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EFFECT OF AGGREGATE TYPE ON THE FIRE RESISTANC OF NORMAL AND SELF-COMPACTING CONCRETES

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ABSTRACT

In this research, the influence of coarse aggregate type and incorporation of polypropylene fibres on the mechanical properties of normal concrete (NC) and self compacting concrete (SCC) were investigated. Three types of local aggregates namely natural gravel, basalt and dolomite were used. Fire resistance of the produced concrete in terms of residual strengths and spalling was studied. Different elevated degrees of temperature of 200, 400, 600 and 800 °C were considered. The latter degree of temperature (800 °C) was maintained constant while the effect of exposure durations of 15, 30, 60 and 120 minutes were investigated. Compressive strength, indirect tensile strength, porosity, near surface absorption and spalling were measured before and after exposure to elevated degrees of temperature.

The results indicated that, aggregate type has a minor effect on the concrete resistance to fire. However dolomite aggregates provided the highest resistance to fire while natural aggregate gave the least resistance. The incorporation of polypropylene fibres improved the indirect tensile strength results as well as the concrete resistance to spalling. It was also recorded that the degradation of the mechanical and permeation properties of SCC increases with increasing the degree of elevated temperature. It is worth mentioning that the performance of SCC exposed to high elevated degrees of temperature is better than that of the NC.

Key words: Self-compacting concrete, Fire, Coarse aggregate, Polypropylene fibres.

1. INTRODUCTION

Spalling is one of the major problems facing concrete structures subjected to elevated degrees of temperature. During exposure to fire, free and combined water inside the concrete start to evaporate and form pore pressure. This pressure builds up and induces stresses on the internal structure of the concrete elements. As long as the fire continues, the induced stresses increase gradually to a limit that exceeds the concrete tensile strength and consequently small scales and sometimes big portions fall out from the concrete surface which is known as spalling [1]. As a result, fire can be easily transmitted to the concrete cores and creates more pore pressure associated with more internal stresses that leads to a major reduction in the concrete strength and strength/stiffness of the reinforcing bars [2]. Due to the above negative effects, bonding between concrete and reinforcing bars will be greatly reduced [3] and as a result, differential thermal elongation between concrete and reinforcing bars as well as severe damage to the joints and connections between various structural elements will take place. Both structural integrity and load bearing capacity of the concrete structures will be jeopardized accordingly [2].

It was suggested that concretes with compressive strengths higher than 55 MPa are susceptible to spalling and are having lower fire resistance [5]. This could be attributed to the reduced permeability associated with the high strength concrete which hinders the release of the internal pore pressure and eventually causes concrete spalling. Moisture content of concrete sample expressed in terms of Relative Humidity also influences the extent of spalling, the higher the RH, the greater the spalling will be and the vice is versa [5, 6]. The extent of spalling was found to be much greater when light weight aggregate is used. This is because light weight aggregate contains more free moisture which creates higher vapour pressure under fire exposure [6]. The higher the fire intensity and heating rate the higher the concrete spalling will be. It was also suggested that, loaded high strength concrete members spall to a greater extent compared with the unloaded members, since the load adds more stresses to those created by the vapour pressure of the evaporated water [5, 6].

It has been advised that, bond strength between aggregate and the cement matrix depends on the mechanical keying of the hydration products of cement matrix with the rough aggregate surface. It also relies on the phyisco-chemical bond between the hydrating cement paste and the aggregate surface as a result of the chemical reaction at the interfacial transition zone [7-9]. It is quite clear that aggregate expands during heating while cement paste shrinks which is mainly due to loss of water. This leads to breaking the bond between the cement matrix and the coarse aggregates. The movement of the concrete during heating almost follows the deformation of the aggregate. Therefore, large deformations are imposed on the cement paste when concrete is subjected to high temperature [10, 11]. On the other hand, aggregate type plays an important role on the concrete spalling under fire conditions. Concrete made with carbonate aggregate (dolomite aggregate) provides better spalling resistance compared with natural siliceous aggregate concrete. This is because carbonate aggregate has a substantially higher heat capacity which is beneficial in preventing spalling [10]. As previously advised, polypropylene fibres improve the concrete efficiency against spalling in the case of fires [11].

Despite the fact that, the effect of aggregates type on the performance of normal concrete was previously studied however the subject was not fully covered for self-compacting concrete exposed to different degrees of fire temperature. In this study, the performance of SCC and NC made with three different types of local coarse aggregates under various degrees of temperature of 200, 400, 600 and 800^{o}C was investigated. Performance of SCC and NC has also been investigated under a constant fire temperature of 800^{o}C but with different exposure durations of 15, 30, 60 and 120 minutes. The present work extended to study the effect of incorporation of polypropylene fibres on the performance of SCC and on the extent of spalling when exposed to elevated degrees of temperature similar to those described above. Therefore the objectives of this study are summarized as follows:

1. Studying the effect of aggregate type namely natural gravel, dolomite and basalt aggregates on the fire resistance of NC and SCC. This resistance was evaluated in terms of residual compressive and tensile strength along with spalling, porosity and absorpativity of the produced normal and self compacting concrete. These concrete were exposed to elevated degrees of temperature of 200, 400, 600 and 800 °C. In addition, fire temperature was maintained at 800 °C and the concrete samples were exposed to different time durations of 15, 30, 60 and 120 minutes.

2. The research programme extended to study the effect of incorporation of polypropylene fibres on the mechanical and microstructure properties as well as spalling of NC and SCC exposed to elevated degrees of temperature similar to those explained above.

2. EXPERIMENTAL

2.1 Materials and Concrete Mix Proportions.

Local ordinary Portland cement (OPC) complying with the BS EN 197-1 and ESS 1658/1988 was used in all concrete mixes with a constant content of 400 kg/m3. Natural siliceous sand with a fineness modulus of 2.75 was used. Three coarse aggregates namely, natural gravel (G), basalt (B) and dolomite (D), with maximum aggregate size of 20 mm, were considered. The physical properties of the used coarse aggregates are presented in Table 1. Polypropylene fibres (PF) with a constant content of 0.5% of the cement mass was used in the preparation of concrete mixes wherever applicable as presented in Table 2. Limestone powder and self-compacting admixture (a mixture of high range water reducer and viscosity modifying agent, Sika Viscocrete- 5400) were utilized for producing SCC, at which a constant self-compacting admixture content of 0.75% of cement mass was regarded. Clean tap water with a constant free w/c ratio of 0.45 was used in concrete mixing. Twelve concrete mixes of NC and SCC were used to study the previously mentioned parameters. In each mix, 42 cubic specimens of 100 mm side length were cast for measuring the compressive strength, porosity and surface absorption before and after fire and the extent of spalling. While 15 cylindrical specimens of 100 mm diameter and 200 mm depth were also cast to evaluate the indirect tensile strength (splitting tensile strength) of concrete before and after exposure to fire.

2.2 Test Techniques and Procedures

The cast specimens were stored in water curing tanks at 21±2°C until testing age of 3, 7, 14 and 28 days for cubic specimens and only 28 days for cylindrical specimens. The samples were exposed to varying degrees of temperature of 200, 400, 600 and 800 °C. Heating rate of 8.8°C/min was applied to reach the desired degree of temperature. The samples were then left to cool in air at room temperature and then tested. The average compressive strength and the indirect tensile strength were then calculated using triplicate specimens.

Table 1 Physical properties of coarse aggregates.

Property	Dolomite		Basalt		Gravel
	Size1	Size2	Size1	Size2	
Specific weight	2.71	2.71	2.99	2.99	2.76
Bulk density (t/m^3)	1.85	1.7	1.89	1.8	1.82
Water absorption, %	2.85	2.15	2.86	2.17	1.85
Crushing value, %	19.3	18.65	19.5	18.75	14.3
Coefficient of abrasion	15	14.2	15	14.3	15.4
Clay and fine dust content	0.95	0.73	0.98	0.75	0.55

Table 2 Normal and self-compacting concrete mix proportions.

Mix Code	OPC, kg/m^3	Water, kg/m^3	Sand, kg/m^3	Coarse Aggregate Content , kg/m^3			Limestone Powder content kg/m^3	Self-compacting admixture, % wt of OPC	PF, % wt of OPC
				Type	Size 1 5-10 mm	Size 2 10-20 mm			
G NC	400	180	660	Gravel	720	660	-	-	-
G SCC	400	180	750	Gravel	500	550	80	0.75	-
D NC	400	180	660	Dolomite	720	660	-	-	-
D SCC	400	180	750	Dolomite	500	550	80	0.75	-
B NC	400	180	660	Basalt	670	730	-	-	-
B SCC	400	180	750	Basalt	500	550	80	0.75	-
PF GNC	400	180	660	Gravel	660	720	-	-	0.50
PFGSCC	400	180	750	Gravel	500	550	80	0.75	0.50
PF DNC	400	180	660	Dolomite	720	660	-	-	0.50
PFDSCC	400	180	750	Dolomite	500	550	80	0.75	0.50
PF BNC	400	180	660	Basalt	720	660	-	-	0.50
PFBSCC	400	180	750	Basalt	500	550	80	0.75	0.50

The porosity was determined to evaluate the degradation and the changes in pore structure of the concrete specimens. The test was carried out on 100 mm concrete cubes at an age of 28 days, before and after exposure to fire. After curing, the specimens were weighed in saturated-surface–dry condition (W1) and then oven dried at 105°C for 24 hours. The values of oven-dried weight of specimens (W2) and volume were measured. The value of porosity was then calculated using equation (1). The average result of triplicate specimens was regarded.

Porosity, % = [(W1 – W2) / V] x 100. ………………………..………… (EQ.1)

Water absorption by capillary action at an age of 28 days was also measured before and after exposure to fire to evaluate the degradation of surface layers. The test was carried out using a plastic container filled with water up to a depth of 20 mm. Steel bars of 18 mm diameter were placed at the bottom of container to maintain the water level to just above the top surface of the steel bars. The oven dried specimens were weighed (W2) after greasing and placing in the container over the steel bars for two hours such that the water level in the container was not more than 5.0 mm above the tested surface. The tested specimen was taken out from water and the surface water was removed using a damp cloth. The weight of the specimen was then recorded (W3), followed by estimating the % of surface absorption using equation (2). The average result of triplicate specimens was regarded.

Surface absorption, % = [(W3 – W2) / W2] x100………...………… (EQ.2)

2.3 FIRE PROGRAM

The aim of this research is to study the concrete resistance to fire through an exposure to a variable degree of elevated temperatures of 200, 400, 600 and 800 °C. In addition, the degree of temperature was maintained at 800°C while the exposure durations increased from 15 minutes to 120 minutes and passes by 30 and 60 minutes. To achieve these settings, the oven was set at a degree of temperature of 200°C with a heating rate of 8.8 °C/minute. Upon reaching the desired temperature degree, the concrete samples to be tested, were then removed from the oven and firing was continued to reach the following degree of temperature of 400 °C. The procedures were repeated for the remaining degrees of temperatures of 600 and 800 °C. Upon reaching the degree of temperature of 800 °C, the oven was kept on and the degree of temperature was maintained constant for a period of 120 minutes. While concrete samples were removed for testing at intermediate durations of 15, 30 and 60 minutes.

3. RESULTS AND DISCUSSION

Prior exposure to fire, the compressive and indirect tensile strength of normal concrete (NC) and self-compacting concrete (NC), that made with various aggregate types, were initially assessed at ages of 3, 7, 14 and 28 days. The effect of Polypropylene fibres on these parameters was also investigated. The results are presented in Table 3 and Figs. 1 to 4. As seen from the results plotted in Figs 1 and 2, dolomite aggregates provided the highest compressive strength results compared with that of basalt and natural aggregates for both SCC and NC at all ages of assessment. On the contrary, natural aggregate provided the least values. The recorded difference is about 5%. Polypropylene fibres have no effect on the obtained results of compressive strength. However, it greatly improved the splitting tensile strength results of NC and SCC, see Figs. 3 and 4.

Table 3 Compressive and indirect tensile strength of NC and SCC at different ages

Testing Age	Compressive strength of NC, kg/cm^2						Compressive strength of SCC, kg/cm^2					
	Gravel		Dolomite		Basalt		Gravel		Dolomite		Basalt	
	GNC	PF GNC	DNC	PF DNC	BNC	PF BNC	GSCC	PF GSCC	DSCC	PF DSCC	BSCC	PF BSCC
3-day	107	107	108	109	108	107	119	118	120	120.	119	120
7-day	266	266	270	271	269	269	293	292	296	295	294	294
14-day	302	302	310	311	306	306	330	330	334	334	331	331
28-day	355	355	360	360	357	357	390	391	396	395	394	394
28-day	Tensile Strength of NC, kg/cm^2						Tensile Strength of SCC, kg/cm^2					
	36	46	39	47	38	46	41	49	41	49	42	49

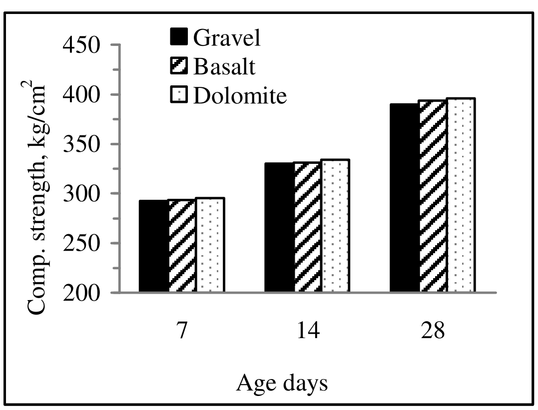


Fig. 1 Compressive strength of NC made with various types of coarse aggregates.

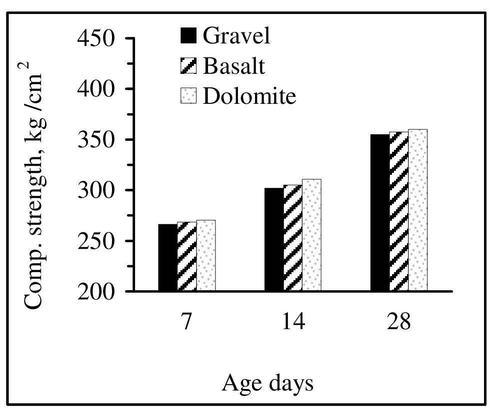


Fig. 2 Compressive strength of SCC made with various types of coarse aggregates.

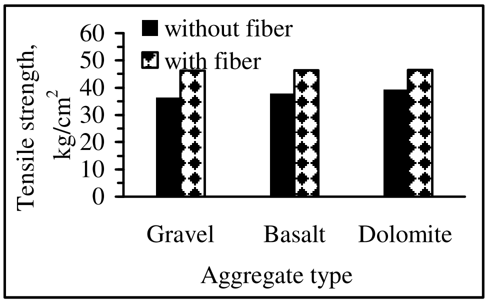


Fig. 3 Tensile strength of NC made with various types of coarse aggregates.

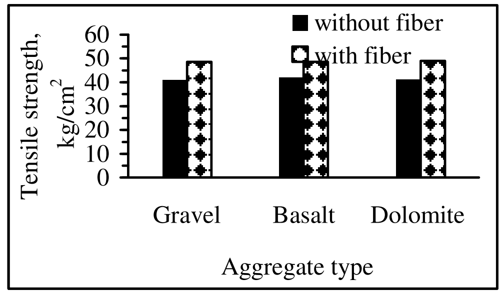
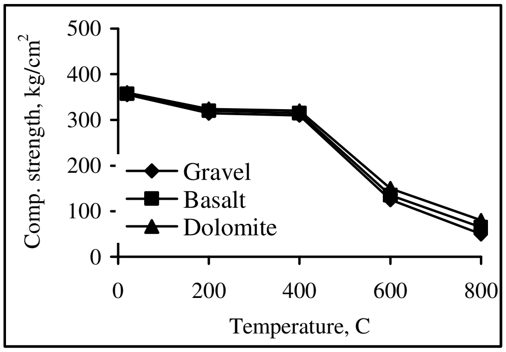


Fig. 4 Tensile strength of SCC made with various types of coarse aggregates.

This could be attributed to the bridging effect of the Polypropylene fibbers which postpones the initiation of cracks [13]. It can also be noticed that at the considered ages, compressive and tensile strength results of SCCs are higher than those of the NC (control). This could be attributed to the imperviousness achieved with the SCC as a result of using the fine filling particles that fill the concrete pores and thereby increasing the packing density of concrete which in turn improves both compressive and tensile strength values of concrete [14].

The effects of aggregate type on the compressive strength and % of residual compressive strength of NC and SCC after exposure to elevated degrees of temperature of 200, 400, 600 and 800°C are demonstrated in Figs. 5 to 8. As shown, the behaviour of NC and SCC at different elevated temperatures are almost similar. It was also noticed that the aggregate type has a minor effect on the obtained results of compressive strength and % of residual compressive strength for both NC and SCC up to 400 ºC. Beyond this level of temperature, increasing the exposure temperature caused a major reduction in the concrete compressive strength. However, dolomite aggregates concrete provided higher values of compressive strength in the range of 5 to 10% compared with that of basalt and natural gravel. Violeta [14] returned this to the rapid volume change resulting from the inversion of α to β- quartz in the siliceous (natural) aggregate when exposed to an elevated degree of temperature of about 570°C.



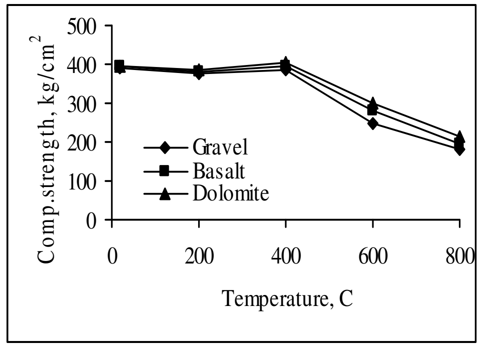
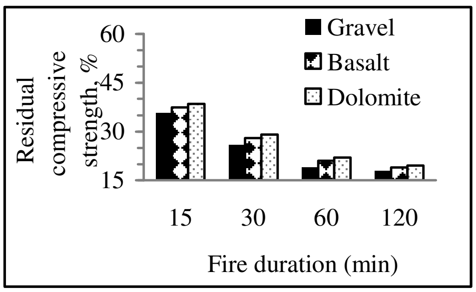


Fig. 5 Compressive strength of NC exposed to various elevated temperatures.

Fig. 6 Compressive strength of SCC exposed to various elevated temperatures.



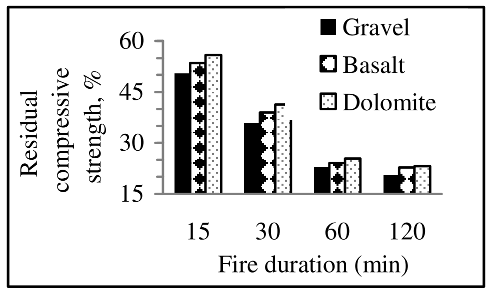


Fig. 7 Effect of aggregate type on the % of residual compressive strength of NC exposed to 800°C.

Fig. 8 Effect of aggregate type on the % of residual compressive strength of SCC exposed to 800°C.

In addition, at a constant degree of fire temperature of 800°C, the residual compressive strength is dramatically reduced with increasing the exposure durations for both NC and SCC regardless of the used aggregate type. This reflects the extent f damage that occurred to the concrete specimens with increasing the fire durations.

The percentage of residual splitting tensile strength of NC and SCC made with different types of coarse aggregates are presented in Fig. 9. It can be seen that, the residual tensile strength decreases with increasing the degree of temperature for both NC and SCC regardless of the used aggregate type. This agrees with previous findings by Ushijima et al 1995 [16] in which percentage of residual tensile strength of NC made with siliceous (natural) aggregate were 85, 75, 60 and 50% when exposed to an elevated degree of temperatures of 150, 250, 350 and 450 °C respectively. Similarly and as mentioned in the same study [16] NC made with dolomites aggregates gave a reduction percentages of residual tensile strength of 55, 45 and 30 when exposed to an elevated degree of temperature of 220, 320 and 420 °C, respectively. As presented in Fig.9 the reduction in the indirect tensile strength is the least for dolomite aggregate concrete and is utmost for natural aggregate concrete when exposed to fire for both NC and SCC. At an elevated degree of temperature of 400 °C, the % of the residual indirect tensile strength of dolomite aggregate concrete is 8% and 6% for NC and SCC, respectively, which is higher than that of natural aggregate concrete.

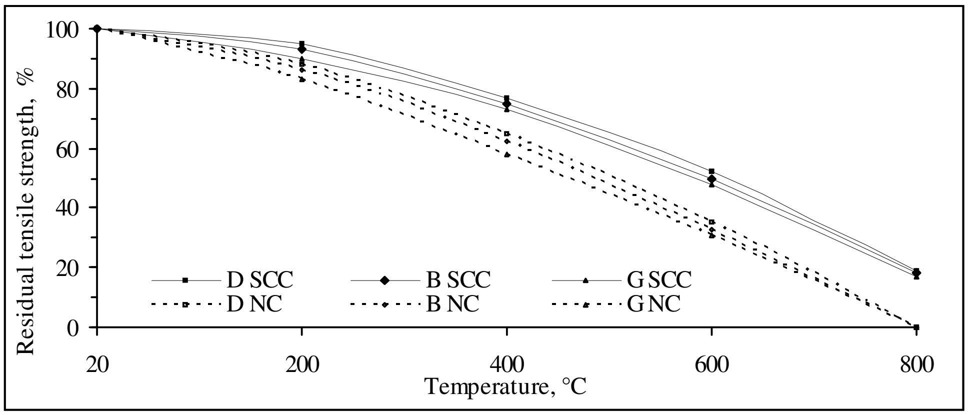


Fig. 9 Effect of aggregate type on the percentage of residual tensile strength of NC and SCC at elevated degrees of temperature.

The results of porosity of NC and SCC made with different aggregate types and exposed to elevated degree of temperatures are presented in Fig. 10. As noted, the total porosity is slightly increased at the initial stage of fire (up to 200°C) for all used aggregate and concrete type. Beyond 200 °C, the increase in the fire temperature is accompanied by an increase in the obtained porosity. Increasing the fire temperature from 200 to 400 °C caused an increase in the total porosity of about 8% for SCC and 12% for NC regardless of the used aggregate type. However at later stage of fire, (between 400 to 800 °C), the rate of increase in the porosity becomes more sharp. For gravel aggregate concrete, the difference in porosity achieved when the fire temperature increased from 400 to 800 is 16% for SCC and 24% for NC. However in case of dolomite aggregate concrete, the obtained difference is 12% for SCC and 18% for NC. This can be attributed to the change of concrete from impermeable to permeable material due to the consumption of fine materials in the concrete matrix as result of burning. In other words the concrete changes from dense material to porous material by the effect of high temperature [17]. Despite the fact that aggregate type has a minor role on the porosity of concrete, it can be noticed that deterioration of the dolomite aggregate specimens is less than that of the siliceous aggregate (natural) due to the fact that dolomite aggregate is less dense compared with other types of aggregates and as previously mentioned more porosity leads to less spalling and less cracking when exposed to fire. In addition the carbon dioxide released during the decomposition of dolomite aggregates acts as a fire suppression system which limit the effect of elevated degree of temperature on dolomite aggregate concrete. In view of the above, it can be recommended that after exposure to elevated degree of temperature and thereby increasing the concrete porosity, most of the structural elements need to be painted to prevent or minimize the moisture penetration.

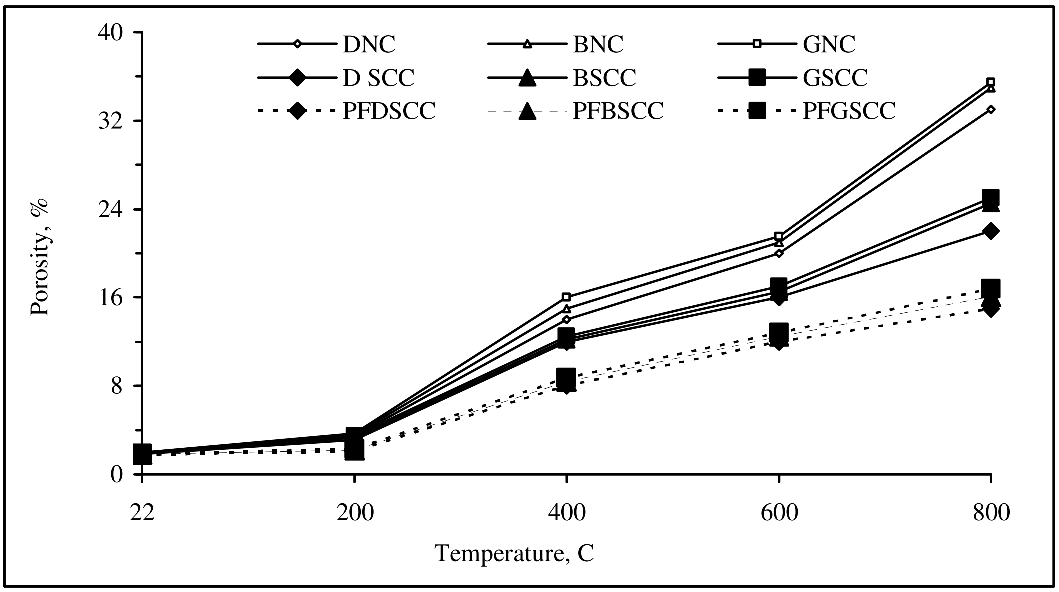


Fig. 10 Effect of aggregate type and incorporation of polypropylene Fibres on the porosity of NC and SCC exposed to various elevated degree of temperatures

Fig.10 also shows that incorporation of polypropylene fibres caused a reduction in the concrete porosity regardless of the used aggregate and concrete type. The reduction increases with increasing the degree of fire temperature. This could be attributed to the increased tensile strength values of concrete and thereby increasing the concrete resistance to cracking. The incorporation of fibres did not change the behaviour of aggregate type on the produced porosity but improved the entire results.

The surface absorpativity of SCC made with different types of aggregates and exposed to elevated degree of temperature are presented in Fig. 11 It is logical that, the absorpativity of concrete sample increase when exposed to fire. As shown in this figure, for a constant degree of temperature of 800^{o}C, increasing the fire exposure duration caused an increase in the absorpativity for all types of the used aggregate. The performance of dolomite aggregate is slightly better than that of basalt while natural aggregates provided the least performance of the three. The trend of the results obtained with the surface absorption after exposure to fire is similar to those of the porosity when exposed to the same conditions.

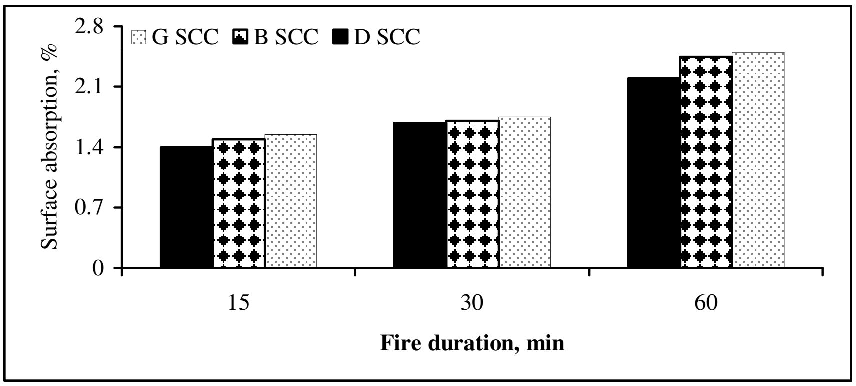


Fig. 11 Effect of aggregate type on the Absorpativity of SCC exposed to an elevated degree of temperature of 800°C for various periods of duration.

Finally, the % of spalling of various concretes investigated in this study was monitored, as illustrated in Figs.12 and 13. It can be noted that, % of spalling for natural gravel NC is about 0.9, 1.6, 8 and 8.7 %, when exposed to an elevated degree of temperature of 800 ºC for time duration of 15, 30, 60 and 120 minutes, respectively. In general the spalling of natural gravel NC is higher than that of SCC under same conditions. It is worth mentioning that the rate of spalling increases sharply when the concrete exposed to an elevated degree of temperature of 800 °C for duration of between 30 and 60 minutes and decreases after that. This is because, up to time duration of 60 minutes, most of concrete water evaporates and induces stresses that exceed the tensile strength of concrete and thereby causing local failure and loss of mass which is known as spalling. However, beyond the exposure duration of 60 minutes, concrete starts to be permeable and most of the concrete water is evaporated. This decreases the pore pressure and accordingly reducing the rate of increasing of spalling.

Fig. 12 illustrated that the presence of fibres led to a large reduction in the percentage of spalling as a result of increasing the tensile strength of concrete that should be overcome by the induced stresses to reach the stage of failure. Similarly spalling as shown in Fig.13 in dolomite SCC specimen is less than of basalt and gravel aggregates. This is because the dolomite aggregate has more porosity and thereby it can accommodate some of the induced pressures in addition to its low conductivity which leads to higher resistance to fire effects compared with the other types of aggregates. It worth mentioning that natural aggregates splits and it peel off from the adjacent cement matrix when it fails under the effect of fire while the dolomite aggregates peels off to fine powder under the effect of fire.

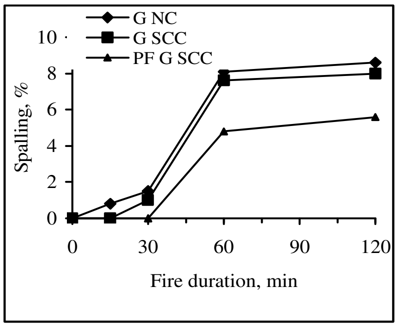


Fig. 12 % spalling for NC, SCC and SCC Containing PF.

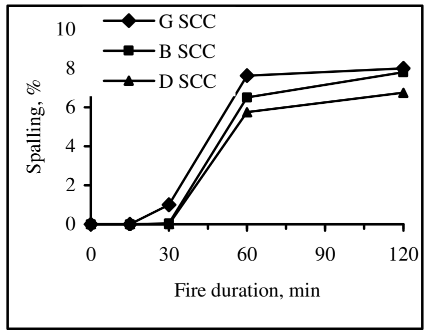


Fig. 13 Effect of aggregate type on the % of spalling.

4. CONCLUSIONS

The following conclusions can be drawn from this research program:

1- Dolomite aggregates provided the highest compressive and indirect tensile strength results compared with that of basalt and natural aggregates for both normal and self-compacting concrete at all ages. On the contrary natural aggregates provided the least values at all ages. Similar behaviour was obtained after concrete exposing the concrete to elevated degrees of temperature.

2- Self-compacting concrete (SCC) provided slightly higher values of compressive and indirect tensile strength results compared with that of normal concrete (NC) before and after exposure to fire regardless of the used aggregate type and testing age.

3- The incorporation of polypropylene fibres improved the values of indirect tensile strength results of NC and SCC before and after exposure to fire.

4- Increasing the degree of fire temperature caused a major reduction to the values of compressive and indirect tensile strength of NC and SCC regardless of the used aggregates type. Residual compressive strength of dolomite aggregate is higher than that of the basalt and natural aggregates for both NC and SCC.

5- Porosity and surface absorpativity of SCC and NC increased substantially with increasing the degree of fire temperature and time duration of exposure to fire. Dolomite aggregates provided the least increase, while the natural aggregates provided the highest ones. However, when these abovementioned properties were regarded, SCC showed better performance compared with that of the NC.

6- Spalling of both NC and SCC decreases with the use of dolomite aggregate, and incorporation of polypropylene fibres.

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