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New Scientific Results

of the PhD Thesis

Shear performance of concrete exposed to elevated temperatures

(Prepared for the internal defence)

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1. Background

Shear failure is generally considered to be among the most studied topics in reinforced concrete structures due to specific features that shear failure possesses such as no warning signs and brittle nature. Therefore, such kind of failures shall be avoided at high priorities. Several attempts have been made to generate a better understanding of the shear behaviour using either large or small scales of experiments. Due to the complexity and high expensive costs, different models and design methods have been proposed by researchers [1]. Push-off is one of the most used models to test shear capacity. The push-off model is a non-standard, but widely recognized, test that has advantages of being relatively small, inexpensive, easy to perform with no need for sophisticated equipment or procedures [2]. There are two main types of the model widely used: (I) pre-cracked and (II) non-precracked specimens.

Fibre-Reinforced Concrete (FRC) is widely used, particularly in recent years. Previous research showed that the strength and ductility of fibre-reinforced concrete are increased by the virtue of the “bridging effect” of the fibres, helping to resist the opening of cracks [2, 3]. When cracks initiate, shear force across the crack is transmitted through mechanism achieved by interaction of several components. Two important components were considered dowel action of the reinforcement, and forces between the rough concrete faces known as aggregate interlock [5].

In recent years, High Strength Concrete (HSC) is increasingly popular in civil engineering practice due to its higher strength and better durability compared to Normal Strength Concrete (NSC). However, with the increasing engineering applications as well as increasing the deepening of related research activities, it was noticed that HSC can be inferior to NSC in the aspects of some mechanical properties after elevated temperatures. Thus, properties of NSC and HSC at elevated temperatures have been widely studied. Yet, there still remain areas need further investigations as well as more clarifications [6]. This could be due to the fact that many of the reported test results are hard to interpret [7]. Differences in the tested types, equipment, procedures and conditions of concretes as well as incompleteness of descriptions of the tests are main causes of the differences in interpretations [8].

2. Objectives

The overall aim of the current study is to evaluate the shear performance of concrete using different types and amounts of fibres in the case of elevated temperatures. To fulfil the targeted aim, the following objectives were performed:

1- To evaluate the influence of fibres with different types and ratios on shear strength at different maximum levels of temperatures.
2- To evaluate the influence of fibres with different types and ratios on shear toughness at different maximum levels of temperatures.
3- To evaluate the influence of fibres with different types and ratios on shear stiffness at different maximum levels of temperatures.
4- To specify the different shear failure modes of the push-off specimens at elevated temperatures regarding FRC.

3. Experimental Program

Experimental program is designed herein to identify the test parameters, adopted methodology and used material with respect to the four objectives mentioned in the previous section.

3.1 Parameters of the study

Three main parameters are investigated in the current study namely; maximum level of temperature, concrete mix and age of concrete. Thus, five maximum temperatures and five concrete mixes, depending on fibres content, are chosen as well. Concrete is tested also in two different ages. Table 1 lists all parameters and the values being investigated in this research.

Table 1 Primary parameters including values

Parameter	Value
Maximum temperature, °C	20, 150, 300, 500 and 700
Concrete mix, kg/m^3	Zero fibres, 40 (steel), 80 (steel), 4 (concrix) and 40+2 (cocktail–steel and concrix)
Age of concrete, time	28-day and one-year old

Regarding fibres content, amounts were chosen within the range that has significant influences on concrete properties. Steel fibres content below 20 kg/m^3 was found to have no significant influence on concrete whereas a concrete mix containing above 150 kg/m^3 of steel fibres was found to reduce the workability. Therefore, two amounts between the abovementioned limits of steel fibres were chosen herein. Additionally, synthetic fibres (concrix) as well as cocktail fibres were also chosen to be within the suggested or preferred by the producers and researchers. Generally, recommended approximate dosage for concrix ES as a structural reinforcement is 2.0 to 7.5 kg/m^3 of concrete. Thus, 4 kg/m^3 of concrix fibres was chosen to be the percentage one mix and 2 kg/m^3 was chosen for the cocktail one.

3.2 Material

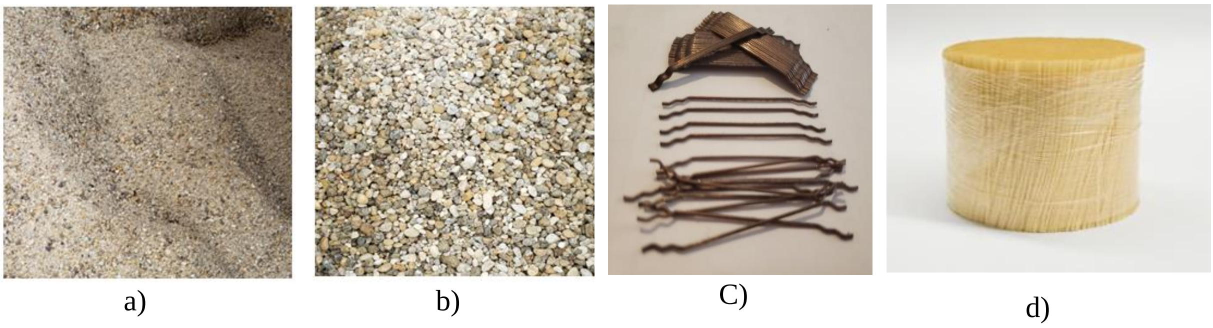

a) b) C) d)

Figure 1: Material used, a) fine aggregate, b) coarse aggregate, c) steel fibres and d) Concrix

One type of ordinary Portland cement was used (CEM I 52.5 N) for all mixes. Natural sand was used as fine aggregate with maximum size 4 mm *(Fig. 1 a)***.** Coarse aggregate (Danube quartz gravel) with size range 4 to 8 mm was used *(Fig. 1 b)*. MasterGlenium 300, a second generation of polycarboxylic ether polymers was also used as superplasticizer. Dramix 5D (5D 65/60BG) was used as steel fibres with length 60 mm, diameter 0.9 mm and aspect ratio 65 *(Fig. 1 c)*. Concrix ES is used with standard lengths of 50 mm, tensile strength is 590 N/mm^2 and modulus of elasticity > 11 GPa *(Fig. 1 d)*.

3.3 Experimental methodology

All specimens were formed in a rectangular metal mould (*Fig. 2 a*).Then after 7-days of water treatment, notches were cut perpendicular to the shear plane (*Fig. 2 b*). Two thermocouples were used to record temperatures at two points in addition to the oven temperature itself. In which one of the thermocouples was fixed at the surface of the specimen whereas the other one was installed inside at 50 mm distance from both edges. A fixed-machine driller was used to drill inside the specimen (*Fig. 2 c*).


a) b) c)

Figure 2: Phases of sample preparations, a) metal mold and table of vibration, b) saw cut-off machine for notches and c) fixed drill-in machine for thermocouples

Chosen dimensions of the push-off specimens should fit dimensions of the available oven in the laboratory and other requirements such as saw-cut machine and LVDTs domains. Thus, the height of the uncracked push-off model is chosen to be 260 mm, and both width and depth are 150 mm (*Fig. 3*).

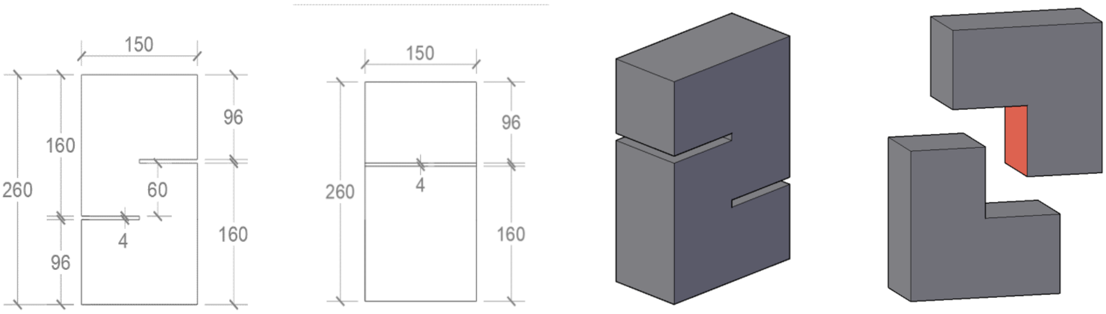
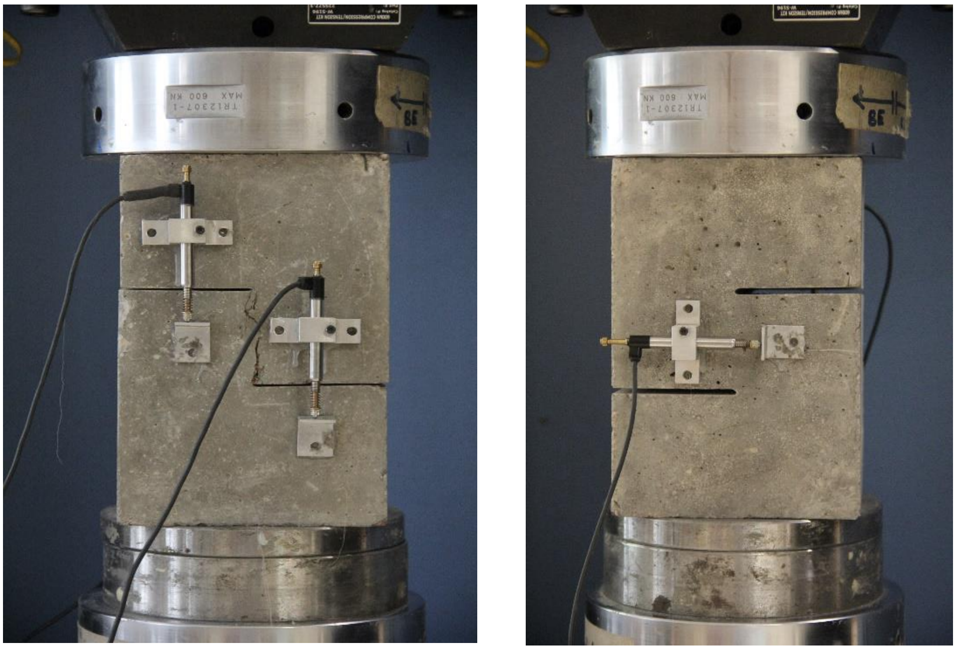


Figure 3: Schematic and 3-D illustrations for the push-off model including dimensions

Some previous researchers [9] used preformed notches instead of cut. In such a way, the preformation could cause a non-uniform fibres distribution near the notches due to wall effects in their experiment [10]. Therefore, in present experimental study notches, 4 mm width by 75 mm length, were cut after two weeks of casting perpendicular to the axis of the specimen using saw cut-off machine. After 7-days of curing, specimens were stored at laboratory conditions before loading tests. Specimens were exposed to heating regime using an electric oven. Five maximum degrees of temperature are chosen. Once the oven temperature reaches the target max temperature, then this temperature is kept the same for two hours. Afterward specimen was taken out to be air cooled for 24-48 hours before loading test in the laboratory using INSTRON 5989 with force capacity of 600 kN.

The push-off specimens were tested in a displacement-controlled compression testing machine. Tests were carried out at the cold state 24-48 hours after heating exposure using the INSTRON testing machine. Two different deformations are investigated, i.e., vertical displacement (in parallel to the load direction) considered as "*crack slip*" and horizontal displacement (perpendicular to the load direction) considered as "*crack width*". Displacement values were measured by means of Linear Variable Differential Transformers (LVDTs) fixed horizontally and vertically on both faces of the specimen. Three LVDTs were used with a 10 mm of capacity of measurement. Two vertical LVDTs (*Fig. 4 a*) give displacement of the crack slip whereas one horizontal LVDT (*Fig. 4 b*) gives the dilatation of the crack width during the loading. All measurements were automatically recorded each half a second using software.



a)

b)

Figure 4: Push-off loading illustrating a) LVDTs, vertically fixed (crack slip) and b) LVDT, horizontally fixed in middle of specimens (crack width)

4. New Scientific Results (NSR)

NSR 1: Influence of fibres on shear strength at elevated temperatures

I have designed and performed an extensive series of experiments to study the influence of different types and ratios of fibres on shear strength in concrete. I have tested 5D Dramix steel fibres in two different ratios 40 or 80 kg/m^3, bicomponent macrofibres known as concrix ES fibres (4 kg/m^3) and cocktail fibres (steel fibres simultaneously mixed with concrix ES, i.e. 40 + 2 kg/m^3, respectively) in addition to the plain concrete mix as a reference. Tests were carried out at five different maximum levels of temperature, i.e., 20, 150, 300, 500 or 700 °C using the so-called push-off model. I have tested 75 specimens at 28-days and another 75 specimens at 365-days for all mixes. The average was obtained from the results of three measurements in all conditions. Amounts and types of the concrete constituents including type and amount of cement, w/c and aggregates were fixed. The compressive strength of reference concrete was approximately 78 MPa. The experiments are based on results of push-off tests using Instron servo-hydraulic machine.

1.1 **I have experimentally proved that *steel fibres* have significant influence on increasing the shear strength of concrete. The higher is the fibre content the more is the increase of shear strength. Increase of the shear strength due to steel fibres is more pronounced at specimens of age 28-days compared to specimens of 365-days old, and more pronounce at ambient temperature compared to elevated temperatures as well.**

Related to publications NA11 and NA13, as well as NA1-10

Presence of steel fibres generally develops the strength of concrete mixes in shear as shown in *Figure 1*. Results showed significant increase of shear strength due to steel fibres at ambient temperature by about 131.4 and 128.9 % for mixes SFRC-40-28 and SFRC-80-28 whereas developments were about 31.2 and 54.3 % for SFRC-40-365 and SFRC-80-365, respectively. (*Fig. 1*)

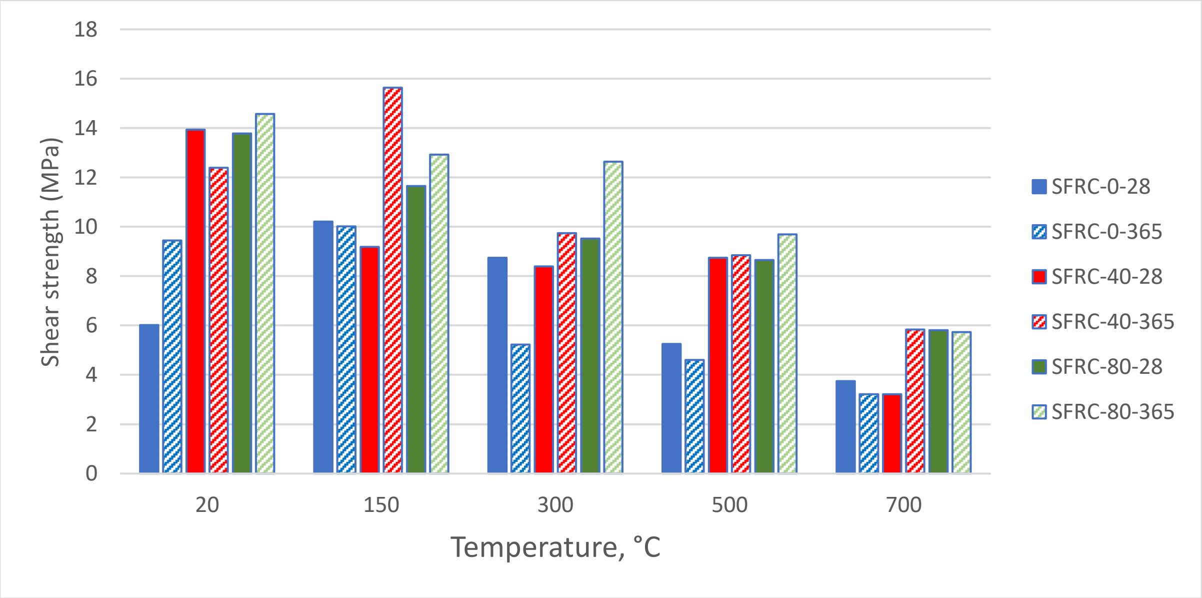


Figure 1: Average values of the shear strength tests on steel fibres concrete

1.2 I have demonstrated that adding *polymeric fibres (pp)* increases the shear strength at ambient temperature. The increase is higher at specimens of 28-days than specimens of 365-days old. However, by elevating temperatures up to 700 °C, significant decrease is noticed for the specimens containing pp fibres compared to no-fibre specimens, for both ages.

Related to publications NA12 and NA15, as well as NA1-10

Although presence of pp fibres contributes to increase the shear strength at ambient temperature to reach 22.4% at age 28-day, a negligible influence is noticed for specimens of age 365-days old to reach 0.6%. This could be attributed to concrete enhancement obtained by reducing water content by time in addition to the possible degradations that could occur to the pp fibres by time. By increasing temperatures up to 700 °C, where pp fibres are totally vanished, a reduction in shear strength is noticed for the specimens that contain pp fibres to reach 44.0 and 31.7% for both ages 28-days and 365-days old, respectively. *Figure 2* shows average values of the shear strength of concrete using polymeric fibres.

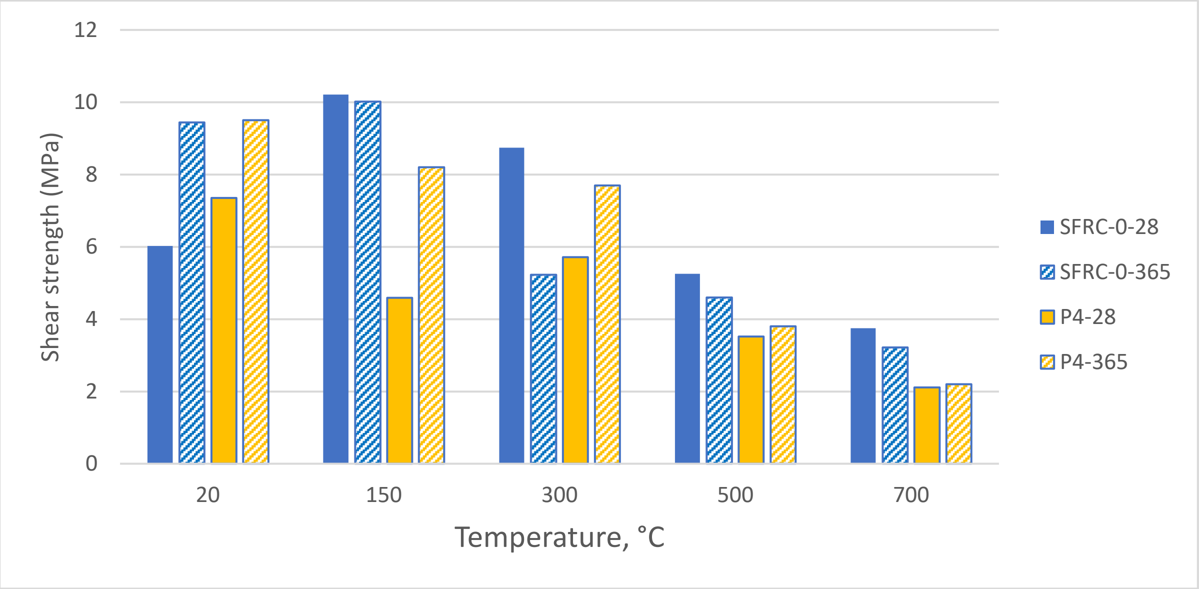


Figure 2: Average values of the shear strength tests on polymeric fibres concrete

1.3 I have demonstrated that adding *cocktail fibres* significantly increases the shear strength at ambient temperature for specimens of both ages 28-days and 365-days old. However, insignificant increase is observed when temperatures are elevated up to 700 °C for specimens of both ages as well.

Related to publications NA12 and NA15, as well as NA1-10

Mixing pp fibres with the steel fibres in order to produce hybrid or cocktail fibres has found to increase shear strength of concrete at ambient temperature. The increase of the shear strength compared to the plain concrete is measured to be 71.6 and 58.9% for specimens of 28-days and 365-days old, respectively. However, increasing temperatures up to 700 °C, the increase in shear strength for specimens containing cocktail fibres is found to be 16.5 and 27.3% for specimens of both ages 28-days and 365-days old, respectively. *Figure 3* shows average values of the shear strength of concrete using cocktail fibres.

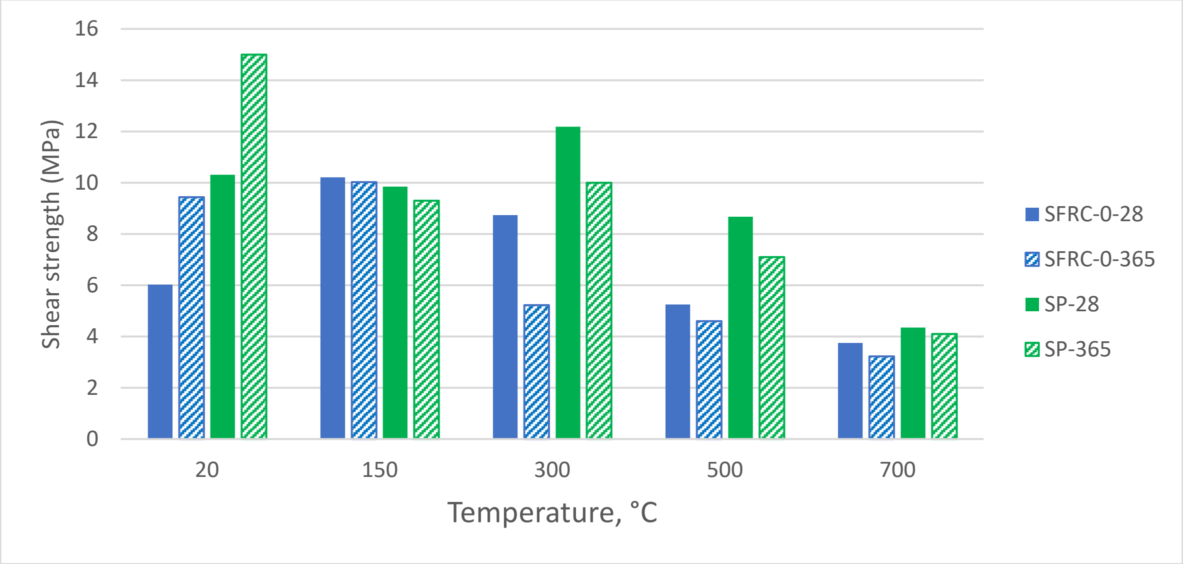


Figure 3: Average values of the shear strength tests on cocktail fibres concrete

NSR 2: Enhancement of shear toughness

I have designed and performed an extensive experimental series to study the performance of the FRC after exposed to elevated temperatures in terms of shear toughness. I have evaluated the shear toughness using the method that is already developed and adopted by ASTM C 1018 Standard [11]. I have determined the shear toughness index I_5 as ratio of the area of the shear load-deflection curve up to deflection of 3 times the first-crack deflection, divided by the area of the shear load-deflection curve up to the first-crack deflection (first-crack toughness), as follow:

$$I_5 = \frac{\text{Area under load}-\text{deflection curve up to } 3\delta}{\text{Area under load}-\text{deflection curve up to } \delta}$$

I have defined the first crack as the first drop in load or reduction of stiffness (slope). Thus, δ is the deformation (mm) at the first crack. I have measured crack deformations in both directions using means of Linear Variable Differential Transformers (LVDTs). Consequently, I have calculated the shear toughness depending on the previous formulations in both directions, i.e., parallel to the load as *shear toughness related to crack slip* and perpendicular to the load as *shear toughness related to crack width.*

2.1 I have experimentally demonstrated that existence of fibres increases the shear toughness at both directions, parallel and perpendicular to the load.

Related to publications NA14, NA16 and NA17

Shear toughness, indicated by toughness Index I_5, is generally increased at concrete mixes containing fibres, regardless the type of fibres [11]. *Figure 4* shows that mixes containing 80 kg/m^3 of steel fibres have the highest shear toughness values among other mixes at both directions of loading. The relative increases of the shear toughness related to the crack slip due to existence of fibres at the ambient temperatures are 3.1, 23.1, 16.9 and 14.3 % for the mixes SFRC-40, SFRC-80, P4 and SP, respectively.

The relative increases of the shear toughness related to the crack width due to existence of fibres at the ambient temperatures are found to be 15.1, 32.3, 29.9 and 30.7 % for the mixes SFRC-40, SFRC-80, P4 and SP, respectively. *Figure 4* shows shear toughness related to crack slip as well as crack width, at ambient temperature for all mixes.

Figure 4: Shear toughness at 20 °C

2.2 I have experimentally demonstrated that shear toughness related to crack width have higher values than shear toughness related to crack slip. This result is valid regardless the type of the fibres used or the degree of the maximum temperatures.

Related to publications NA14, NA16 and NA17

Figure 5 shows the difference between the shear toughness related to crack slip and crack width at 20 and 700 °C temperatures.

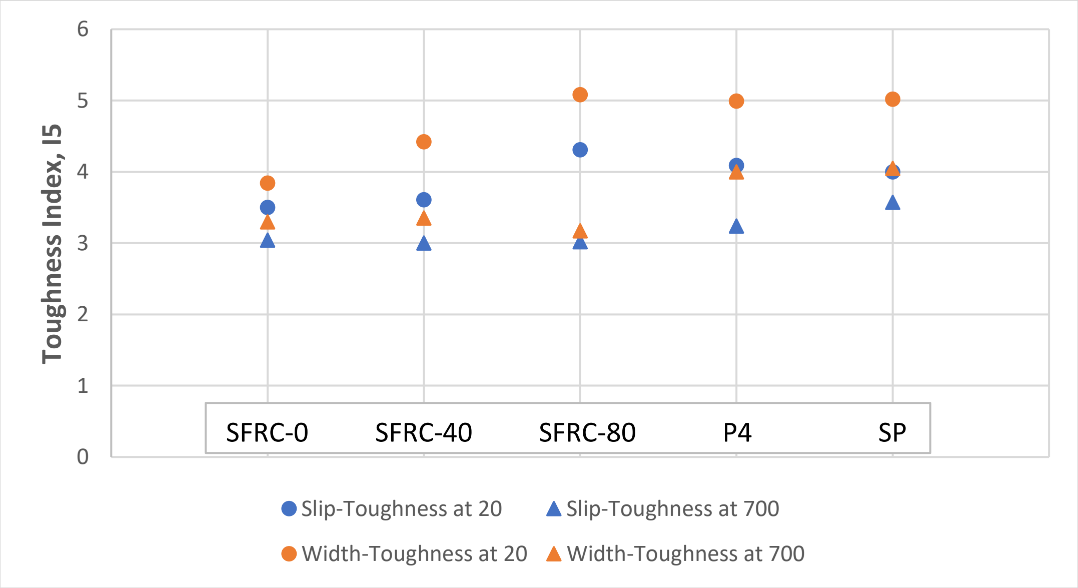


Figure 5: Shear toughness related to crack slip and crack width at 20 and 700 °C temperatures

This result could be attributed to the fact that loading has direct influence on the crack slip deformation since they are both at the same direction, whereas the influence of loading is less at the perpendicular direction (crack width deformation). In addition, fibres have direct influence on bridging the opening of the cracks. Consequently, shear toughness keeps higher values at the perpendicular direction compared to the parallel one.

2.3 I have experimentally demonstrated that by elevating temperatures, the shear toughness decreases in both directions at all mixes, regardless types or amount of the fibres contents.

Related to publications NA14, NA16 and NA17

The decrease of the shear toughness related to crack slip due to elevated temperatures, i.e., at 700 °C is found to be 13.1, 16.9, 29.9, 20.7 and 10.8 % for the mixes SFRC-0, SFRC-40, SFRC-80, P4 and SP, respectively. The decrease of the shear toughness related to crack width due to elevated temperature, i.e., at 700 °C is found to be 14.1, 24.2, 37.6, 19.8 and 19.3 % for the mixes SFRC-0, SFRC-40, SFRC-80, P4 and SP, respectively. Furthermore, the highest value of the relative shear toughness, compared to the shear toughness of the plain concrete, was belong to the cocktail mix (SP) at high temperature levels, i.e., 700 °C for both directions. This could be the result of the influence of the presence of the steel fibres as well as the enhancement obtained by presence of polymeric fibres after melted, similarly to the case of spalling [17-20]. Similar results were confirmed regarding using hybrid fibres to increase toughness after elevating temperatures, but on compressive strength [21]. In addition, adding steel fibres in high amounts, i.e., 80 kg/m3 will result in decreasing the cross-section of the shear plane and increasing the entrained air, thus decreasing the stress intensity factor in shear [22]. Simultaneously, elevating temperatures will result in decrease the mechanical properties of steel fibres. Therefore, results of the SFRC-80 mix show the highest decrease among other mixes. See *Figure 5.*

NSR 3: Enhancement of shear stiffness

I have defined the *shear stiffness* as the value obtained within 1/3 of the shear strength divided by the corresponding values of the crack slip or crack width. The 1/3 approach is adopted from previous studies [13, 14]. The calculations of shear stiffness related to crack width and crack slip are based on measurements obtained by using LVDTs.

3.1 I have experimentally demonstrated that the shear stiffness related to crack width has higher values than shear stiffness values related to the crack slip. This result is valid for all mixes and at more pronounce at elevated temperatures than at ambient temperature.

Related to publications NA14, NA16 and NA17

Results show that crack width is nearly zero before first crack initiates whereas crack slip is slightly more than zero, indicating that the shear stiffness of the perpendicular-to-load direction is higher than shear stiffness of the parallel-to-load direction [15, 16]. This observation was confirmed for all types of mixes at all levels of elevated temperatures.

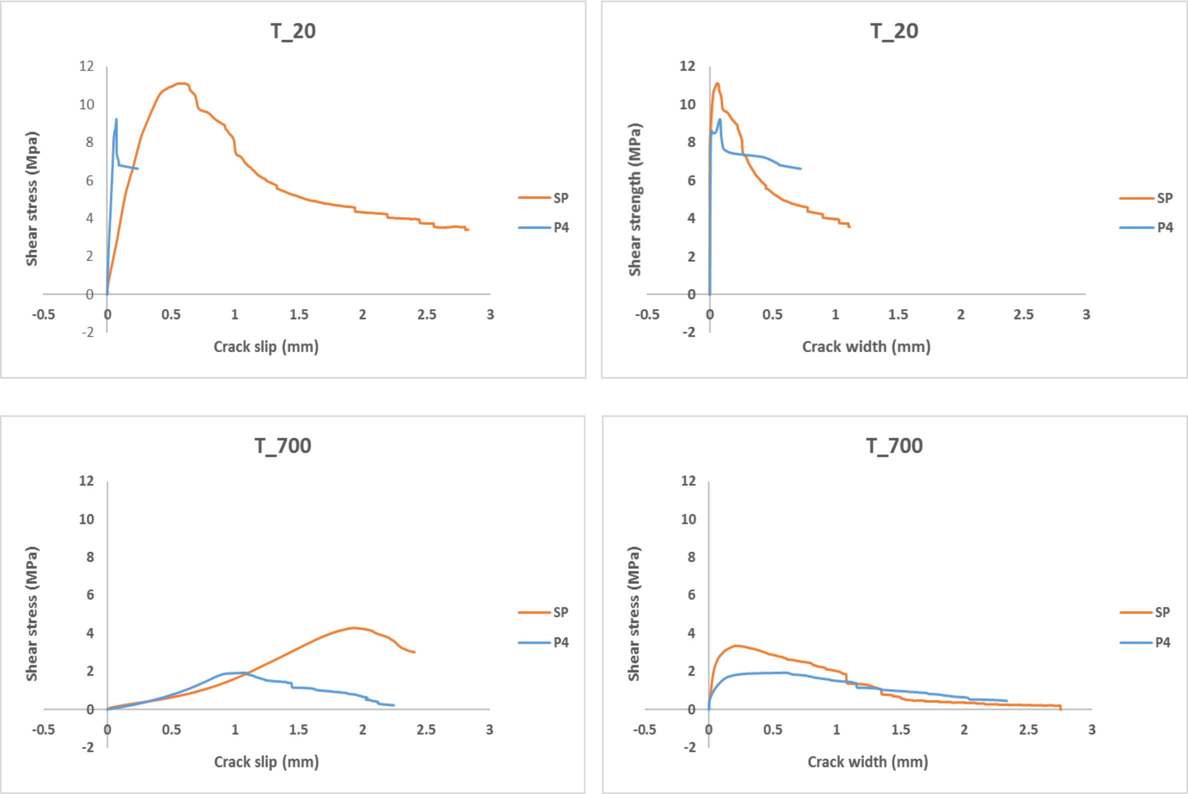


Figure 8: Shear stress-crack width and crack slip curves of P4 and SP at maximum temperatures 20 and 700 °C

Furthermore, at high maximum temperatures, i.e., 500 or 700 °C, both crack width and crack slip have higher values, relating to the shear strength, than values of crack width and crack slip, relating to shear strength, at ambient temperature. See an example of two mixes, i.e., P4 and SP, as shown in *Figure 8*. A possible interpretation for the previous result could be due to the fact that load on specimens was vertical and the loading was in parallel to the shear plane, thus values of the crack deformation were more influenced (higher) in the vertical direction compared to the horizontal one, resulting in less stiffness. Moreover, ratios of the increase of the shear stiffness related to the crack width, to shear stiffness related to the crack slip at ambient temperature were 177, 45, 167, 1128 and 256% for the mixes SFRC-0, SFRC-40, SFRC-80, P4 and SP, respectively. From another hand, ratios of the increase of the shear stiffness related to the crack width, to shear stiffness related to the crack slip at elevated temperatures, i.e., 700 °C were 917, 554, 734, 1666 and 766% for the mixes SFRC-0, SFRC-40, SFRC-80, P4 and SP, respectively.

3.2 I have experimentally demonstrated that elevating temperatures significantly decreases the shear stiffness of all mixes tested. This result is valid for both directions-to-load, i.e., parallelly or perpendicularly. By elevating temperatures up to 700 °C, the highest residual shear stiffness, at both directions, was measured for the cocktail fibres mixes.

Related to publications NA14, NA16 and NA17

Shear stiffness is significantly decreased by increasing temperatures. This notice is valid for all mixes at both crack deformations as well. Previous studies reported stiffness degradations for compression in case of FRC due to elevated temperatures [13]. I have measured the crack deformations at all levels of temperatures. I calculated the relative residual shear stiffness through dividing the shear stiffness value at 700 °C by the shear stiffness value at 20 °C. The results of the relative residual stiffness for all mixes at both directions are illustrated in *Figure 9*. The figure shows significant decline of the shear stiffness at both directions by increasing temperatures, in which values of decrease are higher than 95% for all mixes. Results show also that the residual shear stiffness has higher values for the cocktail fibres mixes.

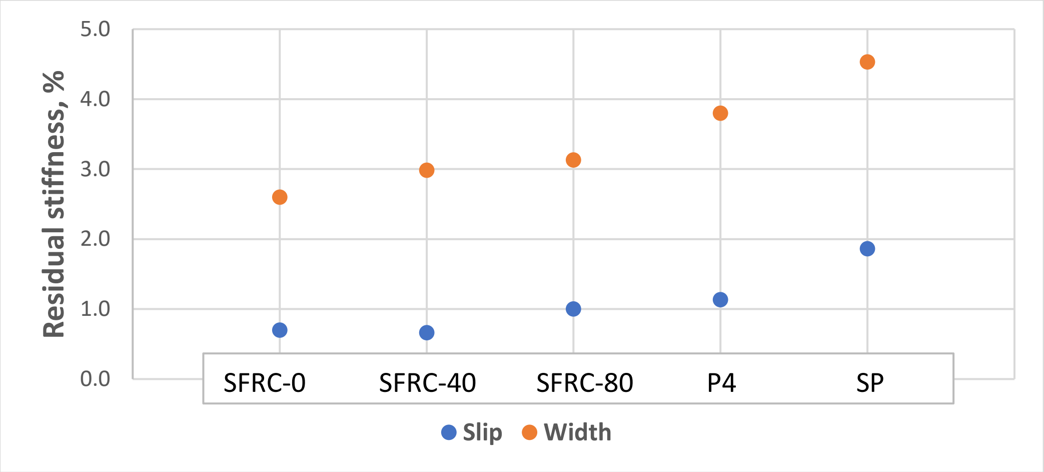


Figure 9: Relative residual stiffness of the mixes after exposed to 700 °C

NSR 4: Influence of fibres on shear failure modes at elevated temperatures

I have demonstrated that presence of fibres has significant influence on controlling the cracks occurred at the shear planes, thus affecting the shear failure modes at different levels of elevated temperatures.

Related to publications NA11, NA12, NA13 and NA15

In general, the mode of the failure in plain concrete is significantly different from mixes containing fibres at both ambient and elevated temperatures. First observations reported in the plain concrete specimens were the continuous propagations across the shear plane once the first crack initiates, completely splitting the specimen into two separate parts. However, at the presence of the fibres, the failure mode is different. Some specimens, particularly containing steel fibres, experienced the first crack to be occur near the shear plane, called in some studies *secondary tensile crack* [3]. Moreover, the secondary tensile crack does not control the failure to the end, but another crack follows across the shear plane to control the failure of the specimen without complete separation, as shown in *Figure 10*. In some cases, especially in higher amounts of steel fibres, spalling at the surface of the specimens is noticed near the shear plane due to the existence of the steel fibres, in which thin tiny layers of the concrete covers are spalled.

Finally, regarding the mixes contain pp fibres (P4), failure at ambient temperature has similar mode to the mixes containing steel fibres, yet once the temperature exceeds the melting point, the specimens are noticed to fall apart similarly to the mixes cast from plain concrete.

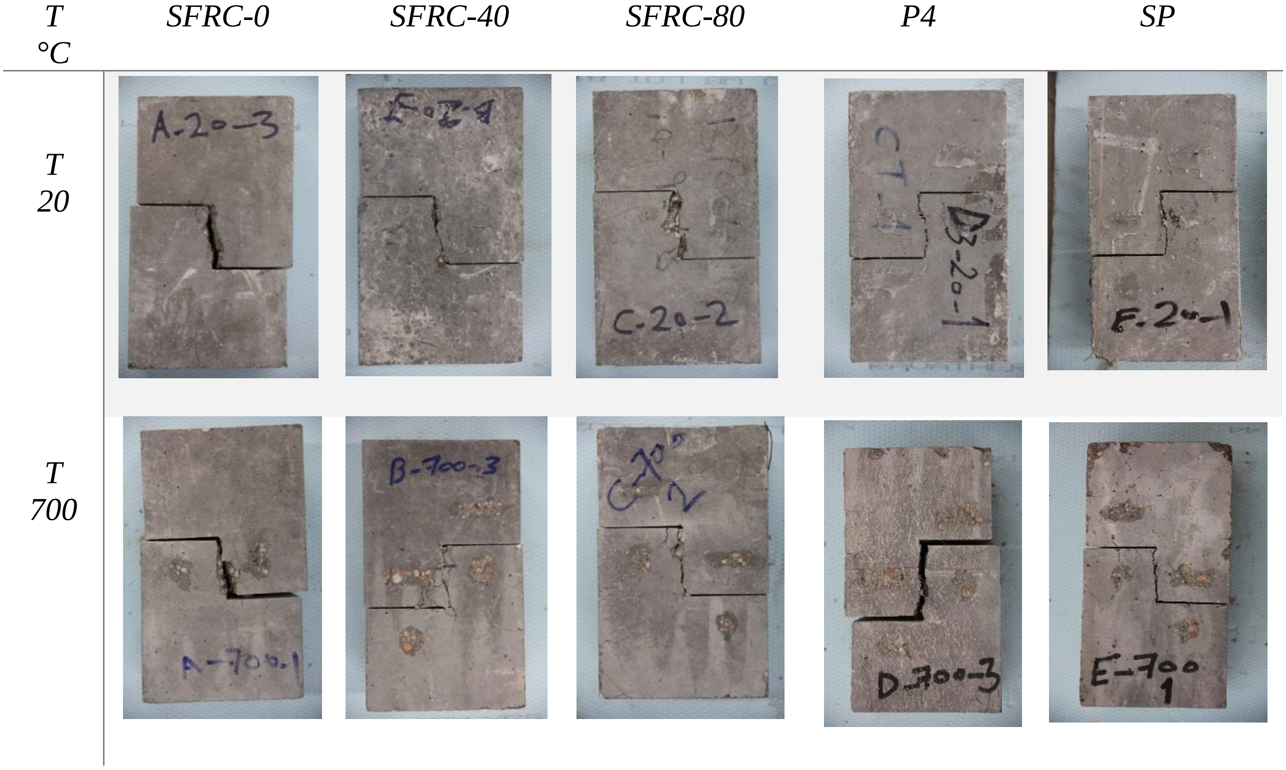


Figure 10: Different failure modes of the push-off specimens at 20 and 700 °C

5. Applications of the New Scientific Results and future perspectives

The experimental data presented in this thesis provides a comprehensive understanding of the shear performance of fibre reinforced concrete exposed to elevated temperatures. Using fibres as a substitutional material for the conventional reinforcement, partially or totally, has only been accepted recently in construction codes. Therefore, investigating the fibre reinforced concrete regarding the shear is of great importance. The adopted methodology includes using push-off model as the main model to represent the shear performance, in addition to several specimens of prisms and cubes for the other mechanical properties. Moreover, using LVDTs enables the research to cover several measurements for the shear performance, i.e., shear strength, shear toughness and shear stiffness that provided a better understanding for the targeted mechanical properties.

The current study establishes for further studies to be carried out using several parameters not used at the current study, such as investigating different types of fibres, investigating the size effect of the push-off model, investigating the difference between using uncracked or pre-cracked push-off model, investigating elevated temperatures above 700 °C, and investigating the difference between testing at the cold or hot state. Additionally, there was a lack of study in the research regarding shear toughness and shear stiffness at elevated temperatures, thus presenting the shear toughness and shear stiffness at the current study could be useful for the future studies regarding similar investigations. Finally, analytical model is necessary for future studies for the standardization process for the shear performance at elevated temperatures in FRC to be used in modelling or codes.

6. List of own publications

[NA1] **Alimrani, N**., Abdelmelek, N., Balázs, G.L. Lublóy, É, “Fire behaviour of concrete – influencing parameters”, *Journal Concrete Structures*, 2017, Vol 18, pp. 36-44. http://fib.bme.hu/folyoirat/cs/cs2017.pdf

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[NA7] **Alimrani, N**.,Balázs, G.L.,"Behavior of concrete at elevated temperatures in terms of shear failure using push-off model” *fib Symposium* 2019, pp 171-172 Krakow, Poland.

[NA8] **Alimrani, N**.,Balázs, G.L.,"Steel fibers on shear strength of concrete at room and elevated temperatures", *Third International Fire Safety Symposium* 2019, pp 331-339. Ottawa, Canada.

[NA9] Abdelmelek N., **Alimrani, N**., Krelias, N., Lublóy, É, “Metakaolin-based High Strength Concrete Exposed to Elevated Temperatures”. Submitted to *Journal of Building Engineering,* 2020.

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[NA11] **Alimrani, N.,** Balázs, G.L., “Effect of steel fibres on concrete at different temperatures in terms of shear failure. *Magazine of Concrete Research*, 2020. https://doi.org/10.1680/jmacr.19.00479. **IF: 2.088**

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[NA13] **Alimrani, N.S**. and Balazs, G.L., “Investigations of direct shear of one-year old SFRC after exposed to elevated temperatures”. *Construction and Building Materials*, 2020. https://doi.org/10.1016/j.conbuildmat.2020.119308. **IF: 4.419**

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