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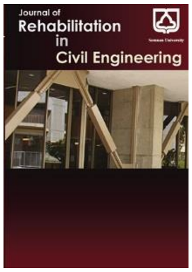

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Strength Assessment of Steel Fibre Reinforced Recycled Aggregate Concrete by Means of Correlation between Ultrasonic and Point Load Tests

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ABSTRACT

This paper aimed at assessing the in-situ strength of steel fibre reinforced concrete containing recycled coarse aggregate (RCA) using the correlation between ultrasonic and point load tests. The mechanical properties of recycled aggregate concrete can be improved by adding fibres in concrete mixes. On the other hand, the importance of strength estimation of existing concrete at the building site has led to use non-destructive and partially testing methods. So, in this research, the compressive strength of wet and dry cured mixes made with RCA and steel fibre (SF) at 1.5% by volume was evaluated by mean of point load test (PLT) and ultrasonic method. As per the experimental outputs, the standard deviation (SD) values increased up to 20% by increasing the substitution amount of natural aggregate with RCA from 50% to 100%. In addition, the point load index (PLI) of wet cured concrete mixes was obtained averagely about 14.3% more than that of dry cured concrete mixes. Furthermore, the strength estimation of conventional concrete or fibre reinforced recycled aggregate concrete at different ages was carried out using a two-variable equation between ultrasonic pulse velocity (UPV) and PLI values.

1. Introduction

Over the past decades, the concrete materials' mechanical strength has been evaluated using some standard test methods. However, the mechanical strength of existing concrete at the building site is different to that of standard specimens in lab-scale. Therefore, non-destructive and partially testing methods were found to be useful for realistically predict the on-site concrete materials' strength [1-4]. Each of these methods has a unique feature that should be accurately considered in the testing procedure. As a partially destructive testing method, point load test (PLT) is capable of predicting the in-situ concrete materials' strength. This test is according to the ISRM standard [5] and it

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consists of applying an increasingly concentrated point load to the lateral surface of the core sample extracted from the concrete member. The PLT can be easily prepared and operated at the building site owing to the portability and cheapness of its device. [6-8]. The PLT was employed by Robins [7] to predict concrete samples' strength and then it was developed by other researchers to be used in the construction sector. Concerning this, Zacoeb and Ishibashi [9] showed that more reliable results were obtained for drilled core specimens with the L/D ratio of 2. Recently, Madandoust et al. [8] obtained reliable correlation curves between concrete strength and its point load index (PLI). Meanwhile, they demonstrated that the PLI values of dry cured mixes were averagely 12% lower than those of wet cured mixes. Generally, the in-situ strength of normal concrete has been widely assessed using PLT; however, few tests have been carried out on recycled aggregate concrete have been performed using this testing method.

As one of the applicable non-destructive methods, the ultrasonic pulse velocity (UPV) test has been proposed and widely employed by researchers to reliably predict concrete in-situ strength. The value of velocity for high-strength concrete materials is found to be high, while the low values are obtained for concrete with poor quality [10]. Parker [11] showed that the concrete strength can be effectively predicted using correlation curves between the outputs of UPV method and standard cube test. However, there was no unique standard correlation between these two tests; therefore, it is required to introduce a suitable correlation curve for each concrete mixture to realistically predict concrete strength as reported by Turgut [12].

The overutilization of construction aggregates, extracted from mineral resources, has led to the generation of detrimental effects on the environment [13-15]. The partial replacement of natural aggregates with recycled coarse aggregate (RCA) in the construction sector can be considered as a viable solution to reduce ruinous impacts on the environment [16-22]. However, the mechanical strength of concrete, as a brittle material, decreases with replacing the natural aggregate with RCA. This issue can be somewhat solved using appropriate additions in concrete materials [23-25]. Among different types of additions, Pozzolanic materials such as microcilica are capable of improving the recycled aggregate concrete strength. Microcilica includes high amount of chemical components of Al_2O_3 and SiO_2 and it is finer than cement particles; so, the surface area of Microcilica is higher than that of cement particles to complete the hydration process and subsequently increase the concrete strength [26-28]. As another addition to concrete materials, the steel fibre (SF) with a high strain-hardening response has been proposed and widely employed by researchers. This addition can improve the concrete strength by bridging the macro-cracks and delaying the failure of concrete members [29-31]. Generally, it seems that mechanical properties of recycled aggregate concrete can be improved by adding microcilica and SF.

The compressive strength of concrete containing RCA has been estimated by means of some partially and non-destructive testing methods. Regarding this, Soares et al. [2] assessed the compressive strength of concrete containing RCA using UPV test. A reliable linear correlation curve was obtained between the UPV and various amount of RCA in concrete materials by Soares et al. [2] and they showed that the UPV values decreased by increasing the amount of RCA. In another study by Singh et al. [32], the coarse natural aggregates were replaced at 25, 50, and 100% with RCA for the strength estimation of self-compacting concrete containing coal bottom ash by means of UPV test. They introduced concrete with 25% and 50% RCA as optimum mix designs to achieve the intended compressive strength and workability properties of self-compacting concrete. Al-Nu'man et al. [33] showed that the UPV value should be more than 3.5 km/s to achieve concrete samples with an adequate strength. Karaiskos et al. [34] showed that the UPV method could provide high-potential solutions for non-destructive evaluation of new and existing concrete infrastructure. Moreover, the UPV value was dependent on the elastic modulus of concrete. Besides, some factors including the water-to-cement ratio, steel reinforcement, the hydration and curing conditions, and the type and amount of aggregates influenced the relationship between the UPV and compressive strength.

By considering the fact that there was a difference between the results of standard samples in lab-scale and those at the building site, it is required to generate the correlation between non-destructive testing methods at the building site to attain a reliable in-site strength estimation of specific types of concrete materials without performing the compression test in the laboratory. In addition, few tests on specific types of concrete materials have been performed using UPV test and the mechanical strength of steel fibre reinforced recycled aggregate concrete has not been predicted using the PLT. Therefore, the aim of this work was to realistically predict the in-situ strength of recycled aggregate concrete containing SF and microsilica using the correlation between UPV test and PLT in which it was not required to use the compression test for the strength prediction of concrete specimens. By considering the fact that the concrete strength can be influenced by the curing conditions [35, 36], steel fibre reinforced recycled aggregate concrete specimens were tested and evaluated under different curing regimes. Furthermore, the combination of the methods was employed for the suggestion of a two-variable equation between the UPV and PLI to estimate the in-situ strength of concrete samples without need for performing the compression test in the laboratory.

2. Experimental Program

2.1. Materials

The chemical compositions of cement particles and microcilica are presented in Table 1. Type II Portland cement was provided from Bojnourd cement Company, with the surface area of 3300 cm^2/g and a bulk density of 3164 kg/m^3. The bulk density of microcilica was equal to 200 kg/m^3. The gravel with the maximum size of 19 mm was provided from natural mines around the Chalous city with bulk density of 2700 kg/m^3 (Fig. 1 (a)). The bulk density of sand was 2650 kg/m^3 and it was provided from river with the size in the range of 0-4.75 mm. The RCA with the maximum size of 19 mm and the bulk density of 2440 kg/m^3 was used as shown in Fig. 1(b). To achieve the intended concrete workability, the superplasticizer of polycarboxylic ether-type was used [37]. The size grading curves of all aggregates, microcilica and cement particles are depicted in Fig. 2. The physical and mechanical characteristics of hooked-end SF, consumed in concrete mixes, are presented in Table 2.

Table.1. Chemical properties of cement and microcilica.

Item	Cement (%)	Microcilica (%)
SIO_2	20.6	90.9
AL_2O_3	4.2	0.56
Fe_2O_3	3.8	0.73
CaO	64.2	0.58
MgO	1.94	1.34
SOP_3	2.7	-
K_2O	0.67	1.33
N_2O	0.32	0.34
LOI	2	1.91

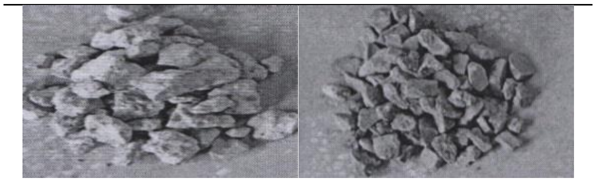

(a) (b)

Fig. 1. Coarse natural aggregate (a); RCA (b).

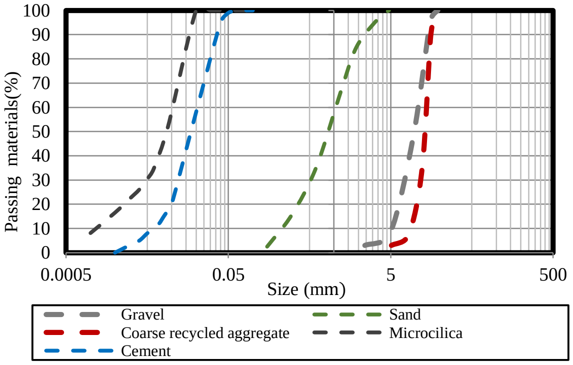


Fig. 2. Aggregates' size distribution.

Table 2. Properties of SF.

Length (mm)	Diameter (mm)	Bulk density ($^{gr}/_{cm^3}$)	Tensile strength (MPa)
30	0.8	7.8	1220

2.2. Mix proportioning and sample preparation

12 concrete mix designs were made in this study as shown in Table 3. Of all these mix designs, 6 mixes were made with SF at 1.5% by volume. Two effective water/binder (W/B) ratios of 0.4 and 0.55 were considered for mix proportioning. Micricilica and superplasticizer were added to concrete mixes with low W/B ratio (0.4). To saturate the aggregates and subsequently reduce the amount of the water absorption particularly by RCA, they were maintained in the saturated surface-dry condition.

Table 3. Mix details.

Mix ID	Cement (kg/m^3)	W/B	Micricilica (kg/m^3)	Gravel		Sand (kg/m^3)	Fibre (%)	Superplasticizer (kg/m^3)
				Natural (kg/m^3)	Recycled (kg/m^3)			
N[a]CS[b]	360	0.4	40	1024	0	743	0	0.8
NCSF[c]	360	0.4	40	1024	0	743	1.5	1
R[c]C50S	360	0.4	40	512.3	462.97	743	0	0.8
RC50SF	360	0.4	40	512.3	462.97	743	1.5	1
RC100S	360	0.4	40	0	925.94	743	0	0.8
RC100SF	360	0.4	40	0	925.94	743	1.5	1
NC	350	0.5	0	1009	0	732	0	-
NCF	350	0.55	0	1009	0	732	1.5	-
RC50	350	0.55	0	504.56	455.98	732	0	-
RC50F	350	0.55	0	504.56	455.98	732	1.5	-
RC100	350	0.55	0	0	911.95	732	0	-
RC100F	350	0.55	0	0	911.95	732	1.5	-

[a] Natural aggregate

[b] Superplasticizer

[c] Fibre

[d] RCA

For mix preparation, first, the mixer revolved for 30 s to combine the fine and coarse aggregates. Later on, by adding half of the tap water to the aggregates, the mixing was continued for one more minute. Then, cement and micricilica were introduced and mixed for one more minute. To prevent clustering of the SF, this content, along with the remaining water and superplasticizer, was slowly added into the mixer, and the mixing was continued three more minutes. Finally, to obtain 5-, 7-, 28-, and 56-day compressive strength of concrete mixes, concrete slabs and 10 cm cubes specimens were made and cast.

The molds were covered with a wet sack and a plastic layer and kept for 24 hours under laboratory condition at 22 -24 °C. Then, the concrete slabs and 10 cm cubes specimens were demoulded 24 hours after casting and they were kept under lab condition (dry curing regime) until the date of testing at 22 -24 °C temperature. Under wet curing condition, the demoulded concrete specimens were immersed in a water tank at 24 °C up to the time of testing.

To evaluate the strength of 10 cm cubic samples, they were subjected to UPV test. After that, they were broken using the compression testing machine. The results of cube testing were the average number of three cubic samples. In the PLT (Fig. 3), the results were the average number of three cylindrical samples, extracted from slab specimens. In addition, the diameter of core samples in the PLT was 70 mm and the length to diameter ratio was equal to 2. It is noteworthy that the UPV test and PLT were carried out according to ASTM C597-16 [38] and ISRM standard [5], respectively.

Fig. 3. PLT machine.

3. Results and discussion

3.1. Slump

The consistency of fresh concrete mixes was assessed using the slump test. The slump value for recycled aggregate concrete with and without SF was ranging from 66 to75 mm as presented in Table 4. The range of 70-90 mm was obtained by Ferreira et al. [39] for concrete mixes with different replacements of coarse natural aggregate with RCA. Different W/B ratios didn’t have a significant effect on slump values. It can be stated that, for low W/B ratio (0.4), the superplasticizer provided an appropriate workability for mixes. RCA had high porosity and SF content generated high cohesion and bond in conjunction with cement particles. These two features contributed to reducing the slump values of concrete mixes by adding RCA and SF more to mixes.

Table 4. Slump values.

Mix ID	Slump (mm)	W/B	Fibre (%)	Superplasticizer (kg/m^3)
NCS	78	0.4	0	0.8
NCSF	75	0.4	1.5	1
RC50S	74	0.4	0	0.8
RC50SF	72	0.4	1.5	1
RC100S	69	0.4	0	0.8
RC100SF	66	0.4	1.5	1
NC	79	0.55	0	-
NCF	77	0.55	1.5	-
RC50	75	0.55	0	-
RC50F	72	0.55	1.5	-
RC100	68	0.55	0	-
RC100F	66	0.55	1.5	-

3.2. Cube compressive strength

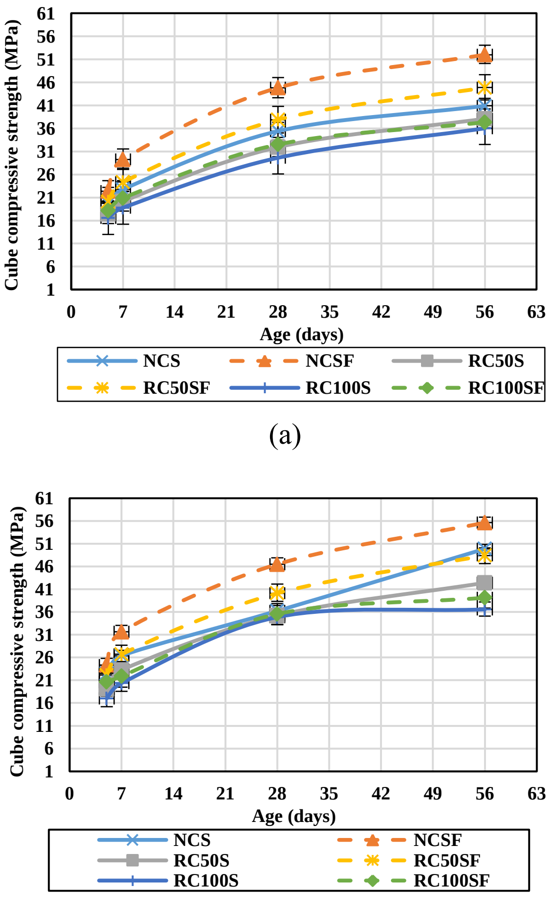
The concrete strength of specimens made by SF and 50% and 100% replacements of natural aggregates with RCA at 5, 7, 28 and 56 days is presented in Figs. 4 and 5. As shown in Fig. 4, the cube compressive strengths of concrete specimens with the W/B ratio of 0.4 under dry and wet curing regimes were in the range of 16.6–52 MPa and 17–55.6 MPa, respectively. The corresponding values for concrete specimens with W/B ratio of 0.55 under dry and wet curing regimes were in the range of 17-55.6 MPa and 15.1–41.3 MPa, respectively (Fig. 5). The strength of wet cured mixes with 100% incorporation of RCA and W/B ratio of 0.4 at 28 days was found to be 34.9 MPa, as shown in Fig. 4 (b). A study by Soares et al. [2] showed this value was equal to 32.4 MPa. As per the outputs, the cube compressive strength of concrete mixes with the W/B ratio of 0.4 was averagely about 33.4% more than that with the W/B ratio of 0.55. In addition, the cube compressive strength of the wet cured mixes was obtained averagely about 15.2% more than that of the dry cured mixes. Mamlouk and Zaniewski [40] showed that this difference can increase up to 50%.

As seen in Fig. 4, for the W/B ratio of 0.4 under different curing conditions, the maximum and minimum of compressive strength were attained for NCSF and RC100S, respectively. For the W/B ratio of 0.55, NCF and RC100 attained the highest and lowest values of the compressive strength, respectively, as shown in Fig. 5. These results showed that an effective interlocking joint was generated between SF and concrete matrix to improve the mechanical strength of NCSF, similarly to what Madandoust et al. [30] concluded, while the replacement of natural aggregate with RCA led to a remarkable decrease in the compressive strength of RC100S and RC100. As shown in Figs. 4 and 5, the decrease in the substitution level of coarse natural aggregate with RCA from 100% to 50% moderately improved the concrete strength, similarly to what occurred by using SF in the specimens incorporating 100% substitution of RCA (RC100SF and RC100F).

The concrete strength of specimens at middle age (28 days) was on average about 86% more than that at early ages (5 or 7 days). The aforementioned strength at old age (56 days) was 11.1% more than that at middle age (28 days). So, a remarkable increase was observed for the concrete strength from early ages (5 and 7 days) to middle age (28 days), while the corresponding increase from the middle age to older age was moderate. At higher ages, the free water in concrete mixes evaporated contributing to the limited access to adequate water to improve the rate of hydration process, particularly at old age (56 days) as reported by Kazemi et al. [3].

As per Fig. 4 (b), the 28-day standard deviation (SD) of wet cured mixes with the W/B ratio of 0.4 and 100% substitution of coarse natural aggregate with RCA was 1.9

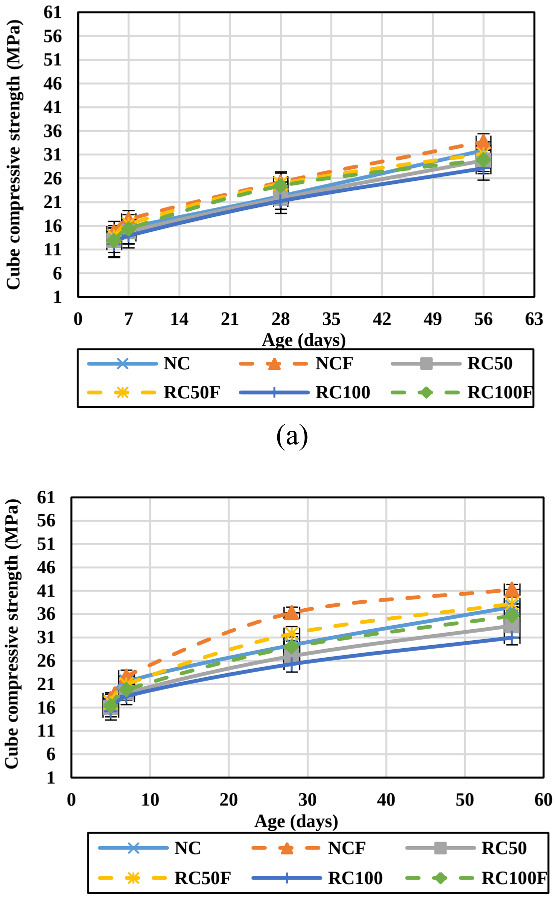
MPa. A study by Soares et al. [2] reported that the aforementioned value was 2.3 MPa. As per the results, the SD value of concrete specimens made with superplasticizer was averagely 17.1% more than that without superplasticizer. Similar to what was observed by Madandoust et al. [8], the SD value of the wet cured mixes was averagely scattered 16.8% lower than that of the dry cured mixes as expected. The addition of steel fibre led to the dissipation of data 26.6% more. The reason is that the presence of this addition creates air-voids in concrete specimens, leading to more dissipation of results. 50% and 100% substitutions of RCA were associated with an increase in SD value of concrete mixes up to 24.4% and 63.4%, respectively.



(a)

(b)

Fig. 4. Results of dry (a); and wet (b) cured mixes (W/B ratio = 0.4).



(a)

(b)

Fig. 5. Results of dry (a); and wet (b) cured mixes (W/B ratio = 0.55).

3.3. PLT

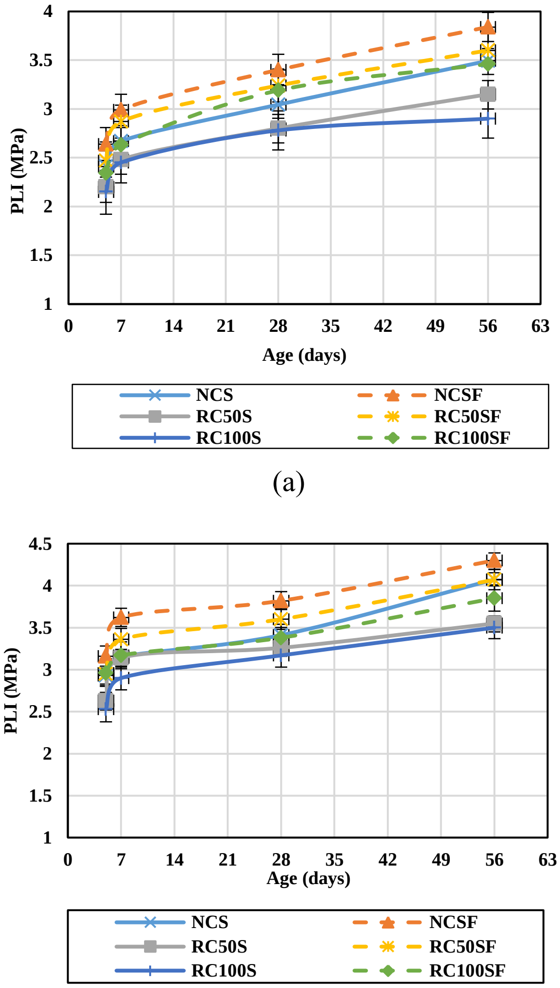
Figs. 6 and 7 show PLI values of concrete specimens made by SF and substitution of coarse natural aggregates with RCA at 5, 7, 28 and 56 days. The PLI ranges of concrete specimens with a W/B ratio of 0.4 under dry and wet curing regimes were 2.15–3.84 MPa and 2.53–4.3 MPa, respectively as shown in Fig. 6. As per Fig. 7, the corresponding ranges of concrete samples with a W/B ratio of 0.55 under dry and wet curing regimes were 1.55–2.42 MPa and 1.64–3.84 MPa, respectively. The PLI of control concrete specimen with a W/B ratio of 0.55 (NC) under wet curing condition at 28 days was obtained 1.9 MPa. As per the experimental outputs, the PLI of concrete samples with a W/B ratio of 0.4 was averagely about 48.8%

higher than that with a W/B ratio of 0.55. In addition, the PLI value of the wet cured mixes was obtained averagely about 14.3% more than that of the dry cured mixes. As per the results provided by Madandoust et al. [8], the aforementioned difference was 12% for normal concrete specimens.

Similarly to the compression test, the highest and lowest PLI values of concrete mixes with a W/B ratio of 0.4 under different curing regimes were obtained for NCSF and RC100S, respectively (Fig. 6). As shown in Fig. 7, for the W/B ratio of 0.55, NCF and RC100 mixes accounted for the highest and lowest PLI values. The addition of SF increased the PLI values of RC100SF and RC100F up to 10% owing to its positive bridging effect on the post-cracking behaviour of concrete specimens [12] as shown in Fig. 8.

In most cases, no specific enhancement for PLI values appeared by increasing the curing age which can be owing to the sensitivity of concrete samples to the concentrated point load in the PLT. However, the PLI at middle age (28 days) was obtained averagely about 18.6% more than that at middle at early ages (5 or 7 days). The corresponding value at old age (56 days) was on average about 10.7% more than that at middle age (28 days).

The amounts of 0.07 MPa and 0.09 MPa were obtained for 28-day SD of wet cured control mixes with W/B ratios of 0.55 (NC) and 0.4 (NCS), respectively. The PLI values obtained by Madandoust et al. [8] for normal concrete specimens with core diameter of 70 mm were in the range of 0.08-0.13 MPa. Therefore, the PLI values of this work were nearly within the values reported by Madandoust et al. [8]. The use of superplasticizer contributed to increasing the SD values of concrete mixes up to 17.7%. The reason is that it scattered cement particles from each other [27], leading to scattering the SD values more. The SD value of the wet cured mixes was averagely dissipated 38.8% lower than that of the wet cured mixes as expected. Because of the generation of air-voids in concrete samples by SF [8], the SD values increased up to 20.7%. Therefore, it seems that the concentrated point load in the PLT, applied to concrete specimens created more sensitivity to air-voids generated by SF, thereby the SD values being dissipated more. 50% and 100% substitutions of RCA caused to dissipate the SD values up to 17.9% and 42.8%. Therefore, the SD values increased up to 20% by increasing the replacement level of coarse natural aggregate with RCA from 50% to 100%.



(a)

(b)

Fig. 6. PLI values of dry (a); and wet (b) cured mixes (W/B ratio = 0.4).

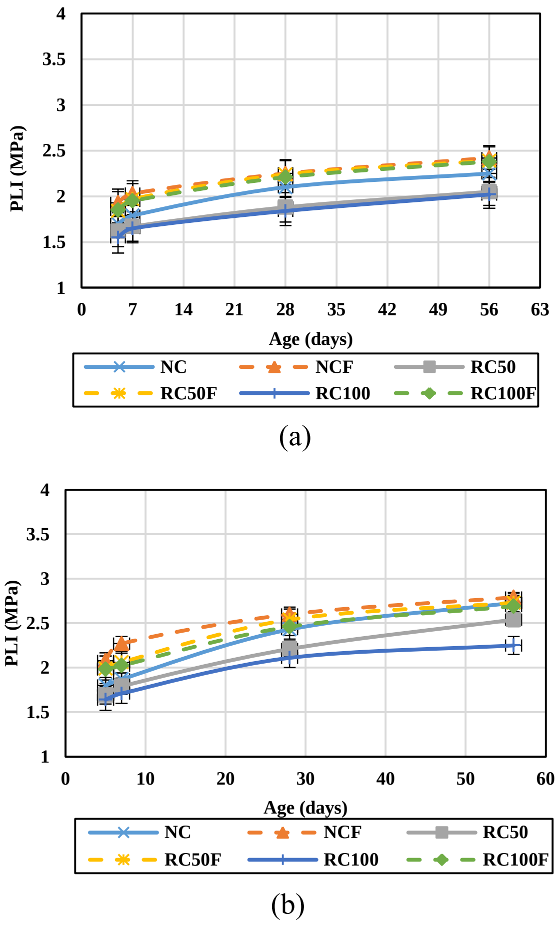


Fig. 7. PLI values of dry (a); and wet (b) cured mixes (W/B ratio = 0.55).

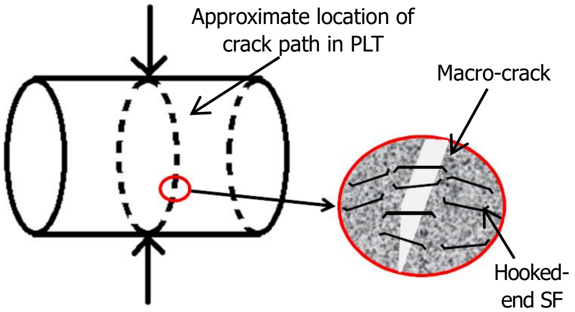


Fig. 8. SF bridging effect on the past-cracking behaviour of concrete in the PLT.

3.3.1. Relationship between PLI and compressive strength

To achieve reliable correlation curves with high coefficient factors (R^2) between PLI and compressive strength, in each case, the data of concrete mixes with and without superplasticizer was combined to each other. Therefore, 12 separate single-variable equations for different cases were proposed as shown in Fig. 9. Under dry curing regime, the equations of $f_c = 2.717PLI^{2.2156}$, $f_c = 2.9753PLI^{2.7073}$, $f_c = 3.591PLI^{1.949}$, $f_c = 4.6072PLI^{2.1507}$, $f_c = 3.1822PLI^{2.0917}$, and $f_c = 4.3835PLI^{2.2543}$ were proposed for NCF and NCSF, NC and NCS, RC100F and RC100SF, RC100 and RC100S, RC50 and RC50S, and RC50 and RC50F, respectively. The corresponding equations under wet curing regime were $f_c = 1.5303PLI^{2.4761}$, $f_c = 5.3684PLI^{1.926}$, $f_c = 1.8566PLI^{2.3248}$, $f_c = 6.5079PLI^{1.7094}$, $f_c = 1.7675PLI^{2.3906}$, $f_c = 5.9243PLI^{1.8255}$. As shown in Fig. 9, R^2 for all mixes were higher than 0.73, demonstrating a high reliability of single-variable equations between PLI and compressive strength. The general trend of these equations were found to be nearly similar to each other; however, the highest strength estimation was obtained using the equation proposed for NCS and NCSF mixes under wet curing regime, as expected. The contrary was obtained using the equation proposed for RC100 and RC100S mixes under dry curing regime.

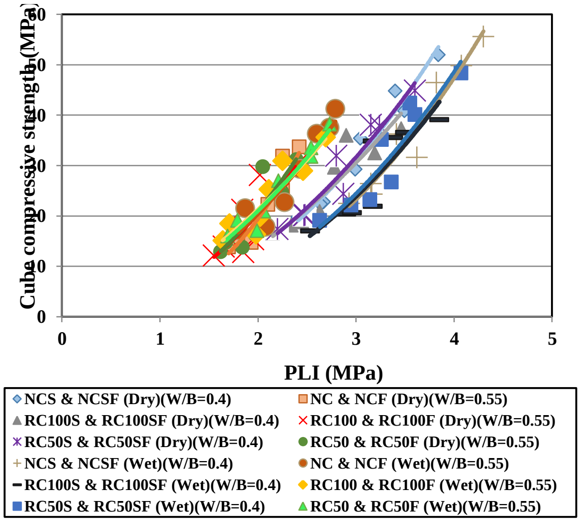


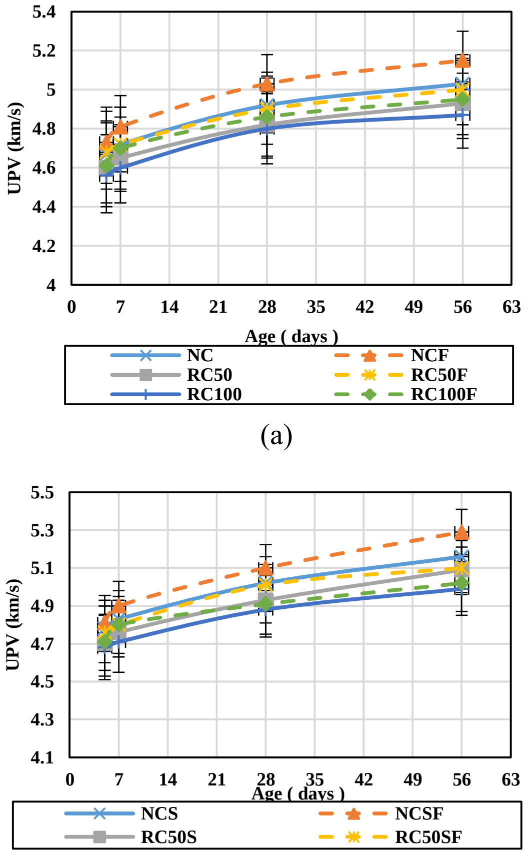
Fig. 9. Compressive strength and PLI correlation for recycled and natural aggregates with and without fibres.

3.4. UPV test

Figs. 10 and 11 show UPV values of concrete specimens made by SF and different replacement levels of natural aggregates with RCA at 5, 7, 28 and 56 days. The UPV ranges of mixes with the W/B ratio of 0.4 under dry and wet curing regimes were 4.56–5.15 km/s and 4.68–5.29 km/s, respectively. The corresponding ranges for mixes with the W/B ratio of 0.55 were 4.33-4.88 km/s and 4.43–4.92 km/s, respectively. The UPV value of the wet cured mixes with 100% incorporation of RCA and W/B ratio of 0.4 at 28 days was found to be 4.8 km/s, as shown in Fig. 10 (b). As reported by Soares et al. [2], this value was about 4 km/s.

According to the results, 100% substitution of coarse natural aggregate with RCA resulted in the reduction of UPV values up to the 4.1%. The corresponding value given by Soares et al. [2] was 5.4%. By considering the fact that the UPV shows the porosity of materials, it can be stated that the high porosity and macro-cracks of RCA led to obtaining low values of UPV for concrete mixes (Fig. 12). According to Fig. 10, for the W/B ratio of 0.4 under different curing conditions the highest and lowest UPV values were obtained for NCSF and RC100S, respectively. The corresponding values for the W/B ratio of 0.55 were obtained for NCF and RC100, respectively, as indicated in Fig. 11. Therefore, the SF content generated a strong bond in conjunction with the concrete matrix and compensated low mechanical strength of RCA in NCSF mixture.

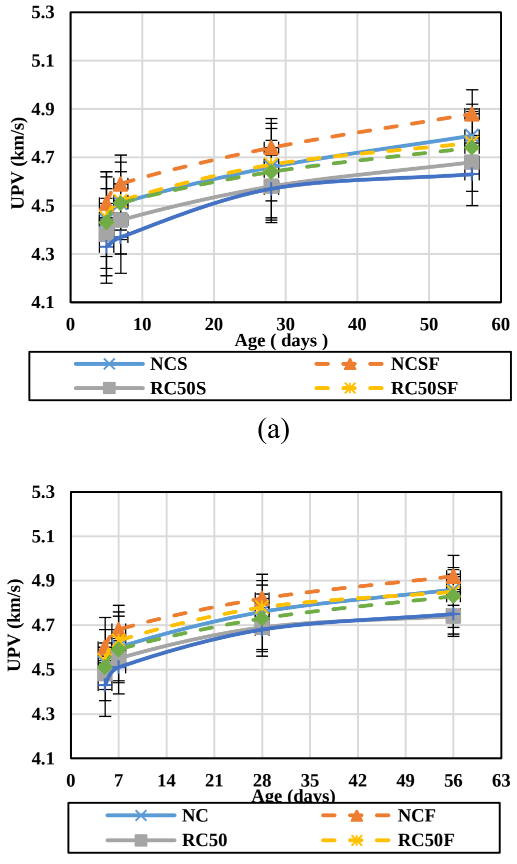
In the ultrasonic test, the SD value of the wet cured mixes with 100% incorporation of RCA and W/B ratio of 0.4 at 28 days was found to be 0.12 km/s. The corresponding value given by Soares et al. [2] was about 0.13 km/s. The ultrasonic waves propagate faster in the solid mass than liquids such as superplasticizer. By considering this, since the superplasticizer flowed among cement particles and aggregates to dissipate them more, the SD value of concrete specimens with superplasticizer was averagely obtained 23.5% more than that without superplasticizer. The SD value of the wet cured mixes was averagely scattered 25% lower than that of the wet cured mixes. SF content caused to dissipate SD values 19.2% more owing to the generation of air-voids in concrete specimens. Due to the high porosity of RCA, 50% and 100% replacements of RCA were associated with increasing the SD value of concrete mixes up to 20% and 41.2%, respectively. Therefore, an increase in the replacement level of natural aggregate with RCA from 50% to 100% caused an increase in SD values about 20%.



(a)

(b)

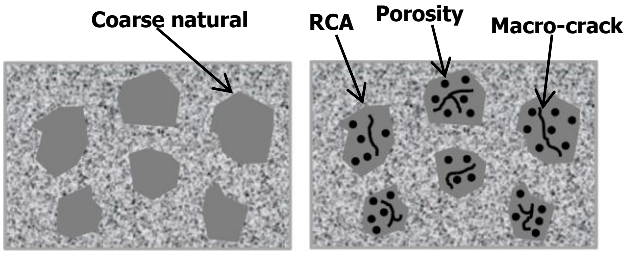
Fig. 10. UPV values of dry (a); and wet (b) cured mixes (W/B ratio = 0.4).



(a)

(b)

Fig. 11. UPV values of dry (a); and wet (b) cured mixes (W/B ratio = 0.55).



(a) (b)

Fig. 12. Scheme of aggregate natural concrete (a); and recycled aggregate concrete (b)

3.4.1. Compressive strength and UPV correlation

The results of concrete mixes with and without superplasticizer were combined to each other to obtain reliable correlation equations with high R^2 between UPV and compressive strength. So, 12 separate single-variable equations for different cases were proposed as indicated in Fig. 13. Under dry curing regime, the equations of $f_c=0.000005UPV^{9.9206}$, $f_c=0.000002UPV^{10.431}$, $f_c=0.000002UPV^{10.682}$, $f_c=0.000001UPV^{10.989}$, $f_c=0.0000004UPV^{11.617}$, and $f_c=0.0000004UPV^{11.707}$ were proposed for NCF and NCSF, NC and NCS, RC100F and RC100SF, RC100 and RC100S, RC50 and RC50S, and RC50F and RC50F, respectively. The corresponding equations under wet curing regime were $f_c=0.00001UPV^{9.2139}$, $f_c=0.0000005UPV^{11.46}$, $f_c=0.0000003UPV^{11.724}$, $f_c=0.000003UPV^{10.375}$, $f_c=0.000002UPV^{10.46}$, and $f_c=0.0000004UPV^{11.71}$. In all cases, R^2 were obtained more than 0.91. As depicted in Fig. 13, similar trends were observed among different correlation curves. However, the highest and lowest strength estimations were obtained for the equations proposed for NCS and NCSF mixes under wet curing regime and RC100 and RC100S mixes under dry curing regime, respectively, similarly to what occurred for the relationship between PLI and compressive strength.

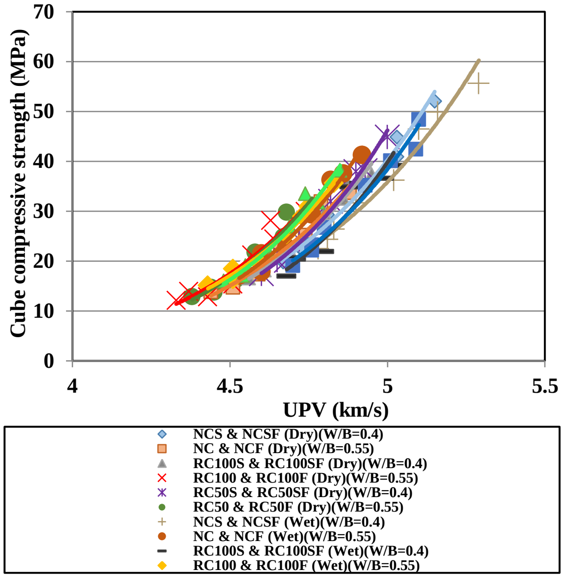


Fig. 13. Relationship between compressive strength and ultrasonic waves of recycled and natural aggregates with and without fibres in wet and dry curing conditions.

3.5. Two-variable equation between PLI and UPV values

A combination of the methods was used to propose a two-variable equation between PLI and UPV values and reliably estimate the cube compressive strength of concrete mixes. For each test, the total number of data was equal to 96. As presented in Table 5, among these, 12 data from each test was randomly chosen to check the reliability of the two-variable equation. The remaining data was employed to obtain the aforementioned equation with high R^2 of 0.92 using the combination of the methods as presented in Eq. 1.

$$f_c=-7.104PLI+70.67UPV-289.349 \qquad (1)$$

Table 5. Comparisons between measured and predicted in-situ cube strength.

No.	Concrete type	Measured cube strength (MPa)	Estimated cube strength		
			By PLT (MPa)	By UPV (MPa)	By the two-variable equation (MPa)
1	NCSF (Dry) (W/C=0.4)	44.8	40.9(8.7%)	45.6(1.8%)	42.1(6%)
2	NCF (Dry) (W/C=0.55)	14.7	17.6(19.7%)	13.3(9.5%)	15.6(6.1%)
3	RC100SF (Dry) (W/C=0.55)	18.2	18.8(3.2%)	24.6(35.1%)	19.8(8.7%)
4	RC100 (Dry) (W/C=0.55)	21.2	17.1(19.3%)	17.9(15.5%)	20.4(3.8%)
5	RC50S (Dry) (W/C=0.4)	31.9	27.4(14.1%)	34.4(7.8%)	31.4(1.6%)
6	RC50 (Dry) (W/C=0.55)	21.8	18.2(16.5%)	21.8(0%)	20.8(4.6%)
7	NCS (Wet) (W/C=0.4)	46.4	42.3(8.8%)	33.1(28.6%)	44.2(4.7%)
8	NCF (Wet) (W/C=0.55)	41.2	38.7(6.1%)	42.6(3.4%)	38.5(6.6%)
9	RC100SF (Wet) (W/C=0.4)	35.5	31.5(11.3%)	37.9(6.8%)	33.9(4.5%)
10	RC100F (Wet) (W/C=0.55)	19.8	21.7(9.6%)	22.1(11.6%)	20.6(4%)
11	RC50S (Wet) (W/C=0.4)	35.2	29.8(15.3%)	35.3(0.1%)	36(2.2%)
12	RC50F (Wet) (W/C=0.55)	31.8	32.5(2.2%)	36.1(13.5%)	30.4(%)

The strength estimations obtained by the PLT, ultrasonic test and the two-variable equation were compared to each other and the differences between them and the measured cube strength were expressed as percentages in parentheses as presented in Table 5. The estimated cube strengths by PLT and ultrasonic test were calculated using one-variable equations of correlation curves as seen in Figs. 9 and 13. The maximum difference between the results of the standard cube test and PLT was found to be equal to 19.7%. This difference was obtained 35.1% between the standard cube test and the ultrasonic test. However, the estimated strength by the two-variable equation had 8.7% difference with the results of the standard cube test at the most. So, it can be stated that although high coefficient factors (R^2) were obtained for all one-variable equations by PLT and ultrasonic method, the difference between the measured cube strength and estimated cube strength using the two-variable equation was lower than that by one-variable equations. Moreover, the two-variable equation between PLI and UPV values can be employed to reliably estimate either strength of convetional concrete or recycled aggregate concrete incorporating SF.

4. Conclusion

This paper aimed at estimating the compressive strength of steel fibre reinforced recycled aggregate concrete using PLT, ultrasonic test and the correlation between these two tests. The main conclusions are:

- Similarly to the PLT, the results of 10 cm cube specimens showed that for the W/B ratio of 0.4 under different curing conditions, the highest and lowest values of compressive strength were obtained for NCSF and RC100S, respectively. The corresponding values for the W/B ratio of 0.55 were obtained for NCF and RC100;
- The PLI of concrete samples with the W/B ratio of 0.4 was averagely 48.8 % higher than that with the W/B ratio of 0.55. In addition, the PLI value of the wet cured mixes was obtained averagely about 14.3% more than that of the dry cured mixes;
- In the PLT, the use of superplasticizer contributed to the enhancement of SD values up to 17.7%. The SD value of the wet cured mixes was averagely scattered 38.8% lower than that of the dry cured mixes. The SF caused to increase the SD values up to 20.7%. The PLI values of concrete mixes made with 100% substitution of RCA were dissipated

about 20% more than those with 50% substitution of RCA;

- According to the results of the ultrasonic method, the high porosity, and micro-cracks of RCA resulted in decreasing UPV values up to the 4.1% by 100% substitution of coarse natural aggregate with RCA;
- In the ultrasonic method, the use of superplasticizer increased the SD values averagely about 23.5%. The SD value of the wet cured mixes was on average about 25% lower than that of the wet cured mixes. SF content caused to dissipate the SD values 19.2% more. Moreover, an increase in the replacement of natural aggregate with RCA from 50% to 100% was associated with increasing the SD values up to 20%;
- The maximum difference between the outputs of the standard cube test and PLT was found to be equal to 19.7%. The corresponding value increased up to 35.1% between the standard cube test and the ultrasonic method. However, there was 8.7% difference at the most between the predicted strength using the two-variable equation and the results of the standard cube test. Therefore, the estimated strength by the two-variable equation was found to be more promising than that by single-variable equations and it seems that the correlation between PLI and UPV values can be employed to reliably estimate either strength of conventional concrete or steel fibre reinforced recycled aggregate concrete.

Conflict of Interest

None

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