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Effect of aggregate type on linear thermal expansion of self-consolidating concrete at elevated temperatures

Abstract: In this study, the effects of aggregate type on the coefficient of thermal expansion of self-consolidating concrete (SCC) produced with normal and lightweight (porous) aggregate (SCLC) were investigated. In experiments, three aggregate types, gravel, volcanic tuff, and diatomite, were used. Different combinations of water/cement ratio and superplasticizer dosage levels were prepared for the SCC and SCLC mixtures. Thermal tests were performed to accurately characterize the coefficient of thermal expansion (CTE) of SCC and SCLC aged 28 days using the dilatometer. The CTEs of SCC and SCLC were defined by measuring the linear change in length of concrete specimens subjected to a range of temperatures from 20°C to 1000°C. The results, in general, showed that SCLC has a lower CTE than that of SCC above 100°C. Moreover, CTE values of SCC and SCLC were decreased with increase in porous structure. The aggregate type has significant influence on the thermal properties of SCC.

Keywords: aggregate type; linear thermal expansion; self-consolidating concrete.

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1 Introduction

Restrained thermal stresses have been shown to significantly increase the risk of explosive spalling of high-performance concrete exposed to fire [1]. Thermal expansion is an important factor in all types of concrete. It must be known to manage the expansion of concrete due to ranging temperatures in bridges, roads, railways, and buildings. The differential expansion that occurs between the cement paste and the aggregate will give rise to high internal stresses, which may be critical in the case of large temperature changes [2–4]. As aggregates make up the bulk of concrete, their properties largely determine concrete properties. Also, high temperatures can cause many changes depending on the concrete constituent materials, moisture content, aggregate type, and cement content [5]. Hardened cement paste has a higher coefficient of thermal expansion (CTE) value than the aggregate. The aggregate restrains the thermal movement of the cement paste. Typical values of the CTE of cement paste vary between 11.0×10^{-6} and 20×10^{-6} per degree [6, 7]. As lightweight aggregates are exposed to a preheating process during their formation, they have a lower CTE than limestone or gravel [8].

In the literature, thermal expansion of concrete was investigated by some authors, but however, most of them are in low elevated temperatures such as between -30°C and 65°C [6]. Moreover, different methods were proposed in obtaining the CTE value of concrete with different composition and moisture content [9, 10]. However, the length change, strain ability, and thermal expansion of concrete at a high level of temperature, such as 500°C or 1000°C, is very limited in the literature [10–12]. This is a gap for thermal behavior of concrete at elevated temperature. In general, in the studies that were carried out on the effect of elevated temperature on properties of concrete, it was focused on those mechanical properties such as compressive strength, flexure strength, and elastic moduli. However, the behavior of properties of normal weight and lightweight concrete is highly related with the thermal behavior of concrete under the elevated temperatures. Consequently, in this study, it was focused on thermal strain ability, phase diagrams, and thermal expansion of SCC and self-consolidating lightweight concrete (SCLC) with different aggregates at high levels of temperatures from 20°C to 1000°C.

2 Research significance

Self-consolidating concrete (SCC) is a new concrete type used in construction for the last decade. The European Ready-Mix Concrete Organisation (ERMCO) proposed that the CTE of SCC is between 10×10^{-6} and 13×10^{-6} 1/°C [13], unless more accurate information is available. SCC, however, contains more fine aggregates and materials that incorporate quartz-based natural sand, cement, and mineral filler than traditional concrete due to its design requirement for good workability [14]. Consequently, the CTE of SCC will be higher than that of ordinary concrete. Research on the CTE of SCC produced with normal aggregate or lightweight aggregate has not been carried out, yet. On the other hand, determination of CTE of concrete is very hard because it is very much depending on parameters of concrete such as aggregate type, mixture content, and composition materials. Recently, studies on the thermal expansion of both ordinary and lightweight concrete at elevated temperature, especially in a high level of temperature, is very limited. Thus, this study's primary objective is the determination of the CTE of SCC produced with gravel and lightweight aggregates such as volcanic tuff and diatomite under the high level of temperatures.

3 Experimental program

3.1 Materials

The cement used was ordinary Portland cement (CEM I 42.5R), which complies with the requirement of the European Standards EN 197-1. Limestone powder and fly ash were used as fine material to enhance the viscosity. The fly ash (F Class) was supplied from Seyitömer/Turkey Thermal Power. Limestone powder was supplied by Kolsan ready-mix concrete. Table 1 gives the chemical, physical, and mechanical properties of the fine materials that composed the cement, limestone powder, and fly ash. The admixture was polycarboxylate-based superplasticizer (SP) produced by Chryso. Its specific gravity and solid content were 1.1% and 20%, respectively. Natural river sand was used in all the mixtures with a specific gravity of 2.6, fineness modulus of 2.1, and water absorption by weight of 3.7%, respectively. Coarse aggregates were gravel, volcanic tuff, and diatomite with a maximum size of 16 mm, and chemical properties of tuff and diatomite are presented in Table 1. All the aggregates used in the study were collected from the mines. The characteristic properties of aggregates are presented in Table 2.

3.2 Concrete mixes and tests

The constituents of the SCC mix were proportioned to achieve maximum packing of the particles and, thus, minimum voids. SCC mixtures were designed with different actual water-powder ratios, 0.28, 0.31, 0.34, and 0.36, to obtain different fresh-state properties. In SCC, the fine particles in the sand also must be considered as powder material. The powder ratio in the natural sand was also considered in determining the water to powder ratio (w/p). The powder ratio in the sand was 4.55% by weight. Therefore, the water to binder ratios (w/b) were 0.36, 0.40, 0.43, and 0.46. When

Chemical properties		Cement, %	Fly ash, %	Limestone, %	Tuff, %	Diatomite, %
CaO		63.56	4.26	54.97	0.53	1.36
SiO_2		19.3	54.49	0.01	73	67.2
Al_2O_3		5.57	20.58	0.17	14.14	10.09
Fe_2O_3		3.46	9.27	0.05	1.03	2.74
MgO		0.86	4.48	0.64	0.08	0.63
SO_3		2.96	0.52	–	–	–
K_2O		0.8	2.01	–	3.66	0.67
Na_2O		0.13	0.65	–	1.16	0.36
LOI		1.15	3.01	43.66	6.3	8
C_3S		66.75	–	–	–	–
C_2S		5.15	–	–	–	–
C_3A		8.9	–	–	–	–
C_4AF		10.53	–	–	–	–
Physical properties						
Fineness by Blaine (cm^2/g)		3212	3445	856	–	–
Specific gravity		3.07	2.13	2.72	2.24	2.31
Mechanical properties						
Comp. Str.,	7 days	38.7	–	–	–	–
MPa	28 days	46	–	–	–	–

Table 1 Characteristic properties of cement, fly ash, limestone powder, tuff, and diatomite.
–, not measured items.

Properties	4/16 mm Coarse aggregates			Sand	Standard
	Gravel	Tuff	Diatomite		
Loose bulk density (kg/m^3)	1455	762	435	1520	EN 1097-3
Specific gravity	2.61	2.24	2.31	2.59	EN 1097-6
Water absorption by weight (%)	0.7	23.82	94.24	3.73	EN 1097-6
Wear resistance Los Angeles (%)	24.8 (LA_{25})	48.66 (LA_{50})	64.1 (LA_{65})	–	EN 1097-2

Table 2 Characteristic properties of aggregates.

the water content increased, the SP dosage was decreased by ratios of 2.6%, 2.3%, 2.0%, and 1.7% by the weight of fine material at the same time. The fine material content, which includes cement, fly ash and limestone powder, and aggregate grading, was kept constant in all mixtures. The aggregate grade was designed as between Turkish Standard curves A-16 and B-16 (Figure 1). SCLC was produced by replacing the gravel with tuff and diatomite that have the same grade as shown in Figure 1. Air-entrained admixture was used in the production of SCLC to prevent segregation. Lightweight aggregates and gravel aggregates were used in the mixes as saturated and dry surface. The composition of the mixes is presented in Table 3.

On the fresh SCC produced with three different aggregates, slump flow and V-box flowing time were measured to determine the workability of the concrete. Slump flow test is used to determine the ability of the concrete to flow in a non-restricted condition. To determine the slump flow, the traditional hollow Abrams cone is placed on a slump flow plate with an edge length of 1000×1000 mm and is filled with SCC and lifted slowly. In order to prevent any thixotropic effect, the Abrams cone was lifted immediately after having been filled with the SCC. The slump flow of the final deformed, or slumped, SCC was measured from two perpendicular diameters 2 min after cone lifting (Figure 2). The flow time of self-compacting concrete was measured with a V-box. With the outlet flap closed, the funnel is filled

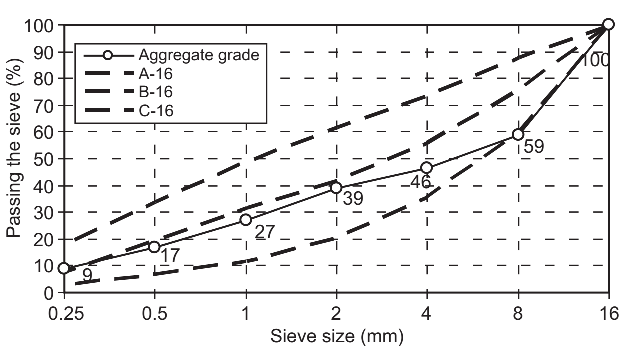

Figure 1 Aggregate grading used in the mixes.

with the sample of SCC to the top. The flap is then opened. The time taken by the concrete to flow out of the funnel is measured. The fresh mixes were filled in 150×150×150 mm molds using without vibration. The specimens were demolded after 24 h and cured in water for 28 days.

On the 28-day-aged specimens, compressive strength was defined by 2000 kN compressive machine with a rate of loading controller. Moreover, apparent porosity (AP) was defined on 70×70×70 -mm-sized specimens according to the Archimedes principle by the weight measurements of saturated specimens in air and in water, and dry weight (oven drying at 105°C to constant weight). The average of the three specimens for each series was used in defining of the strength and apparent porosity values.

3.3 Measuring of CTE of concretes

For measuring of length change of specimens, a dilatometric measuring method was used (Figure 3). Actually, this measurement method is presented alternatively in this study according to the method that is given in the literature for concrete. Moreover, this method was proposed by Toman et al. [15] for the determination of the linear thermal expansion of porous materials at elevated temperatures. The measurement of the CTE of concrete at elevated temperature is very hard and limited in the literature. Measurements of the CTE were carried out on 5×5×25-mm prismatic specimens that were carefully sliced from the 70×70×70-mm specimens (Figure 4). The ends of the specimens were parallel. The small-sized specimens were used in applying the high level of temperatures such as 1000°C. Each specimen that was prepared for the thermal expansion measurement contains the aggregate. In other words, they are still a composite material. Neither distribution nor cracks were observed on the specimens after the slice of specimens because of the thin section saw machine that was used to prepare the specimens. Thermal strain and the CTE of the specimens were determined by using the DIL

Series	Materials (kg/m^3)										w/b[1]	w/p
	Cement	Fly ash	Limestone powder	Sand	Gravel	Tuff	Diatomite	Water	SP	AE		
SCC 1	445	49.4	98.8	707	803	–	–	184	14.8	–	0.36	0.28
SCC 2	448	49.7	99.5	689	783	–	–	203	13	–	0.40	0.31
SCC 3	452	50.2	100.4	674	766	–	–	223	10.8	–	0.43	0.34
SCC 4	452	50.3	100.5	667	758	–	–	229	10.3	–	0.46	0.36
SCLC 1	411	45.7	91.3	660	–	488	–	164	14.2	2.7	0.36	0.28
SCLC 2	415	46.1	92.1	645	–	477	–	182	12.7	2.8	0.40	0.31
SCLC 3	406	45.1	90.1	611	–	452	–	195	10.3	2.7	0.43	0.34
SCLC 4	402	44.7	89.4	593	–	438	–	204	9.1	2.7	0.46	0.36
SCLC 5	414	46	92	664	–	–	401	166	14.3	2.8	0.36	0.28
SCLC 6	413	45.8	91.7	642	–	–	388	182	12.7	2.8	0.40	0.31
SCLC 7	406	45.1	90.2	612	–	–	370	195	10.3	2.7	0.43	0.34
SCLC 8	404	44.9	89.8	596	–	–	360	205	9.2	2.7	0.46	0.36

Table 3 Actual constituent of concretes per cubic meter.
[1]Cement+fly ash.

402 CD/4/G type Netzsch dilatometer according to ASTM E 831-03 [16] and ASTM E 228-95 [17]. The specimens were dried in the oven at 50°C until they maintained a constant weight before the CTE measurement. In other words, the moisture content of the concretes was kept as oven dry in all the measurements. The measured sample and the standard are put into the furnace, provided with contact ceramic rods, and the initial reading on the dial indicators is taken. Then, the electric heating regulation system is adjusted for the desired temperature (it was room temperature in this study) in the furnace, and the length changes are monitored. The data acquisition from the digital dial indicators is done on a PC using specially developed software. The linear change in the length of each specimen was measured by the instrument under temperatures from 20°C to 1000°C at a heating rate of 5°C/min.

Figure 2 Measuring of flow diameter of SCC and SCLC after slump flow test.

The average of the three specimens for each series was used in defining the CTE values. After measurements of each specimen's change in length were taken, the thermal

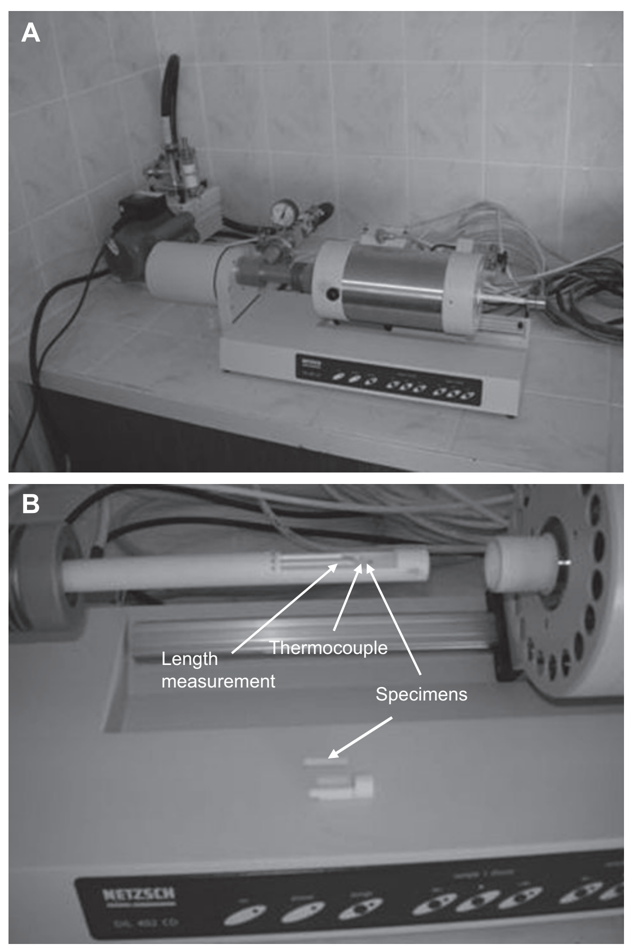

Figure 3 (A and B) Dilatometer used in the experiments.

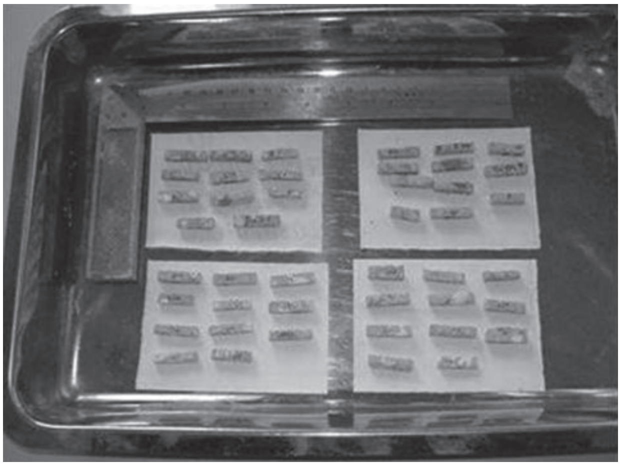

Figure 4 Prepared specimens for thermal expansion measurements.

strain and the CTE were determined by using Eqs. (1) and (2), respectively, given below:

$$\varepsilon = \Delta L/L_0; \quad (1)$$

$$\Delta L = \alpha \cdot L_0 \cdot \Delta T, \quad (2)$$

where ε is the thermal strain, α is the coefficient of thermal expansion (1/°C), ΔL is the length change (mm), ΔT is the temperature difference (°C), and L_0 is the initial length of the specimen.

4 Results and discussions

4.1 Fresh concrete properties

Slump flow values of SCC and SCLC were presented in Table 4. The slump flow of both concrete types was increased by enhancing the water-powder ratio. When the slump flow of SCC varied between 556 and 813 mm, the slump flow varied between 529 and 728 mm and between 655 and 817 mm for the SCLC series with tuff and diatomite, respectively, depending on the water-powder ratio. The SCLC has a lower slump flow value than that of the SCC in the highest water-powder ratio. The effects of the air-entraining admixture (AE) used in the production of SCLC caused this difference. The AE prevented the segregation of SCLC in high water-powder ratios.

V-box flow times can be used as indicators of viscosity of flow-able concrete mixes [18]. If the V-box flow time is long, then the concrete's viscosity is high. The viscosity of the SCC is higher than that of the SCLC. Because the tuff and diatomite aggregates are moved easily by mortar, the SCLC series has lower viscosity. The fresh unit weight of both concrete types was decreased by enhancing the water-powder ratio. Moreover, the fresh unit weight value of the SCLC was lower than that of the SCC. When the unit weight of the SCC varied between 2301 and 2268 kg/m^3, the unit weight varied between 1814 and 1727 kg/m^3 and between 1737 and 1635 kg/m^3 for the SCLC series with tuff and diatomite, respectively, depending on the water-powder ratio. The unit weight of the SCC was decreased in the ratio of 21–24% and 25–28% by replacing the gravel with tuff and diatomite, respectively.

4.2 Hardened concrete properties

Compressive strength values of the SCC and the SCLC are given in Table 4. It is clearly seen that the compressive strength substantially decreases as the w/p for each series is increased from 0.28 to 0.36. Moreover, a

Series	Fresh concrete			Hardened concrete at 28 days	
	Slump flow (mm)	V-box flow time (s)	Unit weight (kg/m^3)	Comp. Str. (MPa)	Apparent porosity (%)
SCC 1	556	15.61	2301	51.3	11.8
SCC 2	756	8.84	2285	49.3	13.8
SCC 3	805	3.94	2276	42.0	14.3
SCC 4	813	2.63	2268	38.4	17.5
SCLC 1	529	5.78	1814	22.4	22.3
SCLC 2	578	4.67	1811	21.1	24.1
SCLC 3	670	3.48	1754	18.7	24.2
SCLC 4	728	2.72	1727	17.4	24.5
SCLC 5	655	4.19	1737	19.5	29.9
SCLC 6	770	4.14	1716	16.3	31.0
SCLC 7	776	2.92	1673	14.5	32.1
SCLC 8	817	1.87	1655	13.7	33.6

Table 4 Fresh and hardened concrete properties of SCC and SCLC.

replace of gravel with lightweight aggregate resulted in a decrease in compressive strength of concretes. The reduction in compressive strength is related to the weakness of lightweight aggregates. This means that the compressive strength of SCC is better than that of the SCLC with all the types of LWA regardless of w/b. This is based upon the fact that lightweight aggregates are not as strong as gravel. Furthermore, it must be noted that gravel aggregates have a higher wear resistance than all types of LWAs (see Table 2). When the compressive strength of the SCC varied between 51.3 and 38.4 MPa, the compressive strength for the SCLC series with tuff and diatomite varied between 22.4 and 17.4 MPa and between 19.5 and 13.7 MPa, respectively, depending on the water-powder ratio. When the aggregate type was considered in the SCC mixtures, it was found that the compressive strength of the SCC was decreased in the ratio of 56–55% and 62–64% by replacing the gravel with tuff and diatomite, respectively, depending on the w-p ratio. However, when the compressive strength of the SCCs in different w/p ratios was considered, it was observed that there was about 25% reduction in the 28-day compressive strength by an increase of w-p ratio from 0.28 to 0.36. The reduction ratio was 22% and 30% for the SCLC with tuff and diatomite, respectively, for the same w-p ratios. This was expected because of the increase of porous structure in the specimens due to free water, thus providing a decrease adherence between the aggregates and the cement matrix. On the other hand, from the compressive strength value point of view, the SCLC with both tuff and diatomite are in the class of structural lightweight concrete [19].

In general, the apparent porosity of each series increased with increasing w/p. As seen in Table 4, using lightweight aggregate replacement with normal aggregate allows increasing the apparent porosity of concrete. The apparent porosity of SCLC was approximately two times higher than that of SCC. It is due to the higher pore size of tuff and diatomite lightweight aggregates.

4.3 Thermal strain

The thermal strain of the SCC series produced with gravel is given in Figure 5 for temperatures between 20°C and 1000°C. The thermal strain of the SCC was increased in all the water-powder ratios by increasing the temperature. In general, it was varied between 0% and 0.4% in the temperature range from 20°C to 300°C. Above 550°C, the thermal strain of the SCC slightly increased.

The loss of the bound water in the hydrates may cause shrinkage of the concrete [20]. However, siliceous aggregates containing quartz, such as natural sand and gravel, may cause distress in the concrete at about 573°C as the transformation of quartz from α to β form is associated with a sudden expansion of concrete. Thus, the concrete strength may deteriorate under these conditions [21, 22]. This transformation, especially in the natural sand, caused a slight volume and length expansion in SCC and SCLC above 550°C, and the thermal strain of specimens increased suddenly after this temperature in all the series produced with different water-powder ratios. An examination of Figure 6 suggests that the thermal strain of the SCC was slightly reduced above 750°C and 800°C. At these stages, after the free interlayer water from the deformed cement matrix evaporated, the concrete shrunk, and the crystal structure of the cement matrix was completely deformed [21, 23]. It was noted, however, that the maximum thermal strain of the SCC, which was observed at 1000°C was decreased by increasing the w/p from 0.28 to 0.36. This shows that the thermal behavior of the SCC corresponds to its air void system, which relates to the w/p. When the w/p was increased, it resulted in an increase in the apparent porosity in the SCC (see Table 3). Evaporated water at high temperatures would lead to internal pressure and, thus, an increase of thermal expansion. The internal pressure may, however, be decreased with an increase of voids in the concrete by either increasing the w/p or using the AE. However, it must be kept in mind that increasing

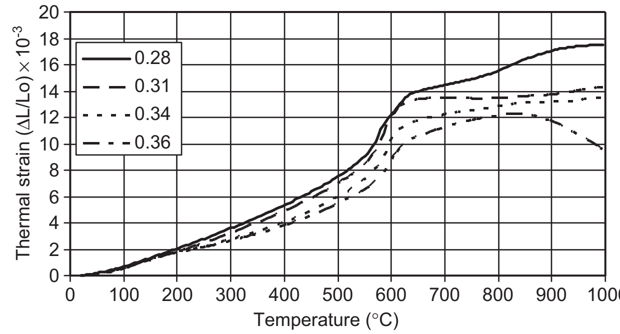

Figure 5 Thermal strain ratios of SCC vs. temperature.

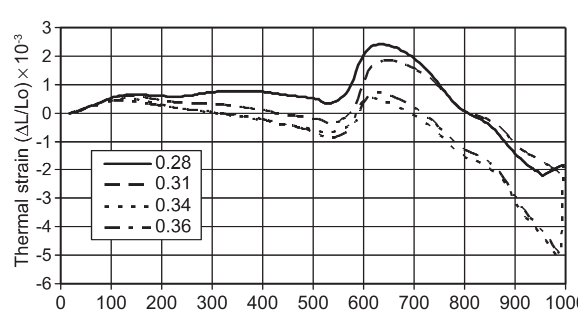

Figure 6 Thermal strain ratios of SCLC with tuff vs. temperature.

the w/p resulted in a significant decrease in the concrete strength. Fu et al. [11] investigated the micro/macrocrack development and stress-strain relations of cement-based composite materials at elevated temperatures, and they reported that the total thermal strain of cement mortar at 500°C was approximately 9×10^{-3}. In this study, it was found that thermal strain of the SCC at 500°C ranged between approximately 7.7×10^{-3} and 5.7×10^{-3} depending on the w-p ratio.

The thermal strain values for the SCLC with tuff and diatomite vs. elevated temperature are presented in Figures 6 and 7, respectively, depending on the w/p. In general, the thermal strain was increased by increasing the temperature from 20°C to 150°C in all the SCLC series. Strain ratios begin to slightly decrease in the SCLC with tuff and diatomite because of the remaining free water, which is in the C-S-H interlayer of the cement matrix, above the temperature of 150°C. The thermal strain of both types of SCLC produced in the w/p of 0.31, 0.34, and 0.36 trends to decrease until 550°C. As with the SCC, the thermal strain ratio of the SCLC suddenly increased at about 550°C due to variation in the phase of natural sand. An investigation of Figures 6 and 7 suggests that the thermal strain of the SCLC with tuff and diatomite slightly reduced above 650°C. Although the SCC and the SCLC series contain the similar types of mortar, the length of the SCLC specimens was considerably shortened after 700°C and 800°C due to the characteristic properties of the lightweight aggregates. It was because of the shrinking tuff and diatomite aggregates at high temperatures, and also, the crystal structure of the cement matrix was completely deformed. Tuff and diatomite are lightweight aggregates with shrinking properties under elevated temperatures, in contrast with normal aggregates that have expanding characteristics [21, 24, 25]. The highest strain values for the SCLC with tuff and diatomite were obtained in the series that had the lowest water-powder ratio, but the lowest strain ratio was obtained in the series that had the highest w/p at elevated temperatures from 150°C to 1000°C. This was due to the thermal stresses in the specimens that were decreased by increasing the w/p, and thus increasing the apparent porosity.

The first derivation of the thermal strain curves gives the phase variation in the specimens at elevated temperatures. In Figure 8, the phase diagrams of the SCC depending on w-p ratio were presented. In Figures 9 and 10, the first derivation of the thermal strain curves of the SCLC with tuff and diatomite, respectively, were presented. The peaks in all figures related with the first derivation of the thermal strain curves show that the phase transformation depends on temperature. There was no big change in the phase of the SCC until 500°C for each w-p ratio. The same condition is true for both types of SCLC. Above 500°C, the phase transformation occurs in the specimens produced with different types of aggregates. The transformation of the phase was obtained between 580°C and 590°C for both the SCC and the SCLC types due to transformation of quartz from α to β in natural sand, which was used in both the SCC and the SCLC as a common component. However, because the SCC contains quartz-based sand and gravel, the highest peak was observed for each w/p.

4.4 Thermal expansion

The CTE of the SCC produced with different w/p is given in Figure 11 vs. elevated temperatures from 20°C to 1000°C. It can be clearly seen that the SCC has positive CTE values in all the elevated temperatures. When the increase of the CTE of the SCC was high until about 170°C, it was slightly from 170°C to 590°C because of the evaporation of free internal water in the C-S-H gel. Decomposition of the C-S-H gel resulted in an increase in the CTE between 150°C and 500°C. The CTE of the SCC 1, which was oven dried was changed between 6×10^{-6} and 11×10^{-6} 1/°C up to 150°C in the w/p of 0.28. In Figure 11, it can be also noted

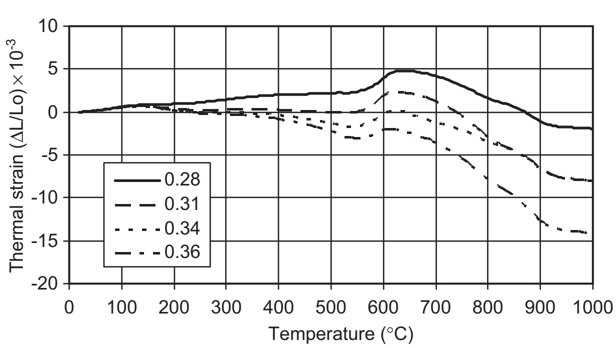

Figure 7 Thermal strain ratios of SCLC with diatomite vs. temperature.

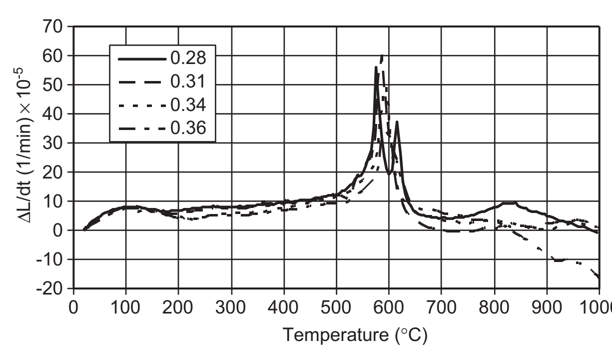

Figure 8 The first derivation of thermal strain curve of SCC.

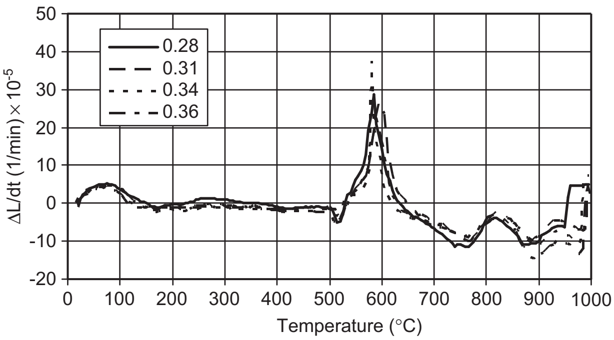

Figure 9 The first derivation of thermal strain curve of SCLC with tuff.

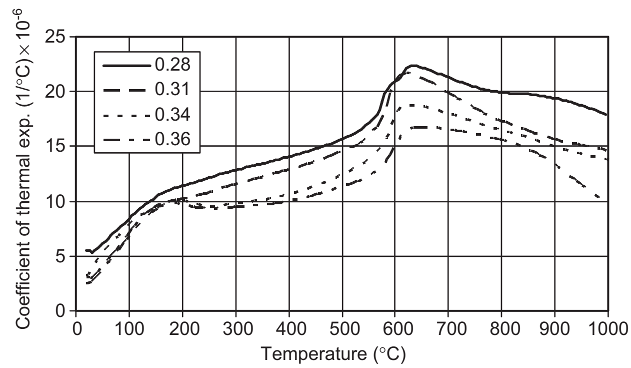

Figure 11 CTE of SCC vs. temperature.

that the CTE of SCCs decreased with the increasing w/p from 0.28 to 0.36 for all the temperatures. While the CTE values of SCC 1 was 6×10^{-6} 1/°C at 20°C, on the other hand, the CTE values of SCC 2, SCC 3, and SCC 4 were 2.6×10^{-6} 1/°C, 3.0×10^{-6} 1/°C, and 3.3×10^{-6} 1/°C, at 20°C for 0.31, 0.34, and 0.36 w/p ratios, respectively, in oven dry conditions. Similar to thermal strain, an increase in w/p resulted in a decrease in the CTE for a given temperature in the SCC. The CTE of the SCCs was, however, enhanced significantly between 550°C and 650°C because of the transition of quartz in the natural sand and gravel. Consequently, the maximum CTE values in all the SCC were obtained at the transition phase of quartz from α to β. The CTE values of the SCC varied between 22.35×10^{-6} and 16.8×10^{-6} 1/°C at 650°C, where the range reflects changes in the w/p from 0.28 to 0.36. Above 650°C, the CTE values of the SCCs decreased suddenly because of the shrinking specimens due to the evaporation of the free interlayer water from the deformed cement matrix. Similar definitions were made by Kodur and Sultan [12]. The authors measured the thermal expansion of the high strength concrete using the dilatometric methods. They defined that thermal expansion of the high strength concrete, produced with siliceous aggregate, increases with temperature up to about 700°C and then remains constant. The increase in the thermal expansion near 550°C can be attributed to the transformation of quartz in the siliceous aggregate. Above 800°C, the thermal expansion of the high strength concrete decreases due to further dehydration and shrinkage of the concrete.

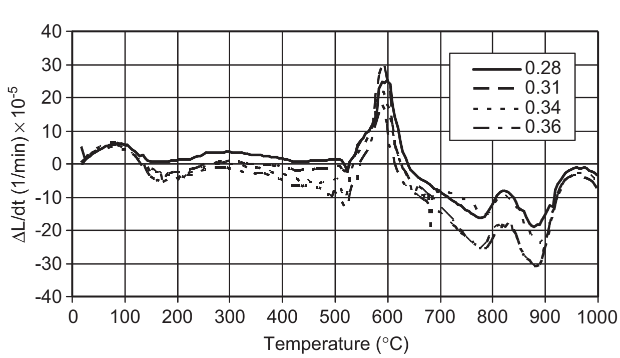

Figure 10 The first derivation of thermal strain curve of SCLC with diatomite.

The CTE values of the SCCs changed between 17.93×10^{-6} and 9.57×10^{-6} 1/°C at 1000°C. Also, Zuda and Černý [9] performed thermal tests on the aluminosilicate composite prepared with quartz sand. They investigated the effect of high temperatures from 20°C to 1000°C on the length changes of alkali-activated aluminosilicate composite with quartz sand aggregates. It was reported that the highest CTE value was obtained at about 450°C at 16.5×10^{-6} 1/°C.

It would also be expected from Figure 11 that reinforced concrete structures are under the spalling and collapsing risk when they are exposed to temperatures above 650°C during the fire because of the highest thermal expansion that occurs at this stage. When comparing the SCC 1, the decrease in the CTE values of SCC 2, SCC 3, and SCC 4 at 650°C was 3%, 15.9%, and 24.8%, respectively, due to the increase of the w-p ratio from 0.28 to 0.36 and, thus, a decrease in internal thermal stress with an increase in apparent porosity. In other words, an increase of the w/p ratio from 0.28 to 0.36 for the SCC causes the decrease risk of spalling and collapsing of concrete members, especially columns, between 3% and 24.8%. Kodur and McGrath [26] carried out a study on fire durability of high strength concrete columns, and they reported that the strength of high strength concrete columns after fire exposure was lower than that of normal strength concrete columns. This was because the normal strength concretes have higher porous structure than the high strength concretes [27]. Similar results were obtained by Yao and Zheng [15]. Authors reported that the CTE of concrete increases with the amount of water and paste-aggregate ratio. When the amount of water is fixed, the CTE reduces with the increase in water-cement ratio and increases when cement content is fixed.

The corresponding typical CTE values-elevated temperature for the SCLC with tuff and diatomite are illustrated in Figures 12 and 13, respectively, in different w/p. Similar to the SCC, the CTE of the SCLC with tuff and diatomite increased until 100°C. The CTE of the SCLC with tuff took on values between 6.53×10^{-6} and 5.35×10^{-6} 1/°C and the CTE of the SCLC with diatomite took on values between 7.46×10^{-6} and 6.3×10^{-6} 1/°C depending on the w-p ratio at 100°C because of the internal pressure effects of evaporation of the free interlayer of water in C-S-H. After the water evaporated from the specimen, the CTE of the SCLC began to decrease due to shrinkage of tuff and diatomite with increasing temperature from 100°C to 550°C. The CTE increased suddenly after 550°C because of the transition of quartz in the natural sand. When the water-powder ratio was increased, it resulted in a substantial decrease in the CTE of the SCLC because of the increasing ratio of the apparent porosity and the number of voids in the concrete. Another factor that influenced the CTE values of the SCLC was the AE. By using the AE, the voids content was increased in the SCLC, thus significantly decreasing the thermal expansions of the concretes. The CTE values of the SCLC with diatomite were lower than those of the SCLC series produced with tuff aggregates because of the porous nature of the diatomite. However, all the SCLC series with tuff and diatomite have lower CTE values than the SCC series for all the temperatures after 100°C. Brooks et al. [28] investigated the thermal strain capability of lightweight aggregate concrete. After experimental studies, the authors observed that lightweight aggregate concretes have lower coefficients of thermal expansion and reach slightly higher maximum temperatures due to hydration. It was interestingly found that CTE values of the SCLCs were almost the same with the CTE values of the SCC in all the w-p ratios below temperatures of 100°C. The CTE values of the SCC and the SCLC were compared in Figure 14 depending on the w-p ratio for a temperature of 55°C.

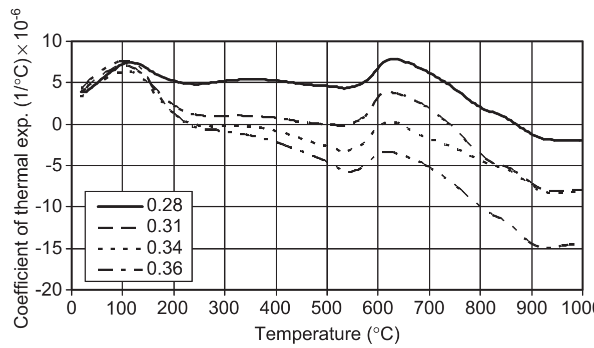

Figure 13 CTE of SCLC with diatomite vs. temperature.

As seen in Figure 14, there was no regular decrease in the CTE of the SCC and the SCLC with the increase in the w-p ratio from 0.28 to 0.36 at low temperature. It was probably due to the internal vapor stress in the hydrated cement matrix because of the water that was located in the porous structure of lightweight aggregates. When the CTE values of the SCC at temperatures of 55°C varied between 6.3×10^{-6} and 4.0×10^{-6} 1/°C, the CTE values for the same temperatures varied between 5.9×10^{-6} and 4.5×10^{-6} 1/°C, and between 5.2×10^{-6} and 6.1×10^{-6} 1/°C, for the SCLC series with tuff and diatomite, respectively, depending on the water-powder ratio.

When the effect of the aggregate type on the CTE values of the SCC and the SCLC at 635°C was considered (Figure 15), it can be noted that the CTE of concretes showed a considerable decrease depending on the decrease in the w-p ratio from 0.28 to 0.36. The SCLC with tuff had CTE values between 3.92×10^{-6} and 1.15×10^{-6} 1/°C at 635°C; however, the SCLC with diatomite had CTE values between 7.86×10^{-6} and -3.47×10^{-6} 1/°C at 635°C depending on the w/p. On the other hand, the CTE of SCC ranges from 22.4×10^{-6} to 16.74×10^{-6} 1/°C for the same temperature value. When comparing the SCC, a decrease in the CTE at 635°C, due to the replacement of gravel with tuff aggregate, was between 82.5% and 93% for the w-p ratio of 0.28–0.36. However, the decrease in the SCLC with

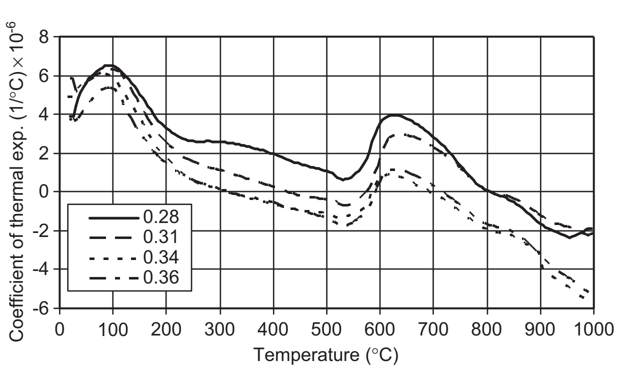

Figure 12 CTE of SCLC with tuff vs. temperature.

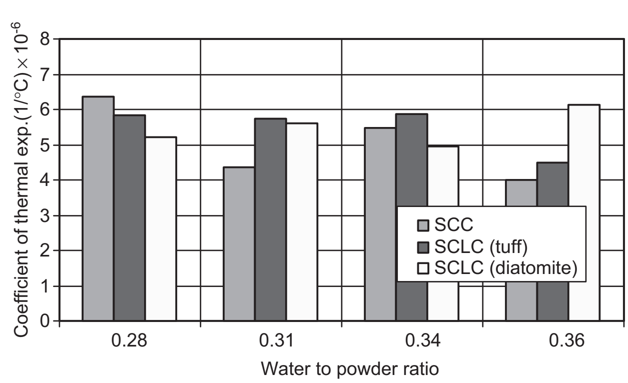

Figure 14 Comparison of CTE values of SCC and SCLC at 55°C.

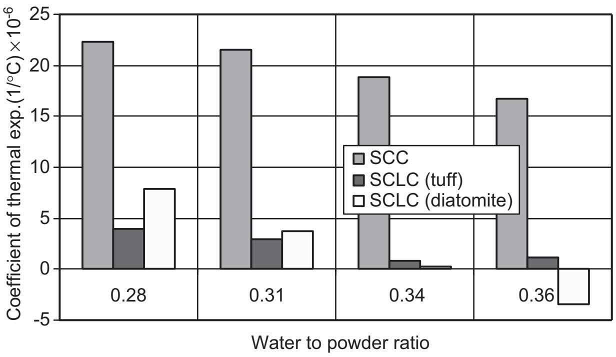

Figure 15 Comparison of CTE values of SCC and SCLC at 635°C.

diatomite was between 65% and 121% for the w-p ratios for the same temperature value.

In Figure 16, the CTE values of the SCC and the SCLC with tuff and diatomite at 1000°C were compared. The CTE substantially decreases as the w/b for each series is increased. Moreover, a replacement in gravel with lightweight aggregate resulted in a considerable decrease in the CTE values because of shrinkage of the lightweight aggregates under the high temperatures. Diatomite has a higher shrinkage value than tuff; thus, it resulted with a lower CTE of the SCLC with diatomite than the SCLC with tuff at a temperature of 1000°C. Owing to the gravel expansion characteristic under the elevated temperature, the highest CTE values were obtained on the SCC for all the w-p ratios. As seen in Figure 16, when comparing with the SCC, a decrease in the CTE value of the SCLC of those made up of tuff and diatomite was 110% and 111%, respectively, for the w/p of 0.28; and it was 152% and 181%, respectively, for the 0.36 w-p ratio.

5 Conclusions

An extensive study was performed on the CTE values of the SCC and the SCLC at elevated temperatures (from 20°C to 1000°C) related with different w/p. Obtained results are summarized below:

- The fresh and hardened concrete test results reported in this paper show that the slump flow value of the SCLC was lower than that of the SCC in the highest water-powder ratio. The AE prevented the segregation of SCLC in high water-powder ratios. The viscosity of the SCC is higher than that of the SCLC. Because the tuff and diatomite aggregates are moved easily by mortar, the SCLC series has a lower viscosity. The fresh unit weight of the SCC was decreased in the ratio of 21–24% and 25–28% by replacing the gravel with tuff and diatomite, respectively.
- A replacement of gravel with lightweight aggregate resulted in a decrease in compressive strength of the SCC. It was found that the compressive strength of the SCC was decreased in the ratio of 56–55% and 62–64% by replacing the gravel with tuff and diatomite, respectively, depending on the w-p ratio.
- Replacement of gravel aggregates with natural LWA in the SCC causes an increase in absorption because of the high water absorption ability of lightweight aggregates compared with gravel. The apparent porosity of the SCLC was approximately two times higher than that of the SCC.
- The transformation of quartz from α to β form caused a slight volume and length expansion in the SCC and the SCLC above 550°C, and the thermal strain of specimens increased suddenly after this temperature in all the series produced with different water-powder ratios.
- The SCC has positive CTE values in all the elevated temperatures. The CTE values of the SCC were varied between 6×10^{-6} 1/°C and 3.3×10^{-6} 1/°C, at 20°C for 0.28–0.36 w/p ratios, respectively, in oven dried conditions. The CTE values of the SCC varied between 22.35×10^{-6} and 16.8×10^{-6} 1/°C at 650°C, where the range reflects changes in the w/p from 0.28 to 0.36. However, the CTE values of the SCCs changed between 17.93×10^{-6} and 9.57×10^{-6} 1/°C at 1000°C.
- When comparing the SCC 1, a decrease in the CTE values of SCC 2, SCC 3, and SCC 4 at 650°C were 3%, 15.9%, and 24.8%, respectively, due to the increase in the w-p ratio from 0.28 to 0.36. When comparing the SCC, a decrease in the CTE at 635°C, due to the replacement of gravel with tuff aggregate, was between 82.5% and 93% for the w-p ratio of 0.28–0.36. However, the decrease in the SCLC with diatomite was between 65% and 121% for the w-p ratios for the same temperature value.

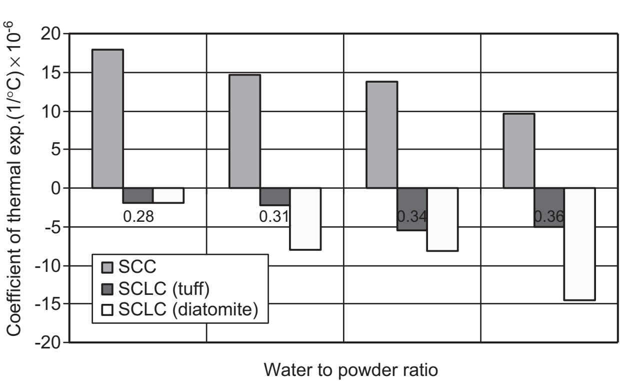

Figure 16 Comparison of CTE values of SCC and SCLC at 1000°C.

Consequently, the CTE values of the series produced with the lightweight aggregates were much lower than those of the series produced with normal aggregates above 100°C. The behavior of the aggregates under the thermal stress and voids content in the concrete significantly impacts the CTE of the concrete. An increase of the voids and apparent porosity in the specimens resulted in a significant decrease in thermal expansion. For this reason, the use of an AE in the production of the SCC with gravel, which has very low porosity, is proposed. At the same time, when the strength properties were considered, it would prevent excessive expansion of the concrete and, thus, collapsing and spalling of the concrete structures under the elevated temperatures, especially above 600°C, by using lightweight aggregates such as tuff and diatomite in the production of the SCC.

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