ARCHITECTURE CIVIL ENGINEERING ENVIRONMENT
The Silesian University of Technology No. 2/2021

doi: 10.21307/ACEE-2021-016

HIGH TEMPERATURE PERFORMANCE OF SELF-COMPACTING CONCRETE CONTAINING BORON ACTIVE BELITE CEMENT

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Received: 29.09.2020; Revised: 20.01.2021; Accepted: 25.02.2021

Abstract

The boron active belite cement is a cement type different from the Portland Cement due to the presence of B_2O_3 at 3–4%. The prominent properties are low hydration temperature, low early strength, and high final strength for the boron active belite cement concrete. The aim of this study is to observe self-compacting concrete properties, which includes boron active belite cement and silica fume, at the high temperatures. Withal, the cement types were decided as CEM I, CEM II, and boron active belite cement. Some mechanical and durability properties of manufactured samples were also investigated, experimentally. The samples were designed for 0.35 water/binder ratio and 2% hyper plasticizer, while the silica fume is replaced 7.5% for cement. Some rheological properties of self-compacting concrete, such as the experiments of flow diameter, flow time (t_{50}), V-flow time, L-box and J-ring were observed at fresh stage. As high temperature related parameters, the samples were planned to be tested for 100, 200, 300, 400, 600 and 750°C, to acquire the compressive strength, tensile splitting strength, ultrasonic pulse velocity, and the unit weight. All the samples met the mentioned relevant criteria of self-compacting concrete. Withal, the presence of the boron active belite cement was enhanced by the flowability of the fresh concrete. The long time resulting compressive and splitting tensile strengths of the samples, which were produced with boron active belite cement implied greater values, then the CEM I and CEM II ones. The increasing high-temperature, decreased the strengths for all samples, and weight loss for the boron active belite cement used samples.

Keywords: **Self-compacting concrete; Boron active belite cement; High temperature.**

1. INTRODUCTION

Concrete generally consists of cement, water and aggregate. The cement constitutes about 30% of concrete by volume. Therefore, the varying cement composition plays a crucial role in the behavior of concrete. Since the reinforced concrete (RC) structures could be exposed to very different climatic conditions, as a result of geographic location and altitude, it is important to evaluate the performance of cement based composites [1–3]. Cement is widely used in concrete applications such as: bridges, dams, cohesionless soil grouting, cement-based mortar, drainage channels, and foundation planning and tunnels as well as RC structures. The binding ability of cement provided a compact system between coarse and fine aggregates in the concrete mix [4–7]. The cement-based materials (such as fly ash, silica fume, polymers, blast furnace slag, and etc.) have been used to improve the characteristic properties of cementing system. Besides, the water/binder and curing time significantly affect the rheological and mechanical properties of the composite [6–11]. Temperature variation causes major problems for cement, mortar, and concrete due to the accelerated hydration of conventional cements and the rapid evaporation of mixing water. High temperature leads the fresh mix to gain strength much faster with time compared to similar ones at moderate temperatures [7, 12].

Cement is one of the most basic components of the concrete. Because of the predominance of Portland cement it consists of tri-and-di calcium silicates, which increase the strength of concrete, it is widely referred to simply as cement. Portland cement is referred to by the name of the place where it is produced. The Portland Cement is really cheap and has minimal environmental impacts compared to other materials. Nonetheless, the production process of the Portland Cement causes environmental damage, too [13, 14]. Boron active belite cement (BABC) is an alternative cement type that produced by presence of B_2O_3 at 3–4%, allows low heat of hydration and greater ultimate strength values at later ages. Its clinker comprises by product of boric acid and borate. BABC causes reduction of the decarbonation due to low levels of $CaCO_3$ content and thus lower CO_2 and NOx emissions as well as the reduction in energy consumption and CO_2 emission up to 25% [14–20]. However, Turkey has 803 million tons of boron reserves, which constitute 63% of the total boron reserves around the world. The most important boron ores are tincal, colemanite and ulexite in Turkey. The main products of them are tincal, borax pentahydrate, decahydrate borax, anhydrous borax, boric acid and sodium perborate. Nonetheless, tincal is more commonly known internationally simply as borax. Although, Turkey has 63% of the total boron reserves of the world, the second country boron producer in this field is Turkey. It could be produced 1.72 million tons each year [21–25]. The use of various industrial wastes is important to protect the environment against deterioration. Therefore, the researchers have focused on the utilization of more environmentally friendly binders instead of environmentally harmful materials, such as in recent years. On the other hand, the rapid development of social community, resource's deprivation, energy crisis and environment pollution will be very important issue for humanity soon. The traditional cement industry is one of the industries that harm the environment the most for its high resource and energy consumption, massive green-house gases emission as well as the micro-particle release. Therefore, more sustainable development in cement industry becomes the focus of engineers and government officials all over the world. Thus, the belite cement is thought as an alternative to Portland Cement, as a result of low energy and environmentally-kind [26, 27].

Segregation and workability are some of the most important disadvantages of concrete. One way to avoid these disadvantages is to use Self-compacting concrete (SCC). The SCC is a special type of concrete that settles in the mold without the need for operator and vibration through its own weight. SCC was first applied in Japan in the 1980s, in order to reduce costs and improve the quality of the concrete industry [21, 28–32]. Although, the materials used in the mix are the same both SCC and conventional concrete, the mixing and the composition are different from each other. While designing a SCC mix, the variation of the aggregates shapes, cements, industrial and/or mineral powders, plasticizers (neither super or hyper), and viscosity enhancing admixtures have to be considered carefully. Despite the fact that, the amount of Portland cement is affected negatively the properties of concrete such as cost, concrete temperature, etc. Withal, the increase of cement usage, which increased the cement production, also, endangers the environment with huge amount of carbondioxide (CO_2) emission. Furthermore, the cement production consumes energy between 110 and 120 kW [28, 33, 34]. A more environment friendly cement type is necessary to use in concrete technology. This has made serious concern of the practitioners and researchers to bring alternative materials of cement such as fly ash and boron active belite cement (BAB) [35, 36].

The aim of this study is to experimentally investigate the mechanical and rheological properties of SCC produced with three different cement types such as CEM I and CEM II and Boron Active Belite Cement (BABC). For this purpose, both the fresh concrete tests such as flow diameter, flow time to 50 cm diameter, L-box, V flow time and J-ring tests and mechanical properties like compressive strength, splitting tensile strength, ultrasonic pulse velocity (UPV), and unit weight at high temperatures were investigated.

2. EXPERIMENTAL PROGRAM

2.1. Materials

In the present study, CEM I 42.5 R and CEM II B-M (P-LL) 32.5 R and BABC type of cements were used in accordance with TS EN 197/1 [37] standard. Physical, mechanical and chemical properties of three types of cement are given in Table 1. The main physical phase of cement paste, the calcium–silicate–hydrate $(C–S–H)_2$ phase, is a random complex composite at the nanometer scale. Ettringite is another phase that can appear in some quantity in some cement pastes, but probably

Table 1.
Chemical, physical and mechanical properties of cements

Composition (%)	CEM I 42,5R	CEM II B-M (P-LL)32,5R	BAB
SiO_2	20.79	19.15	21.56
Fe_2O_3	2.23	2.2	2.76
Al_2O_3	4.78	4.7	5.15
CaO	63.41	56.16	60.74
MgO	2.26	2.99	3.38
SO_3	2.65	1.94	2.25
CI-	0.0172	0.0187	0.0354
Loss on Ignition	2.36	11.38	2.43
Na_2O	0.38	0.34	0.47
Specific Surface (cm^2/g)	4089	4911	3646
Specific Gravity (gr/cm^3)	3.11	2.96	3.08
Comp. Strength (2 days)	30.4	22	12.7
(MPa) (28 days)	59.8	45	35.8

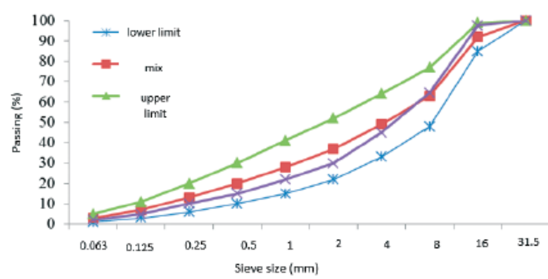

Figure 1.
Grading curve of fine and coarse aggregates

only plays a minor elastic role [38, 39]. Belite cement contains the belite phase – $2CaO{\cdot}SiO_2(C_2S)$ in the amount of 40 to 50%. Its main disadvantage is the low early strength due to the poor hydraulic activity of the belite. The hydration rate of the belite in Portland cement after 28 days may be even four times lower compared to the alite phase. The belite-phase consists of 5 polymorhps namely, α, α'H, α'L, β and γ. The stable-phase is γ–$2CaO{\cdot}SiO_2(\gamma\text{-}C_2S)$ at the temperature below 650°C. γ-phase is transformed into β-phase at the temperature of 675°C. However, β-phase is stable between the temperature range of 675°C and 1420°C. β-phase is changed into α-phase in the temperature range above 1420°C. β-phase is stable between the temperature range of 1410°C and 2130°C. The ability to react with water of belite phases is different from each other. The ability to react with water of β-phase is the best, which the γ-phase usually does not hydrate. β-C_2S phase or α-C_2S phase can be transformed into the γ-C_2S phase while the fired belite clinker is cooled. Therefore, the stabilization of those two phases is a very important issue to prevent their transformation into γ-C_2S phase [40, 41].

Polycarboxylic ether polymer based Draco-Levelcon FX10 hyperplasticizer was used in concrete mixtures at the maximum value of 2% at the end of preliminary tests to ensure the workability of all concrete samples. This product is particularly suitable for the production of high–performance concrete mixtures with high-water reduction capacity and excellent fluidity required for consistency-retaining.

The fine aggregate was 0–4 mm and the coarse aggregate was 4–16 mm and they conformed to the according to TS 706 EN 12620 [42] and TS 802 [43] standards. Maximum grain diameter of the aggregate used in the experiments is 16 mm. Aggregates were classified according to 0–4 and 4–16 for fine and coarse aggregates. The granulometry curve was prepared using coarse and fine aggregate in the volume rates of 38% and 62% in concrete mixtures, respectively. Since the properties of the concrete mix are significantly affected by aggregate granulometry, a single granulometry curve was used in the mixtures. Aggregate granulometry was used as a granulometry adjusted according to TS 802 standard [43]. The granulometry curve used in the concrete mixtures used in the experiments is presented in Figure 1.

2.2. Mixing, casting and curing

Water/binder ratio (w/b) was adopted to be 0.36 for all concrete mixes. The silica fume (SF) ratio used in the mixtures was taken by replacing with cement in the rate of 7.5%. Hyper plasticizer was used up to 2% of the cement weight in order to ensure sufficient fluidity in the mixtures.

Concrete mixes were prepared for three cement types in convenience with TS 802 [43] standards. The dosage of binder in the test mixtures was fixed, and the air volume was preferred as 1%. In addition, the total binder rate used was 500 kg and 7.5% SF were replaced with cement. Mixing ratios are given in Table 2. A laboratory type concrete mixer was used while preparing the mixtures. The mixing process in the concrete mixer was completed in 5 minutes according to ASTM C 192 [44].

Table 2.
Concrete mix composition

Concrete type	Quantities (kg/m^3)				
	Cement	Water	Silica fume	Coarse agg.	Fine agg.
CEM I	462	175	38	607	1014
CEM II	462	175	38	607	1014
BABC	462	175	38	607	1014

No rodding or tamping was performed when placing concrete into the molds. The samples stored under laboratory conditions for 24 hours and after removing the casts were transferred in a cure pool saturated with lime and set at a temperature of 23±1°C. The samples were taken out of the cure pool one day before the tests and stored under laboratory conditions again for one day, and then the experiments were completed. For high temperature tests, the samples were taken out of water after 28 days of curing time and unit weight, UPV, splitting tensile strength and compressive strength tests were conducted after 3 hours of exposure to 100, 200, 400, 600 and 750°C. Three samples were produced from each sample in the experimental program, and the average of the results measured from the three samples was used in the relevant tables and graphics.

2.3. Testing methods

The flow diameter test was conducted in order to measure the self-flowing ability of concrete. In this method, the concrete is permitted to flow freely across a flow table by letting it fall through a cone with its own weight without any obstacles. In order to determine the fluidity of SCC and its ability to pass through reinforcements, the blocking risk of concrete was evaluated with the L-box test. V-funnel test was carried out in order to measure the viscosity and transition ability of SCC. With this experiment, the passing ability of the concrete was examined by providing flow with its own weight from a narrow section, as the greatest aggregate diameter below 20 mm.

The 100x200 mm cylindrical specimens were used conveniently with TS EN 12390-3 [45]. All samples were tested under a constant loading rate. The load on the samples increased consistently with a uniform rate of approximately 3.16 $kg/cm^2/s$ and the compressive strength related values were obtained from the digital display of the press when the sample was fractured. All results are the average of three samples for each group.

While the ultrasonic waves were sent from one surface to the other surface of the concrete sample, they encountered gaps on their paths. Since these waves cannot cross the gap as fast as a solid section, they will go through the gap. Multiple repetitions of this action will increase the distance the ultrasonic waves must go between predetermined points. The decrease in the speed of ultrasound indicates strength of the material, also. The speedy ultrasonic wave means a full section without voids, which generally decreases the strength for conventional concretes. Direct measurement method was used to determine ultrasonic velocities. Ultrasonic velocity measurements were conducted using 100x200 mm cylindrical specimens according to ASTM C597-09 [46].

Three cylindrical specimens with 100 x 200 mm dimensions were used in convenience with TS EN 12390-5 [47] in order to determine the splitting tensile strength, also.

High-strength SCC is of low fire resistance due to its relatively compact structure. Under high temperature, the free water in the body of the concrete sample and the chemically bonded water in the cement paste evaporates, but due to the dense structure of high-performance concretes, evaporation becomes relatively hard. As a result of this phenomenon, spills appear on the concrete surface, and the reinforcement steel cannot be protected from high temperatures. For high temperature tests, the relevant samples are taken out of the curing tank at the 27th day and at the 28^{th} day they are transferred to the furnace to exposure to the at 100, 200, 400, 600 and 750°C for 3 hours, then cooled to ambient temperature and subjected to unit weight, UPV, splitting tensile strength and compressive strength tests.

3. RESULTS AND DISCUSSION

In the fresh concrete tests, flow diameter, flow time to 50-cm diameter, L box, V flow time and J-ring tests were performed on the samples. Among the mechanical properties, compressive strength, splitting tensile strength and UPV, and at high temperature's unit weight, UPV, compressive strength and tensile splitting strength were investigated.

3.1 Fresh concrete properties

According to the concrete mixture types, flow diameter, flow time to 50-cm diameter, L-box, V-funnel flow time, and J-ring tests were performed immediately after the concrete mixing. Results are presented in Table 3. The effect of different cement types on workability was determined due to the use of different cements and hyper plasticizer in a fixed ratio in all mixtures. Although, the cement ratio was fixed, the variation of cement type influenced the mentioned flow diameters, as expected. Figure 2 shows the flow of the BABC mixes.

It was found that SCC represents suitable viscosity properties within its general criteria. The low viscosity causes the concrete to undergo segregation on moving with its own weight, while the high viscosity makes it difficult for the concrete to move through

Table 3.
Effect of different cement types on rheological properties

Mix	Flow diameter		J-ring (mm)	L-box	V-funnel (s)
	D (mm)	t_{500} (s)			
CEM I	700	2.5	20	0.8	9.6
CEM II	630	5.0	40	0.7	10.5
BABC	710	2.4	10	0.9	8.0

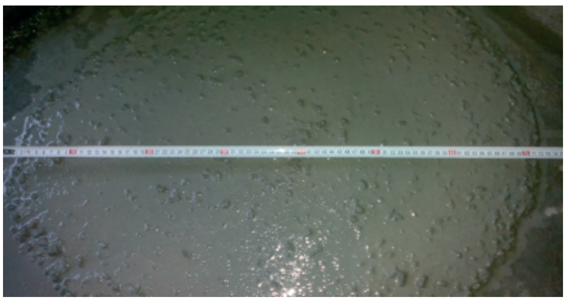

Figure 2.
Flow diameter of BABC mix

the narrowest reinforcements. It was seen when the test results were evaluated that the highest viscosity value was obtained in the CEM II mixture and the lowest viscosity value was in the BABC mixture. Replacing SF with cement as a mineral additive also increased viscosity. This can be attributed to the lower specific gravity of SF, compared to cement. The material with lower specific gravity needs more water to provide the similar strength values.

The J-ring value in the BABC cement mixture was measured to be 10 mm, while 20 mm and 40 mm in CEM I and CEM II cement mixtures. It was stated that for the 300 – mm diameter J-ring proposed in EFNARC [48], J-ring values greater than 10 mm indicate the tendency to block in the mixture. Withal, there is no blocking tendency for the BABC mixes and there may be a blocking tendency for the others.

3.2 Hardened concrete properties

In this section hardened properties of the concrete samples, such as compressive strength, splitting tensile strength, and UPV were evaluated. The results of the mechanical properties of SCC produced in three different groups are given at Table 4. Lower w/b ratios increased high compressive strength values due to reasons like minimizing the pores by adding mineral additive, SF, within the concrete mixes. The observed 28th days compressive strength values are obtained from greatest to the least is as BABC, CEM I and CEM II included samples, respectively. The compressive strength of the samples produced with BABC is 4.75% and 51.7% greater than the ones with CEM I and CEM II type cement, respectively.

The observed tensile splitting strengths for all three groups are presented at Table 4. The splitting tensile strength of the samples were found to be in the range of 5.13–3.40 MPa. Although the w/b ratio was the constant for all compared groups of samples. As a result, the SF addition improved the splitting tensile strength for all samples, as expected like the compressive strength values. The observed minimum tensile strength was for the samples including CEM II type cement, while the samples with BABC present the maximum. Withal, the samples with BABC presented the highest UPV result. The UPV results of the BABC samples are 4.81% and 9.56% greater than the ones with CEM I and CEM II cement, respectively.

As shown in Table 4, the unit weights of the samples are very close to each other. The SF addition as a

Table 4.
Experimental results

	Control	100°C	200°C	300°C	400°C	600°C	750°C
Compressive strength (MPa)							
BABC	45.21	43.91	35.37	34.59	32.6	20.49	8.3
CEM I	39.40	35.10	34.36	29.21	27.81	14.75	5.3
CEM II	29.80	26.74	24.98	22.79	20.61	12.31	3.5
Splitting tensile strength (MPa)							
BABC	5.13	5.07	4.11	4.00	3.75	2.37	0.95
CEM I	4.37	4.04	3.96	3.38	3.21	1.61	0.61
CEM II	3.40	3.11	2.88	2.63	2.37	1.43	0.40
UPV (m/sn)							
BABC	4250	4201	3905	3756	2945	1750	1560
CEM I	4055	4049	3750	3456	2875	1659	1458
CEM II	3879	3854	3423	3105	2469	1480	1210
Unit weight (kg/m^3)							
BABC	2271	2269	2250	2201	2156	2140	2079
CEM I	2266	2255	2216	2198	2145	2120	2018
CEM II	2250	2247	2213	2174	2153	2059	2042

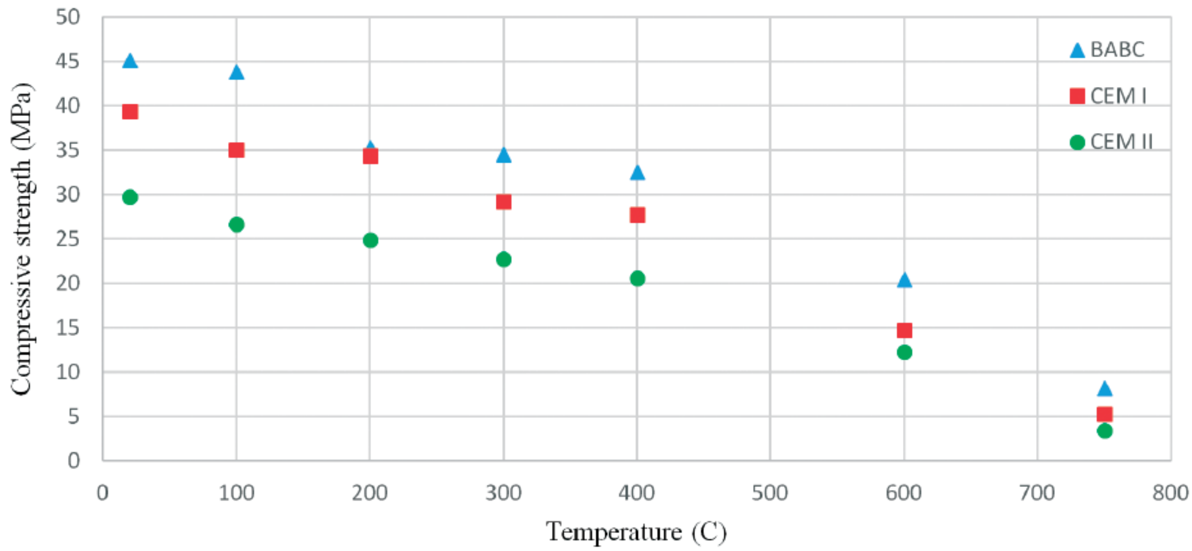

Figure 3.
Compressive strength results

replacement of the cement, resulted in a decrease in unit weights. The relatively lower specific gravity of the SF comparing to the cement's resulted in this behavior, as expected. Withal, the lowest and the greatest unit weights are observed for the samples manufactured with CEM II and BABC, respectively.

3.3. High temperature effect

In this section, compressive strength, tensile splitting strength, UPV, and weight loss result from the SCC samples subjected to six different temperatures that were evaluated. In order to determine the effectiveness of BABC, CEM I and CEM II in concrete samples were subjected to 100°C, 200°C, 300°C, 400°C, 600°C and 750°C, at the age of 28th days, in accordance with the relevant standards. The results are presented at Table 4. In addition, all samples exposed to high temperature are compared with the control samples at ambient conditions, 20°C.

Aydın et all. [21] reported that although the 3-day and 7-day compressive strengths of concrete with BABC were lower than the samples produced with Portland Cement, the 28-day and 90-day related ones with BABC were greater than the samples produced by the others. Figure 3 shows the compressive strength results of the samples exposed to high temperatures. As the temperature increased, the compressive strength values decreased, for all the samples, as expected. When the SCC samples produced with BABC cement were exposed to 100, 200, 300, 400, 600 and 750°C, the compressive strength values decreased by 3%, 22%, 23%, 28%, 55% and 82% compared to the control samples. However, the compressive strength values of the SCC samples with CEM I were decreased about 11%, 13%, 26%, 29%, 63% and 87%. Similarly, for the SCC samples with CEM II, the decrements were about 10%, 16%, 24%, 31%, 59% and 88%, respectively. Above-mentioned results indicate that, the BABC samples have less strength loss than the other ones. Among all the samples, the best performance was observed for the SCC mixture produced with BABC, and the strength losses of the concretes produced with the CEM I and CEM II were similar. Davraz et all. [49] stated that the compressive strength of concrete with BABC decreased in the temperature range of 500°C. Hence, it suddenly decreased at the 750°C. Liu and Zheng [50] stated that although the early strength of concrete (3-day and 7-day) with BABC was low, it increased compressive strength at 28 days.

All SCC samples lost their strength to a great extent, especially when exposed to a temperature of 750°C. When compared to conventional concrete samples with the same w/b ratio and strength, the damage caused by high temperature in SCC is greater. This situation may be attributed to the destruction caused by the increased vapor pressure due to the high internal pressure under the effect of high temperature as a result of the compact microstructure of the SCC samples. The decrease in compressive strength occurring at temperatures exceeding 200°C can be attributed to the loss of water in the alumina and iron oxide components within the cement, causing a decrease in the strength values, especially for the compressive ones. In addition, the volatility of bound water which does not evaporate under normal conditions at temperatures exceeding 300°C, increases the degree of damage and decreases the sample's compressive strength. As it is known, $Ca(OH)_2$ is one of the components found in cement paste in concrete. The conversion of $Ca(OH)_2$ to quick lime (CaO) occurs above 400°C. The transformation of lime in concrete into quicklime means a shrinkage of approximately 33%. Parasitic stresses that occur in concrete, which shrinks and expands in a short time, cause the damage to grow. At temperatures exceeding 400°C, it is seen that the C–S–H begin to be destroyed, the strength of the concrete decreases rapidly, and around 900°C the C–S–H structure is completely dissolved. Aygörmez et all. [51] showed that the conversion from $Ca(OH)_2$ to CO begins around 400°C and the C–S–H structures is quickly destroyed as it approaches 600°C.

Tang et all. [52] reported the tensile strength of concrete decreases after being subjected to the high temperature above 400°C and these characteristics are closely related to the expansion of mica in iron tailings and the dehydration and decomposition of cementing material hydration products, such as ettringite and C-S-H phase at high temperature. However, Cao et all. [53] and Abid et all. [54] stated that the dehydration of calcium hydroxide and damage of C-S-H bond at 400°C to 600°C lead to the decrease of strength and decomposition of calcium carbonate and C-S-H structure destroy the strength of cementitious composites completely.

The result that fly ash used as a substitute with cement in SCC production performs better at high temperatures compared to other mineral additives can be attributed to the fact that the tobermolite gel formation as a product of fly ash and lime at high temperatures and pressure is two or three times stronger and durable than C-S-H gel. SCC, which is among high-performance concretes, has a tighter micro structure than conventional ones. And therefore, the concrete cover discharges may occur as a result of the damage caused by the increased vapor pressure due to the high internal pressures under the effect of high temperature. It was observed that these cover discharges are relatively less for the BABC concrete samples.

The low tensile strength of concrete is the one of the most important problem for building structures. However, the researchers and civil engineers work to eliminate this disadvantage. The use of the BABC in the concrete mixture decreased the splitting tensile strength of conventional concrete. Figure 4 represents the tensile splitting strength results of SCC samples exposed to high temperatures. It is observed that as the temperature exposure of SCC specimen's increases, splitting tensile strength decreases. When specimens with BABC cement are exposed to temperatures at 100°C, 200°C, 300°C, 400°C, 600°C and 750°C, the splitting tensile strength values decreased in the rates of 1%, 20%, 22%, 27%, 54% and 81% respectively. While this decrement is about 8%, 9%, 23%, 27%, 63% and 86%, for the CEM I including samples, respectively, it is understood that BABC samples have less strength loss than the others. Among all the samples, the SCC samples with BABC gave the best results. The strength losses of the concretes produced with CEM I, and CEM II were similar. This also indicates the parallel strength loss of the compressive and splitting tensile strength, as expected.

The UPV test was employed due to assessments of the permeability and microstructure of samples for inspected cement types, CEM I, CEM II, and BABC. As known, the variations in velocity are related to physical changes in the microstructure of the samples. Figure 5 shows the UPV results of the SCC samples exposed to high temperatures. It was observed that UPV values decreased as the temperature increased. These reductions were found to be 1%, 8%, 12%, 31%, %59 and 63% respectively, for the samples exposed to 100, 200, 300, 400, 600 and 750°C compared to control samples. Withal, the control samples were 0%, 8%, 15%, 30%, 60% and 64%, respectively, compared to CEM I cement samples, and finally, the control samples were 0%, 12%, 20%, 26%, %62 and %69 respectively, compared to CEM II cement samples. As seen in Figure 5, UPV values decreased seriously at temperatures above 400°C. The wave velocity passing through the concrete is also affected by the cracks in the concrete at high temperatures. Another reason for the decrease in UPV with the increase of temperature is a measure of the progress of the cracks within the composite/material. Aygörmez et all. [51] and Öz et all. [55] showed that increasing the temperature have an important effect on the UPV values of concrete which affects unfavorably. As the water in the concrete evaporates with the increasing temperature, the volume of the pores in the microstructure increase. The voids that leads to lower UPV values are formed instead of evaporating water.

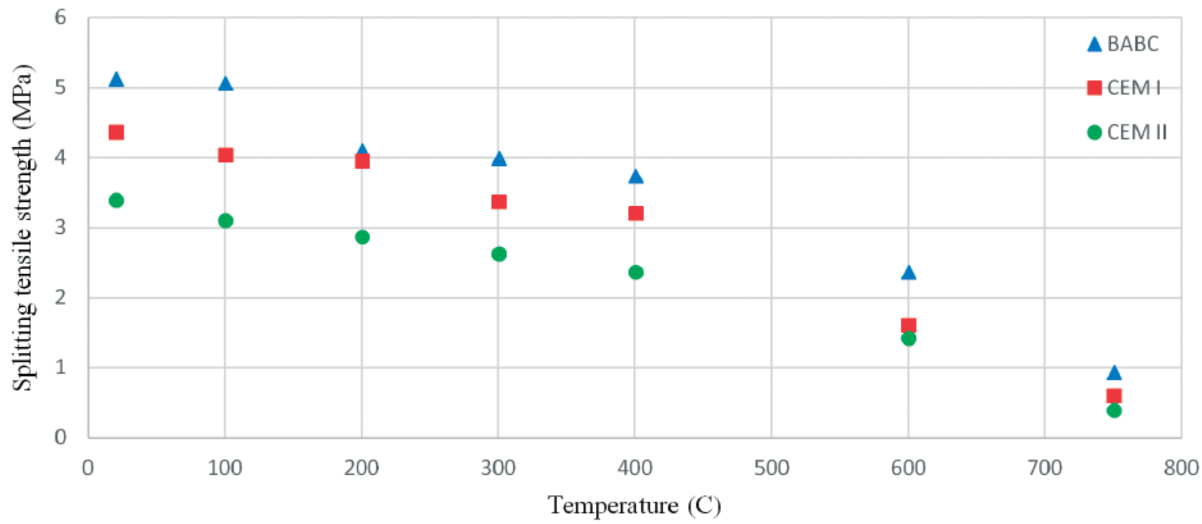

Figure 4.
Splitting tensile strength results

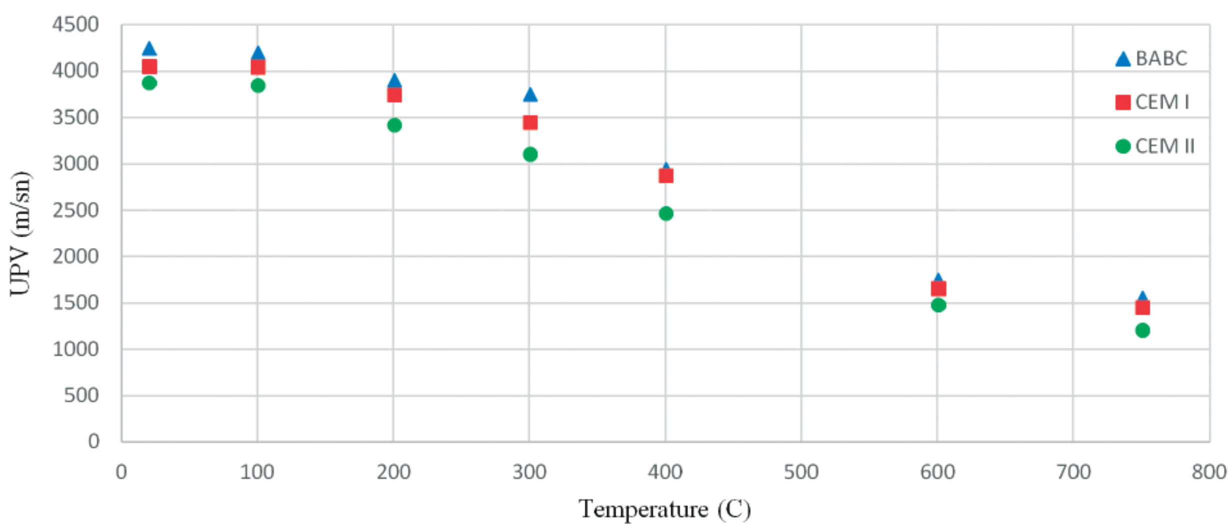

Figure 5.
UPV results

The unit weight results of the SCC samples exposed to high temperatures are presented in Figure 6. It was observed that the unit weight values decreased as the temperature in the mixtures increased. In BABC cement samples exposed to high temperatures of 100, 200, 300, 400, 600 and 750°C, these reduction amounts were 0%, 1%, 3%, 5%, 6% and 8%, respectively, for CEM I cement samples 0%, 2%, 3%, 5%, 6% and 11% and for CEM II cement samples 0%, 2%, 3%, 4%, 8% and 9%, respectively. With the dehydration reaction, moisture in the matrix moves to the surface of the sample, causing internal damage to the microstructure and, consequently, weight loss. It was observed that a serious weight loss occurred in all samples as the temperature increased.

The main reason for weight loss at the high temperature is the piece spalling the surface of concrete. However, the greatest weight loss at 600°C is in CEM II type cement. After being exposed to a temperature of 600°C, the weight loss of CEM I type cement is more than CEM II type cement. The best and the least weight loss performance in samples exposed to high temperature was obtained with BABC samples.

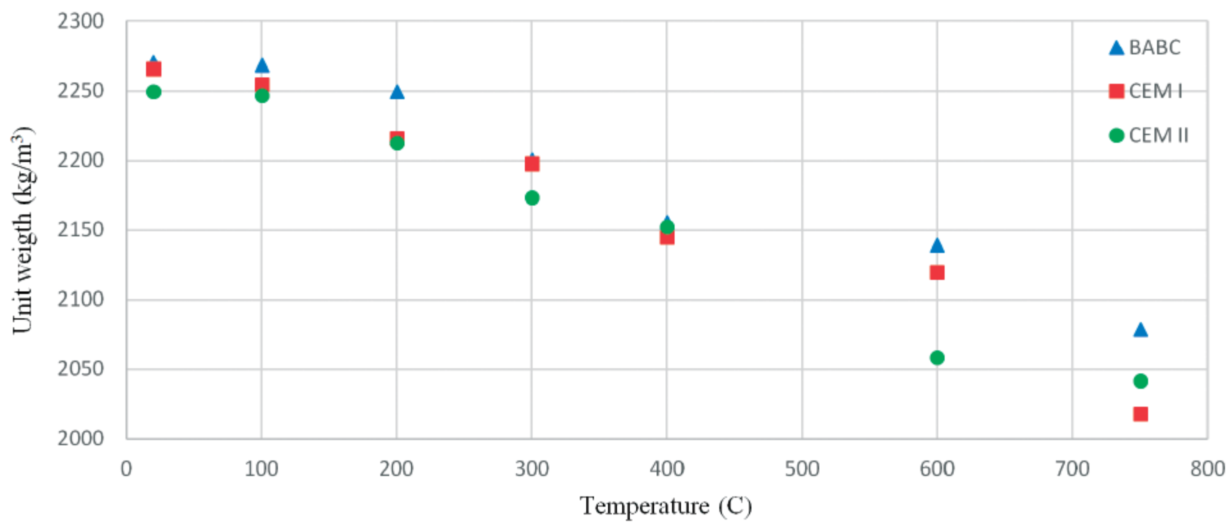

Figure 6.
Unit weight results

The weight loss of samples exposed to high temperature is close to each other up to 400°C. Nevertheless, being exposed to a temperature of 400°C, the difference between weight loss increases. Since the void ratio and impermeability of the samples produced with BAB cement is less, it has the compact structure. Therefore, the samples with BAB cement exhibited better weight loss performance than samples produced with conventional cements used. Aygörmez et all. [51] showed that the effect of high temperature on the moisture in the matrix decreased the weight loss of concrete. The biggest weight loss occurred between 400°C and 600°C. The most important point of this mechanism is due to the evaporation of free water and condensed hydroxyl groups [19, 51, 56].

4. CONCLUSION

The main purpose of this study is to experimentally compare the some mechanical and rheological properties of SCC samples with BABC with those with CEM I and CEM II type cement. It is also aimed to evaluate the performance of SCC samples with BABC exposed to high temperatures. The results obtained are summarized as follows:

- SF additive increased the SCC flow diameter values and the workability of the fresh mix by positively affecting this parameter.
- It was observed that, when the mixture types were examined, the flow diameters of the BABC samples were presenting the greatest values, which were 630 mm, 700 mm and 710 mm for the CEM II, CEM I and BABC fresh mixes, respectively.
- The greatest compressive and splitting tensile strength values were found for the samples of BABC, CEM I and CEM II, respectively.
- BABC samples lost less strength by high temperature exposure, than the others. Among all the samples, the best performance was obtained by the SCC with BABC, and it was determined that the strength losses of the concretes produced with others, the CEM I and CEM II were similar.
- All samples designed for SCC lost their strength to a great extent, especially when exposed to temperatures like 750°C. When compared to conventional concrete samples with the same w/b ratio and strength, the damage caused by high temperature is obtained as much bigger.
- The UPV values of all SCC mixtures exposed to high temperatures decreased with increasing temperature. There was a serious decrease in UPV values, especially for the temperatures above 400°C.
- A serious weight loss occurred in all samples with the temperature increase. It was determined that the weight losses of the samples are generally close to each other, but the weight loss in BABC samples is smaller than the others, which is a result of relatively little spalling within the surfaces of the BABC samples.

REFERENCES

[1] Gonzalez, A., Parraguez, A., Corvalan, L., Correa, N., Castro, J., Stuckrath, C., & Gonzalez, M. (2020). Evaluation of Portland and Pozzolanic cement on the self-healing of mortars with calcium lactate and bacteria. *Construction and Building Materials*, 257, 119558.

[2] Aydın, A. C., Nasl, V. J., & Kotan, T. (2018). The synergic influence of nano-silica and carbon nano tube on self-compacting concrete. *Journal of Building Engineering*, 20, 467–475.

[3] Türkmen, İ., A. Öz, & A.C. Aydın, (2010). Characteristics of workability, strength, and ultrasonic pulse velocity of SCC containing zeolite and slag. *Scientific Research and Essays, 5*(15), 2055–2064.

[4] Mahmood, W., Mohammed, A., & Ghafor, K. (2019). Viscosity, yield stress and compressive strength of cement-based grout modified with polymers. *Results in materials*, 4, 100043.

[5] Mohammed, A., Rafiq, S., Mahmood, W., Noaman, R., Ghafor, K., Qadir, W., & Kadhum, Q. (2020). Characterization and modeling the flow behavior and compression strength of the cement paste modified with silica nano-size at different temperature conditions. *Construction and Building Materials*, 257, 119590.

[6] Qadir, W., Ghafor, K., & Mohammed, A. (2019). Characterizing and modeling the mechanical properties of the cement mortar modified with fly ash for various water-to-cement ratios and curing times. *Advances in Civil Engineering*.

[7] Sarwar, W., Ghafor, K., & Mohammed, A. (2019). Modeling the rheological properties with shear stress limit and compressive strength of ordinary Portland cement modified with polymers. *Journal of Building Pathology and Rehabilitation, 4*(1), 1–12.

[8] Abdalla, L. B., Ghafor, K., & Mohammed, A. (2019). Testing and modeling the young age compressive strength for high workability concrete modified with PCE polymers. *Results in Materials*, 1, 100004.

[9] Aydın, A. C., Öz, A., Polat, R., & Mindivan, H. (2015). Effects of the different atmospheric steam curing processes on the properties of self-compacting-concrete containing microsilica. *Sadhana, 40*(4), 1361–1371.

[10] Kurt, M., Kotan, T., Gül, M. S., Gül, R., & Aydın, A. C. (2016). The effect of blast furnace slag on the self-compactability of pumice aggregate lightweight concrete. *Sadhana, 41*(2), 253–264.

[11] Oğuz, E., & Aydın, A. C. (2003). Prediction of adsorption rate of phosphate removal from wastewater with gas concrete. *International journal of environment and pollution, 19*(6), 603–614.

[12] Al-Martini, S., & Nehdi, M. (2007). Effect of chemical admixtures on rheology of cement paste at high temperature. *Journal of ASTM international, 4*(3), 1–17.

[13] Berriel, S. S., Ruiz, Y., Sánchez, I. R., Martirena, J. F., Rosa, E., & Habert, G. (2018). Introducing Low Carbon Cement in Cuba-A Life Cycle Sustainability Assessment Study. *In Calcined Clays for Sustainable Concrete*, 415-421.

[14] Gökçe, H. S. (2019). High temperature resistance of boron active belite cement mortars containing fly ash. *Journal of Cleaner Production*, 211, 992–1000.

[15] Kunt, K., Dur, F., Ertınmaz, B., Yıldırım, M., Derun, E. M., & Pişkin, S. (2015). Utilization of boron waste as an additive for cement production. *CBU J Sci, 11*(3), 383–389.

[16] Saglık, A., Sumer, O., Tunc, E., Kocabeyler, M. F., & Celik, R. S. (2008, May). The characteristics of Boron modified active belite cement and its utilization in mass and conventional concrete. In Proceedings of the 11th International Conference on Durability of Building Materials and Components, Istanbul, Turkey, 585–594.

[17] Yeşilmen, S., & Gürbüz, A. (2012). Evaluation of boron ore in cement production. *Materials and Manufacturing Processes, 27*(11), 1245–1250.

[18] Bullerjahn, F., Zajac, M., Skocek, J., & Haha, M. B. (2019). The role of boron during the early hydration of belite ye'elimite ferrite cements. *Construction and Building Materials*, 215, 252-263.

[19] Celik, A., Yilmaz, K., Canpolat, O., Al-Mashhadani, M. M., Aygörmez, Y., & Uysal, M. (2018). High-temperature behavior and mechanical characteristics of boron waste additive metakaolin based geopolymer composites reinforced with synthetic fibers. *Construction and Building Materials*, 187, 1190–1203.

[20] Hasar, U. C., Simsek, O., & Aydın, A. C. (2010). Application of varying frequency amplitude only technique for electrical characterization of hardened cement based materials. *Microwave and Optical Technology Letters, 52*(4), 801–805.

[21] Aydın, A. C., Aras, Ü. G. H., Kotan, T., & Öz, A. (2018). Effect of boron active belite cement on the compressive strength of concrete exposed to high temperatures. *Journal of Civil, Construction and Environmental Engineering, 3*(3), 47.

[22] Güyagüler, T. (2001). The Boron Potential of Turkey. In 4th Industrial Minerals Symposium, 118–19.

[23] Smith, R. and R. McBroom, (1992). Boron compounds. Kirk Othmer Encyclopedia of Chemical Technology, 4th ed., John Wiley & Sons, 365.

[24] Ozturk, M., Sevim, U. K., Akgol, O., Unal, E., & Karaaslan, M. (2020). Investigation of the mechanic, electromagnetic characteristics and shielding effectiveness of concrete with boron ores and boron containing wastes. *Construction and Building Materials*, 252, 119058.

[25] Kaman, D. Ö., Köroğlu, L., Ayas, E., & Güney, Y. (2017). The effect of heat-treated boron derivative waste at 600° C on the mechanical and microstructural properties of cement mortar. *Construction and Building Materials*, 154, 743–751.

[26] Hewlett, P., & Liska, M. (Eds.). (2019). Lea's chemistry of cement and concrete. Butterworth-Heinemann.

[27] Liu, Y. J., & Zheng, Y. C. (2013). Active belite cement clinker produced with mineral waste. *In Advanced Materials Research*, 610, 2378–2385.

[28] Afshoon, I., & Sharifi, Y. (2020). Utilization of micro copper slag in SCC subjected to high temperature. *Journal of Building Engineering*, 29, 101128.

[29] Aydın, A. C., & Bayrak, B. (2019). The torsional behavior of reinforced self-compacting concrete beams. *Advances in concrete construction, 8*(3), 187–198.

[30] Okamura, H., Ozawa, K., & Ouchi, M. (2000). Self-compacting concrete. *Structural concrete, 1*(1), 3–17.

[31] Raisi, E. M., Amiri, J. V., & Davoodi, M. R. (2018). Mechanical performance of self-compacting concrete incorporating rice husk ash. *Construction and Building Materials*, 177, 148–157.

[32] Aydın, A. C., Alcan, H. G., Bayrak, B., Kılıç, M., & Maali, M. (2020). The mechanical behavior of thermally enhanced polypropylene concrete. *Construction and Building Materials*, 262, 120578.

[33] Khodair, Y., & Raza, M. (2017). Sustainable self-consolidating concrete using recycled asphalt pavement and high volume of supplementary cementitious materials. *Construction and building materials*, 131, 245-253.

[34] Aydın, A. C., Karakoccedil, M. B., Duuml, O. A., & Bayraktutan, M. S. (2010). Effect of low quality aggregates on the mechanical properties of lightweight concrete. *Scientific Research and Essays, 5*(10), 1133–1140.

[35] Memon, M. A., Memon, N. A., & Memon, B. A. (2020). Effect of Fly Ash and Un-crushed Coarse Aggregates on Characteristics of SCC. *Civil Engineering Journal, 6*(4), 693–701.

[36] Kurt, M., Aydın, A. C., Gül, M. S., Gül, R., & Kotan, T. (2015). The effect of fly ash to self-compactability of pumice aggregate lightweight concrete. *Sadhana, 40*(4), 1343–1359.

[37] EN, T., 197-1 (2012). Cement–Part 1: Composition, specifications and conformity criteria for common cements. Ankara: Turkish Standard Institution.

[38] Haecker, C. J., Garboczi, E. J., Bullard, J. W., Bohn, R. B., Sun, Z., Shah, S. P., & Voigt, T. (2005). Modeling the linear elastic properties of Portland cement paste. *Cement and Concrete Research, 35*(10), 1948–1960.

[39] Zohdi, T. I., Monteiro, P. J. M., & Lamour, V. (2002). Extraction of elastic moduli from granular compacts. *International journal of fracture, 115*(3), 49–54.

[40] Kotsay, G., & Jaskulski, R. (2019). Belite cement as an ecological alternative to Portland cement – a review, *Materials Structures Technology, 2*(1), 70–76.

[41] El-Didamony, H., Heikal, M., El-Sokkary, T. M., KhaliL, K., & Ahmed, I. A. (2014). Active belite – C2S and the hydration of calcium sulfoaluminates prepared from nano-materials. *Ceramics – Silikáty, 58*(2), 165–171.

[42] TS EN 932, (2009). Aggregates for concrete. TSE, Ankara, Turkey.

[43] TS802, (2016). Design of concrete mixes. TSE, Ankara, Turkey.

[44] Standard, A., C192/C192M. (2007). Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory, ASTM International, West Conshohocken PA.

[45] EN, B., 12390-3, (2002). Testing hardened concrete-Part 3: Compressive strength of test specimens. British Standards Institution.

[46] Standard, A., C597-09 (2003). Standard Test Method for Pulse Velocity Through Concrete, ASTM International, West Conshohocken, PA.

[47] EN, B.S., 12390-5, (2009). Testing hardened concrete–Part 5: flexural strength of test specimens. British Standards Institution-BSI and CEN European Committee for Standardization.

[48] EFNARC, S., (2002). Guidelines for self-compacting concrete. EFNARC Publication, London, UK, 1–32.

[49] Davraz, M. E. T. İ. N., Pehlivanoğlu, H. E., & Kilinçarslan, Ş. (2017). Influence of High Temperature on Concrete Produced from Portland Cement with Boron Additives. *Acta Physica Polonica A, 132*(3), 872–874.

[50] Liu, Y. J., & Zheng, Y. C. (2013). Mineral Waste Coupled with Boron Oxide for Producing Active Belite Cement Clinker. *In Applied Mechanics and Materials*, 405, 2564–2575.

[51] Aygörmez, Y., Al-mashhadani, M. M., & Canpolat, O. (2020). High-temperature effects on white cement-based slurry infiltrated fiber concrete with metakaolin and fly ash additive. *Revista de la construcción, 19*(2), 324–333.

[52] Tang, J., Li, P., Chen, X., & Bai, Y. (2020). Experimental study of strength, pore structure and phase evolution characteristics of iron tailings cemented paste backfill under high-temperature. *Cement Wapno Beton, 25*(2), 78–94.

[53] Cao, M., Li, L., Yin, H., & Ming, X. (2019). Microstructure and strength of calcium carbonate (CaCO 3) whisker reinforced cement paste after exposed to high temperatures. *Fire Technology, 55*(6), 1983–2003.

[54] Abid, M., Hou, X., Zheng, W., & Hussain, R. R. (2017). High temperature and residual properties of reactive powder concrete–A review. *Construction and Building Materials*, 147, 339–351.

[55] Öz, A., Bayrak, B., & Aydın, A. C. (2021). The effect of trio-fiber reinforcement on the properties of self-compacting fly ash concrete. *Construction and Building Materials*, 274, 121825.

[56] Akyuncu, V., Uysal, M., Tanyildizi, H., & Sumer, M. (2019). Modeling the weight and length changes of the concrete exposed to sulfate using artificial neural network. *Journal of Construction, 17*(3), 337–353.