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Mix design, compressive strength and resistance to elevated temperature (500°C) of self-compacting concretes containing limestone and quartz fillers

S. Bakhtiyari[1], A. Allahverdi[2,*], M. Rais-Ghasemi[3], A. A. Ramezanianpour[4], T. Parhizkar[5], B. A. Zarrabi[6]

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Abstract

Self Compacting Concrete (SCC) specimens with limestone (L) and quartz (Q) powders were formulated. The influence of the type of the powder on the properties of fresh and hardened concrete was evaluated. Dense packing theories were used for mix design of samples. The equation of Fuller and Thompson for particle size distribution (PSD) of aggregates was modified with considering fine particles and a proper PSD curve was obtained for SCC. Experimental results showed that this method needs use of less powder content and results in higher strength/cement ratio compared to traditional mixing methods. No significant difference was observed between the compressive strengths of specimens containing limestone (L-specimens) and quartz (Q-specimens) powders, with similar proportions of materials. The residual compressive strength of specimens was examined at 500°C and contradictory behaviors were observed. One Q-specimen suffered from explosive spalling, while no spalling was occurred for L-specimens. On the other hand, the residual strength of remained Q-specimens showed considerable increase compared to L-specimens. The results show the necessity for more detailed investigations considering different effective parameters.

Keywords: Concrete, Self-compacting, Mix design, Packing density, Fire resistance.

1. Introduction

Self-compacting concrete (SCC) is a fairly new type of concrete [1-3]. It fills all sections of forms without mechanical vibration and has reasonable flow-ability, homogeneity, resistance against segregation and mechanical strengths [1-9]. The key point to achieve self-compacting property is providing high flow-ability and deformability, while maintaining resistance to segregation and sedimentation. This can be achieved by proper balance between constituent materials. Okamura and Ozawa [1, 2, 10] proposed limiting of volume of coarse aggregates, along with use of high amount of powders, controlling the water-powder ratio by volume and use of proper super-plasticizers.

Domone [11] showed the wide use of these mixing rules in application with a wide statistical analysis on 68 commercial projects through the world. Nan-Su [12] presented a mixing method for SCC, in which the packing factor of aggregates determines the need to paste. Packing density is a key concept for achieving high performance concretes. Higher packing density of aggregates means less space between the grains and less paste demand. A better packing of powders will also decrease water demand, which in turn decrease the porosity of hardened paste in the vicinity of the wall of aggregates and improves the quality of transition zone [13-16]. Ideal and Good grading curves have been presented for minimizing the space between grains, among them modified Fuller and Thompson curves should be mentioned [17]:

$$YT_i = 100\left(\frac{x_i - x_0}{x_{\max} - x_0}\right)^n$$

in which: YT_i: percentage of material passing sieve x_i, x_i: size (mm) of the sieve i, xmax: maximum aggregate size (mm) and x_0 = 0.075 mm (for removing clays and silt sizes).

* *Corresponding Author: ali.allahverdi@iust.ac.ir*
1 1. PhD student, School of Chem. Eng., Iran University of Science and Technology (IUST), Tehran, Iran
2 Associate Professor, Cement Research Center, School of Chemical Engineering, IUST, Tehran, Iran
3 Associate Professor, Cement Research Center, School of Chemical Engineering, IUST, Tehran, Iran
4 Professor, School of Civil Engineering, Amirkabir University of Technology, Tehran, Iran
5 Assistant Professor, BHRC, Dep. of Concrete Technology, Tehran, Iran
6 PhD, Fire Technology Dept., SP Technical Research Institute, Sweden

Andreasen and Andersen (A&A) [18] showed that the optimum packing is obtained with n = 0.37. Brouwers showed that for various sizes of the sand (for ranges 0-1, 0-2 and 0-4 mm), ratios of 40/60 to 60/40 of the sand/gravel results in the best packing and the lowest void fraction in both loose and compacted condition [19]. Coarse sand (0-4 mm) attained minimum void fraction at 60% in combination with gravel [19]. Ghoddousi has presented a model for estimating the aggregate content of self compacting fiber reinforced concrete [20].

The mechanical properties of SCC have been reviewed by Domone [21]. He concluded that the sufficient data had been obtained to give confidence in the general behavior of SCC, and future studies would be in need for focused on specific or confirmatory data for particular applications. Foroughi et. al. investigated the bond strength of reinforcement steel in SCC [22].

Fire resistance is one of the important requirements for construction elements. It is a property of building materials that prevents or retards the passage of excessive heat or flame under conditions of use. The fire test methods and philosophies are discussed in reference [23]. The main reasons for failure of a concrete element at high temperatures are spalling and loss of strength. The kind of powder in SCC may significantly affect both of these behaviors. Moreover, the compressive strength of concrete has an important influence on its fire behavior. A higher compressive strength is usually seen with more packing and less porosity, which may lead to higher pore pressures and spalling [24-26]. As SCC is a fairly new type of concrete, therefore only a few researches have been carried out on its fire resistance yet [27]. Boström [27] showed with full scale fire resistance tests that the SCC is more sensitive to spalling relative to the normal concretes (NC). It has been shown that the SCC pastes have different behavior and microstructure at high temperatures relative to the NC and the HPC pastes [28, 29]. Boström et. al. [30] investigated the effects of size and loading condition on spalling of SCC. Blontrock [31] studied the spalling behavior of some SCC samples and concluded that the type of filling powders, moisture content and the compressive strength are important parameters that their influences on fire behavior and spalling of SCC should be investigated. Bakhtiyari et. al. [32] investigated the influence of curing condition on the fire resistance of SCC with limestone powder and normal concrete. They cured the specimens in the insulating concrete formwork (ICF) and compared it with the specimens cured at normal traditional condition. They showed that the SCC is more susceptible to spalling than the normal vibrated concretes. They also concluded that the ICF permanent form raises the risk of spalling at early ages of the concrete, relative to normal traditional curing condition, due to high moisture content of the concrete in the ICF system.

In this study, SCC mixes with two different classes of compressive strengths have been formulated. Dense packing theories were used for mix design of samples. The use of this method can be useful for reducing cement consumption, while grasping reasonable compressive strength and more durability. The addition of silica fume (SF) is common in high strength concretes, as well as in concretes exposed to severe conditions, like marine environments [33]. It has pozzolanic effect and can change the microstructure of the concrete. Therefore; SF was also added in the formulation of the produced high strength mixtures, for examining its effect on fire behavior of the samples. The compressive strength and fire resistance of the hardened samples were tested. The effects of the type of the used powders and the compressive strength on fire behavior of samples were investigated. The results can show how these parameters (compressive strength and filling powders) can affect the fire resistance of the SCC and whether the type of filling powder can importantly influence the fire resistance of the SCC. As the SCC is a fairly new type of concrete, the resulted data are also significant for assessment of fire behavior of SCC and especially its risk to spalling, which is very important in application.

2. Experimental procedure

2.1. Materials

The used powders consisted of ASTM standard type 2 Portland cement (PC) and very fine L- and Q-fillers. Specific surface (Blaine) of PC was 2810 cm^2/gr, its expansion in autoclave was 0.24% and its 3-, 7- and 28-day compressive strengths were acceptable according to the standard specification. The results of chemical analysis of powders, including PC and fillers, are given in Table 1. Using Bogue's equation, the cement phases were computed as following: C_3S = 48.43, C_2S = 24.19, C_3A = 4.01, C_4AF = 12.32. As it is seen in Table 1, the used powders have good purity; hence the influence of the main compositions of powders ($CaCO_3$ and SiO_2) can be well assessed without worry about the influence of the other one.

Standard aggregates, complied with ASTM C33 were used. The used aggregates were of three size fractions, consisting natural sand (0-4.75 mm), crushed coarse aggregate (4.75-12.5 mm) (gravel 1) and partial-crushed coarse aggregate (9.5-19 mm) (gravel 2). The PSD-curves of aggregates are shown in Figure 1.

The water absorption and density of aggregates and percentage of particles passed from the 75 μm sieve are presented in Table 2. All the three fractions of aggregates were analyzed chemically. The results were quite close to each other, showing that aggregates consisted of about 61% SiO_2, 12% Al_2O_3, 9.8% CaO and 8.5% ignition loss.

A commercial Ether-carboxylic based product was used as super-plasticizer.

Table 1. Chemical analysis of powders

Constituent	PC	Q-powder	L-powder
Ignition loss	2.80	0.22	43.42
SiO_2	21.18	96.94	0.3
CaO	61.72	0.82	54.32
Al_2O_3	4.10	1.18	0.48
Fe_2O_3	4.05		
MgO	1.20		
$Na_2O + 0.658\ K_2O$	0.60		
SO_3	2.99		
Free Lime	1.56		

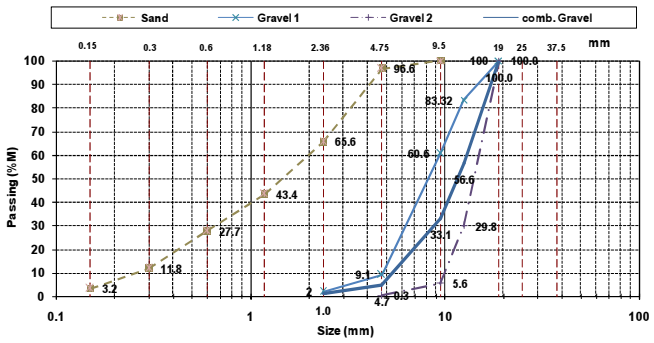

Fig. 1. The PSD-curves of the used aggregates

2.2. Test methods

Slump flow test was carried out by using a traditional slump cone according to ASTM C 1611:2006. The average spread flow diameter and T50 was measured. V funnel and L box tests were also carried out according to the European guidelines for self compacting concrete [34]. Good discussions on test methods for SCC flow properties of SCC concretes are presented in [8, 35]. Specific gravity of fresh concrete was determined based on EN 12350-6:2000.

Compressive and tensile strengths were measured according to EN 12390-3:2000 and ASTM C496 (Brazilian splitting method) respectively. Cubic specimens with 150 mm sides and cylindrical specimens with 150 mm diameter × 300 mm height was made for compressive and tensile tests respectively. For trial mixes, only compressive strength was tested. Tests were carried out at two different ages of 7 and 28 days. The reported values are average of 3 specimens.

For evaluating the fire resistance of the specimens, the residual compressive strength of specimens was measured after 2 hours exposure to 500 °C in a laboratory furnace. The fire resistance was evaluated at the age of 28 days and two specimens were tested for each mixture. Twenty minutes was required for the furnace to reach the temperature 500°C. After 2 hours of exposure, the furnace was turned off and the specimens were left in the furnace for about 24 hours to reach to room temperature. The residual mass and compressive strength of the specimens were measured after assessing their appearance visually and photographing.

DSC/TG thermal analysis tests were performed with a Netsch apparatus, STA 449C, Jupiter. A temperature rise rate of 10°C/min was used for the tests, at atmospheric pressure, in air.

2.3. Mixing method

A Pan mixer with the nominal capacity of 250 liters was utilized. After correcting the moisture content of the aggregates, all the components were weighted. At first, aggregate and filler were mixed for 30 seconds. Then cement was added and the mixer was turned on. For mixes containing SF, SF slurry was prepared and added during mixing. After two minutes mixing, super-plasticizer was added to achieve an apparent proper flow-ability and mixing was continued for about one more minute. Then the mixer was turned off for two minutes for aggregates to have enough time to absorb water. Next, the mixer was turned on again for two minutes and if a loss of flow-ability was seen, more super-plasticizer was added.

2.4. Specimens molding and curing

Castings of the specimens were carried out according to EN 12390-2:2000 standard. After keeping in moist condition for approximately 24 hours, they were demolded and maintained under water at 23 C for 7 days. Thereafter, they were kept in controlled laboratory condition (25± 5°C and 42± 3% humidity) until testing time. This curing condition was preferred because it was closer to the actual conditions of use in comparison to curing under water for the entire 28 days. The other reason was that if the samples were kept under water for the entire curing time, before testing in the furnace, the tendency to explosive spalling had been very high. This viewpoint was also taken into account by other researchers [30, 36, 37] for the same reasons.

3. Results and discussion

3.1. Mix design and fresh concrete properties

The principle of dense packing was considered in mix design of samples. The Fuller-Thompson curve was considered as a base for this purpose. The data presented in Domone analyses [11] and mixing methods for normal vibrated concretes (ACI 211.1) were considered for determining the proportions of initial trial mixes. It should be noted that acquiring a maximum packing was not an objective of the study, therefore very fine powders were not used in the mixes. Necessary tests were carried out on the fresh concretes to check the self-compacting properties of mixes. This included slump flow, flow velocity T50, V funnel and L box tests. For evaluating the test results, the class 2 of filling ability of the recommendations of the Japanese Society of Civil Engineering (JSCE) [38] was considered as a reference.

Table 2. Some characteristics of the used aggregates

Characteristic	SSD (g/cm^3)	Dry density (g/cm^3)	Water abs. in SSD (%)	Particles < 75 μm (%)
Sand	2.56	2.49	3.22	1.86
Gravel 1	2.58	2.53	1.99	0.3
Gravel 2	2.57	2.54	1.98	0.25

SSD = surface saturated density

At first a number of trial mixes were made using type II PC and Q-powder as filler. Finally, the mixture S4 in the Table 3 fulfilled the needed properties, in both fresh and hardened concrete (Table 4 and Table 5), as discussed in the following. The given instructions of JSCE [38] recommend a T_{50} in the range of 3-15 seconds for class 2 SCC. The accepted value for T_{50} is 2 to 5 seconds in Germany and the Netherlands, as addressed by Brouwers [19]. The acceptable V funnel flowing time range is mentioned 5-15 and 7-20 seconds by Brouwers [19] and JSCE [38], respectively. Acceptable values for fresh SCC test results have been mentioned by Bosiljkov [39] as following: slump flow between 650-750 mm, V funnel flowing time: 5-15 seconds, blockage ratio (h_2/h_1) in L-box: greater than 0.8. The behavior of S4 mixture was in good agreement with these values. A modified curve of Fuller-Thompson was acquired for aggregate grading of S4 mixture with n=0.3 and x0=0.002 mm.

Based on this mix, the composition with compressive strength of 50 MPa (on cubic specimen) was set. As the study on effects of fillers types was one of the aims of this research, hence the same proportions were used for mixes containing L-powder. It was attempted to achieve similar flow-ability properties by controlling the amount of super-plasticizer. The final mixtures and their properties in the fresh concrete state are depicted in Table 3 and Table 4, respectively.

The results showed that Q-specimens required more super-plasticizer (about 1.5-1.8 times) than L-specimens to satisfy approximately the equal slump-flow values. This was probably due to the shape of L-particles and/or their nature of having no or less tendency to flocculate in aqueous media.

3.1.1. The influences of packing density theories on mix design

A modified curve of Fuller-Thompson was acquired for aggregate grading of SCC mixtures, which has been introduced as modified Fuller and Thompson (F & T) curve in Figure 2, with n = 0.3 and D_{min} = 0.002 mm. A comparison of the resulted mixes with those obtained by Bosiljkov [39], gives interesting results from the viewpoint of mix design methods of SCC. Bosiljkov used the Japanese method presented by Okamura and Ozawa [10]. High volume of the paste used in this method usually causes compressive strengths higher than design requirements [19, 40]. Comparison of his achieved mixture, consisting of 380 kg/m^3 Portland cement, with our mixtures shows the good influences of application of packing density theories in mix design of SCC. In Bosiljkov experience, viscosity modifying agent (VMA) was used in all mixes. The used powder was a limestone type with fineness and composition similar to ours, but the used PC was finer (80% below 30 microns). The flow-abilities of his final mixes were very similar to ours. Comparison of the results of our work with the results of Brouwers [19] and Bosiljkov [39] shows the advantages of dense packing principles in optimizing the composition of SCC. Particularly, the needed amount of cement and the total amount of powders can be considerably reduced.

Table 3. Proportions of final SCC mixes with Limestone and Quartz fillers

Code	PC (kg/m^3)	SF (kg/m^3)	CA (kg/m^3)		FA (kg/m^3)		P (kg/m^3)	Powder type	W (kg/m^3)	SP (% of PC)
			4.75-12.5 (mm)	12.5-19 (mm)	0-2 (mm)	0-5 (mm)				
S4	320	0	313	313	306	715	185	Q	175	1.35
S5	372	28	312	317	301	728	120	Q	160	1.55
C4	320	0	313	313	306	715	185	L	175	0.88
C5	372	28	312	317	301	728	120	L	160	0.85

PC = Portland cement, SF = Silica fume, CA = Coarse aggregate, FA = Fine aggregate, P = Powder content, W = Water content, SP = super-plasticizer.

Table 4. Test results on fresh SCC mixes

Code	SLF (mm)	T_{500} (s)	h_2/h_1 in box test	V flowing time (s)	V funnel T5 (s)	Specific gravity (kg/m^3)
S4	640	2.0	0.84	4.0	4.0	2265
S5	670	2.2	0.89	4.0	5.5	2338
C4	710	1.0	0.85	3.5	4.0	2290
C5	630	1.5	0.85	4.0	4.0	2310

SLF = slump flow

Table 5. Compressive and tensile strengths of final mixes

Code	28-day comp. strength (cube) (MPa)	x parameter (MPa/kg cement)	28-day tensile Strength (MPa)
S4	41.0	0.128	3.5
S5	52.2	0.140	3.7
C4	40.4	0.126	3.2
C5	52.6	0.141	3.4

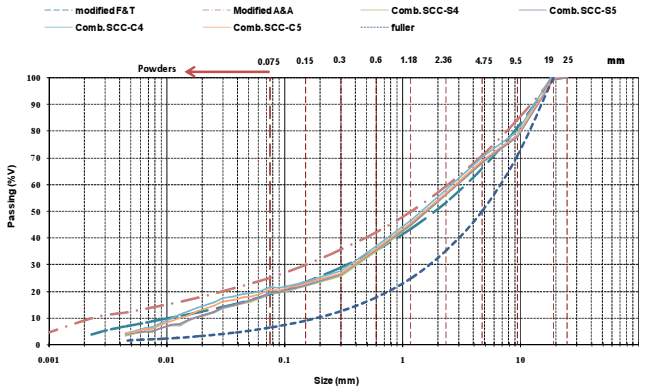

Fig. 2. Comparison of PSD curves of different SCC mixes and dense packing grading curves

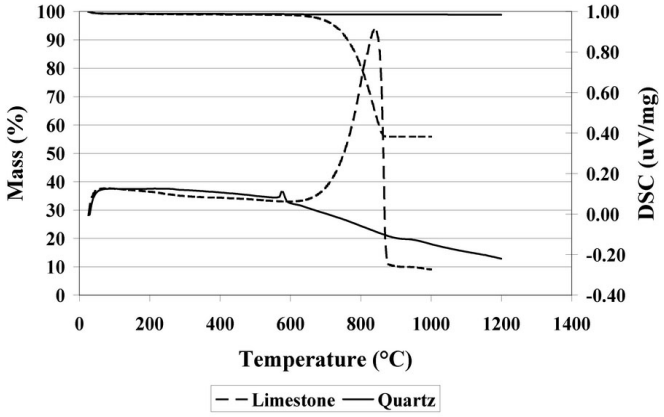

Fig. 3. DSC/TG curves of limestone and quartz powders

3.2 Evaluation of Pozzolanic activity of quartz powder

Pozzolanic activity of Q-powder was assessed with thermal analysis method. This test was needed for discussions on fire resistance results, which is presented in the following sections. A paste of powder/hydrated lime of equal proportions was prepared and was cured for 9 days in a sealed cylinder in 50°C. After 9 days, DSC/TG analysis tests carried out on the specimens and their pozzolanic activity was computed based on the remaining mass of the free lime. Q-powder showed about 26% pozzolanic activity.

3.3 Thermal analysis of powders

For a better assessment of the effects of thermal behavior of the used powders on the fire behavior of the concretes, DSC/TG tests were performed on the powders. The results are presented in Figure 3. The mass of the Q-powder was almost constant up to 1200°C, indicating that it did not decompose with temperature. The peak at 576.2°C and the slope change at 893°C on the DSC curve of the Q-powder are related to the changes of the crystalline structure of quartz from α to β and from β-quartz to tridymite, respectively. As the crystalline change from α to β is along with a partial expansion, it can produce some distress in concrete at temperatures around 570 °C.

The TG curve of calcium carbonate showed 43% weight loss, which started at about 650°C and continued up to about 860°C. The peak of 841°C on DSC curve of calcium carbonate is related to decomposition of $CaCO_3$ to CaO and CO_2. This also means distresses to concrete due to carbonation of the powder (and also carbonate aggregates) around 700-800°C temperatures.

3.4. Compressive and tensile strengths

The 28-day compressive and the tensile strengths of final mixes, along with their indices of cement content function, are presented in Table 5. Compressive strengths of mixes containing Q- and L-powder didn't show a significant difference. Addition of each of these powders helps in hydration and strength development. As seen in above sections, the tests confirmed about 26% partial pozzolanic activity of the Q powder. Hence it doesn't act only as inert filler, but also it can improve mechanical strength of concrete through changes brought about by pozzolanic reactions. On the other hand, the used L-powder was finer than Q-powder and therefore, as shown by the other researchers [14, 43-45] could better improve the packing density of the mix. It has been also shown that fine fillers can improve the quality of transition zone of the hardened concrete [43-47].

Su [12] introduced index of cement content function or x-parameter as "compressive strength/cement content" ratio. It is a useful parameter for comparing the performance of cement content of different mixes. The achieved x parameters for our mixes were 0.127 and 0.14 for 40 and 50 MPa samples, respectively, based on the amount of the used PC. Adding the amount of SF to the total cement content in S5 and C5 samples, an average x parameter of 0.13 is achieved. Su [12] and Brouwers [19] reported values of 0.14 and 0.15 for x-parameters of their experiments, respectively. The used cement was normal PC in experiments of Su and CEM III/42.5 in Brouwer's one. A comparison of x-parameters obtained in this research with those reported by Brouwers [19] and Bosiljkov [39] indicates again the advantage of using principles of dense packing in mix design of SCC, which can results in reduction of cement consumption for achieving a specified strength, in comparison to traditional SCC mix designs presented by Okammura and his coworkers [1, 2 and 10].

3.5. Fire resistance

The residual mass and compressive strengths of the tested specimens, after exposure to elevated temperature, are shown in Table 6. Two specimens were tested for each recipe to acquire more reliable results. The reported compressive strength of the control samples represents average of 3 specimens, cured for 28 days in a condition similar to the fire test specimens.

Time needed for reaching to the target temperature was 20 minutes. This duration is much closer to the standard fire curves (like ISO 834-1:1999) in comparison with the most of the studied published works in scientific literature, which have

Table 6. The residual strength and mass loss of specimens after furnace test

Code	Comp St. of control specimen, av. (MPa)	Residual Comp. St, av. (MPa)	Relative strength, av. (%)	Mass loss, av. (%)	No. of spalled specimens
SCC-S4	43.2 ± 1.1	(51.3)*	(1.19)*	6.4#	1
SCC-S5	56.3 ± 0.3	76.7	1.36	6.1	0
SCC-C4	42.4 ± 0.9	37.2	0.88	5.5	0
SCC-C5	55.3 ± 0.8	49.0	0.89	5.8	0

*. One specimen was explosively spalled at 500 °C
#. For unspalled specimen

been carried out in small-scale. For example, the temperature increase rate was 1°C/min, in Noumowe studies [48]. The possibility of spalling of a concrete is very low at such a condition. Many researchers have also used a rising rate of 5-10°C/min (like ref. 24), which still is a relatively low rate compared to standard time-temperature curves in fire resistance tests and reduces the possibility of spalling of concrete samples [25].

One of the SCC-S4 specimens failed with an explosive spalling during its exposure to high temperature in the furnace. The residual strength of the second specimen of the sample SCC-S4 was higher than the reference specimen. SCC-S5 specimens showed different behavior in comparison to SCC-S4 ones. They didn't experience any spalling and their relative residual strength was considerably higher than those of class 40 MPa specimens. The increases of residual strengths of Q-powder contained specimens were considerable (about 18% for SCC-S4 and 36% for SCC-S5).

The partial pozzolanic activity of the used Q-powder, the pozzolanic effect of SF and the accelerated hydration of cement at high temperature can be the reasons of these behaviors. The accelerated hydration of the cement phases at high temperatures has been also shown by Peng [?49] with XRD studies on hardened cement pastes. According to his studies, the contents of C2S and C3S phases were reduced at about 400-500°C and the content of CSH was conversely increased, which was considerable at 500°C. The existence of Q-powder (in S4 specimens) and Q-powder and SF (in S5 specimens) helped this process due to their pozzolanic effects. This effect could be even increased in the tested high temperature and in presence of water vapor, which could produce an internal autoclaved condition. The effect was much higher for S5 specimens, because of the existence of SF, which had a much higher pozzolanic effect compared to the Q-powder. Such a hydration could produce a more compact structure in the cement paste and therefore resulted in higher pore pressure. In one S4 specimen, this pore pressure could overcome the tensile strength of the specimen and lead to explosive spalling. For S5 specimens, however, no spalling was observed. This may be due to considerable increase of the residual tensile strength of S5 specimens at the tested high temperature. The existence of SF can improve the strength of transition zone [50 and?51] and consequently the tensile strength. Therefore the pore pressure couldn't prevail over the tensile strength of the specimen and no spalling was occurred at the test condition. It is also notable that no change of crystalline structure of the Q-powder has been occurred in the tested temperature, regarding the thermal analysis results.

SCC-C4 and SCC-C5 specimens, showed different behavior compared to Q-powder containing specimens. The residual compressive strength didn't show an increase relative to the control specimen. However the strength loss was not drastic. About 86-89% of the initial strength was maintained and no spalling was occurred.

The comparison of behaviors of Q- and L-specimens is notable. Although L particles can act as nucleation sites for reactions in the first stages of the hydration [39, 42], however, at later time it acts only as inert filler and play no role in strength development of the hardened concrete at ambient or high temperatures. The L-specimens therefore not only didn't show any increased residual compressive strength, but also suffered from a compressive strength reduction, which may be due to partial decomposition of cement paste and development of thermal cracks. The thermal analysis results showed that decomposition of the used $CaCO_3$ started after the temperature 600°C. Therefore $CaCO_3$ didn't cause a distress in concrete at the test condition. In the other side, because of the kind of materials, it didn't lead to more packing in the concrete at high temperature (unlike the Q-powder) and no spalling was occurred in the test condition.

The complicated behavior of specimens in the elevated temperature showed the necessity for more detailed investigations considering different effective parameters. Tests on the residual strengths at higher temperatures need to be carried out. Especially tests on the phase changes of the paste at different temperatures are necessary for understanding the micro-structural reasons of the observed behavior of the paste at high temperatures.

4.Conclusion

A modified Fuller-Thomson curve for PSD of solid particles was acquired for mix design of SCC. Use of this type of mix design caused saving in cement and powder consumption in comparison with traditional methods of SCC mix design (like Japanese method) and, moreover, was accompanied with higher compressive strength. It was successfully examined for two types of powders (quartz and limestone) and two classes of normal and high strength. No significant difference between compressive strengths of SCC samples containing quartz and limestone powders, with equal proportions of constituents, was observed.

The type of powder plays an important role in behavior of SCC at high temperatures. The use of the quartz powder

accelerates the hydration reactions and development of the mechanical strengths at high temperatures, around 500°C. The reason for this phenomenon is the partial pozzolanic effect of the quartz, which is increased in an internal autoclaved condition produced at these temperatures. Therefore, the porosity of concrete is decreased and consequently the pore pressure is increased, which in turn can increase the tendency of spalling of concrete. However, as the mechanical strength of sample is also increased with development of hydration and improve of transition zone, it may overcome the produced pore pressure. In this situation, if tensile strength of the concrete prevails over the pore pressure and thermal stresses, spalling is not occurred and the compressive strength of the concrete is considerably increased. Such a behavior can be also seen for concretes containing silica fume, because of its high pozollanic activity.

The SCC containing limestone powder has lower risk for spalling, but its mechanical strength is decreased with increasing temperature. About 15% reduction of the compressive strength can be expected at temperatures around 500°C.

More researches and tests at higher temperatures are needed, with considering the different effective parameters and with use of tests on phase composition changes. The influence of transport phenomena (heat and moisture/gas pressure), composition of materials and time-temperature curve are parameters that need to be studied. Furthermore, the age of concrete has influence on the strength development, change of microstructure and moisture content of samples; hence it is also an important effective parameter, which should be studied.

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