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Lightweight self-compacting concrete at high temperatures

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Preliminary report

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Lightweight self-compacting concrete at high temperatures

Results of experimental investigation of the lightweight self-compacting concrete subjected to elevated temperatures, with coconut shells added to coarse aggregate, are presented in this paper. Variations in the concrete properties, such as the compressive strength and weight loss, were observed after the concrete was subjected to the temperature of 800 °C. The investigation was carried out on concrete samples with varying proportions of coconut shells. The rice husk ash and silica fume were used to develop two reference concrete mixtures. The results show that the properties of hardened concrete decrease at temperatures of more than 400 °C.

Key words:
lightweight self-compacting concrete, coconut shells, rice husk ash, silica fume, high temperature

Prethodno priopćenje

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Samozbijajući lagani beton na visokim temperaturama

U radu su prikazani rezultati eksperimentalnog ispitivanja laganog samozbijajućeg betona s dodatkom kokosovih ljuski krupnom agregatu, pod utjecajem visokih temperatura. Nakon izlaganja betona temperaturi od 800 °C, zabilježene su promjene svojstava betona, poput tlačne čvrstoće i gubitka težine. Istraživanje je provedeno na uzorcima betona s dodatkom kokosovih ljuski u različitim omjerima kao zamjenu za krupni agregat. Za pripremanje mješavina betona upotrijebljeni su pepeo rižinih ljuski i silikatna prašina. Rezultati su pokazali da se svojstva očvrsnulog betona smanjuju na temperaturama većim od 400 °C.

Ključne riječi:
lagani samozbijajući beton, kokosove ljuske, pepeo rižinih ljuski, silikatna prašina, visoka temperatura

Vorherige Mitteilung

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Selbstverdichtender Leichtbeton bei hohen Temperaturen

In dieser Arbeit sind Resultate experimenteller Untersuchungen von Leichtbeton mit dem Zusatz von Kokosnussschalen in der groben Gesteinskörnung bei hohen Temperaturen dargestellt. Nachdem der Beton Temperaturen von 800 °C ausgesetzt wurde, sind Veränderungen seiner Eigenschaften, z. B. der Druckfestigkeit und des Gewichts, festgestellt worden. Die Prüfungen umfassen Betonproben mit unterschiedlichen Anteilen zugesetzter Kokosnussschalen, als Ersatz grober Gesteinskörnung. Zur Zubereitung zwei Referenzbetonmischungen wurden Reisschalenasche und Quarzstaub benutzt. Resultate zeigen, dass die Eigenschaften erhärteten Betons bei Temperaturen über 400 °C abklingen.

Schlüsselwörter:
Selbstverdichtender Leichtbeton, Kokosnussschalen, Reisschalenasche, Quarzstaub, hohe Temperaturen

1. Introduction

The volume concentration of aggregate in concrete amounts to about 60 %. However, the production of concrete consumes a large amount of natural resources. Various attempts have been made all over the world to identify alternate materials that would replace conventional aggregates due to depletion of natural resources. Lightweight aggregate is believed to be one of materials that could replace coarse aggregate (CA) in concrete. The application of lightweight aggregate concrete reduces the size of structural members due to its lower density [1]. The coconut shell (CS), a solid waste organic material obtained from agricultural industries, was found to be an alternate to CA [2, 3]. India produces one fourth of the global production of coconut, and it generates more than 10 million tonnes of solid waste. The Coconut Shell Aggregate (CSA) is lighter [3] than the conventional CA, and its density amounts to 1750 kg/m^3.

The literature evidence shows that the Oil Palm Shell (OPS) can be used as CA in the lightweight structural concrete [4, 5]. Similar to the OPS, the CSA presents ample opportunities for use as the lightweight aggregate in concrete. A comparative study was conducted to determine concrete properties in case the CS and Palm Kernel Shell (PKS) are added as CA. It was concluded that the CSA is more suitable than the PKS based on the strength and durability performance [6]. Moreover, only a few studies have been reported on the use of agriculture waste materials as lightweight aggregate in conventional concrete [7, 8].

The Self Consolidating Concrete (SCC) is a futuristic construction material and one of the most outstanding advancements in concrete technology over the past two decades. The SCC is a non-segregating highly flowable, durable and reliable structural concrete [9], which encapsulates the reinforcement without any mechanical vibration for complete filling of the formwork. In order to eliminate the SCC segregation while in flowing state, the size of the coarse aggregate normally varies from 12 to 16 mm instead of the 20-25 mm range used in normal concrete. This reduces the self weight of the coarse aggregate. It has therefore been established that the lightweight aggregate is suitable for preparation of the SCC. The effect of the CSA on the production of the lightweight SCC has not as yet been investigated. A detailed investigation is under way to evaluate suitability of the CSA for use in the lightweight SCC. As a part of this work, the effects of elevated temperature on the properties of the CSA based lightweight concrete were investigated since the organic waste products burn easily at higher temperatures. The study of fire resistance properties of concrete is indispensable, and it is highly dependent on constituent materials. Tanyildizi and Coskun [10] reported that the lightweight concrete containing fly ash is suitable for structural applications in the temperature range of up to 400 °C only. The compressive strength and tensile strength of the silica fume based lightweight concrete drops with the temperatures starting from 200 °C [11]. This paper discusses the effects of high temperature on mechanical properties of the CSA based lightweight SCC.

2. Materials and methods

2.1. Materials

The Ordinary Portland Cement (OPC), grade 43, was used in this investigation. The rice husk ash (RHA), an agriculture based mineral admixture, was used to develop the binary blended concrete and the combination of the RHA and silica fume (SF) was used to develop the ternary blended concrete. The specific gravity of cement was measured, and it amounted to 3.15. The specific gravity of the RHA and SF was also determined and it amounted to 2.92 and 2.28, respectively. The fineness of cement amounted to 2950 cm^2/g, while that of the RHA and SF amounted to 3170 and 21650 cm^2/g, respectively. The chemical composition of cement and other mineral admixtures was estimated by the energy-dispersive X-ray microanalysis, as presented in Table 1. The local river (Cauvery) sand was used as fine aggregate with the fineness modulus of 2.67, which belongs to the grade limit zone II as per IS:383-1978 [12], and with the specific gravity of 2.71.

12 mm blue granite metal was used as coarse aggregate (CA). The fineness modulus and specific gravity of the CA were 7.19 and 2.78, respectively. The CA density amounted to 2172 kg/m^3. The locally available coconut shells were collected from a local field and allowed to sun-dry for a month before being crushed. The crushed CSA was washed and allowed to dry under ambient temperature for another month. The shape of the dried CSA was observed as rough parabolic and flakey. The CSA surface was observed as smooth concave and convex, and edges were rough and spiky. The majority of CSA exhibited the thickness between 3 mm and 5mm. Figure 1 shows the results of the particle size distribution analysis of 5mm to 12 mm size CA and CSA with the replacement level of 25 %, 50 %, 75 % and 100 %, and expressed as well graded aggregates. The density and specific gravity of CSA were found to be 1683 kg/m^3 and 1.71, respectively. The polycarboxylate-based superplasticizer (SP) with the specific gravity of 1.07 was used to achieve the desired workability. Figure 2.a and Figure 2.b show the CSA and conventional granite aggregates that were used in this experimental investigation.

Table 1. Chemical composition of cement and mineral admixtures

Chemical composition / Materials	SiO_2 [%]	Al_2O_3 [%]	Fe_2O_3 [%]	CaO [%]	MgO [%]	Loss on ignition [%]
Cement	22.40	5.20	3.80	61.60	1.70	1.40
Rice husk ash (RHA)	91.85	0.31	0.26	0.78	0.55	3.49
Silica fume (SF)	87.10	0.78	2.10	0.90	1.40	1.09

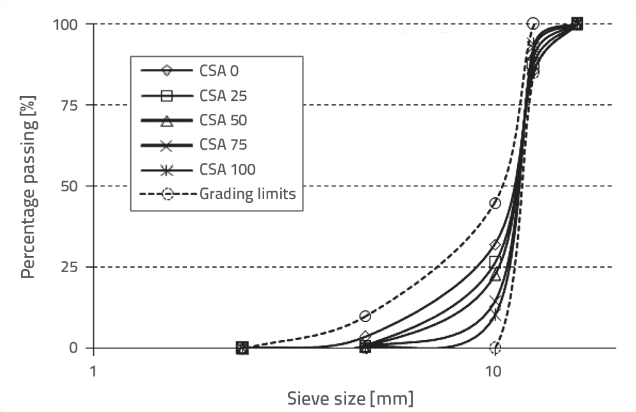

Figure 1. Grading curves of all aggregates (CSA - Coconut Shell Aggregate)

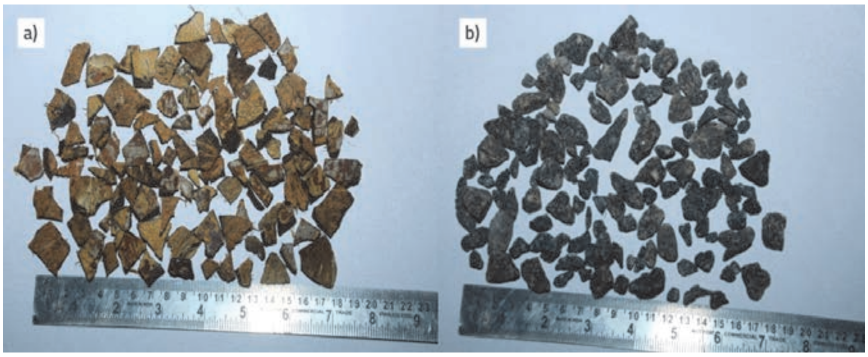

Figure 2. Coarse aggregates: a) Coconut shell aggregate; b) Granite aggregates

2.2. Mix proportions

Two concrete mixture series, with the total powder content of 450 and 550 kg/m^3, respectively, were considered in this investigation. The cement and mineral admixture (RHA and SF) contents were assorted to develop the binary and ternary blended concrete. The cement was replaced with the RHA to develop the binary blended concrete, and the SF was added in the mixture to develop the ternary blended concrete, by adjusting the cement and RHA content with reference to the compressive strength. After several trials based on the modified method for the design of mix proportions for the lightweight self compacting concrete (LWSCC), as proposed by Su and Miao [13] and Choi et al [14], the final combinations were defined and designated as SCC450 and SCC550. The proportions of control concrete mixes considered in this experimental investigation are given in Table 2. The dry granular coconut shells in the proportion of 25 %, 50 %, 75 % and 100 % were used in each case as substitutes for the CA. The water requirement was estimated based on the percentage by weight of cementitious materials (powder content) present in the mixture. The mix proportioning of CSA based LWSCC is shown in Table 3.

Table 2. Mix proportions for SCC

Mix designation		Ingredient [kg/m^3]					w/p	Superplasticizer [kg/m^3]
		Cement	Rice husk ash (RHA)	Silica fume (SF)	Sand	Coarse aggregate (CA)		
SCC450 (1 : 1.89 : 2.09)	Binary (B450)	330	120	-	850	940	0.35	2.61
	Ternary (B450)	318	100	32			0.37	2.68
SCC550 (1 : 1.47 : 1.56)	Binary (T550)	400	150	-	810	860	0.33	2.61
	Ternary (T550)	385	125	40			0.35	2.68

Table 3. Mix proportions for LWSCC

Mix	Cementitious material (C) [kg/m^3]	Sand (FA) [kg/m^3]	Coarse aggregate (CA) [kg/m^3]		Coconut shell aggregate (CSA) [kg/m^3]		Mix ratio
			%	Wt.	%	Wt.	(C:FA:CA:CSA)
SCC450	450	850	100	940	0	0	1 : 1.89 : 2.09 : 0
			75	705	25	90.5	1 : 1.89 : 1.57 : 0.2
			50	470	50	181	1 : 1.89 : 1.04 : 0.4
			25	235	75	271.5	1 : 1.89 : 0.52 : 0.6
			0	0	100	362	1 : 1.89 : 0 : 0.8
SCC550	550	810	100	860	0	0	1 : 1.47 : 1.56 : 0
			75	645	25	131	1 : 1.47 : 1.17 : 0.24
			50	430	50	262	1 : 1.47 : 0.78 : 0.48
			25	215	75	393	1 : 1.47 : 0.39 : 0.71
			0	0	100	524	1 : 1.47 : 0 : 0.95

Table 4. Slump flow and density of lightweight self-consolidating concrete (LWSCC)

Mix designation		Test	Replacement level of coarse aggregate by coconut shell aggregate				
				25 [%]	50 [%]	75 [%]	100 [%]
LWSCC450	Binary (B450)	Slump [mm]	680	705	736	758	780
		Density [kg/m^3]	2270	2050	1925	1840	1765
	Ternary (T450)	Slump [mm]	700	725	748	765	795
		Density [kg/m^3]	2220	2025	1890	1810	1735
LWSCC550	Binary (B550)	Slump [mm]	705	715	735	760	785
		Density [kg/m^3]	2305	2070	1950	1845	1775
	Ternary (T550)	Slump [mm]	720	735	745	770	795
		Density [kg/m^3]	2265	2030	1910	1825	1740

2.3. Tests

The slump flow test was conducted to find the final diameter of the concrete circle, which was measured in two directions (D1 and D2) perpendicular to each other as per EN 12350 - 8 [15]. The V-funnel test was conducted according to EN 12350 - 9 [16] to evaluate the flowability of LWSCC by measuring the time the concrete needs to flow through the V-funnel by its own weight. The L-box test was conducted according to EN 12350 - 10 [17] to evaluate the passing ability of LWSCC. The L-box test blocking ratio indicated the capacity of concrete flow through the rebars. The SCC proved a good passing ability when the ratio exceeded 0.8. The density of concrete was calculated for the 28-day aged specimens according to the Archimedes Principle by measuring the weight of saturated specimens in air and in water and the dry weight (by oven drying at 105 °C to constant weight). Concrete cube specimens measuring 100 x 100 x 100 mm were prepared to determine the effect of different temperatures on the compressive strength. The compressive strength test was conducted using the 2000 kN compression testing machine as per IS: 516-1959 [18]. The compressive strength was determined by dividing the load at which the specimen fails by the contact surface area, and an average of three specimen results was considered in this investigation. The specimens were cured in water for 28 days and then the oven dried specimens were exposed to 100 °C, 200 °C, 400 °C and 800 °C in an electric muffle furnace, where the load was increased at the rate of 2.5 °C per min. After reaching the target temperature, the temperature was kept constant for 1 hour to achieve the thermal steady state. The specimens were allowed to cool to room temperature. After cooling, tests were performed to determine the compressive strength of the specimens The change of weight of the specimens was determined by calculating the difference between the initial weight of specimens before heating (w_i) and the final weight of cooled specimens after heating to the required temperature (w_h) with respect to the initial weight of the specimens, with an accuracy of 0.01 g [19].

3. Results and discussion

3.1. Effects of coconut shell aggregate on fresh concrete

The slump flow test was conducted to determine the homogeneity and workability of LWSCC. The results are shown in Table 4. Any concrete mix having the slump-flow of less than 500mm, the average diameter of the concrete circle, should be considered as being highly viscous, and it does not flow easily. Slump-flows between 500 and 600 mm indicate that the mixture changes its viscosity and develops fluidity. When the fluid-flow reaches 600 mm, the viscosity would be considered as being optimum, and the mixture would tend to flow freely by virtue of its own weight [15]. As shown in Table 4, the slump-flow test results ranged between 650 mm and 800 mm, the target range of slump-flow. The slump-flow values of control concrete (0 % replacement level of CA) amounted to 680 mm and 700mm in the case of B450 and T450 concrete mixes, respectively, and the corresponding values were 705 mm and 720mm in the case of B550 and T550 mixes, respectively. It was observed that the increase in the replacement level of CA by the CSA also contributes to an increase in the slump-flow value of the LWSCC. The slump-flow of 100 % CSA based LWSCC was observed as 780 mm for the RHA based binary blended concrete, and the result was 795 mm for the RHA and SF based ternary blended concrete (B450 and T450) mixes. In the case of B550 and T550, the slump values were also within the target range for the SCC.

The V-funnel test was conducted to determine the flowability of fresh concrete. The time required to make the SCC flow through the V-funnel by its own weight was determined in this test. The target range of the V-funnel time was suggested to be between 11 sec. and 15 sec. [16]. The relationship between the time required to reach the 500 mm slump flow and V-funnel flow to determine the segregation resistance is shown in Figure 3. The results were within the target range, which indicates the concrete mixtures have a good viscosity and segregation resistance by complying with the target range, except for the control concrete specimen with the total powder content of 450 kg/m^3. The dashed line in Figure 4 denotes that the critical value of the blocking ratio (H2/H1) and the field of H2/H1 > 0.8 is called the self flow zone [17]. The blocking ratio results are mentioned in Figure 6. It can be seen that incorporating CSA as aggregate in the SCC meets the passing ability requirements for the SCC based on the L-box test. Therefore, the CSA based LWSCC possesses a good filling ability, passing ability, and segregation resistance.

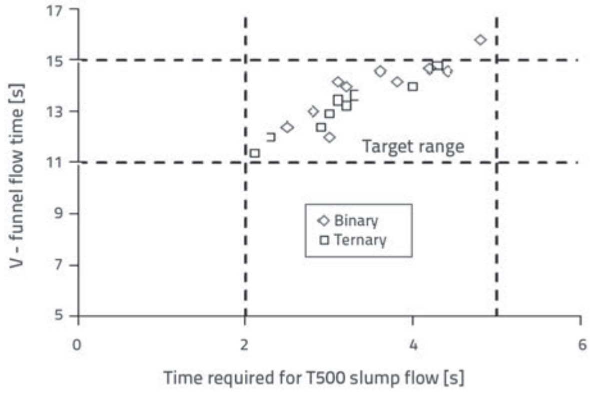

Figure 3. V-funnel time vs.T500

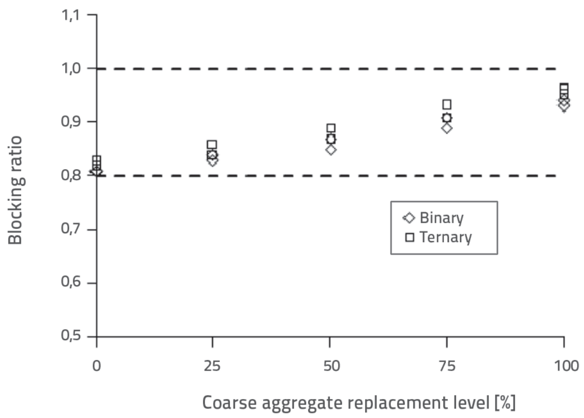

Figure 4. Blocking ratio of coconut shell aggregate

3.2. Effect of coconut shell aggregate on density

The density of specimens at 28 days was determined as shown in Table 4. The density of SCC specimens decreased with an increase in the replacement of the conventional CA by the CSA. The density of B450 and B550 mixes with the conventional CA (0 % replacement) at 28 days curing age was 2060 kg/m^3 and 2090 kg/m^3, respectively. The density of T450 and T550 mixes of the SCC with 0 % of CA replacement was 2005 kg/m^3 and 2025 kg/m^3, respectively. According to ASTM C 330 [20], the structural lightweight concrete should not exceed 1850 kg/m^3 in the dry state, and it usually ranges from 1400 kg/m^3 to 1850 kg/m^3. At 75 % and 100 % CSA substitution levels, the density of designated mixes decreased below the lightweight concrete threshold, and the B450 mix decreased to 1840 kg/m^3 and 1765kg/m^3, respectively. In case of the ternary blended concrete (T450), the density of LWSCC decreased to 1810 kg/m^3 and 1735 kg/m^3, respectively. In LWSCC550, the density of the B550 mix decreased to 1845 kg/m^3 and 1775 kg/m^3 at 75 % and 100 % CSA substitution levels, respectively. In case of the T550 mix, the density of LWSCC decreased to 1825 kg/m^3 and 1740kg/m^3, respectively. However, the results derived from both the binary and ternary blended SCC, with the CSA content of more than 75 %, are comparable with the results obtained by other authors [2, 6] and the concrete is considered to be a structural lightweight concrete. The results indicate that the presence of a higher percentage of the lightweight CSA in the SCC strongly contributes to the reduction of density of concrete, and it that it can decrease the self weight of structural elements, which implies a reduction in structural construction costs.

3.3. Effect of high temperature on weight loss

The loss of weight of the CSA-based concrete samples of all designated mixes are calculated with reference to the control concrete results (0 % replacement of CA). Weight loss results of LWSCC specimens after exposure to high temperatures are shown in Figure 5 and Figure 6. The weight loss was not observed on all control concrete specimens of both binary and ternary blended concrete of the designated mixes (LWSCC450 and LWSCC550) until 100 °C. This is probably due to the presence of free water in micro-pores of the matrix. The reduction in weight of the control concrete specimens was observed above 100 °C, which can be attributed to the expulsion of free water due to high temperatures. The rate of weight loss of control concrete relatively increases after 200 °C. However, the rate of weight loss increment slightly lowers above 400 °C due to the complete expulsion of free water.

The comparison of Figure 5.a and Figure 5.b reveals that the weight losses for the SF based ternary blended concrete were slightly higher compared to the RHA-based binary blended concrete of the LWSCC450 mix. Similar results were observed for the LWSCC550 concrete mix shown in Figure 6.a and Figure 6.b. This may be due to the reduction in the $Ca(OH)_2$ content in the ternary blended concrete since the presence of SF increases the rate of secondary hydration. In a research by Sancak et al [19], the use of the 10 % SF in the lightweight concrete increases the weight loss compared to the normal concrete by forming an additional C-S-H gel. The addition of SF highly densifies the pore structure of concrete, which can result in an explosive spelling due to the build-up of pore pressure by steam. It can be observed from Figure 5 and Figure 6 that there is no significant variation in the rate of weight loss up to 100 °C in all CA by CSA replacement levels. The lower relative weight loss of the LWSCC450 and LWSCC550 specimens, observed up to 200 °C, may be due to the lower heat conductivity of the blended concrete, and smaller evaporation of water from the concrete matrix. The capillary pores and micro-pores of the lightweight

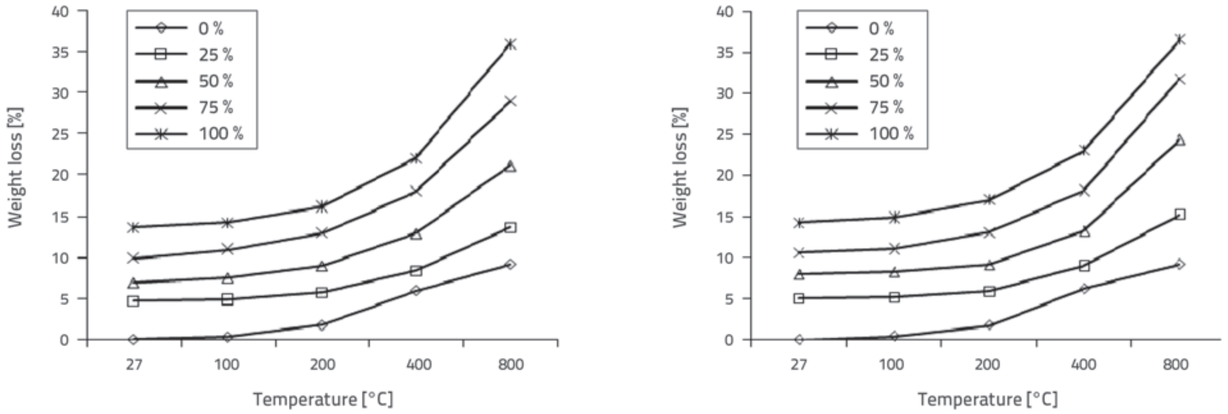

Figure 5. Weight loss of LWSCC450 exposed to high temperature: a) RHA based binary blended concrete; b) RHA + SF based ternary blended concrete

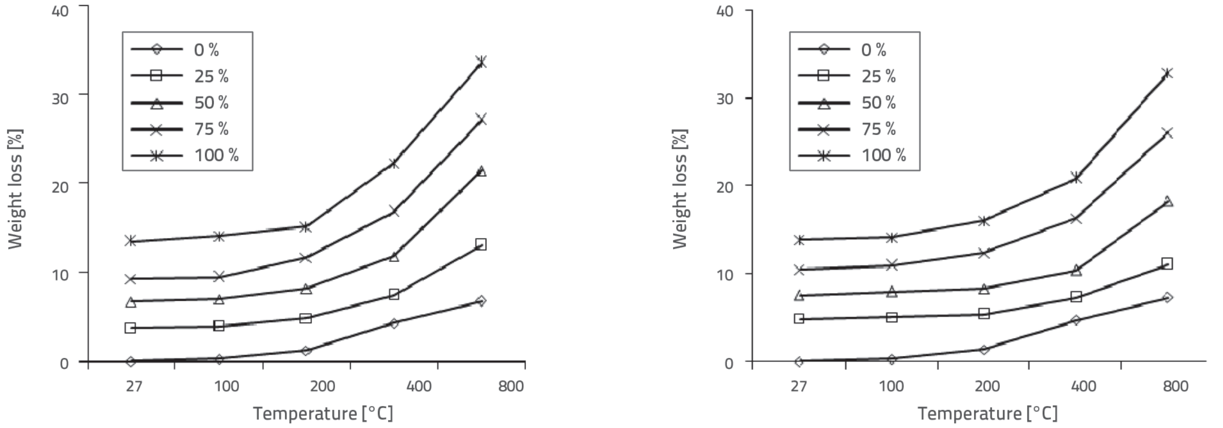

Figure 6. Weight loss of LWSCC550 exposed to high temperature: a) RHA based binary blended concrete; b) RHA + SF based ternary blended concrete

blended concrete are filled and denser. The cement paste is formed by the presence of RHA and SF. However Figure 5 and Figure 6 show that the weight of the LWSCC specimens drops at a higher rate with the temperature starting at 200 °C.

This may be caused due to the CSA presence in concrete. The different rate of weight loss depends on the replacement level of CA by the CSA when exposed to high temperatures, owing to the decomposition of aggregate. Thus the homogeneity of the lightweight concrete microstructure is adversely affected by high thermal stresses, which causes an increasing rate of weight loss above 400 °C compared to the control concrete.

3.4. Effect of high temperature on compressive strength

The change in compressive strength of concrete specimens subjected to high temperatures is shown in Figure 7 and Figure 8. The results indicate that the changes in strength with respect to ambient temperature (27 °C) were highest in the control concrete (0 % replacement of CA). The addition of the CSA as a partial replacement for CA, aimed at developing the lightweight concrete, reduces the strength compared to the control concrete in all designated mixes. The initial strength was only slightly altered depending on the binder type in the range of up to 100 °C. After the specimens were exposed to the temperatures of 100, 200, 400, and 800 °C, the compressive strength test results of all specimens varied as shown in Figure 7 and Figure 8. The test results indicate that each temperature range had a distinct pattern of strength loss. The reduction of compressive strength can be attributed to the expulsion of free water from micro pores, and to the dehydration [19, 21] of concrete due to high temperatures. Thus, the changes of compressive strength of concrete subject to high temperatures depend on the ingredients present in concrete, as well as on environmental factors such as the temperature, moisture content, heating rate, dehydration of C-S-H gel, thermal incompatibility between aggregates, and cement paste [22, 23]. The residual compressive strength [24] after heating at different temperatures was expressed as a ratio of f_T/f_i, where f_T is the strength after heating at T °C, and f_i is the initial strength at ambient temperature condition and the residual compressive strength of all specimens of the designated concrete after heating at 100 °C, 200 °C, 400 °C and 800 °C, as shown in Table 5. According to Figure 7 and Figure

Table 5. Relative residual strength

Powder content [kg/m^3]	CSA content [%]	RHA based binary blended SCC					RHA + SF based ternary blended SCC				
		27 [°C]	100 [°C]	200 [°C]	400 [°C]	800 [°C]	27 [°C]	100 [°C]	200 [°C]	400 [°C]	800 [°C]
450	0	1	0.99	0.97	0.92	0.46	1.07	1.05	1.03	0.97	0.56
	25	0.89	0.87	0.85	0.76	0.27	0.99	0.94	0.90	0.83	0.41
	50	0.79	0.77	0.76	0.65	0.19	0.90	0.88	0.84	0.68	0.29
	75	0.75	0.73	0.70	0.55	0.13	0.84	0.82	0.77	0.59	0.24
	100	0.70	0.68	0.61	0.42	0.10	0.73	0.71	0.63	0.48	0.17
550	0	1	0.98	0.96	0.90	0.47	1.11	1.07	1.02	0.94	0.52
	25	0.90	0.88	0.84	0.70	0.26	1.03	1.01	0.93	0.82	0.33
	50	0.85	0.82	0.73	0.56	0.18	0.96	0.92	0.79	0.62	0.26
	75	0.79	0.74	0.63	0.47	0.14	0.92	0.87	0.71	0.55	0.21
	100	0.71	0.67	0.56	0.39	0.11	0.88	0.82	0.64	0.46	0.18

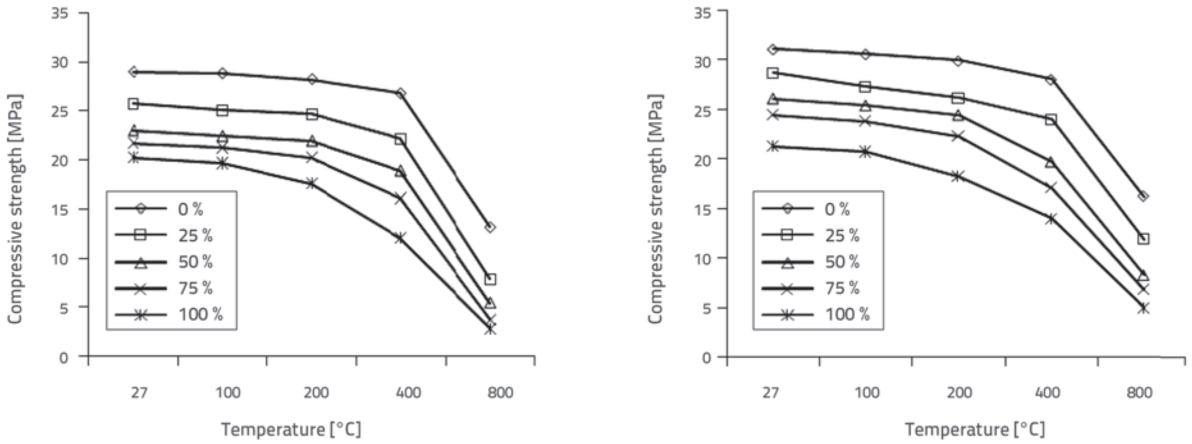

Figure 7. Compressive strength of LWSCC exposed to high temperatures (Powder content = 450kg/m^3): a) RHA based binary blended concrete; b) RHA + SF based ternary blended concrete

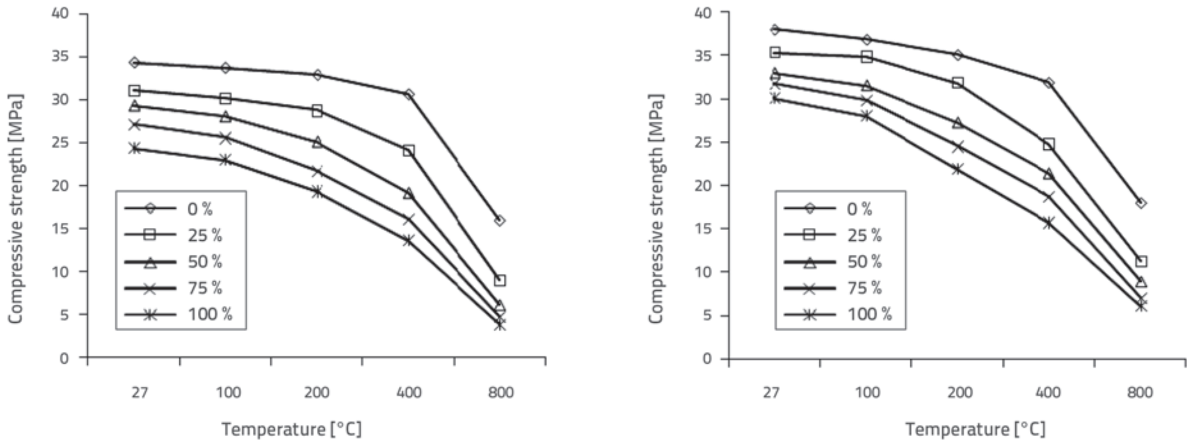

Figure 8. Compressive strength of LWSCC exposed to high temperatures (Powder content = 550kg/m^3): a) RHA based binary blended concrete; b) RHA + SF based ternary blended concrete

8, the rate of compressive strength decrease in control concrete was observed to be lower than that for the CSA based LWSCC. In other words, the addition of the CSA as aggregate increases the reduction of compressive strength at an increasing rate.

According to Table 5, only a minimum amount of loss in compressive strength was noticed up to 400 °C in both control concrete mixes. At 400 °C, 8 % and 3 % reduction in compressive strength was observed in the RHA based binary blended and RHA + SF based ternary blended control concrete, respectively, in the LWSCC450 mix with respect to the binary blended control concrete. The results amounted to 10 % and 6 %, respectively, in the LWSCC550 mix. Similar results were observed in the ternary blended 25 % CSA based SCC.

It can be seen from the figures that the compressive strength value drops sharply above 400 °C. The compressive strength decreases due to the replacement of CA by CSA in the proportion of 25 %, 50 % and 75 % from 200 °C onwards, and it decreases from 100°C onwards for the 100 % CSA based LWSCC. Poor micro structure of concrete matrix due to higher temperatures creates undesirable configuration of the C-S-H gel and an increased cracking at higher temperatures. At 400 °C, 58 % the reduction in compressive strength was observed in the 100 % RHA based binary blended concrete, and 52 % reduction in the RHA + SF based ternary blended control concrete in the LWSCC450 mix, and the results were calculated as 61 % and 54 %, respectively, in the LWSCC550 mix. The test results indicate that a decrease in the compressive strength of concrete was prevented with silica fume admixtures due to formation of the tobermorite gel as a result of the pozzolanic reaction of $Ca(OH)_2$ in OPC with the reactive silica [25, 26]. The presence of CSA as aggregate causes an excessive deterioration in all mixes compared to the control concrete specimens above 400 °C. This is due to an increase in micro cracking and high thermal stresses. At about 800 °C, all mixes were almost completely dehydrated and suffered deterioration.

3.5. Statistical modelling

The statistical relationship between the compressive strength of the CSA based LWSCC and its temperature condition is proposed in this experimental investigation for predicting the compressive strength of all the designated mixes. The non-linear regression analysis was used to establish the relationship between the experimentally obtained compressive strength and temperature. Tanyildizi and Coskun [10] have established a similar non-linear relationship between the compressive strength, splitting strength, and temperature, to predict mechanical properties of the flysch based lightweight concrete. Figure 9 shows the relationship between the compressive strength and temperature of the control SCC. The high correlation coefficient (R^2=0.947) obtained from the regression analysis pointed to the suitability of the equation. Figure 10.a to Figure 10.d show the plot of compressive strength in relation to the LWSCC temperature, with the CSA as coarse aggregate. It can be seen that the shape of the profile between the compressive strength and temperature changes with an increase in the CSA content from 0 % to 100 % due to the disintegrated CSA based poor microstructure of concrete matrix, which indicates that an increase in the CSA content decreases the temperature resistance of the LWSCC. The models obtained from all CA replacement levels are given in Table 6 with a high correlation coefficient (0.947 to 0.969), which shows that the equation obtained from the regression analysis is used to predict the compressive strength without experimentation with minimum deviation. The equation varies from actual results from 3.1 % for the 100 % replacement of CA by the CSA mix, to 5.3 % for the 0 % replacement of CA.

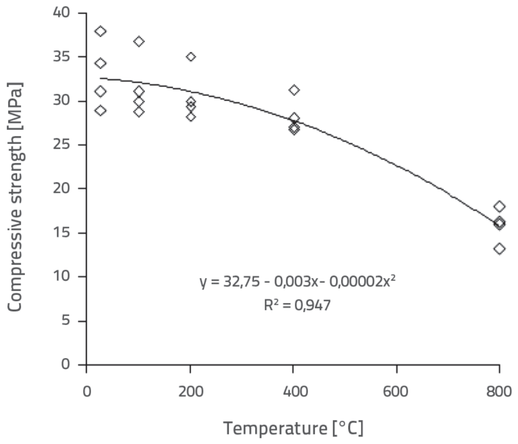

Figure 9. Relation between compressive strength and various temperatures of control SCC

Table 6. Statistical models of compressive strength of LWSCC in relation to temperature

S. No	Coarse aggregate replacement [%]	Regression equation	Coefficient (R^2)
1	0	$y = 32,75 - 0,003x - 0,00002x^2$	0.947
2	25	$y = 30,45- 0,007x - 0,00002x^2$	0.965
3	50	$y = 28,58 - 0,016x - 0,00001x^2$	0.962
4	75	$y = 27,15 - 0,023x - 0,000005x^2$	0.966
5	100	$y = 25,21 - 0,030x - 0,000005x^2$	0.969

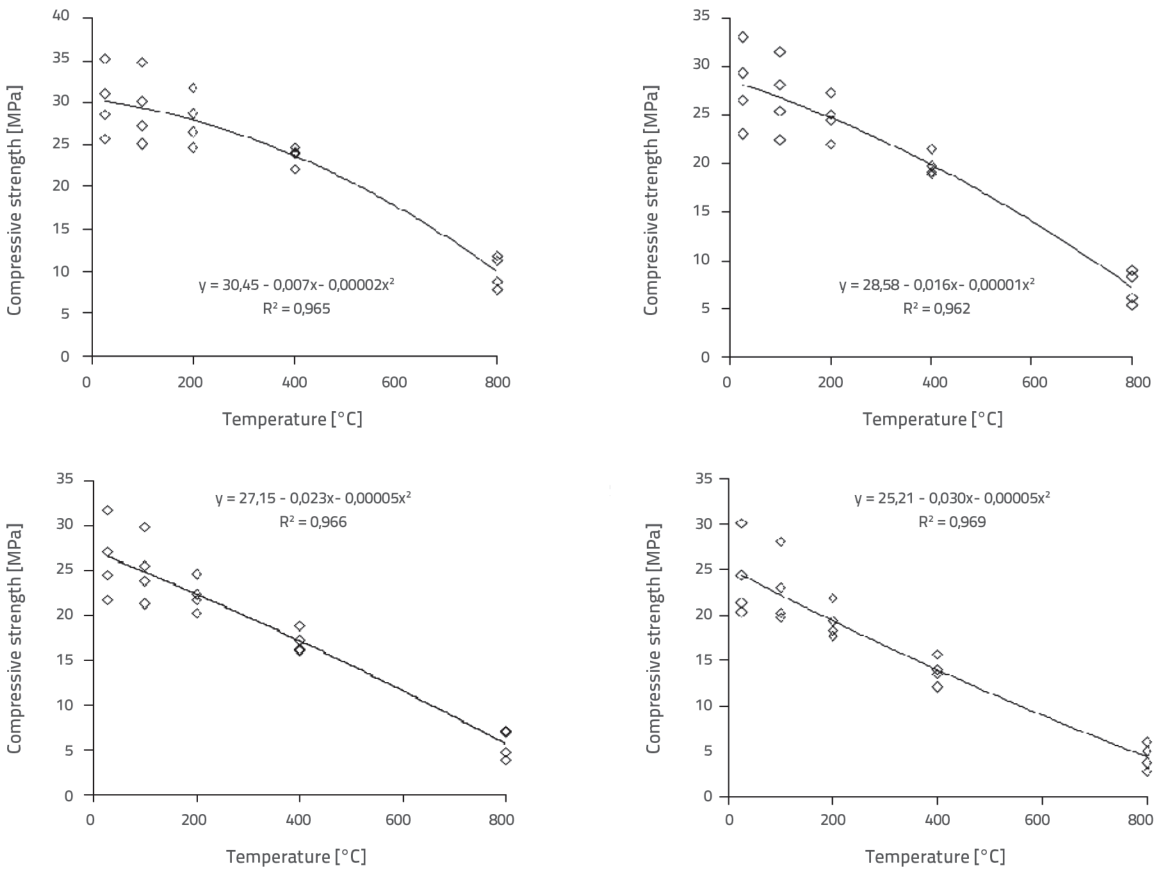

Figure 10. Relation between compressive strength and various LWSCC temperatures: a) 25 % replacement of CA; b) 50 % replacement of CA; c) 75 % replacement of CA; d) 100 % replacement of CA

4. Conclusions

Experimental results revealed that no weight loss was observed for all concrete specimens of both binary and ternary blended concrete of designated mixes (LWSCC450 and LWSCC550) up to 100 °C. The 50 % replacement of CA with the CSA in the LWSCC does not affect the mix up to 400 °C, but the rate of weight loss increases when the CSA percentage increases to more than 50 %. The use of 10 % of SF in lightweight concrete slightly increased the weight loss due to reduction of the $Ca(OH)_2$ content, but not due to the CSA presence. However, the compressive strength of the RHA + SF based ternary blended concrete was higher than that of the RHA based binary blended LWSCC in both the LWSCC450 and LWSCC550 mixes. In addition, the compressive strength reduction rate in the binary blended concrete was greater than that of the ternary blended concrete specimens. The rate of reduction in compressive strength was higher in the 75 % and 100 % CSA based LWSCC after 200 °C , and all mixes were almost completely dehydrated and suffered deteriorated at about 800 °C. Statistical models for finding the compressive strength of the LWSCC in relation to the temperature were predicted with high correlation coefficients.

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