrete slab 4

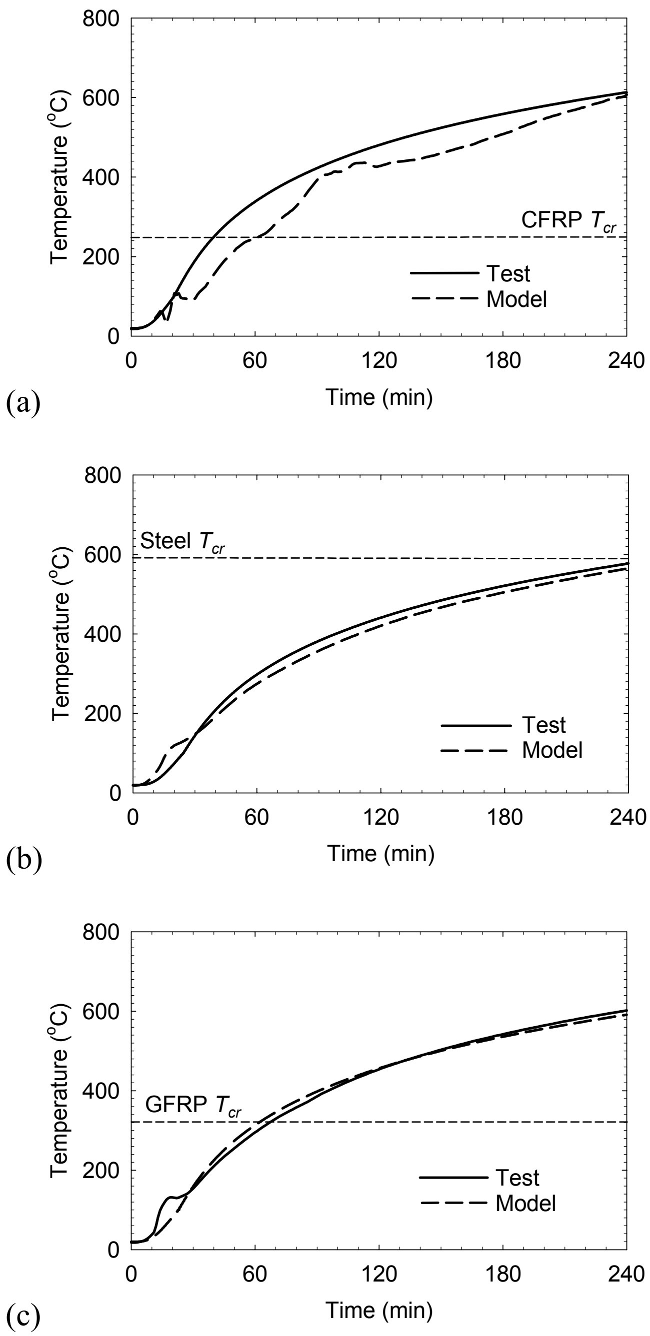

Figure 7: Measured and predicted temperatures at the middle of the reinforcement

(a) Slab 3 (CFRP reinforcement)

(b) Slab 4 (steel reinforcement)

(c) Slab 5 (GFRP reinforcement)

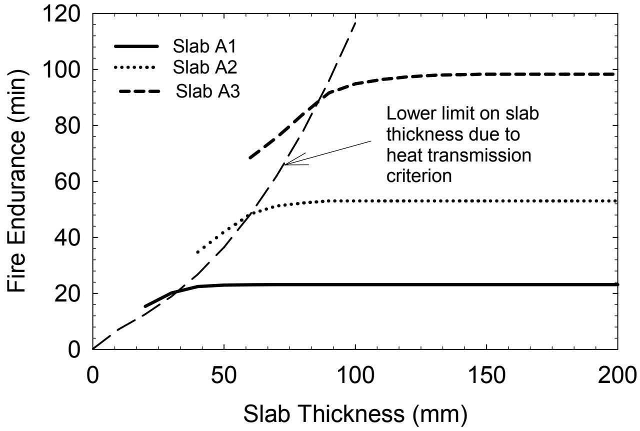

Figure 8: Effect of slab thickness on the fire resistance of reinforced concrete slabs

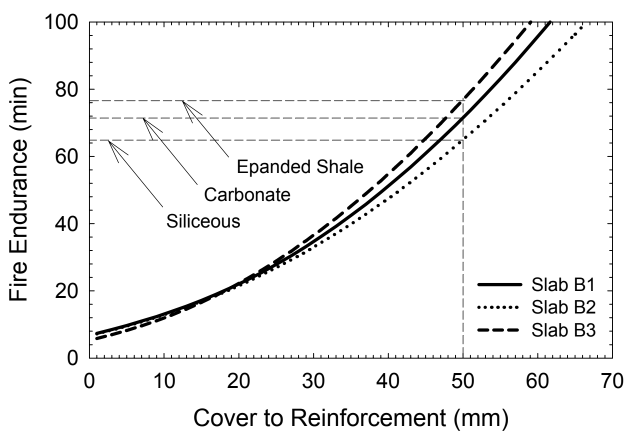

Figure 9: Effect of concrete cover thickness and aggregate type on the fire resistance of reinforced concrete slabs

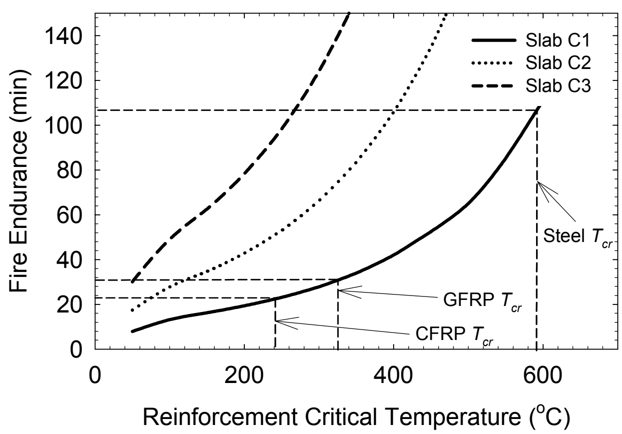

Figure 10: Effect of reinforcement type on the fire resistance of reinforced concrete slabs

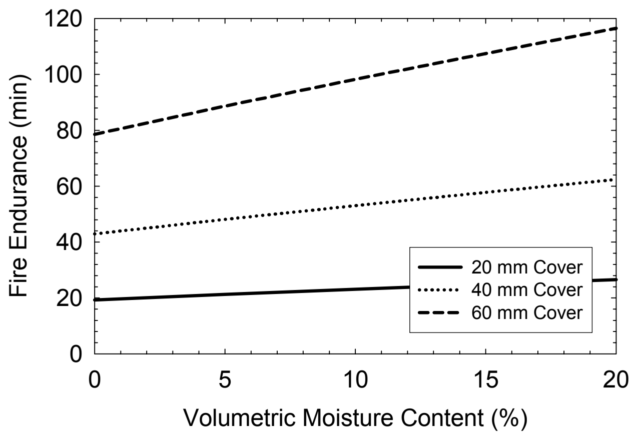

Figure 11: Effect of concrete moisture content on the fire resistance of reinforced concrete slabs

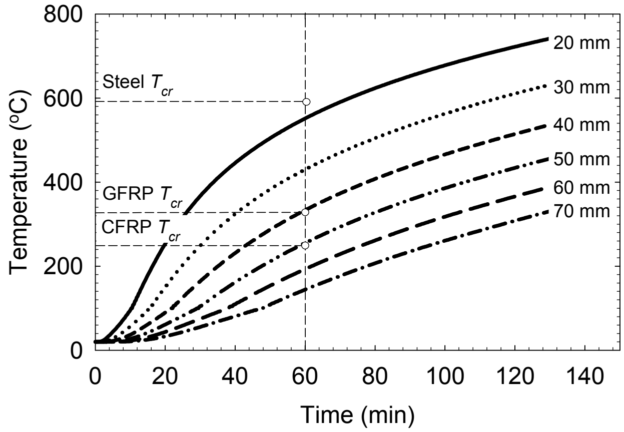

Figure 12: Design chart for 120 mm thick carbonate aggregate concrete slab

LIST OF FIGURE CAPTIONS

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