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ACOUSTIC METHODS

Effect of Mineral Admixtures on the Correlation between Ultrasonic Velocity and Compressive Strength for Self-Compacting Concrete[1]

Zülfü Ç. Ulucan, Kazím Türk, and Mehmet Karataş

Department of Civil Engineering, Faculty of Engineering, Fírat University, Elaziğ, Turkey

e-mail: kturk@firat.edu.tr; kturk23@hotmail.com

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Abstract—Nondestructive testing of concrete is preferred due to its distinct advantage over conventional compression tests. The evaluation by nondestructive methods of the actual compressive strength of concrete in existing structures is based on empirical relations between strength and nondestructive parameters. The aim of the study was to investigate the effects of different types and dosages of mineral admixtures on the correlation between ultrasonic pulse velocity (UPV) and compressive strength for self-compacting concrete (SCC). Different proportions of fly ash (FA) and silica fume (SF) are used as the mineral admixtures in replacement of portland cement (PC) in SCC. The work focused on concrete mixes having a slump flow between 700 and 710 mm. Specimens were prepared and cured in standard 20 ± 3°C water for periods of 3, 7, 28, and 130 days. At the end of each curing period, compressive strength and UPV were determined. Tests were carried out on 150-mm cubic specimens to evaluate the compressive strength and UPV of SCC. The results of this research indicate that reductions in the compressive strength due to SF were lower than those for FA at all levels of replacement at 3 days, while both UPV and compressive strength at early ages were very low at all levels of mineral admixtures. However, with the increase of the curing period, both UPV and compressive strength of SCCs containing both FA and SF increased. The correlation between UPV and compressive strength is also exponential for SCCs containing both FA and SF. However, constants for each pozzolana were different for each level of replacement of PC in SCCs.

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1. INTRODUCTION

Self-compacting concrete (SCC), developed in Japan [1] in the late 1980s, is defined as a concrete that has excellent deformability and high resistance to segregation and can be used to fill a heavily reinforced area without applying vibration. SCC has brought in a wave of change for the construction industry. SCC has been considered as a "quiet revolution" in the concrete construction process, with major benefits in increased productivity, enhanced construction quality, and much improved working environment on site [2]. These changing characteristics of concrete and the high cost of infrastructure maintenance require improved and reliable testing methods, both in the laboratory and in situ. One of these testing methods at present is measurement of the ultrasonic pulse velocity (UPV) [3, 4], whose application to the nondestructive evaluation of the quality of in situ concrete structures has been widely investigated for decades. There exist many instruments to determine material characteristics in specially made samples of young or hardened concrete through the ultrasonic method. PUNDIT, which uses the through transmission method, is a well-known instrument in this field and was also used in this study. It generates low-frequency ultrasonic pulses and measures the time required for them to pass from one transducer to another. It has become part of many national standards for concrete testing [5] and research [6].

Moreover, methods based on ultrasound are better suited for the characterization of the setting and hardening of cement-based materials than traditional methods because the travel time, attenuation, and frequency content of ultrasonic waves sent through the material are closely correlated with the elastic properties of concrete or mortar. These parameters can be closely monitored during the stiffening of the material [7]. The strength of concrete increases with age and it is thus important to predict its value at any given stage of a construction process. Many investigations have shown a correlation between the increase of the speed of ultrasound and the increase of the equivalent strength of concrete with age [8].

[1] The text was submitted by the authors in English.

Table 1. Chemical analysis and physical properties of PC, FA, and SF (%)

Component	PC (%)	FA (%)	SF (%)
SiO_2	20.2	58.82	91
Al_2O_3	5.8	19.65	0.58
Fe_2O_3	3.23	10.67	0.24
CaO	64.1	2.18	0.71
MgO	–	3.92	0.33
SO_3	2.66	0.48	–
Chloride (Cl^-)	0.006	–	–
LOI	2.58	0.91	1.84
Specific gravity, g/cm^3	3.1	2.08	2.2
Specific surface area, cm^2/g	3484	3812	96.5% <45 μm
Compressive strength, MPa			
2 days	23.7	–	–
7 days	44.0	–	–
28 days	55.2	–	–

The evaluation by nondestructive methods of the actual compressive strength of concrete in existing structures is based on empirical relations between strength and nondestructive parameters. Manufacturers of devices usually give empirical relationships for their own testing system. Such relationships are not suitable for every kind of concrete. Therefore, they need to be calibrated for different mixtures [9]. Numerous data and correlation relationships between the strength and pulse velocity of concrete have been presented and proposed. Galan [10] reported a regression analysis to predict the compressive strength of concrete based on acoustic characteristics such as UPV and the damping constant. Rajagopalan et al. [11] reported a correlation between the UPV and compressive strength of concrete for some typical mixes. The study presented simultaneous measurements of pulse velocity and compressive strength made on 150-mm cubes at different ages from 1 to 28 days, indicating a linear relation between strength and velocity. Lin et al. [12] carried out an experimental study for establishing mathematical models for predicting concrete pulse velocity based on aggregate content and water–cement ratio. Tharmaratram and Tan [13] provided an empirical formula of the combined UPV and ultrasonic pulse amplitude. Demirboga et al. [14] found an exponential relationship between compressive strength and UPV for mineral-admixtured concrete. However, for SCC containing different types and dosages of mineral admixtures, the correlation between UPV and compressive strength has not been investigated until now.

2. MATERIALS AND MIX PROPORTIONS

In this study, the cementitious materials used were portland cement (PC) 42.5, fly ash (FA), and silica fume (SF) from the Set cement factory in Elaziğ, the Electro Metallurgy Enterprise in Antalya, and Tuncbilek Thermal Power Plant in Kutahya (Turkey), respectively. Aggregate was obtained from the Murat River in Elaziğ. The chemical composition and physical properties of PC 42.5 and the mineral admixtures used are given in Table 1. Details of mix proportions for the SCCs containing different levels of FA and SF are summarized in Table 2. Natural sand and gravel with a nominal maximum size of 20 mm were used as the aggregates.

Concrete mixes were prepared by replacing part of the cement with FA and SF at four different replacement levels on a mass-for-mass basis, separately. A superplasticizer (ViscoCrete 3075) was used in the SCC mixes. For the SCC mixes with a slump between 700 and 710 mm, the water–cementitious materials ratio was ~0.38 and ~0.39 for SCCs containing FA and SF, respectively.

Mix designs for SCCs were developed by means of trial mixes based on guidelines given by EFNARC [15]. For SCCs, slump flow, $t_{50\,\text{cm}}$, *L*-box, and sieve segregation resistance tests (Figs. 1a–1c) described by EFNARC were carried out. In carrying out these rheological tests, slump flow values approximately between 700 and 710 mm were targeted. The results obtained from these tests (Table 3) showed that all SCC mixes had good flow, filling, and passing ability, as well as segregation resistance, though the viscosity of SCCs containing 15 and 20% SF replacement was not so good due to an increase in the amount of water.

Table 2. Mix proportions (kg/m^3)

Mixtures	SCC with FA				SCC with SF			
	FA25	FA30	FA35	FA40	SF5	SF10	SF15	SF20
w/cm[a]	0.39	0.38	0.38	0.38	0.36	0.38	0.40	0.40
Cementitious materials	500	500	500	500	450	450	450	450
Cement	375	350	325	300	427.5	405	382.5	360
Fly ash	125	150	175	200	–	–	–	–
Silica fume	–	–	–	–	22.5	45	67.5	90
Aggregate sizes, mm								
0–7	910	910	910	910	990	990	990	990
7–15	450	450	450	450	450	450	450	450
15–20	285	285	285	285	285	285	285	285
ViscoCrete 3075	6.75	6.75	6.75	6.75	8.00	8.00	8.00	8.00

[a] w/cm is the water to cementitious materials (PC + FA or SF) ratio.

Table 3. Properties of fresh concretes

Mixtures	SCC with FA				SCC with SF			
	FA25	FA30	FA35	FA40	SF5	SF10	SF15	SF20
Slump, mm[b]	709	702	705	701	707	701	708	707
$t_{50\ cm}$, s	2.44	2.56	3.00	2.89	2.30	1.80	1.20	1.00
L-box; H_2/H_1	0.910	0.943	0.953	0.959	0.865	0.876	0.888	0.890
Segregation, %	18.4	15.8	15.2	14.4	15.3	17.9	19.8	22.0

[b] Slump flow, mm.

For each mixture, three specimens (150-mm cubes) were prepared and stored in lime-saturated water at 20 ± 3°C until the time of the testing. The specimens were tested at 3, 7, 14, 28, and 130 days for compressive strength and UPV in accordance with ASTM C 39–96 [16] and ASTM C 597–97 [17], respectively. The UPV test method employs the principle of measuring the travel velocity of ultrasonic pulses through a material medium. The pulse velocity equipment consists of an emitter (generating transducer) from which ultrasonic pulses are transmitted, a receiver (receiving transducer) where the pulses are received, and a device for indicating the time of travel from the transmitter to the receiver. Microsoft Excel was used to perform the statistical regression analyses.

(a) Slump flow and $t_{50\ cm}$ test (b) *L*-box test (c) Sieve segregation test

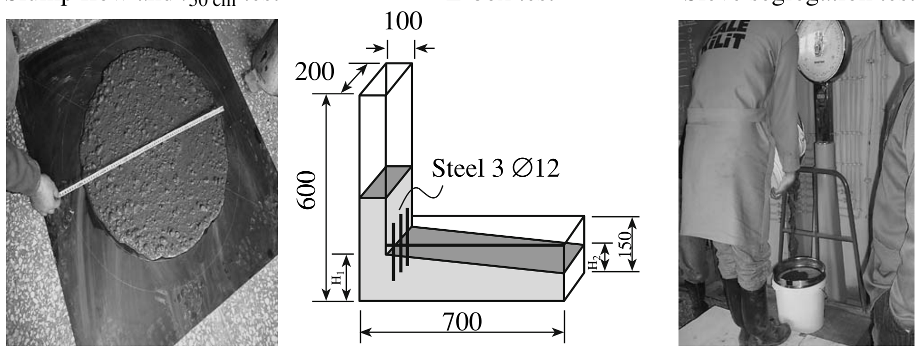

Fig. 1. Rheological tests for SCCs.

Table 4. Properties of hardened concretes

Mixtures	SCC with FA				SCC with SF			
	FA25	FA30	FA35	FA40	SF5	SF10	SF15	SF20
3-day compressive strength, MPa	27.66	24.11	22.36	20.09	36.15	33.18	30.89	31.26
3-day UPV, km/s	4.683	4.620	4.618	4.532	4.608	4.584	4.425	4.414
7-day compressive strength, MPa	30.37	33.57	29.79	27.94	43.93	46.96	40.89	40.44
7-day UPV, km/s	4.695	4.688	4.661	4.598	4.699	4.622	4.625	4.625
28-day compressive strength, MPa	49.39	45.11	42.56	45.26	58.04	62.81	67.95	66.35
28-day UPV, km/s	4.918	4.983	4.878	4.808	4.739	4.780	4.685	4.640
130-day compressive strength, MPa	53.56	55.24	58.11	59.04	68.04	71.92	73.87	70.53
130-day UPV, km/s	4.934	4.987	4.895	4.891	4.869	4.878	4.815	4.759

3. RESULTS AND DISCUSSION

The compressive strength and UPV results of SCCs were determined on the 150-mm cubes for 3, 7, 28, and 130 days. The results obtained in the tests are shown in Table 4 and Figs. 2–7.

3.1. The effect of FA in SCC on compressive strength and UPV. Table 4 shows that FA increased the compressive strengths of SCCs at all levels of FA replacement at 130 days. Due to FA replacement of PC, increases were 1.68, 4.55, and 5.48 MPa compared to 25% FA replacement for 30, 35, and 40% FA replacement at a curing period of 130 days, respectively. However, FA reduced in general the compressive strengths of SCCs at all levels of replacement at 3, 7, and 28 days. The reduction due to 40% FA replacement of PC was 7.57 and 4.13 MPa compared to 25% FA replacement for 3 and 28 days, respectively.

It can be seen that, as the curing time increases, the compressive strength reduction of SCC containing 40% FA was less at 28 days compared to 3- and 7-day curing periods. Moreover, the reductions due to FA replacement of PC in SCC at early ages increased with increasing FA level. Therefore, it can be said that, for early curing periods, the SCCs at all levels of FA replacement exhibited a steady reduction in strength as a function of the replacement percentage; this can be directly related to the properties of FA, which decreases the heat of hydration of concrete and needs a long curing period. Results obtained from many studies have shown that the rate of hardening slows and the early compressive strength of concrete and mortars decreases due to FA replacement [18–20].

It can be seen from Fig. 2 that the UPV values decreased with increasing FA replacement of PC in SCCs at 3 and 7 days, while SCC containing 30% FA replacement had the highest UPV values at 28- and 130-day curing periods. The UPV values increased with increasing curing period at all levels of FA replacement in SCCs. Based on curing time, the minimum increase in the UPV values occurred at 40% FA replacement of PC in SCC and it was 1.5, 6.0, and 7.9% compared to a 3-day curing period at 7, 28, and 130 days, respectively. It was obvious that the UPV values decreased with increasing FA replacement of PC in SCC at all levels of FA at early ages.

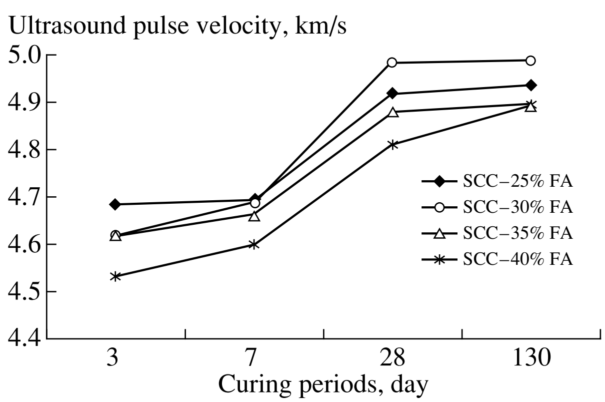

Fig. 2. UPV results for SCC with FA for different curing periods.

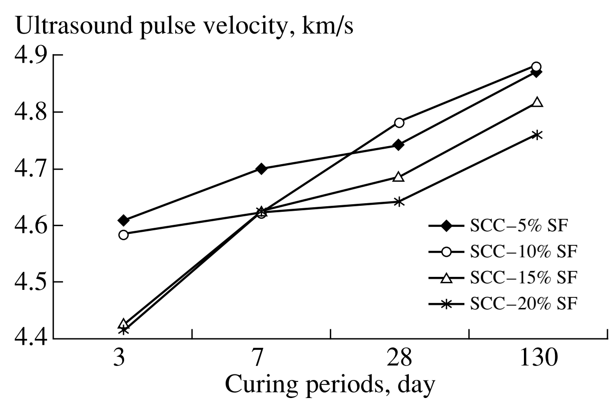

Fig. 3. UPV results for SCC with SF for different curing periods.

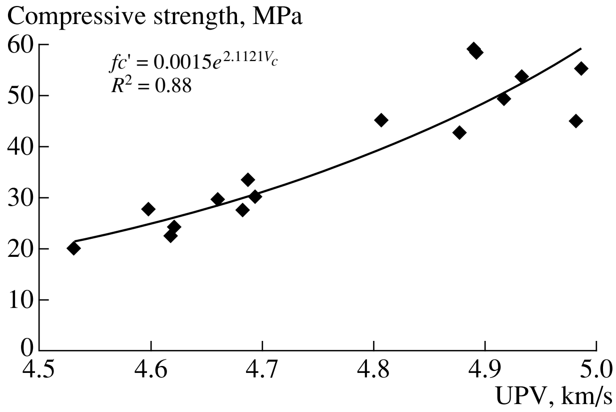

Fig. 4. Correlation between compressive strength and UPV for SCC with FA.

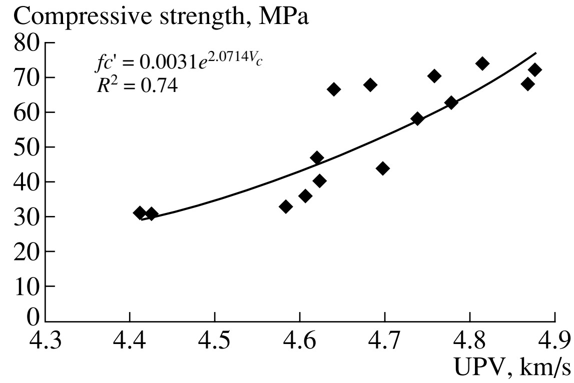

Fig. 5. Correlation between compressive strength and UPV for SCC with SF.

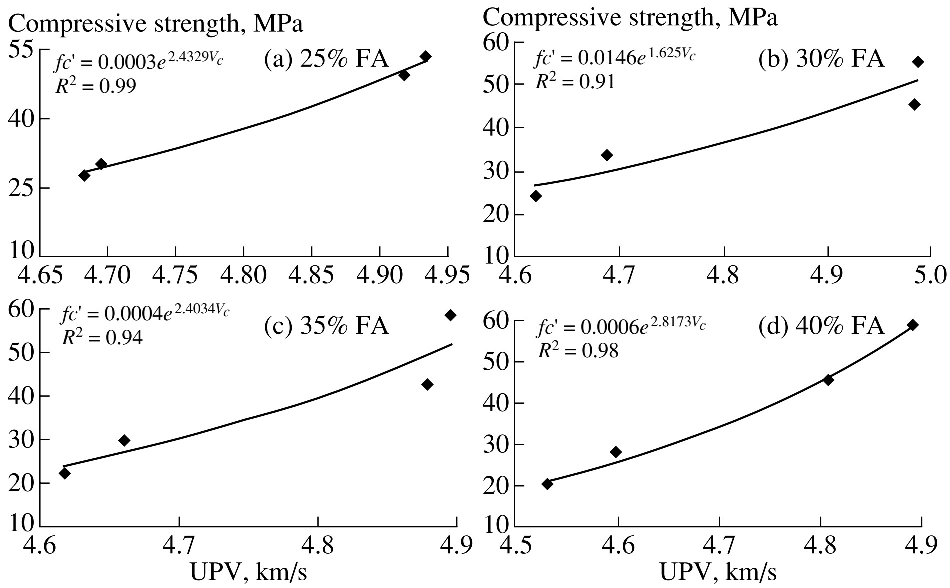

Fig. 6. Correlations between compressive strength and UPV for SCCs with FA, separately.

3.2. The effect of SF in SCC on compressive strength and UPV. SF increased the compressive strengths of SCCs compared to 5% SF replacement at all levels of replacement at 28 and 130 days, while SF increased only the compressive strength of SCC containing 10% SF at a 7-day curing period. SCC containing 15% SF replacement of PC had the highest compressive strength compared to other levels of replacement at 28 and 130 days. Furthermore, the compressive strength of SCC containing 20% SF was close to that of SCC containing 15% SF at a 28-day curing period. It can be said that, as the curing time increases, the strengths of the SCCs containing 15 and 20% SF also increase because the further addition of SF ensures the consumption of $Ca(OH)_2$ released from cement hydration, leading to the formation of further calcium silicate hydrate (C–S–H) and contributing to the interfacial bond strength between aggregate particles and the matrix [21]. SF also induced the compressive strengths of SCCs to decrease compared to 5% SF replacement at all levels of replacement at a 3-day curing period. Reductions due to SF were lower than those for FA at all levels of replacement for a 3-day curing period, indicating that the rate of hydration of SF is very high because of the intense reaction between the SF and PC [22].

The UPV values of SCCs containing different dosages of SF for 3, 7, 28, and 130 days are shown in Fig. 3 and Table 4. The UPV values changed between 4.410 and 4.610, between 4.620 and 4.700, between 4.640 and 4.780, and between 4.750 and 4.880 km/s at 3, 7, 28, and 130 days, respectively. SCC containing

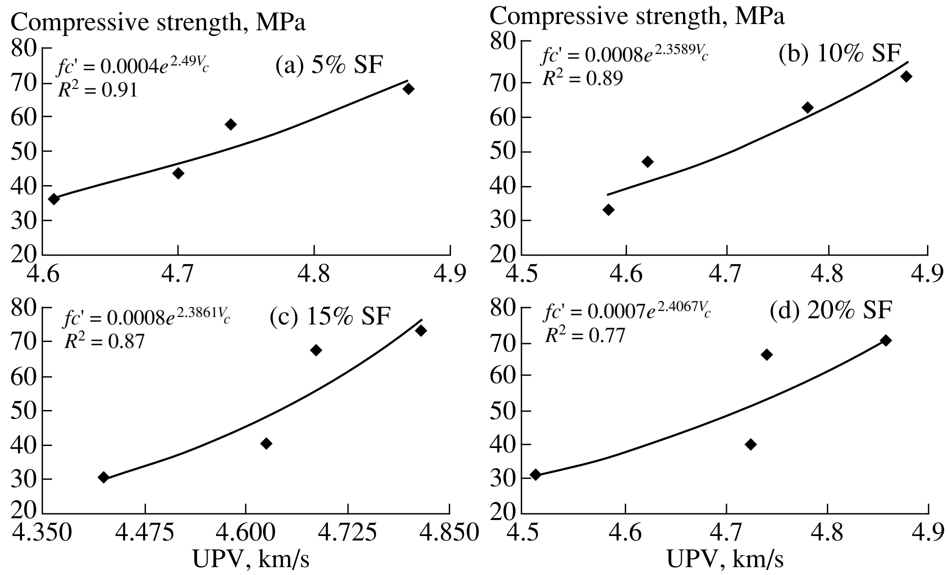

Fig. 7. Correlations between compressive strength and UPV for SCCs with SF, separately.

10% SF replacement had the highest UPV values at all levels of replacement at 28 and 130 days. However, the UPV values decreased with increasing SF at all curing ages, indicating the sensitivity of SF to water during the hydration stage. Because of the small size and the large surface area of SF, it absorbs a lot of water, making the water requirement for SCCs with additional SF especially high [23]. As the curing time increased, the values of UPV also increased because of the formation of further calcium silicate hydrate (C–S–H). On the other hand, the UPV values of SCCs containing SF were lower than those of SCCs containing FA at all levels of replacement for all curing ages. This indicates the filling and packing capacity of FA particles.

3.3. Correlation between compressive strength and UPV for SCC. The UPV method based on the velocity of sound in a material uses a detector to measure the time required for a pulse to pass from one side to the other side of the specimen. The pulse velocity can be determined from the following equation:

$$V_c(x, t) = \frac{x}{t}, \tag{1}$$

where, $V_c(x, t)$ = pulse velocity (km/s), x = path length (cm), and t = transit time (μs).

Tharmaratram and Tan [13] proposed the following equation representing the correlation between UPV in a concrete V_c and concrete compressive strength f'_c based on experimental results. Moreover, Demirboga et al. [14] corroborated that this general equation also was suitable for mineral-admixtured concretes.

$$f'_c = ae^{bV_c}. \tag{2}$$

Taking into account the heterogeneous nature of concrete, the correlation between UPV and compressive strength is pooled for the results of SCCs containing FA and SF for 3, 7, 28, and 130 days in Figs. 4 and 5, respectively. Figures 4 and 5 show the results for SCCs containing FA and SF, separately. In this study, the following models were found for SCCs containing FA and SF, respectively:

$$\begin{aligned} f'_c &= 0.0015e^{2.112V_c}; \\ f'_c &= 0.0031e^{2.0714V_c}. \end{aligned} \tag{3}$$

The models of SCCs containing FA and SF verify the general model of Eq. (2), and their determination coefficients were 0.88 and 0.74, respectively.

When models of SCCs containing 25, 30, 35, and 40% FA, separately, were pooled, it was seen that the correlations were also exponential (Figs. 6a–6d). The coefficients obtained from Figs. 6a–6d for SCCs containing 25, 30, 35, and 40% FA were 0.99, 0.91, 0.94, and 0.98, respectively. FA replacement of PC in SCCs at levels of 25, 30, 35, and 40% confirmed Eqs. (2) and (3). The models were similar but the constants were different from each other.

In Figs. 7a–7d, it can be seen that the correlations between compressive strength and UPV were also exponential at all levels of SF and the coefficients obtained from Figs. 7a–7d for SCCs containing 5, 10, 15, and 20% SF were 0.91, 0.89, 0.87, and 0.77, respectively. Each model of SCCs containing different levels of SF was similar to the general model for concrete reported by Tharmaratram and Tan [13] and similar to the model of Eq. (3). The equations of the models of SCCs containing different levels of SF are shown in Figs. 7a–7d. As seen from Figs. 7a–7d, the constants of Figs. 7b–7d were also similar but that of Fig. 7a was different from them. The constants of Figs. 7b–7d varied between 0.0008 and 2.3589, between 0.0008 and 2.3863, and between 0.0007 and 2.4067, respectively.

This research indicated that the general equation (2) reported by Tharmaratram and Tan [13] is also suitable for SCCs containing different levels of mineral admixtures.

CONCLUSIONS

Based on the experimental results and the analyses performed, the following conclusions can be drawn: In general, FA replacement induced a reduction in compressive strengths of SCCs at all levels of replacement at 3, 7, and 28 days, while FA increased the compressive strengths of SCCs at all levels of replacement at 130 days. That is, the reductions due to FA replacement in SCC at early ages increased with an increase in FA level. The UPV values also increased with increasing curing period at all levels of FA replacement of PC in SCCs.

SF replacement increased the compressive strengths of SCCs compared to 5% SF replacement at all levels of replacement at 28 and 130 days, while SF increased only the compressive strength of SCC containing 10% SF at a 7-day curing period. Reductions in the compressive strength due to SF were lower than those for FA at all levels of replacement for 3 days. The highest values were obtained with an SF replacement of 10% for UPV and 15% for compressive strength compared to other levels of replacement at 28 and 130 days. However, the UPV values decreased with increasing SF at all curing ages. When the UPV values were compared, it was seen that the UPV values of SCCs containing FA were higher than those of SCCs with SF replacement at all levels of replacement for all curing ages, indicating the filling and packing capacity of FA particles.

The correlations between UPV values and compressive strength in SCCs were exponential and only the constants for each pozzolana were different when the results of FA and SF replacements were pooled, separately. Moreover, the same model was determined for each replacement percent for all FA and SF replacements. Coefficients of $R^2 > 0.90$ and $R^2 \cong 0.80$ for all FA and SF replacements, respectively, indicate a good exponential correlation between UPV and compressive strength in SCCs. It can be emphasized that the correlation between UPV and compressive strength is also exponential for SCCs.

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