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Evaluation of Mechanical Properties of Two-Stage Concrete and Conventional Concrete Using Nondestructive Tests

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Abstract: Different types of concrete mixtures are used as building materials. The manufacturing process of two-stage concrete (TSC) differs from that of conventional concrete. This study investigated conventional mechanical properties derive empirical relations for estimation of the mechanical parameters of TSC and conventional concrete mixtures. TSC was used to prepare 216 specimens and conventional concrete was used to prepare 108 specimens that then were aged for 28 days. Uniaxial compression, Brazilian tensile strength, and point load tests were carried out as destructive testing. Schmidt hammer and ultrasonic pulse velocity tests were carried out as nondestructive testing. The data from testing were categorized as regression or test data. Empirical relations were derived between the parameters for the two types of concrete, and these relations were validated. It was concluded that indirect, nondestructive testing of engineering materials, including concrete, considerably increases the speed and decreases the estimation cost of determining the mechanical parameters. This method can be recommended for estimation of these mechanical parameters. **DOI: 10.1061/(ASCE)MT.1943-5533.0003247.** *© 2020 American Society of Civil Engineers.*

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Introduction

Two-stage concrete (TSC), or preplaced aggregate concrete (PAC), is widely employed in underwater and massive concrete structures (ACI 2005). This type of concrete differs from conventional concrete (CC) in a number of ways. In TSC, the mortar is injected into the aggregate (Najjar et al. 2014; Bayer et al. 2019) and the coarse aggregates are in grain-to-grain contact (Abdelgader 1996; Abdelgader et al. 2016), which causes the transfer of stress through the aggregate (O'Malley and Abdelgader 2010). As in conventional methods, the mechanical parameters of TSC can be obtained through both nondestructive tests (NDTs) and destructive tests (DTs). NDTs are more suitable than DTs because of their ease of implementation, lower cost, and nondestructive nature. The drawbacks of these types of tests is their insufficient accuracy; thus, NDTs are not used alone, but as supplementary tests to DTs (Mikulić et al. 1992).

Various empirical relations between mechanical parameters have been presented for different types of concrete. Most of these relations were derived for CC, but a limited number of studies were conducted on TSC. Breysse (2012) presented a literature review of the use of NDTs and assessed their prospects for estimation of the compressive strength of concrete. Breysse reported that the accuracy and quality of parameter estimation is dependent on three factors. The first is the sensitivity of the investigated parameter to NDTs. The second is the direct relationship between the range of variation of the values obtained from NDTs and DTs for the studied parameter. The third factor is the degree of testing error.

To determine the parameter sensitivity and the range of variation, the error should be minimized in NDTs. The most accurate control method for this is the static regression model. Breysse (2012) reported that the Schmidt hammer and ultrasonic pulse velocity tests can be used either separately or in combination to estimate the compressive strength of concrete. Brozovsky (2013) compared the estimated compressive strength of concrete using different Schmidt hammers and concluded that the estimation strength values varied only slightly for the different Schmidt hammers; thus, he recommended use of a single Schmidt hammer type for all measurements.

Jain et al. (2013) estimated concrete strength by conducting both Schmidt hammer and ultrasonic pulse velocity testing. The objective of their study was to employ NDTs to estimate the compressive strength of concrete in structures. Their findings indicated that a combination of the results from the Schmidt hammer and ultrasonic pulse velocity tests was more accurate for estimating the compressive strength than the use of the Schmidt hammer or ultrasonic pulse velocity tests alone. By deriving empirical relations between the mechanical parameters and ultrasonic pulse velocity for fiber-reinforced concrete with different percentages of steel fiber, Benaicha et al. (2015) concluded that the ultrasonic pulse velocity increased as the amount of steel fibers increased. Saint-Pierre et al. (2016) proposed a novel method for determining concrete quality using the ultrasonic pulse velocity test. In situ ultrasonic pulse velocity (UPV) measurements can be indicative of the level of damage in the original concrete. However, UPV is influenced by the concrete mixture characteristics, which can lead to ambiguous interpretation of the results. The purpose of the concrete quality designation (CQD) proposed by Saint-Pierre et al. was to determine the degree of damage in concrete relative to its original and undamaged condition. This CQD was based on a comparison of in situ and laboratory UPVs and was corrected with respect to the characteristics of the investigated concrete mixtures. Saint-Pierre et al. (2016) presented a case study in which the CQD approach was performed on a hydraulic structure. The CQD was based on UPV measurements and therefore offers the same benefits as other nondestructive imaging techniques because it can generate a damage contour map that is diagnostic of the investigated volume and that helps identify damage areas to be repaired. It suffers from the same limitations as other NDT methods based on the propagation of mechanical waves, i.e., lower resolution than drilling, sensitivity to ambient noise, and so forth. The results showed that CQD is an accurate method and is sensitive enough to very low and very high degrees of damage (Saint-Pierre et al. 2016).

Empirical relations between the mechanical parameters for TSC were addressed in a limited number of studies, for example, that between the compressive strength and Young's modulus of TSC proposed by Abdelgader and Górski (2003). They found the relationship between the compressive strength and Young's modulus of TSC to be significantly dependent on the aggregate shape. Empirical relations also have been proposed for estimation of the tensile strength of TSC using compressive strength (Najjar et al. 2014; Abdelgader and Elgalhud 2008; Abdelgader and Górski 2003; Abdul Awal 1984; Abdelgader and Ben-Zeitun 2005; Rajabi and Omidimoaf 2017). Most empirical relations presented for estimation of compressive strength were derived through NDTs. Some of the most important empirical relations between mechanical parameters of different types of concrete are given in Table 1.

A limited number of studies have been carried out on TSC, and there is a need for development of empirical relations between the mechanical parameters of TSC and CC types. This study presents empirical relations between ultrasonic pulse velocity, Schmidt hammer rebound number (R_n), compressive strength (σ_c), tensile strength (σ_t), Young's modulus (E), and point load index ($I_{s(50)}$) for both CC and TSC. TSC was used to prepare 216 specimens and conventional concrete was used to prepare 108 specimens that were aged for 28 days. The destructive testing methods of uniaxial compression, Brazilian tensile, and point load testing and the nondestructive Schmidt hammer and ultrasonic pulse velocity tests then were carried out to produce relations can be used to estimate the mechanical parameters of CC and TSC.

Materials and Methods

For this study, 216 and 108 samples were prepared for TSC and CC, respectively, which were aged for 28 days. The aggregates were of similar origin and comprised rounded coarse aggregate and sand (ACI 2005). The specimens were prepared using the aggregate, Shahrood cement [a Type II portland cement that complies with ASTM C150 (ASTM 2017)], and tap water. Fig. 1 shows the gradation curve for the aggregates. ACI 304.1 (ACI 2005) stipulates that the fineness modulus of fine aggregate for TSC should be 1.3–2.45. The fineness modulus of the TSC in the present study was 2.21 (Fig. 1). The fineness modulus of the sand was assessed as the mean size of the particles by sieve analysis. The mortar mix plan for preparation of the TSC specimens is given in Table 2.

The usual approach for preparing TSC is first to place the coarse aggregate in the mold; 38% of the whole mass of coarse aggregates is voids. These voids were filled with a workable high-performance grout which penetrated through the coarse aggregate in a standard cylindrical mold of 150 × 300 mm. Cement and water then were uniformly mixed for 4 min using a high-speed mixer to develop the mortar according to ASTM C938 (ASTM 2010), which was injected into the mold so that all empty spaces were filled. The mixing and flowability measurements were conducted at room temperature (23°C ± 2°C). To ensure proper consolidation, the molds were placed on a vibrating plate device (Alfayez et al. 2019). For the TSC, the mortar had the specifications given in Table 2. The CC specimens were prepared by mixing all materials in a mixer and pouring the resulting mixture into the mold. The prepared specimens were placed in water in the preservation room for 28 days to cure in accordance with ASTM C192 (ASTM 2016a). Fig. 2 shows the casting process of TSC specimens. In addition, the specifications of the TSC and CC are presented in Table 3. Fig. 3 shows TSC and CC.

To gather information for the empirical relations between the mechanical parameters of the TSC and CC, the cured specimens were subjected to uniaxial compression, Brazilian tensile strength, and point load tests as destructive testing and Schmidt hammer tests and ultrasonic pulse velocity tests as nondestructive testing; according to ASTM C39/C39M (ASTM 2016b), C496/C496M-04 (ASTM 2004), C469/C469M-14 (ASTM 2014), D5731 (ASTM 2016c), C597 (ASTM 2016d), and C805/C805M (ASTM 2013), respectively (Table 4). Because the Schmidt hammer test provides information only about surface hardness, but the ultrasonic pulse velocity tests provide the quality of concrete (degree of homogeneity), both tests were performed (Gupta et al. 2016) The compressive strength and Brazilian tensile tests were conducted using a device (Azmoon, Tehran, Iran) with a 2,000-kN capacity at a rate of 6 kN/s. Ultrasonic testing was conducted using a device (Proceq, Proceq AG, Schwerzenbach, Switzerland) with a frequency of 50 kHz and a voltage of 250 V. The data were classified into regression and test categories for development and validation of the empirical relations. A total of 180 items were used for regression analysis, and 144 items were used for testing. The data used in each category were selected randomly. The specimen specifications and the number of tests performed are given in Table 4.

Results and Discussion

Table 5 presents the statistical parameters of the results obtained from compression strength, Brazilian tensile strength, and point load testing and from the Schmidt hammer rebound and ultrasonic pulse velocity testing. These include values for compressive and tensile strength, Young's modulus, point load index, Schmidt hammer rebound number, and ultrasonic pulse velocity for the CC and TSC.

The regression data were used to develop empirical relations between the mechanical parameters for TSC and CC (σ_c-UPV, σ_c-R_n, σ_t-UPV, E-UPV, E-R_n, $I_{s(50)}$-UPV, R_n-UPV, and $I_{s(50)}$-R_n). The relations and the error bars of the results are illustrated in Figs. 4–11. The equations displayed in these figures in italics are related to CC. The figures also present the validation of the obtained equations on the basis of the test data (Table 4).

As the ultrasonic pulse velocity increased, the compressive strength of both concrete types increased, but that the rate of increase was different (Fig. 4). This could be because in TSC the pulse velocity went throughout the coarse aggregate skeleton, whereas in case of CC the pulse velocity went throughout the mortar. The ultrasonic pulse velocity measurement can be utilized for the determination of concrete uniformity, presence of cracks or voids, and changes in properties with time.

Table 1. Empirical relations between mechanical parameters of different types of concretes proposed by different researchers

Source	Equation	Concrete type
Benaicha et al. (2015)	$E = 1.06 \times 10^{-4}\mathrm{UPV}^2 - 1.156\mathrm{UPV} + 3.210$	FRC
	$\sigma_c = 2.080e^{0.0007\mathrm{UPV}}$	FRC
Brozovsky (2013)	$\sigma_c = 0.0095R_n^2 + 1.0046R_n - 14.998$	CC
	$\sigma_c = 0.0034R_n^2 + 1.3609R_n - 5.9793$	CC
Hajjeh (2012)	$\sigma_c = 1.0501R_n - 11.8402$	CC
	$\sigma_c = -7.8 \times 10^{-3}R_n^2 + 1.5979R_n - 21.1986$	CC
	$\sigma_c = -2.9 \times 10^{-3}R_n^3 + 0.2975R_n^2 - 8.8004R_n + 94.4267$	CC
Kheder (1999)	$\sigma_c = 1.2 \times 10^{-5}\mathrm{UPV}^{1.7447}$	CC
	$\sigma_c = 0.4030R_n^{1.2083}$	CC
	$\sigma_c = 0.0158\mathrm{UPV}^{0.4254}R^{1.1171}$	CC
Elvery and Ibrahim (1976)	$\sigma_c = 0.0012\exp(0.00227\mathrm{UPV})$	CC
Ambrisi et al. (2008)	$\sigma_c = 2.901\exp(0.0006\mathrm{UPV})$	CC
Fabbrocino et al. (2005)	$\sigma_c = 2.09 \times 10^{-7}\mathrm{UPV}^{12.809}$	CC
	$\sigma_c = 3.54 \times 10^{-5}R_n^{3.81}$	CC
Klieger (1957)	$\sigma_c = 0.0141\exp(0.0017\mathrm{UPV})$	CC
Ravindrajah et al. (1988)	$\sigma_c = 0.06\exp(0.00144\mathrm{UPV})$	CC
Atici (2011)	$\sigma_c = 0.0316\exp(0.0013\mathrm{UPV})$	CC
	$\sigma_c = 3.34\exp(0.0598R_n)$	CC
Chang and Lien (2008)	$\sigma_c = 0.15833\exp(0.0014\mathrm{UPV})$	CC
Ferreira et al. (1999)	$\sigma_c = 1.304\mathrm{UPV}^{2.222}$	CC
Biondi and Candigliota (2008)	$\sigma_c = 0.171\mathrm{UPV}^{3.593}$	CC
Machado et al. (2009)	$\sigma_c = 0.036\mathrm{UPV}^{4.696}$	CC
Pascale et al. (2000)	$\sigma_c = 0.000241\mathrm{UPV}^{8.1272}$	CC
Pessiki and Carino (1988)	$\sigma_c = 0.00834\mathrm{UPV}^{6.074}$	CC
Yoo and Ryu (2008)	$\sigma_c = 0.00220\mathrm{UPV}^{6.289}$	CC
CPWD (2002)	$\sigma_c = 0.024R_n^{1.9898}$	CC
Domingo and Hirose (2009)	$\sigma_c = 0.167R_n^{1.4664}$	CC
Bellander (1977)	$\sigma_c = 0.008R_n^{2.466}$	CC
De Almeida (1991)	$\sigma_c = 1.0407R_n^{1.155}$	CC
Nucera and Pucinotti (2010)	$\sigma c = 0.0051R_n^{2.3956}$	CC
Abdelgader and Elgalhud (2008)	$\sigma_t = -49.67 - 0.44\sigma_c + 38.63(\sigma_c)^{0.15}$	TSC
	$\sigma_t = 39.97 + 0.36\sigma_c - 32.28(\sigma_c)^{0.1}$	TSC
	$\sigma_t = -4.3 - 0.3\sigma_c + 1.82(\sigma_c)^{0.658}$	TSC
	$\sigma_t = 162.65 + 1.15\sigma_c - 132.28(\sigma_c)^{0.108}$	TSC
Abdul Awal (1984)	$\sigma_t = 0.677\sigma_c^{0.434}$	TSC
Abdelgader and Ben-Zeitun (2005)	$\sigma_t = 0.768\sigma_c^{0.441}$	TSC
Rajabi and Omidimoaf (2017)	$E = 1.1341\sigma_c + 0.3034$	TSC
	$\sigma_t = 0.6383(\sigma_c)^{0.4601}$	TSC
	$\sigma_c = 17.401I_{s(50)} - 6.854$	TSC
	$\sigma_c = 1.9204(I_{(s)(50)})^{0.638}$	TSC
	$\upsilon = 0.5088e - 0.059\sigma_c$	TSC
	$\sigma_t = 0.5815(E_0)^{0.4694}$	TSC
	$E = 19.887I_{s(50)} - 7.6868$	TSC
Omidi et al. (2019)	$\sigma_t = 0.6383\sigma_c^{0.4601}$	TSC
Abdelgader and Górski (2003)	$E = 28.7 + 0.080\sigma_c$ (rounded aggregate)	TSC
	$E = 33.9 - 0.049\sigma_c$ (crushed aggregate)	TSC
	$E = 34.9 - 0.090\sigma_c$ (mixed aggregate)	TSC

Note: σ_c = compressive strength; σ_t = tensile strength; E = modulus of elasticity; R_n = rebound number; and FRC = fiber-reinforced concrete.

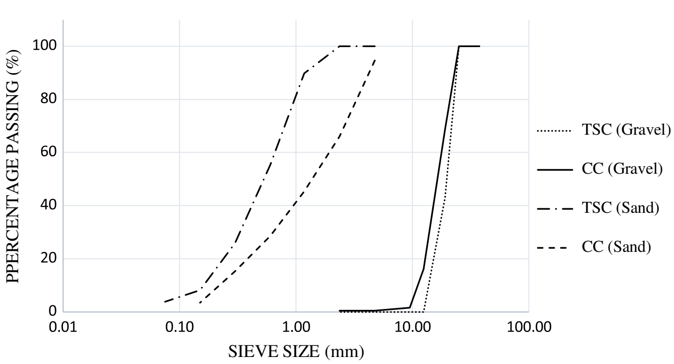

Fig. 1. Gradation curve for the aggregates used in preparation of TSC and CC.

Table 2. Mixture ratios in 1 m^3 of mortar used for TSC specimens

W/C	S/C	C (kg)	S (kg)	W (kg)	EA/C
0.5	1	800	800	400	0.008

Note: W = water; C = cement; S = sand; and EA = expanding admixture.

Fig. 5 shows the relation between compressive strength and the Schmidt hammer rebound number for both TSC and CC. The rebound number (R_n) for TSC was higher than that for CC because of the contact points of the coarse aggregate skeleton, so the coarse aggregate plays an important role in rebound number (R_n). Due to a high result, dispersion fitting of the curve covering the TSC outcomes ($R^2 = 0.762$) was not satisfactory. The tensile strength

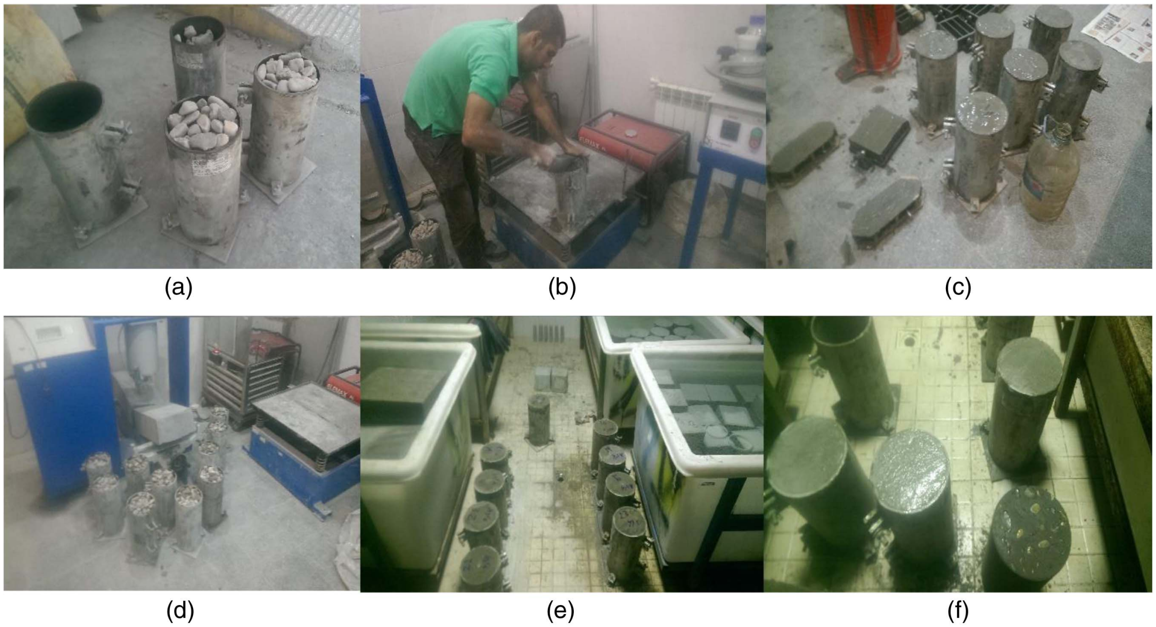

Fig. 2. Casting process of TSC specimens: (a) molds filled with gravel; (b) molds prepared for mortar; (c) adding mortar into the mold on the shaking table; (d) curing; and (e and f) completion of the casting process.

Table 3. Mix proportion of TSC and CC

Type of concrete	W/C	G (kg)	C (kg)	S (kg)	W (kg)
TSC	0.5	1,610	304	304	152
CC	0.57	1,225	300	630	170

Note: W = water; C = cement; G = gravel; S = sand; and EA = expanding admixture.

increased as the ultrasonic pulse velocity increased, but the rate of increase was greater for the CC (Fig. 6).

A linear relationship between the Young's modulus and ultrasonic pulse velocity is shown in Fig. 7. The Young's modulus increased as the ultrasonic pulse velocity increased in a similar manner for both concrete types. The modulus of elasticity (E) is very important for design concrete, and the method of placing the coarse aggregate skeleton is the main factor affecting the modulus of elasticity; in TSC the load transfers first to the aggregate skeleton and then to grout, but in CC the load transfers to mortar. The result scatter in the TSC case (the gap between the highest and the lowest values) was much greater than that in the CC case. However, due to the TSC result scatter and the extraordinary CC layout, the straight-line fitting is illustrative only. Fig. 8 demonstrates the empirical relationship for estimation of the Young's modulus through the Schmidt hammer rebound number. The Young's modulus of TSC was larger than that of CC. The empirical relation between the point load index and the ultrasonic pulse velocity produced a steeper curvature slope for CC than for TSC (Fig. 9). The results

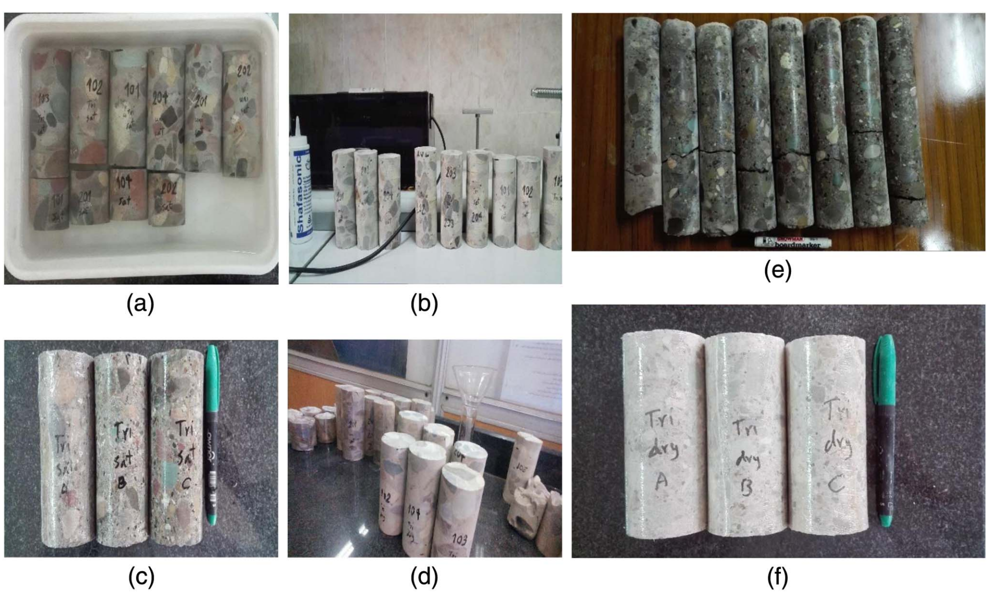

Fig. 3. (a–d) Two-stage concrete specimens; and (e and f) conventional concrete specimens.

Table 4. Specifications of specimens and number of tests carried out

Parameters	Test	Concrete type	Samples diameters (mm)	No. of regression data	No. of test data	Total no. of tests	References
σ_c	Uniaxial compressive strength	TSC	150 × 300	20	16	36	ASTM C39/C39M
		CC		10	8	18	
σ_t	Brazilian	TSC	150 × 300	20	16	36	ASTM C496/C496M
		CC		10	8	18	
E	Uniaxial compressive strength	TSC	50 × 100	20	16	36	ASTM C469/C469M
		CC		10	8	18	
$I_{S(50)}$	Point load	TSC	50 × 50	20	16	36	ASTM D5731
		CC		10	8	18	
UPV	Ultrasonic pulse velocity	TSC	50 × 100	20	16	36	ASTM C597
		CC		10	8	18	
R_n	Schmidt hammer	TSC	150 × 300	20	16	36	ASTM C805/C805M
		CC		10	8	18	
Total sample							324

Note: σ_c = compressive strength; σ_t = tensile strength; E = modulus of elasticity; υ = poison ratio; $I_{s(50)}$ = point load index; and R_n = rebound number.

Table 5. Statistical parameters of results obtained from experiments

Mechanical parameters	Min		Max		Mean		Standard deviation		Relative standard deviation	
	TSC	CC	TSC	CC	TSC	CC	TSC	CC	TSC	CC
σ_c (MPa)	14.97	15.32	22.44	18.65	17.9	17.00	2.05	1.10	11.45	6.47
σ_t (MPa)	2.20	1.80	2.66	2.20	2.40	2.07	0.13	0.07	5.42	3.38
E (GPa)	17.53	17.04	26.40	19.84	20.61	18.31	2.35	0.88	11.4	4.81
$I_{s(50)}$ (MPa)	1.26	1.36	1.70	1.55	1.42	1.43	0.12	0.06	8.45	4.20
UPV (m/s)	3,895	4,134	4,728	4,366	4,362	4,260	229	89	5.25	2.09
R_n	27.33	22.11	33.67	24.33	30.71	23.36	1.44	0.65	4.69	2.78

Note: σ_c = compressive strength; σ_t = tensile strength; E = modulus of elasticity; υ = poison ratio; $I_{s(50)}$ = point load index; R_n = rebound number; Min = minimum; Max = maximum; and Mean = average.

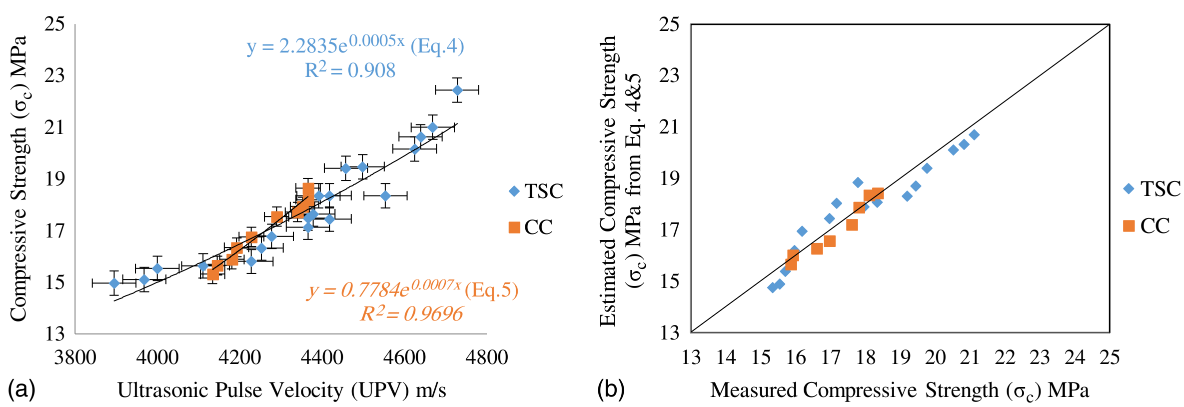

Fig. 4. (a) Relationship between compressive strength and ultrasonic pulse velocity for two-stage concrete and conventional concrete, with error bars; and (b) comparison of measured compressive strength values and predicted values using ultrasonic pulse velocity.

of the nondestructive tests were linearly related, and the Schmidt hammer rebound number can be estimated using the ultrasonic pulse velocity (Fig. 10). Moreover, the point load index can be obtained using the Schmidt hammer rebound number (Fig. 11).

Additionally, the RMS error (RMSE), Nash–Sutcliffe (N-S) value, and R^2 were calculated using Eqs. (1)–(3), respectively, where x_i and x_p represent the real and predicted values, $\bar{x}$ is the average of the data, and n is number of data sets. Values of 0, 1, and 1, for RMSE, R^2, and N-S, respectively, indicate a high level of validity for the empirical relations

$$\mathrm{RMSE} = \sqrt{\frac{1}{n} \times \sum_{i=1}^{n}[(x_i - x_p)^2]} \tag{1}$$

$$\text{N-S} = 1 - \frac{\sum_{i=1}^{n}(x_i - \bar{x}_p)^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{2}$$

$$R^2 = \frac{[\sum_{i=1}^{n}(x_i - \bar{x})^2] - [\sum_{i=1}^{n}(x_i - x_p)^2]}{[\sum_{i=1}^{n}(x_i - \bar{x})^2]} \tag{3}$$

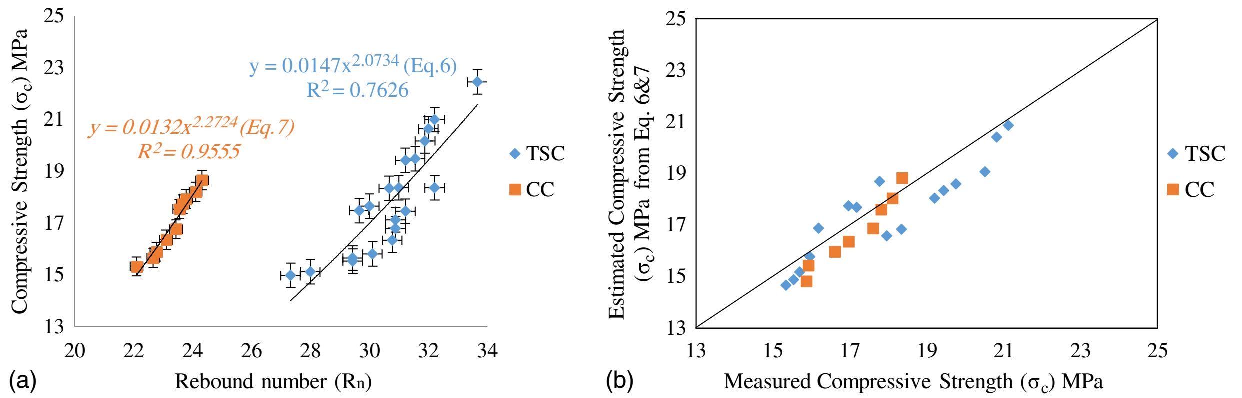

Fig. 5. (a) Relationship between compressive strength and the rebound number of Schmidt hammer, with error bars; and (b) comparison of measured compressive strength values and predicted values using rebound number.

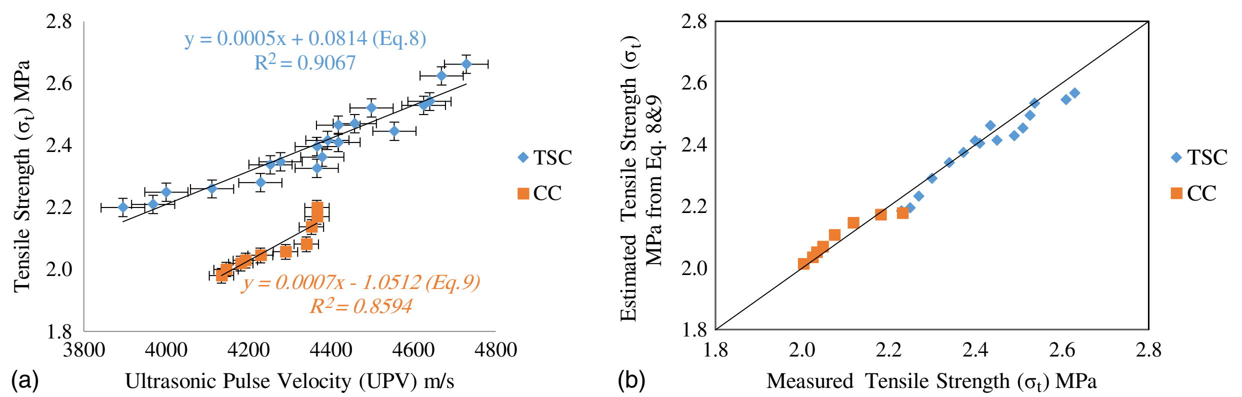

Fig. 6. (a) Relationship between tensile strength and the ultrasonic pulse velocity, with error bars; and (b) comparison of measured tensile strength values and predicted values using ultrasonic pulse velocity.

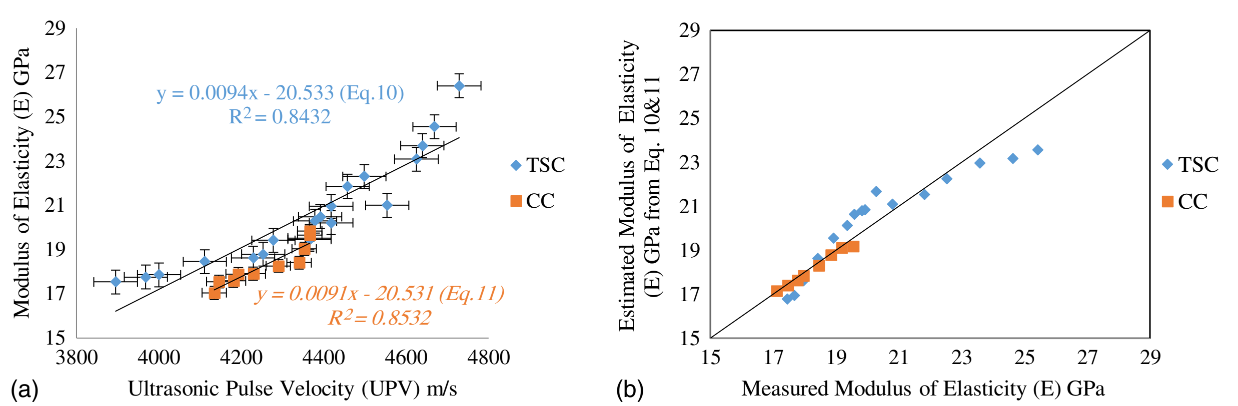

Fig. 7. (a) Relationship between Young's modulus and the ultrasonic pulse velocity, with error bars; and (b) comparison of measured Young's modulus values and predicted values using ultrasonic pulse velocity.

Table 6 presents the validation results of the proposed relations. The results were satisfactorily reliable and can be used for quick estimation of mechanical parameters for both TSC and CC.

Because compressive strength is one of the most important mechanical parameters for concrete, the proposed empirical relationships for CC [Eqs. (5) and (7), and Table 6] were compared with the equations by Fabbrocino et al. (2005), Yoo and Ryu (2008), Domingo and Hirose (2009), and Bellander (1977) for estimating the compressive strength of concrete using the nondestructive ultrasonic pulse velocity and Schmidt hammer tests (Figs. 12 and 13, respectively). All three curves intersect at a specific point (Fig. 12). This means that if the ultrasonic pulse velocity is about 4,100 m/s, all three compressive strength values can be estimated to be about 15 MPa. The proposed equation [Eq. (5) and Table 6] estimated the

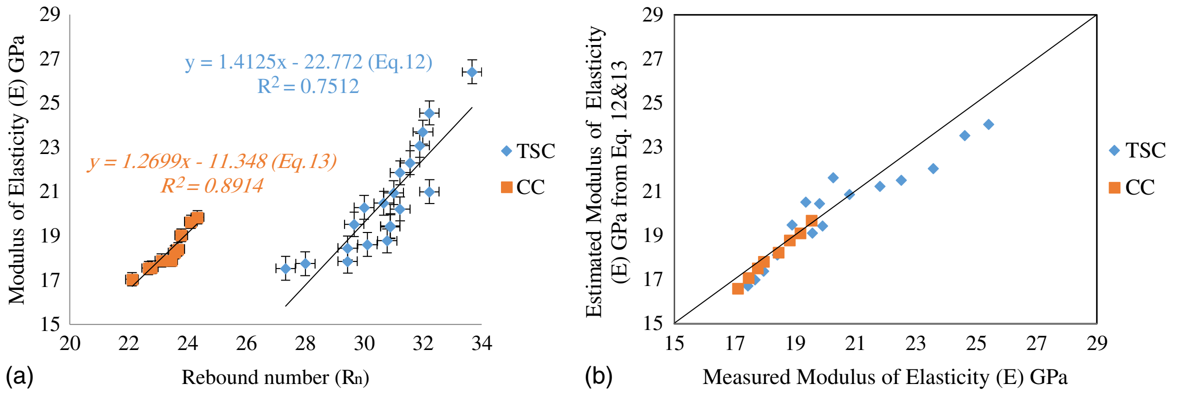

Fig. 8. (a) Relationship between Young's modulus and the rebound number of Schmidt hammer, with error bars; and (b) comparison of measured Young's modulus values and predicted values using rebound number.

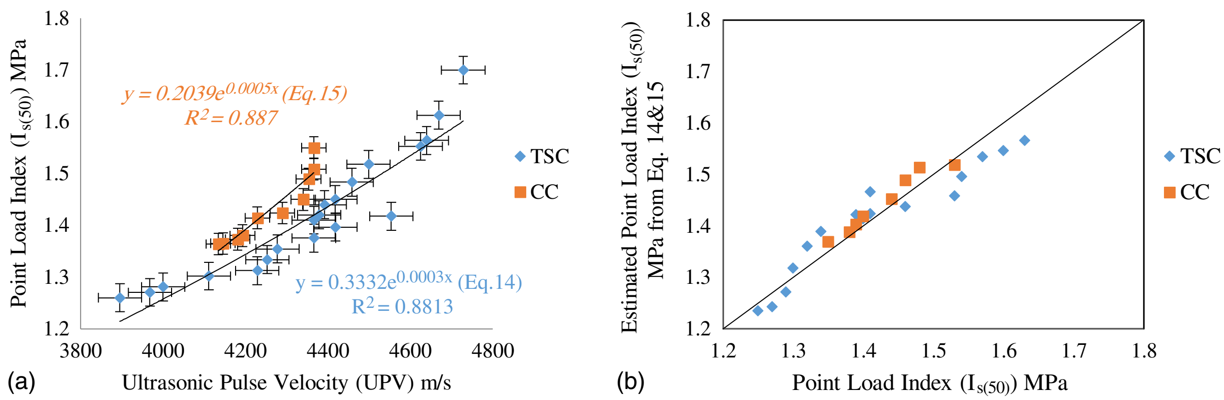

Fig. 9. (a) Relationship between point load index and the ultrasonic pulse velocity, with error bars; and (b) comparison of measured point load index values and predicted values using ultrasonic pulse velocity.

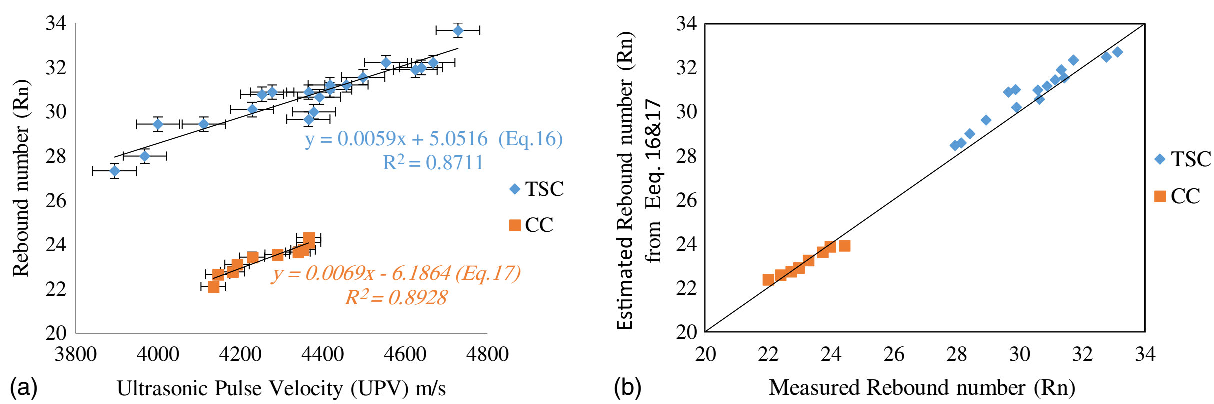

Fig. 10. (a) Relationship between rebound number of Schmidt hammer and the ultrasonic pulse velocity, with error bars; and (b) comparison of measured rebound number values and predicted values using ultrasonic pulse velocity.

compressive strength to be less than that of the other formulas for wave speeds greater than 4,100 m/s and higher for wave speeds less than 4,100 m/s. All three curves had approximately the same pattern (Fig. 13). When the Schmidt hammer rebound number was less than 25, the compressive strength estimated by these relationships varied slightly. The proposed equation [Eq. (7)] for a Schmidt hammer rebound number above 25 was approximately the average of the two other relationships. However, the differences between the relationships presented in this paper (e.g., Figs. 12 and 13) and the equations of other researchers can be attributed to differences in aggregates and cement type, preparation of specimens, mixing ratios, chemical properties of the water used, and so forth.

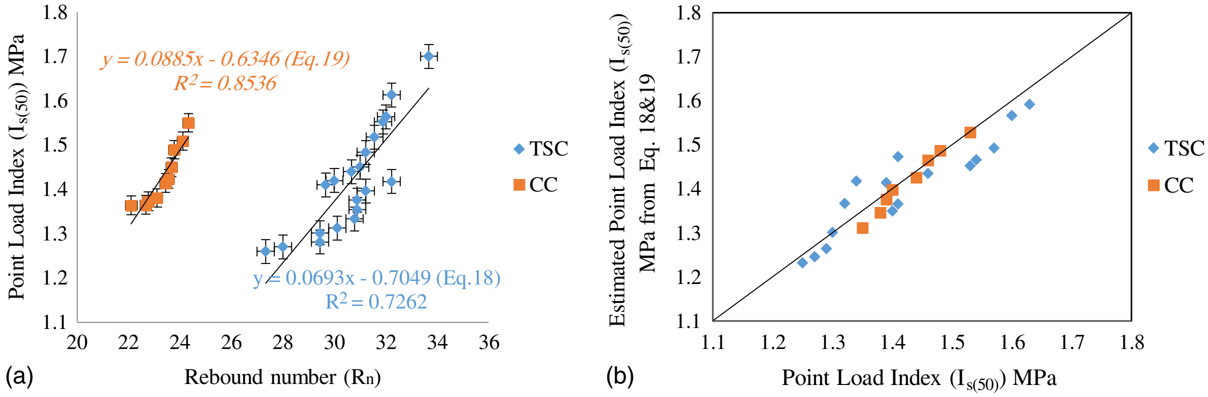

Fig. 11. (a) Relationship between rebound number of Schmidt hammer and the point load index, with error bars; and (b) comparison of point load index values and predicted values using rebound number.

Table 6. Obtained empirical relations and validation of relations between mechanical parameters of TSC and CC obtained from destructive and nondestructive tests

Concrete type	Eq. No.	Equation	R^2	N-S	RMSE
TSC	4	$\sigma_c = 2.2835e^{0.0005}$ UPV	0.908	0.902	0.597
CC	5	$\sigma_c = 0.7784e^{0.0007}$ UPV	0.97	0.913	0.266
TSC	6	$\sigma_c = 0.0147R_n^{2.0734}$	0.763	0.761	0.934
CC	7	$\sigma_c = 0.0132R_n^{2.2724}$	0.956	0.539	0.612
TSC	8	$\sigma_t = 0.00053\,\mathrm{UPV} + 0.0814$	0.907	0.894	0.039
CC	9	$\sigma_t = 0.0007\,\mathrm{UPV} - 1.0512$	0.86	0.875	0.027
TSC	10	$E = 0.0094\,\mathrm{UPV} - 20.533$	0.843	0.854	0.906
CC	11	$E = 0.0091\,\mathrm{UPV} - 20.531$	0.853	0.961	0.159
TSC	12	$E = 1.4125R_n - 22.772$	0.751	0.858	0.894
CC	13	$E = 1.2699R_n - 11.348$	0.891	0.883	0.274
TSC	14	$I_{s(50)} = 0.3332e^{0.0003}$ UPV	0.881	0.886	0.04
CC	15	$I_{s(50)} = 0.2039e^{0.0005}$ UPV	0.887	0.867	0.02
TSC	16	$R_n = 0.0059\,\mathrm{UPV} + 5.0516$	0.871	0.844	0.591
CC	17	$R_n = 0.0069\,\mathrm{UPV} - 6.1864$	0.893	0.902	0.243
TSC	18	$I_{s(50)} = 0.0693R_n - 0.7049$	0.726	0.827	0.05
CC	19	$I_{s(50)} = 0.0885R_n - 0.6346$	0.854	0.881	0.019

Note: σ_c = compressive strength; σ_t = tensile strength; E = modulus of elasticity; υ = Poisson's ratio; and $I_{s(50)}$ = point load index.

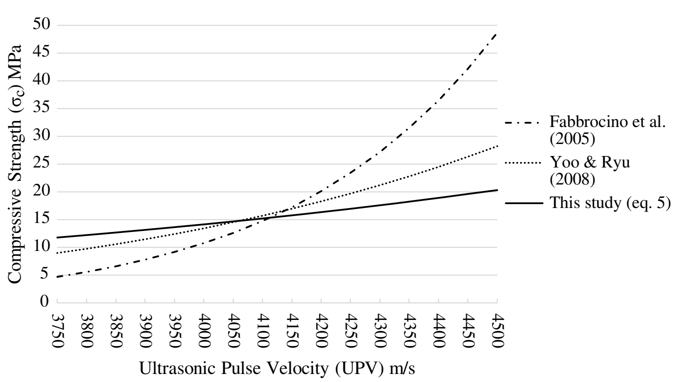

Fig. 12. Comparison of the proposed Eq. (5) with equations of Fabbrocino et al. (2005) and Yoo and Ryu (2008) to estimate the compression strength of conventional concrete with respect to ultrasonic pulse velocity.

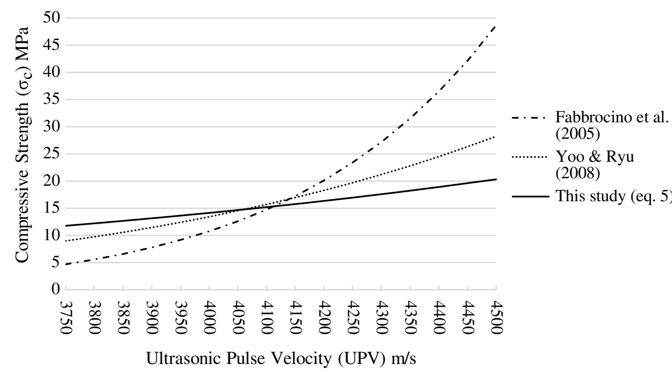

Fig. 13. Comparison of the proposed Eq. (7) with equations of Domingo and Hirose (2009) and Bellander (1977) to estimate the compression strength of conventional concrete with respect to the Schmidt hammer test.

Conclusions

Two-stage concrete and conventional concrete have important applications in the concrete industry, but these types of concrete differ with respect to manufacturing process, structure, and force transfer. This study derived empirical relations between the mechanical parameters of ultrasonic pulse velocity, Schmidt hammer rebound number, compressive strength, tensile strength, Young's modulus, and point load index for TSC and CC. The nondestructive Schmidt hammer and ultrasonic pulse velocity tests and destructive uniaxial compression, Brazilian tensile strength, and point load tests were conducted on specimens of both concrete types that were aged for 28 days. Different sets of data were used for testing and regression analysis, and the statistical parameters were used to validate the relations. Because almost identical material was prepared to form both CC and TSC, the results make it possible to compare both concrete types. The differences were significant due to the magnitudes and the range of the obtained mechanical parameters. The scatter in TSC results indicated its remarkably higher inhomogeneity compared with the CC case. The comparative tests displayed the differences between TSC and CC, making it possible to select a relevant concreting methodology, especially in the case of both techniques available. The tests showed that it is possible to assess mechanical TSC and CC parameters by means of nondestructive

Schmidt hammer and ultrasonic pulse velocity tests. These nondestructive testing techniques may substantially limit the specimen population. Each test piece employed in a nondestructive testing course can be applied in destructive tests. Moreover, the nondestructive test results may be further applied in the in situ experiments.

The results indicated that the compressive strength, tensile strength, Young's modulus, ultrasonic pulse velocity, and Schmidt hammer rebound number were greater for TSC than for CC. The proposed empirical relationships for conventional concrete [Eqs. (2) and (4); Table 6] were compared with relationships developed by other researchers. The results showed that the proposed equations are comparable to those other equations with respect to functional form and accuracy. The obtained relationships are particularly valuable, especially those for TSC, because they add to the limited body of knowledge produced by a limited number of previous studies.

Because of the statistical population and validation results of the current research, it can be said that the mechanical parameters of TSC and CC can be feasibly estimated using these relations. Due to the increasing use of concrete, including TSC concrete, in civil engineering projects, the use of these equations with caution can provide an acceptable estimate of the mechanical parameters of this type of concrete. The correlations presented here are valid only for this type of concrete and sample preparation. For field applications, site-specific calibration would be necessary. The results cannot be assumed to be universally acceptable because the mechanical parameters may change when the type of aggregate or the nature of the concrete changes.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published paper.

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