The effect of elevated temperature on self-compacting concrete: physical and mechanical properties

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Abstract. Concrete's thermal properties are more complex than for most materials because not only is the concrete a composite material whose constituents have different properties, but its properties also depend on moisture and porosity. Exposure of concrete to elevated temperature affects its mechanical and physical properties. In the current study, M40 and M80 grades of plain self-compacting concrete (SCC) mixes are developed using Nan Su mix design principles to investigate the effect of elevated temperatures on 1) weight and compressive strength 2) compressive strength of SCC when tested cool and hot 3) effect of 2, 4 and 6 hrs. exposure duration of elevated temperatures on compressive strength 4) modulus of elasticity 5) size of testing specimen and 5) effect of thermal cycles on SCC mixes. Results derived the following conclusions 1) the M80 specimens lose more strength than M40 SCC specimens when subjected to elevated temperatures ;2) specimens heated and then permitted to cool before testing lose more strength than those tested while hot; 3) the longer the duration of heating before testing, the larger the loss in strength; 4) The decrease in modulus of elasticity caused by elevated-temperature exposure is more pronounced than the decrease in compressive strength. 5) Small test specimens generally incur greater strength losses than larger ones and 6) Specimens subjected to several cycles of heating and cooling lose more strength than those not subjected to thermal cycling.

Keywords: elevated temperatures, self-compacting concrete, SCC, thermal properties, muffle furnace

1 Introduction

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The effects of high temperatures on certain mechanical and physical properties determine whether self-compacting concrete retains its structural integrity. The most important material properties of hydrated Portland cement pastes that affect concrete properties at elevated temperatures include water state, chemical structure (that is, loss of chemically bound water from C-S-H, CaO/ SiO_2 ratio, and amount of $CaOH_2$. Crystalline and physical structure (i.e., total pore volume including cracks, average pore size in solids, amorphous/crystalline structure). Aggregate typically accounts for 65-75% of the concrete volume, so the behavior of concrete at altitude is very temperature dependent [1]. It is thermally stable Changes in the chemical composition and microstructure of hardened Portland cement pastes occur gradually and continuously over the temperature range from room temperature to 1000°C. At room temperature, 30-60% of the volume of saturated cement paste and 2-10% of the volume of saturated structural concrete are occupied by water that can evaporate. As the temperature to which the cement paste is exposed increases, it loses all water that can evaporate up to a temperature of approximately 105 °C with sufficient exposure time [2]. At temperatures above 105°C, the strongly absorbed and chemically bound water (i.e., water of hydration) is gradually lost from the cement paste hydrate, and dehydration is essentially complete at 850°C. Dehydration of calcium hydroxide is essentially zero up to about 400°C, increases most rapidly at about 535°C, and is complete at about 600°C [3]. During initial heating, large amounts of water evaporation occur from large pores near the concrete surface. Above 100°C, evaporation is faster and water is released from the concrete near the surface due to vapor pressure above the atmosphere (i.e. steam flow). At 120°C, the outflow of physically or chemically bound water within the smaller pores begins and continues up to about 500°C, where the process is essentially complete [4]. Between 30 °C and 300 °C, evaporation-related dehydration (stage 1) of the hardened cement paste occurs, with the maximum dewatering rate occurring at approximately 180 °C. Portlandite decomposes in the temperature range of 450 °C to 550 °C. H. Ca(OH)2 → CaO + H2O). Between 600°C and 700°C decomposition of the calcium silicate hydrate phase occurs and between 600°C and 900°C limestone begins to undergo decarbonization (that is, CaCO3 → CaO + CO2). From 1200 °C to 1300 °C some constituents of concrete begin to melt. Above 1300 °C to 1400 °C, concrete becomes molten [5].

2 Testing conditions

During testing, samples are stored in an open environment that allows water vapor to escape (unsealed) or in a closed environment that contains moisture (sealed). Closed environments describe conditions in bulk concrete where moisture has no direct access to the atmosphere, and open environments describe conditions where the elements are ventilated or in free communication with the atmosphere[6-7]. Samples can be loaded or unloaded during heating and cooling. Mechanical properties that allow specimens to return to room temperature prior to testing are called residual properties. A no-load test simulates the condition of concrete exposed to high temperatures without initial stress. Stress testing simulates concrete in compression zones of heat-exposed columns or deflections, and unstressed remnants provide information about the strength of unstressed concrete subjected to thermal excursions. Concrete performance can be measured by changes in its stiffness, strength, or other properties that affect its primary function in use. Concrete has a relatively low tensile strength, so it usually relies on compressive forces, which are supported by rebar. As a result, many studies on concrete at elevated temperatures have focused on compressive strength as a fundamental property in examining degradation. However, it has been found that compressive strength may not be as good an indicator of high temperature degradation as tensile or flexural strength under short-term loading[8-9].

3 Effect of elevated temperatures on mechanical properties

For the evaluation of structures under small strain conditions, a sufficient elastic analysis method is required with knowledge of the elastic modulus and strength of concrete. Elastoplasticity using load-deformation or stress-strain relationships developed for concrete at the temperature levels of interest where large strains are involved, such as may occur when structures are subjected to high temperatures An analytical method has been developed. A number of relationships have been proposed by various authors to explain the stress-strain behavior of concrete. These equations generally agree well with the rising portion of the stress-strain curve, but differ significantly beyond the point of maximum stress. The relationship between stress and strain at elevated temperatures can be derived from the relationship at room temperature if the temperature variation of the maximum stress and corresponding strain is known. Most stress-strain data reported in the literature refer to concrete heated to the test conditions without loading or loaded under stress-controlled conditions. Aggregate-to-cement ratio and aggregate type are the main factors affecting the shape of the stress-strain curve. Under normal environmental conditions, the Poisson's ratio of concrete is generally in the range of 0.15 to 0.20. Some data suggest that Poisson's ratio decreases with increasing temperature. The elastic modulus of concrete, a measure of stiffness or resistance to deformation, is often used in the analysis of reinforced concrete structures to determine the stresses experienced by simple elements and the stresses, moments, and deflections experienced by more complex structures. increase. Since the stress-strain curve of concrete is non-linear, the elastic modulus is determined either by the initial tangent modulus, secant modulus, or tangent modulus method. The results show that the elastic modulus of normal strength concrete decreases monotonically with increasing temperature. The general trend of compressive strength loss with increasing temperature reflects the effect of cement paste and the increasing role of aggregate at high temperature. Factors have been identified that may contribute to the general trend of loss of compressive strength with increasing temperature. Aggregate damage, weakened bond between cement paste and aggregate, weakened cement paste due to increased porosity during drying, and partial deterioration of aggregate. Cement paste C-S-H, chemical change and crack formation during hydrothermal reaction. Since many of the aggregates are thermally stable up to temperatures in the range of 300°C to 350°C, which is the temperature range considered for most applications, the compressive strength of concrete at elevated temperatures is comparable to that of paste cement and cement. highly dependent on action. totalling. Previous studies have suggested that partial replacement of ordinary Portland cement with ground fly ash may improve residual strength and may also improve strength at elevated temperatures. The results show peak intensities at approximately 150°C, with residual intensities 10-30% higher than baseline intensities at room temperature. The strength decreased when the temperature exceeded 300°C and reached 350°C, but it was higher than the reference strength at temperatures from 300°C to 350°C. Temperature cycling can adversely affect the mechanical properties of concrete, even at relatively low temperatures (65°C) (i.e. repeated heating generally results in less strength than a single heating).). The tensile strength of concrete is important because it determines the resistance of concrete to cracking. At room temperature, the tensile strength of concrete generally varies between 7 and 11% of its compressive strength. Direct measurement of tensile strength in concrete is rarely done due to the difficulty of gripping and loading the specimen. Split tensile and bending tests provide an indication of the tensile strength of concrete. A split test is an indirect test of the tensile strength of concrete, in which a horizontal cylinder of concrete is subjected to a compressive load by diametrically opposite bearing strips placed along two axes on the specimen. The flexural strength of concrete is expressed as the modulus of rupture and is measured using beam specimens subjected to four-point bending until failure occurs. The modulus of rupture is calculated based on linear elastic conditions, so it is fictitious, but useful for comparison. For normal strength concrete tested at room temperature, the modulus of rupture is 60-100% higher than the direct tensile strength and 100-133% higher than the split tensile strength. Most tests used to measure the effect of high temperature on concrete tensile strength used split tensile tests, in which residual tensile strength is measured. Investigations showed that the residual tensile strength of both normal and high-strength concrete decreased similarly approximately linearly with increasing temperature. Furthermore, the tensile strength measured by nip tension testing was consistently higher than that obtained by direct tensile testing. Previous studies have shown that raising the temperature above room temperature reduces the modulus of rupture [10-11].

4 Effect of elevated temperatures on physical properties

Temperature changes cause expansion or contraction of concrete structures. Restricted movement of structures can create significant internal stresses that can lead to cracks, deformations and even failures. In general, the density, conductivity and diffusivity of concrete increase with increasing temperature. The coefficient of thermal expansion α is used as a measure of a material's volume change under the influence of a temperature difference. The basic quantities are (1) thermal conductivity k, (2) thermal diffusivity a, and (3) specific heat c. These quantities are related by the term a = k/cp. where p is the density of the material. At temperatures between 150 °C and 600 °C, the density of concrete remains relatively constant. Due to the increased porosity of concrete, weight loss occurs during decarburization until the density increases slightly at higher sintering temperatures. The coefficient of thermal expansion describes the change in volume of a material with a change in temperature, expressed as a change in length per degree of temperature change. This factor is important as a measure of structural motion and thermal stress due to temperature change. The thermal expansion of concrete is a complex phenomenon due to the interaction of two main components, cement paste and aggregate, each with its own coefficient of thermal expansion. Aggregates typically make up the majority of the mixture and thus primarily affect the resulting coefficient of thermal expansion. Apparently, the coefficient of linear expansion also increases as the temperature rises. The literature points out that the main factor affecting the coefficient of thermal expansion is the type of aggregate. Thermal conductivity is a measure of a material's ability to conduct heat. The key factors affecting the thermal conductivity of concrete are cement paste, pore volume, pore distribution, and water content. Cold and wet concrete have very high thermal conductivity values. Thermal conductivity increases slightly with increasing temperature, but decreases when approaching 100 °C. From 300°C to 400°C, the thermal conductivity decreases further, and cracks increase when the temperature exceeds 300°C. According to the literature, the main factors affecting the thermal conductivity of concrete are water content, type of aggregate material, hardened cement paste, pore volume and pore distribution. Conductivity varies linearly with moisture content. As the conductivity of the aggregate material increases, so does the thermal conductivity of concrete. Concrete with low cement paste content is expected to have lower conductivity than lean concrete mixtures. Thermal conductivity is a measure of the speed at which heat diffuses in all directions within a material due to temperature changes, and is an index of how easily heat is transmitted through a material due to temperature changes. Factors that affect thermal conductivity usually have the same effect on thermal conductivity. Specific heat is the amount of heat required to change the temperature of 0.45 kg of material by 0.56°C, and represents the heat capacity of the material. As the water content in concrete increases, the specific heat increases at low temperatures. The heat capacity of concrete increases with temperature up to about 500°C, but levels off or decreases up to 1000°C.

5 Objectives

In the current study, M40 and M80 grades of plain self-compacting concrete (SCC) mixes are developed using Nan Su mix design principles to investigate the following:
1. Effect of Elevated temperatures on weight and compressive strength of SCC mixes (Exposure duration 2hrs)
2. Effect of Elevated temperatures on compressive strength of SCC mixes when tested cool and hot (Exposure duration 2hrs)
3. Effect of exposure duration of elevated temperatures on compressive strength of SCC mixes (Exposure duration 2, 4 and 6 hrs.)
4. Effect of Elevated temperatures on Modulus of elasticity of SCC mixes (Exposure duration 2hrs)
5. Effect of Elevated temperatures on size of testing specimen of SCC mixes (Exposure duration 2hrs)
6. Effect of thermal cycles on SCC mixes (Exposure duration 2hrs)

6 Experimental Investigations

The following table presents the mix quantities arrived using Nan Su mix design principles.

Table 1. Mix quantities arrived using Nan Su mix design principles

Type of Mix	Cement kg	Fly ash kg	Micro silica kg	FA kg	CA kg	Water L	SP L
M40 grade PSCC	342.59	99.83	-	838.82	812.04	216.28	7.91*
M80 grade PSCC	450.00	163.53	36.81ǂ	896.34	722.44	169.16	11.0#

* 0.6% by the weight of cement
\# 1.0% by the weight of cement
ǂ 6% by the weight of powder

The following table presents the compressive strength of M40 and M80 grades of plain self-compacting concrete (SCC) mixes

Table 2. Compressive strength of plain self-compacting concrete (SCC) mixes

Type of Mix	Compressive strength at 60 days N/mm^2
M40 grade PSCC	50.33
M80 grade PSCC	90.06

Specimens lose more strength if moisture is not permitted to escape while heated than those where the moisture escapes. In M80, due to dense microstructure, the moisture is trapped inside the concrete where as in M40 there is probability that moisture escapes. So percentage loss in compressive strength is more in M80 grade SCC then in M40 grade SC which is evident from the table below.

Table 3. Effect of elevated temperatures on weight and compressive strength of SCC mixes (Exposure duration 2hrs)

Type of concrete	Temperature °C	% loss in weight	% loss in UPV	% loss in Compressive Strength
M40 grade SCC	100	0.44	2.67	-1.07
	200	0.57	15.26	-5.23
	400	14.19	43.64	11.91
	600	18.89	63.15	33.07
	800	36.14	75.69	53.14
	1000	68.21	80.69	79.11
M80 grade SCC	100	0.04	3.96	-3.76
	200	2.96	16.17	-7.16
	400	15.93	44.28	20.80
	600	19.17	64.29	43.30
	800	38.14	77.61	64.35
	1000	68.25	82.31	90.33

Specimens heated and then permitted to cool before testing lose more strength than those tested while hot. Literature states that the concrete specimens loaded during heating lose less compressive strength than unloaded specimens.

Table 4. Effect of elevated temperatures on compressive strength of SCC mixes when tested cool and hot (Exposure duration 2hrs)

Type of concrete	Temperature °C	% loss in Compressive Strength when specimens tested while hot	% loss in Compressive Strength when specimens tested while cool
M40 grade SCC	100	-0.75	-1.07
	200	-3.66	-5.23
	400	8.34	11.91
	600	23.15	33.07
	800	37.20	53.14
	1000	55.38	79.11
M80 grade SCC	100	-2.63	-3.76
	200	-5.01	-7.16
	400	14.56	20.80
	600	30.31	43.30
	800	45.05	64.35
	1000	63.23	90.33

The longer the duration of heating before testing, the larger the loss in strength; however, the loss in strength stabilizes after a period of isothermal exposure.

Table 5. Effect of exposure duration of elevated temperatures on compressive strength of SCC mixes

Type of concrete	Temperature °C	% loss in Compressive Strength when exposed to 2hrs	% loss in Compressive Strength when exposed to 4 hrs.	% loss in Compressive Strength when exposed to 6 hrs.
M40 grade SCC	100	-1.07	-1.39	-1.53
	200	-5.23	-6.80	-7.48
	400	11.91	15.48	17.03
	600	33.07	42.99	47.29
	800	53.14	69.08	75.99
	1000	79.11	82.84	93.13
M80 grade SCC	100	-3.76	-4.89	-5.38
	200	-7.16	-9.31	-10.24
	400	20.8	27.04	29.74
	600	43.3	56.29	61.92
	800	64.35	83.66	92.02
	1000	90.33	97.43	Crumpled

Table 6. Effect of elevated temperatures on modulus of elasticity of SCC mixes (Exposure duration 2hrs)

Type of concrete	Temperature °C	Modulus of elasticity N/mm^2	% loss in Compressive Strength
M40 grade SCC	100	42055.05	-1.07
	200	40031.08	-5.23
	400	38356.16	11.91
	600	36668.55	33.07
	800	31304.35	53.14
	1000	23752.02	79.11
M80 grade SCC	100	50680.98	-3.76
	200	46187.38	-7.16
	400	41924.64	20.80
	600	38203.74	43.30
	800	33334.51	64.35
	1000	28020.48	90.33

The decrease in modulus of elasticity caused by elevated-temperature exposure is more pronounced than the decrease in compressive strength.

Table 7. Effect of Elevated temperatures on size of testing specimen of SCC mixes (Exposure duration 2hrs)

Type of concrete	Temperature °C	% loss in Compressive Strength in 150 mm cubes	% loss in Compressive Strength in 100 mm cubes
M40 grade SCC	100	-1.28	-1.07
	200	-6.28	-5.23
	400	14.29	11.91

	600	39.68	33.07
	800	63.77	53.14
	1000	84.93	79.11
M80 grade SCC	100	-4.51	-3.76
	200	-8.59	-7.16
	400	24.96	20.80
	600	51.96	43.30
	800	77.22	64.35
	1000	98.40	90.33

Small test specimens generally incur greater strength losses than larger ones.
As the temperature increases, the compressive strength decreases. At temperatures above 600°C, the M80 grade SCC compound experienced excessive delamination more frequently than the M40 grade SCC compound. The weight loss is due to loss of bound water from the cement paste and lower compressive strength due to reduced Ca(OH)2. The decrease in compressive strength is mainly due to the relaxation of bonds, the generation of high pore pressure and volume change due to aggregate transformation, leading to the propagation of brittle fracture due to the stress energy generated by thermal stress. This situation can be controlled by incorporating fibers into the cement matrix to increase toughness and tensile strength and improve the crack deformation properties of the resulting composites. Steel fibers are reported to be effective in mitigating cracking from plastic shrinkage and delamination when concrete is exposed to high temperatures.

Table 8. Effect of Elevated temperatures on SCC mixes after thermal cycles (Exposure duration 2hrs)

Type of concrete	Temperature °C	% loss in compressive strength	% loss in compressive strength after 2 cycles of heating and cooling
M40 grade SCC	100	-1.07	-1.39
	200	-5.23	-6.80
	400	11.91	15.48
	600	33.07	42.99
	800	53.14	69.08
	1000	79.11	82.84
M80 grade SCC	100	-3.76	-4.89
	200	-7.16	-9.31
	400	20.80	27.04
	600	43.30	56.29
	800	64.35	73.66
	1000	90.33	97.43

7 Discussions

Specimens that have undergone multiple heating and cooling cycles have lower strength than specimens that have not undergone thermal cycling. The M40 grade SCC blends showed much better high temperature resistance than the M80 grade SCC blends. Due to the high brittleness and dense microstructure of high strength concrete, the compressive strength loss

rate of high strength SCC is high. The strength loss of high quality SCC specimens increases with increasing temperature. This is because a chemical change causes the thermal stress in the cement paste to become negative (shrinkage) with increasing temperature, resulting in precipitation on the surface. High-strength SCC appears to delaminate more easily than standard grade SCC at elevated temperatures. This is mainly due to the dense, low-permeability structure of high-quality concrete, where moisture does not easily escape from heated concrete, leading to high pore water pressure and microcrack formation.
His SCC specimens of M80 grade showed much better resistance to high temperatures up to 400 °C than his SCC specimens of M40 grade. Above 400°C, all SCC mixtures behave the same due to concrete degradation.
At 200 °C, pore water is lost by evaporation along with the release of chemically bound water from calcium silicate hydrates, resulting in thermal stress and microcracking. At 400 °C calcium hydroxide decomposes to lime and water vapor, but this is not significant with respect to strength loss. However, this decomposition can cause significant damage due to lime expansion during the cooling period. Calcium hydroxide can therefore be removed by including silica fume, which is beneficial. At 600 °C, decomposition of the C-S-H gel increases the amount of voids in the sample, making the structure more porous. The large changes in concrete morphology exposed to 600 °C are probably due to the prevalence of microcracks, increased concrete porosity due to voids, decomposition of Ca(OH)2, and finally collapse of the C-S-H phase boundary. It is considered. to cause. Above 400 °C, the thermal stress of the cement paste changes negatively (shrinkage) with increasing temperature due to a chemical change, resulting in deposits on the surface of the SCC mixture. High-strength SCCs containing microsilica undergo gradual delamination at elevated temperatures due to two effects:
(1) physical effects due to the reduction of van der Waals forces when water expands on heating, and (2) chemical effects that can lead to deleterious transformations under hydrothermal conditions. The main cause of concrete delamination can be internal steam pressure. This is mainly due to the dense, low-permeability structure of his M80 grade SCC mixtures, where moisture does not readily escape from heated concrete, leading to high pore pressures and microporosity. lead to cracks.

8 Conclusions

Concrete may lose strength slightly in the temperature range of 20°C to 200°C. The strength drop that occurs between 22°C and 120 °C is due to the thermal expansion of physically bound water, which creates a pressure discontinuity. A strength recovery is often observed between 120 °C and 300 °C. This is likely due to van der Waals forces increasing as the cement-gel layers approach each other during heating. Residual compressive strength is almost constant from 200°C to 250°C. Above 350 °C, a rapid loss of strength can occur. Regarding the behavior of SCC at high temperatures, we find the following:
1. If moisture cannot escape during heating, the specimen will be weaker than if moisture escapes.
2. Specimens that are heated and then cooled prior to testing are less strong than specimens tested hot.
3. The longer the pre-test heating time, the greater the strength loss. However, the strength loss stabilizes after a period of isothermal loading.
4. The decrease in modulus due to high temperature exposure is more pronounced than the decrease in compressive strength.
5. Based on the effect of mix ratio, mixtures with low cement-aggregate content lose less strength on heating than rich mixtures. The water-cement ratio has a limited effect on the strength loss of concrete heated to 300°C.

6. In general, smaller specimens lose more strength than larger specimens.
7. Specimens that have undergone multiple heating and cooling cycles lose strength more than specimens that have not undergone temperature cycling.

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