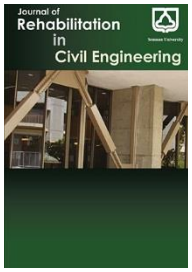

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Studying Tensile Strength of the Recycled Coarse Aggregate Concrete Using Double-Punch Test

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ARTICLE INFO

Article history:
Received: 14 May 2020
Revised: 18 December 2020
Accepted: 26 June 2021

Keywords:
Double-punch test (DPT);
Direct tensile test;
Splitting tensile test;
Recycled coarse aggregate (RCA);
Maximum aggregates̓ size.

ABSTRACT

Using the recycled materials, such as waste concrete aggregates can be considered as a suitable solution for resolving environmental issues. The recycled coarse aggregates (RCA) can be utilized effectively in manufacturing structural concretes. Due to hardness and errors of direct tensile and splitting tensile tests, double - punch test (DPT) can be regarded as a reliable test method for evaluation of tensile strength in concrete specimens. In this study, application of DPT was investigated as a less known test method for RCA concretes considering different effective factors, such as water–to-cement ratio (0.4, 0.5, and 0.6), maximum nominal size of RCA (10 and 19 mm), curing conditions (wet and dry), and replacement level of RCA (0, 50, and 100%) and the results were validated by direct tensile and splitting tensile test results. A statistical analysis was performed to indicate significance of each variable in DPT results of RCA concretes. Also, compressive strength and modulus of elasticity were assessed and their relationships with tensile strength of the specimens were studied. The maximum RCA size, replacement level of RCA, and mechanical properties were diminished in mixtures by increasing water-to-cement ratio. Generally, DPT results showed remarkable proximity to direct tensile test results with a slight increase. In wet curing condition, mean values of splitting tensile, DPT, and direct tensile tests in the specimens containing 19mm of RCA were 11.61, 10.06, and 9.44% higher than those containing 10mm of RCA, respectively. Moreover, results of statistical analysis showed that the studied factors had significant effects on the results and they must be regarded in evaluation of DPT.

How to cite this article:
Hemmmati Pourghashti, H., Madandous, R., Ranjbar, M. (2022). Studying Tensile Strength of the Recycled Coarse Aggregate Concrete Using Double-Punch Test. Journal of Rehabilitation in Civil Engineering, 10(3), 100-120. https://doi.org/10.22075/JRCE.2021.20395.1413

1. Introduction

For conserving resources and protecting the environment by reducing energy consumption, using the recycled aggregates, such as the recycled waste concrete or concretes of damaged structures instead of natural aggregates in concrete manufacturing is considered as an environmentally beneficial strategy all around the world [1]. Residual mortar around the recycled coarse aggregates (RCA) is the main factor in diminishing quality of the final product by decreasing density, increasing water absorption, and reducing abrasion resistance. It has been stated that when the amount of residual adhered mortar around RCA is less than 44%, it can be considered for utilizing of structural concrete elements [2]. Two methods are more recommended for recycling procedure including recycling in-situ and recycling in plant. Efficient method is chosen concerning the distance between source of waste material and recycling plant [3].

Brito and Robles [4] showed that using the recycled aggregates led to reduction of tensile strength, but diminishing rate was found to be less than that of compressive strength. Domingo et al., [5] reported that high replacement level of the recycled aggregates in concrete decreases workability, which may be related to characteristics of the recycled aggregates, such as shape, texture, and absorption. Hansen [6] found that compressive strength of the recycled aggregate concrete (RAC) is considerably changed by interaction effects of water–to-cement ratio (W/C) of the original concrete and W/C ratio of the RAC, when other influencing factors are considered constant, as confirmed in the research by Gesoglu et al., [7] who studied W/C ratios of 0.3 and 0.43. Sasanipour and Aslani [8] concluded that replacement of the recycled aggregates caused a decrease in compressive strength and it had a significant effect on tensile strength. Limbachiya et al., [9] reported that concrete specimens containing up to 30% of RCA showed similar compressive strength with those without RCA in W/C ratios more than 0.25. Muduli and Mukharjee [10] indicated that mechanical properties, such as compressive strength, splitting tensile strength, and flexural strength of RAC were decreased about 20, 15.2 , and 15%, respectively, using 100% of RCA in concrete. They also found that using up to 15% of Metakaolin in RAC can effectively modify the negative effect of RCA by increasing compressive strength up to 18%. Brand et al., [11] improved tensile strength of RCA concrete using 80-100% of the saturated aggregate. Other studies have illustrated a decrease in tensile strength in concretes containing 10% of the recycled aggregates when only coarse natural aggregates were replaced by RCA. In the case of replacement of both coarse and fine natural aggregates by the recycled aggregates, tensile strength was further dwindled up to 20% [12-14]. Angularity of the recycled aggregates is much lower than natural aggregates due to their production process, which may be a reason for adhesion reduction in aggregate/paste and eventually, weaker interfacial transition zone (ITZ) [15]. This phenomenon can be considered as an effective reason for reducing mechanical properties, especially tensile properties of RAC [16].

Uniaxial direct tensile test seems to be the most appropriate method for assessment of tensile strength in concrete specimens, but stability of test results requires a precise and controlled system. Direct tensile tests are difficult because of brittle nature of the concrete and inherent errors of this test. Thus, double-punch test (DPT) was presented by Chen [17] in 1970 to measure tensile strength of plain concrete. Prior to that, direct pull test or indirect methods, such as splitting tensile test (Brazilian test) or bending test were used to determine tensile strength. The main aim for introducing this test method was developing a reliable relation for calculation of tensile strength based on the theory of plasticity in concrete and Mohr-Coulomb (MC) failure criterion of surface. A significant merit of DPT compared to direct pull test is eliminating the problem of eccentricity of the applied load line in direct pull test [17]. Chen and Yuan [18] applied DPT to steel and polymer fiber-reinforced concretes (FRC). They compared the results of DPT with those of splitting tensile test. They concluded that DPT was a more reliable test method since DPT specimens failed at the weakest sections while split cylinder test specimens failed at a predetermined failure plane. Molins et al., compared experimental results between DPT and bending test [19] using various types and contents of fiber in FRCs. Their results showed that DPT provided more consistent results so that, coefficients of variation for peak and residual strengths were found to be smaller than those obtained from bending test. Carmona et al., [20] showed that the results of DPT can be used to determine properties of the concretes containing steel fibers, and the standard definition of toughness index was extended to assess the effects of fibers on the post-peak behavior with respect to matrix response. Choumanidis et al., [21] investigated mechanical behavior of FRCs containing single and hybrid fibers, using one type of steel and two types of polypropylene fibers at 0.5 and 1.0% of volume fractions at two temperatures of 20 and 280 ^{o}C using DPT. Their results illustrated that in single type fibers, tensile strength in DPT was decreased up to 37% at high temperature. This reduction was about 21% in hybrid type of fibers. Kim et al., [22] studied the factors influencing tensile properties of the concretes containing steel fibers at high temperatures. Their results showed that the tensile strength obtained by DPT was decreased along with fracture energy of the mixtures at high temperatures.

In this research, for the first time, tensile strength of RCA concretes is evaluated by DPT and the results are validated by direct tensile and splitting tensile tests. Experimental study and statistical analysis are performed and the effects of influential factors including W/C ratio, curing conditions, maximum RCA size ,and replacement level of RCA on different tensile strength tests are investigated. Also, compressive strength and modulus of elasticity of mixtures are obtained and their relationships with tensile strength of mixtures are studied.

2. Experimental framework

2.1. Materials

Typical commercial Type II Portland cement complying with the requirements of ASTM C150 [23] was used as testing cement with specific gravity of 3.15 and Blain specific surface area of 3165 cm^2/gr. The cement characteristics provided by the manufacturer are presented in Table1. Fine aggregate of the washed river sand was used with fineness modulus of 2.84 and specific gravity of 2.65. Coarse aggregates were obtained from natural crushed gravel with maximum sizes of 10 and 19 mm and specific gravity of 2.65. RCA with apparent density of 2460 kg/m^3 was obtained from waste concrete with a compressive strength ranging from 20 to 30 MPa in a concrete testing laboratory. It was crushed using a jaw crusher and was sieved to achieve the desired particle sizes of 4.75-10 and 4.75-19 mm. Fig. 1 shows gradation curves for natural and recycled aggregates used in this study as obtained through sieve analysis.

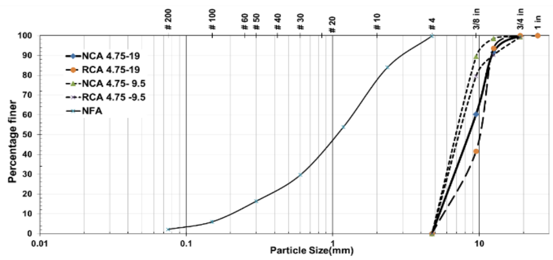


Fig. 1. Gradation curves of aggregates.

2.2. Concrete mixtures and preparation of specimens

In general, various parameters, such as W/C ratio, maximum size of RCA, curing conditions, and replacement level of RCA are selected for further investigation. Assessment of mechanical properties including compressive strength, direct tensile strength, splitting tensile strength, DPT, and modulus of elasticity is performed after 28 days.

Mixing proportions of natural coarse aggregate (NCA) and RCA concretes are presented in Table 2. Cement content was kept constant with a value of 400 and three W/C ratios of 0.4, 0.5, and 0.6 were used to evaluate the influence of this parameter. Two maximum sizes of 10 and 19 mm along with three replacement ratios of 0, 50, and 100%, as mass ratio of RCA to the overall coarse aggregate were considered in fabrication of the specimens. For each mixture, concrete specimens were cast and cured under laboratory conditions with relative humidity and temperature of 70% and approximately 25 ºC, respectively. The cast specimens were covered with polyurethane sheet and damped cloth in a 22 ± 2 ^{o}C chamber and they were left in casting room for 1 day. Then, they were de-molded and half of the specimens were transferred to moist curing room under 100% of relative humidity with the temperature approximately 20 ^{o}C. Remaining of the specimens was kept in a dry-air condition with relative humidity and temperature of 70% and approximately 25 ºC, respectively.

Table 1. Properties of the consumed cement.

Chemical properties	(%)
SiO_2	20.6
Al_2O_3	4.77
Fe_2O_3	3.37
CaO	63.38
MgO	2.18
K_2O	0.42
Na_2O	0.31
SO_3	2.32

Table 2. Mixing proportions of concrete (kg/m^3).

No	Mix	cement	water	Sand	natural gravel	recycled gravel
Maximum aggregate size of 10 mm						
1	C0.4(10)	400	160	825	990	0
2	C0.5(10)	400	200	775	930	0
3	C0.6(10)	400	240	730	876	0
4	R50C0.4(10)	400	160	825	495	467
5	R50C0.5(10)	400	200	775	465	439
6	R50C0.6(10)	400	240	730	438	413
7	R100C0.4(10)	400	160	825	0	934
8	R100C0.5(10)	400	200	775	0	877
9	R100C0.6(10)	400	240	730	0	826
Maximum aggregate size of 19 mm						
10	C0.4(19)	400	160	825	900	0
11	C0.5(19)	400	200	775	930	0
12	C0.6(19)	400	240	730	876	0
13	R50C0.4(19)	400	160	825	495	467
14	R50C0.5(19)	400	200	775	465	439
15	R50C0.6(19)	400	240	730	438	413
16	R100C0.4(19)	400	160	825	0	934
17	R100C0.5(19)	400	200	775	0	877
18	R100C0.6(19)	400	240	730	0	826

2.3. Description of the tests

Compressive strength test was performed on cubic specimens with dimensions of 15 cm according to BS EN 12390-3 [24] with loading speed of 0.3 MPa/s. Modulus of elasticity test was performed on cylindrical specimens with dimensions of 15×30 cm according to ASTM C469 [25]. It should be noted that for each mentioned parameter, three specimens were tested in each series and mean values were reported as the results.

Fig.2 shows preparation of the specimens for direct pull test. As can be seen in Fig.2, for direct pulling, the bars were pre-inserted into the specimens to apply a coaxial load. Direct tensile strength was measured in the universal test device using pre-mounted rebar in a 10×20 cm cylinder specimen at a speed of 2 mm/min (Fig. 2).

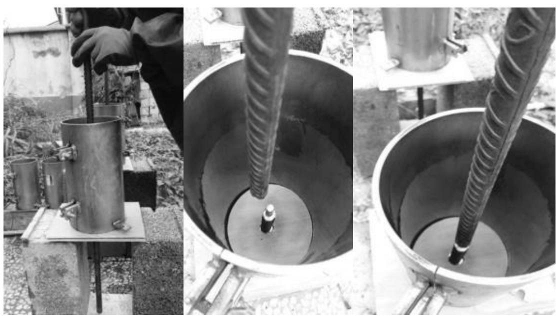


Fig. 2. Preparation of the specimens for direct tensile testing.

Splitting tensile test was also performed on 15×30 cm cylindrical specimens according to ASTM C496 [26]. For performing DPT, a concrete cylinder was placed vertically between loading platens of the machine and was compressed by two steel punches placed parallel to the top and bottom planes according to Fig.3.

Fig. 3. DPT specimen prior to the test.

Fig.4 shows failure modes, consisting of two or three major radial tensile cracks and longitudinal fracture plates as well as two cone-shaped fracture zones below the steel punches. After the fracture cone is formed beneath the steel punch, the stresses at the top of the cone extend toward sides of loading surfaces, resulting in complete failure of the concrete cylinder.

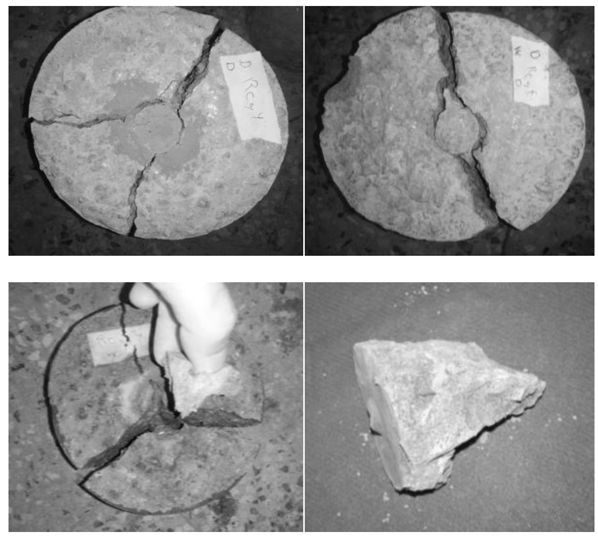


Fig. 4. Failure modes in DPT after failure.

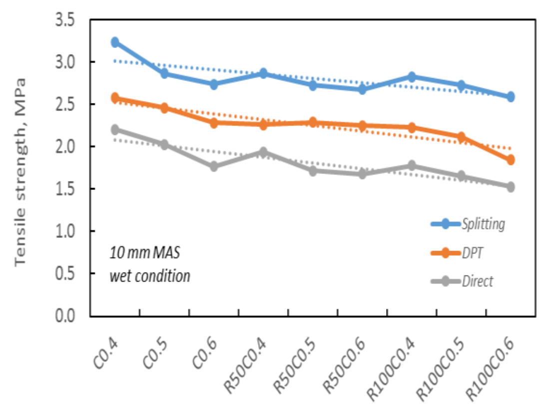
3. Results and discussion

As mentioned before, a variety of concrete tensile testing methods including direct pull test, indirect split cylinder test, and DPT have been used previously to evaluate tensile strength of RCA concretes. Herein, changes in mechanical properties with respect to the considered variables including W/C ratio, maximum size of aggregates, curing conditions, and replacement level of RCA are investigated. Statistical analysis of the considered variables is done regarding explaining the results and their significance level in DPT. Variations of the other measured mechanical properties including compressive strength and modulus of elasticity are also discussed.

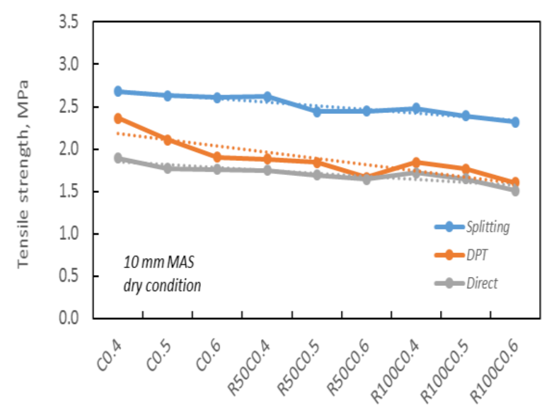
3.1. General variations of tensile strength

Fig.5 shows variations of tensile strength based on different methods. As demonstrated in Fig.5, tensile strength values of RCA concretes in different W/C ratios are presented for 10 mm of aggregate size and two types of curing conditions. Fig.5(a) illustrates the results of wet curing condition. Mean values estimated for splitting tensile strength in wet curing condition were found to be 26 and 54% more than those of DPT and direct tensile tests, respectively. Corresponding values for dry curing condition (Fig.5 (b)) were obtained as 33 and 44%, respectively. Interestingly, the DPT results were close to those of the direct tensile test. This may indicate higher capability of DPT in evaluating tensile strength of concrete rather than conventional split cylinder test method. However, further studies are strongly recommended to establish this finding. In this study, the increment in mean values of DPT with respect to direct pull test was obtained as 18.91 and 11.82% in wet and dry curing conditions, respectively, indicating importance of curing condition factor as a significant parameter. In fact, an advantage of DPT compared to splitting tensile test is that fracture surface is not known in advance and concrete can break through any arbitrary weakest fracture plane in contrary to splitting tensile test, in which fracture plane is predetermined and constrained. Therefore, this is the main reason for lower tensile strength of the DPT compared to splitting tensile strength test [17].

As can be seen from the figures, tensile strength was decreased by increasing replacement level of RCA and W/C ratio, independent of curing conditions. Brito and Robles [4] showed that the use of the recycled aggregates led to a decrease in tensile strength. However, reduction rate was lower than that of compressive strength. This result will be discussed more thoroughly in the next sections of the current paper. Domingo et al., [5] reported that greater consumption of the recycled aggregates reduced workability of the concrete, which could be due to properties of the recycled aggregates including shape, texture, and water absorption, which can ultimately influence resulting concrete properties.



(a)



(b)

Fig. 5. Tensile strength variations in different test methods for 10 mm of maximum aggregate size in (a) wet (b) dry curing conditions.

Fig.6 illustrates variations of tensile strength trends for 19 mm aggregates and two types of curing conditions. The overall trend was in line with 10 mm aggregates. However, lower values of tensile strength compared to 10 mm aggregates were quite evident. It also seems that slope of changes in tensile strength tests performed for wet curing condition is slightly milder than that of dry curing condition, but proximity of the DPT results to those of direct pull test can still be deduced. Mean values obtained for splitting tensile strength in wet curing condition were 24 and 47% higher than the DPT and direct tensile strength test, respectively. Corresponding values for dry curing condition were evaluated as 25 and 42%, respectively. In wet curing condition of the specimens containing 19mm RCA, mean values of splitting tensile, DPT, and direct tensile strength tests were 11.61, 10.06 , and 9.44% higher than those containing 10mm RCA, respectively. Moreover, in dry curing condition, the specimens contained 19mm RCA also showed higher mean values in splitting tensile, DPT, and direct tensile strength tests than those containing 10mm RCA with14.96, 6.18 , and 9.69% of increment, respectively. Reduction in mechanical properties of the concrete made by RA can be attributed to higher porosity and lower strength and density of RCA than natural materials. Also, angularity of RA is much lower than that of natural aggregates due to their production process, which may be a reason for lower effective adhesion of the aggregate/paste and eventually, weaker ITZ. This phenomenon can be considered as an effective cause in reduction of mechanical properties, especially tensile properties of concrete [18].

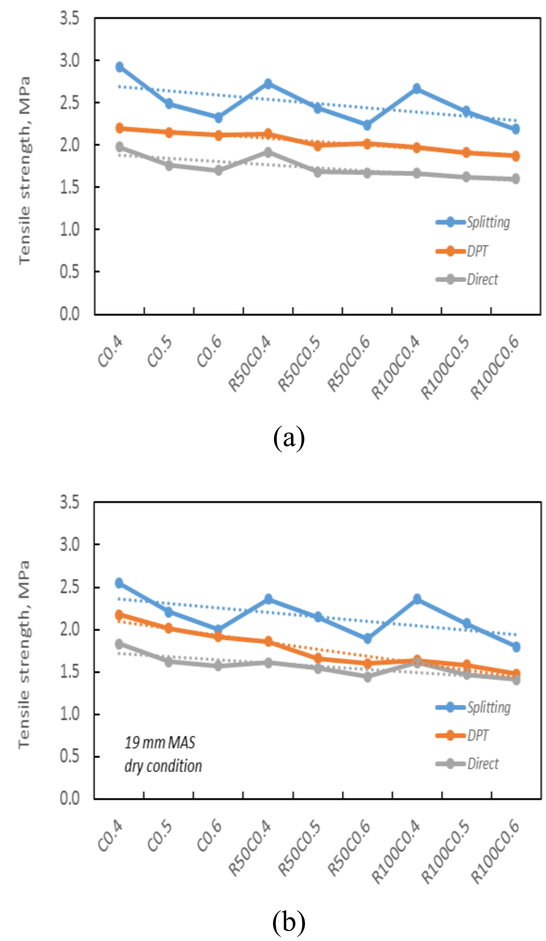
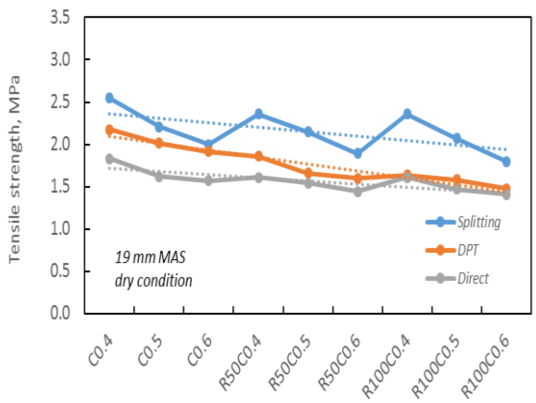


Fig. 6. Tensile strength variations in different methods for 19 mm of maximum aggregate size in (a) wet (b) dry curing conditions.

The general trend of tensile strength changes evaluated by different methods along with W/C ratios is shown in Figs. 7 and 8 for two aggregate sizes of 10 and 19 mm, respectively. According to these figures, increasing W/C ratio led to a decrease in the tensile strength. In dry curing condition, values of DPT and direct pull tensile strength tests were close to each other, regardless of the used RCA size. Moreover, increasing W/C ratio had a little effect on mean differences of results. In wet curing condition, the results of splitting tensile strength test were 9 and 39% higher than DPT and direct pull tensile strength tests for 10 mm RCA, respectively. Corresponding values for 19 mm RCA were found to be 15 and 31%, respectively. Due to significant changes, W/C ratio and maximum coarse aggregate size can be considered as effective factors in evaluating tensile properties of RCA concretes.



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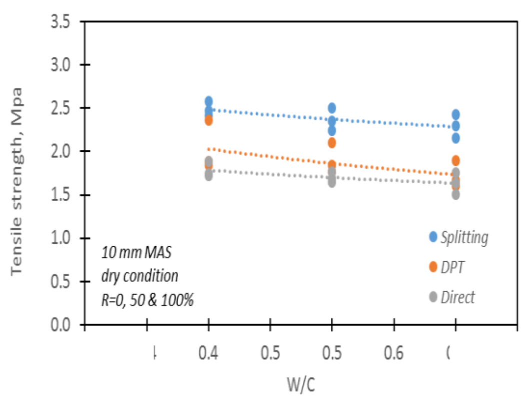
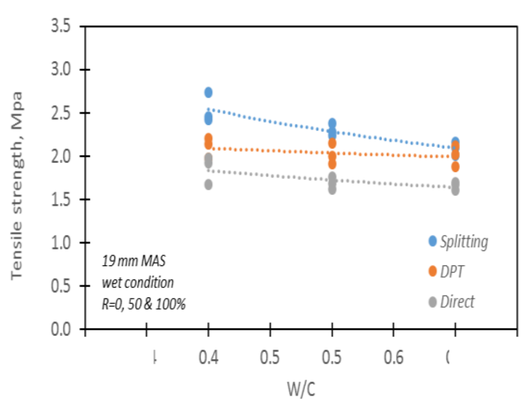


(b)

Fig. 7. Variations of tensile strength versus water-to- cement ratio for 10 mm of aggregate size in (a) wet (b) dry curing conditions.



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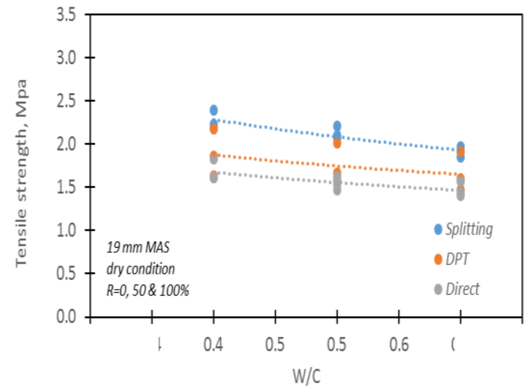
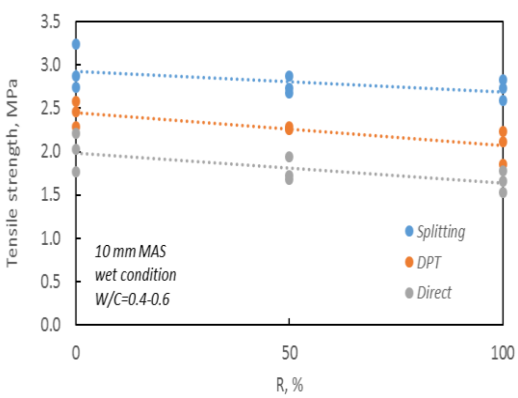


(b)

Fig. 8. Variations of tensile strength versus water-to- cement ratio for 19 mm of aggregate size in (a) wet (b) dry curing conditions.

The relationships between replacement levels of RCA, shown by R factor, and the results of different tensile strength tests, curing conditions, and maximum aggregate sizes are shown in Figs.9 and 10, respectively. The general trend of the results indicated a decrease in tensile strength by increasing replacement level. This effect appears to be greater for wet curing condition, as the difference in results for both aggregate sizes is more significant under this curing condition than dry curing condition. Based on the results, for R=50% and a maximum RCA size of 10 mm in wet curing condition, the increment in mean values of the splitting tensile strength test compared to those of DPT and direct pull tensile strength tests was equal to 16 and 47%, respectively. Corresponding values for 19 mm of aggregate size were found to be 15 and 43%, respectively. Proximity of the DPT results to those of the direct pull tensile strength test especially in dry curing condition was observed, independent of the maximum aggregate size. The difference between mean values of the DPT and direct pull tensile strength tests for R=100% was obtained as 4 and 3.8% for 10 and 19 mm of aggregate size, respectively. According to Xuping [27], uniaxial tensile strength is decreased by increasing replacement level. Also, when value of R does not exceed 20%, the effect of the recycled coarse aggregate replacement on tensile strength is negligible. The results of this study are also in accordance with the results of the study by Tam et al., [28] who reported that splitting tensile and flexural strengths were diminished up to 37 and 45%, respectively by increasing replacement level up to 100%, compared to natural aggregate concretes.



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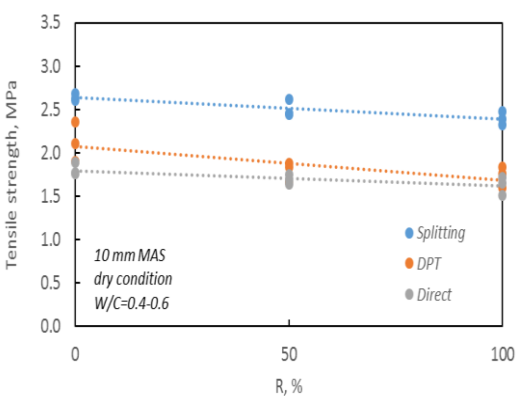

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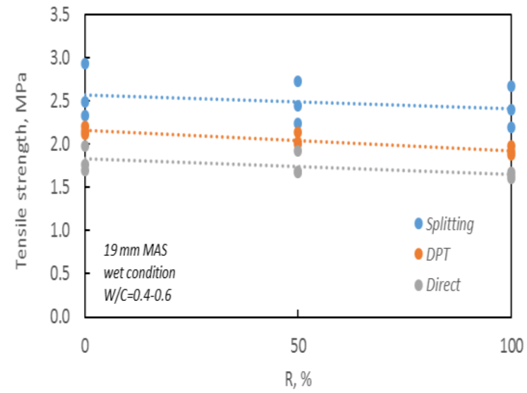
Fig. 9. Variations of tensile strength versus R for 10 mm of aggregate size in (a) wet (b) dry curing conditions.



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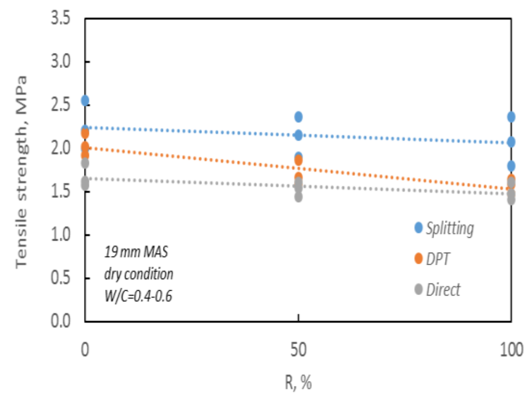
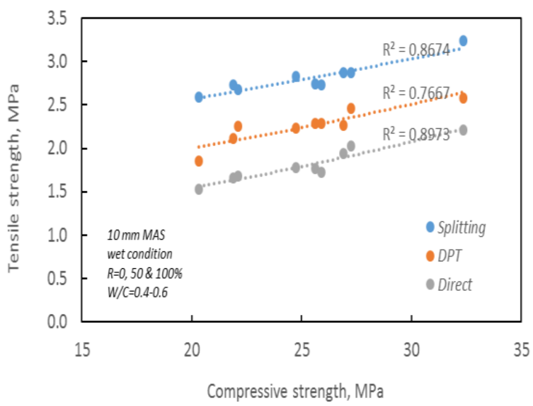


(b)

Fig. 10. Variations of tensile strength versus R for 19 mm of aggregate size in (a) wet (b) dry curing conditions.

Figs.11(a) and (b) show the results of different tensile strength tests in specimens with their corresponding compressive strength in dry and wet cuing conditions for mixtures containing 10mm RCA. This consideration was taken for 10 mm of aggregate size irrespective of W/C ratio and replacement level of RCA. According to the results, a significant correlation was found in the results. Also, in accordance with the previously stated trend, the results of the DPT were generally found to be closer to those of direct pull tensile strength test, especially for dry curing condition.



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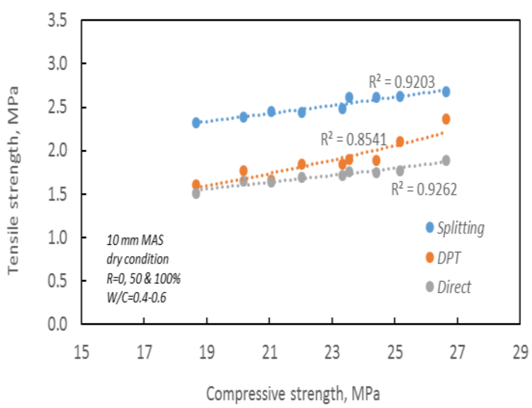
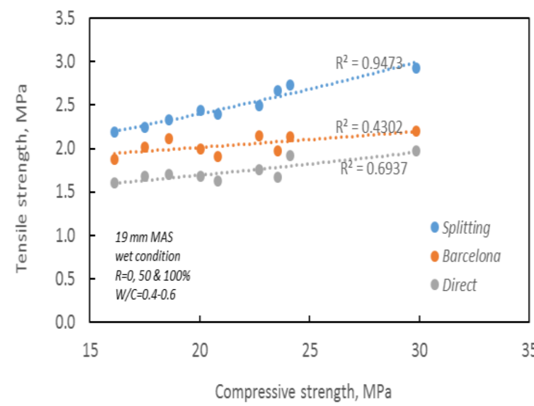


(b)

Fig. 11. Tensile strength variations with respect to compressive strength for 10 mm of aggregate size in (a) wet (b) dry curing conditions.

Fig.12 shows the results for 19 mm RCA. The results also showed a significant relationship between tensile strength and compressive strength values in splitting tensile and direct tensile strength tests. At lower values of compressive strength, the results of estimations were closer to each other, and the difference in results obtained by different approaches was increased by increasing compressive strength values, especially for the splitting tensile strength test. Also, lower correlation coefficient of the DPT results in all the fitted curves compared to other two methods may indicate that this test can be more influenced by other factors, such as replacement level of RCA or W/C ratio. In other words, particular attention should be paid to these factors as important causes of detour in evaluating the DPT results.



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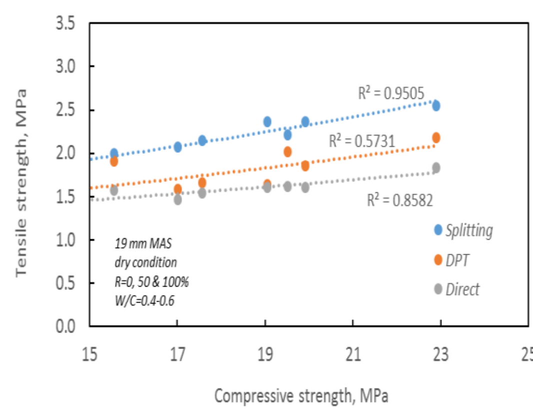


(b)

Fig. 12. Tensile strength variations with respect to compressive strength for 19 mm of aggregate size in (a) wet (b) dry curing conditions.

Fig.13 shows tensile strength correlations with compressive strengths for different methods of tensile strength tests regardless of W/C ratio, curing conditions, maximum aggregate size, and replacement level of RCA (R). As can be seen, correlation coefficient of the DPT was lower than the two other methods, based on a single variable equation, indicating importance of considering other influencing variables in such relations. Also, the overall correlation of the results can be considered as a sign of a significant relationship between DPT with other test methods.

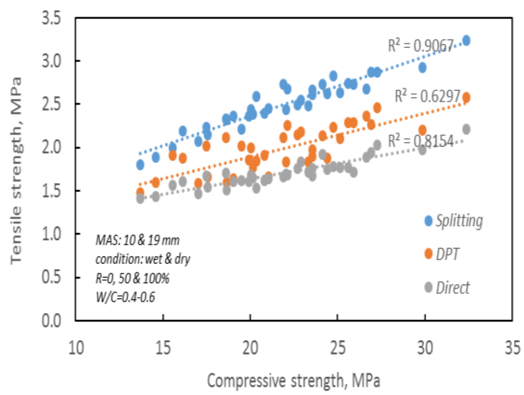


Fig. 13. Tensile strength variations with respect to compressive strength for different test methods.

3.2. Analysis of DPT results

In this research, for the first time, DPT method was performed on RCA concrete mixtures for evaluation of tensile strength and the results were compared with other tensile strength test methods and also the relationship of tensile and compressive strength of the specimens were studied. Also, importance of the factors influencing the results including W/C ratio, replacement level of RCA, maximum coarse aggregate size, and curing condition was investigated. In addition, statistical analysis was performed to evaluate significance of the considered parameters in order to have a better understanding in interpreting the results.

3.2.1. Experimental parametric study

Fig.14 shows the relationship between tensile strength obtained by DPT and compressive strength for different values of RCA replacement (R) regardless of other effective factors. As can be seen in Fig. 14, R plays an important role in more accurate evaluation of strength. In line with the previous findings, it seems that the effect of R for values above 50% may be negligible.

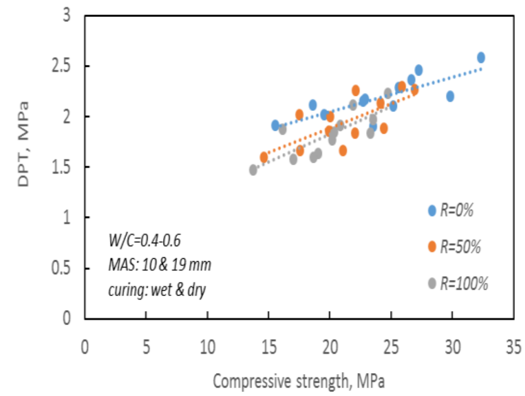


Fig. 14. Relationship between DPT and compressive strength for different values of R.

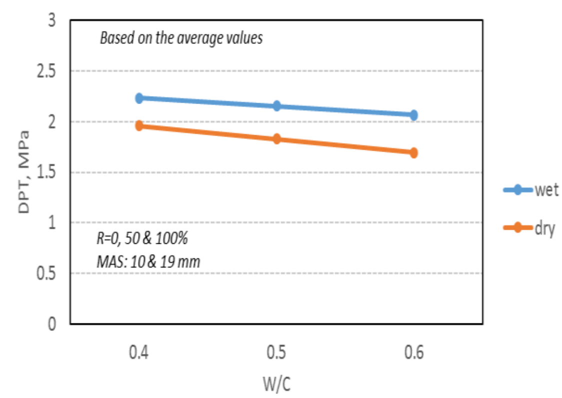


Fig. 15. The effect of curing conditions on the results of DPT.

Fig.15 shows the effect of curing conditions on mean results of the DPT for different W/C ratios regardless of the influence of other factors. As expected, an increase in the W/C ratio resulted in a decrease in the value of DPT. According to Fig.15 and based on mean values, this reduction was found to be 13.8 and 7.2% for dry and wet curing conditions, respectively. This result could also indicate more variability of DPT results in dry curing condition compared to wet curing condition.

Fig.16 demonstrates the influence of W/C ratio on the relationship between DPT and compressive strength, regardless of other influencing parameters. As can be seen, considering dispersion of the results, the effect of this parameter can be confirmed. Moreover, the necessity regarding considering other factors for more accurate explanation of the DPT results can be inferred.

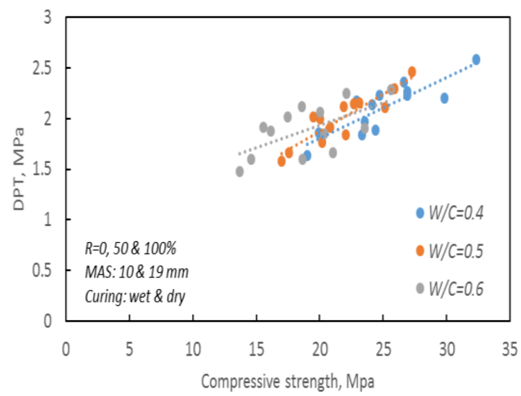


Fig. 16. The effect of W/C ratio on the relationship between DPT and compressive strength.

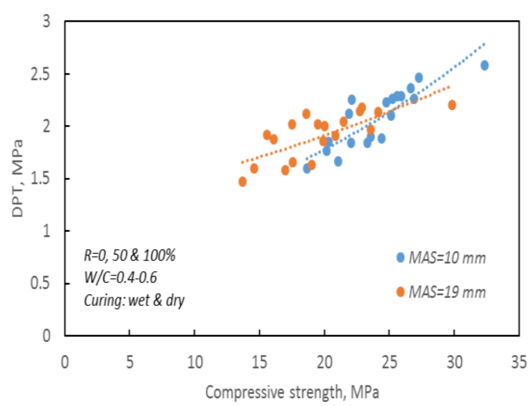


Fig. 17. shows the influence of maximum aggregate size on the relationship of tensile strength of DPT with compressive strength regardless of other parameters, such as replacement level of RCA, W/C ratio, and curing conditions. High dispersion of the results was observed around the fitted curves, which resulted in a decrease in the correlation coefficient. Also, in agreement with the previous findings, a higher correlation coefficient in mixtures containing 10 mm RCA than those containing 19 mm RCA was observed, confirming significance regarding considering aggregate size in explaining and interpreting the results of DPT.

Fig. 17. The effect of maximum aggregate size on the relationship between DPT and compressive strength.

Fig.18 presents mean values of DPT with respect to replacement levels of RCA for different maximum aggregate sizes and curing conditions. As can be observed, increasing values of R diminished the DPT values. So that, for wet curing condition, DPT values experienced a decrease of 15.3 and 10.7% for 10 and 19 mm RCA, respectively by increasing replacement level of RCA from 0 to 100%. Corresponding values for dry curing condition were found to be 19.1 and 23.5%, respectively. The results also indicated importance of curing condition in evaluation of DPT.

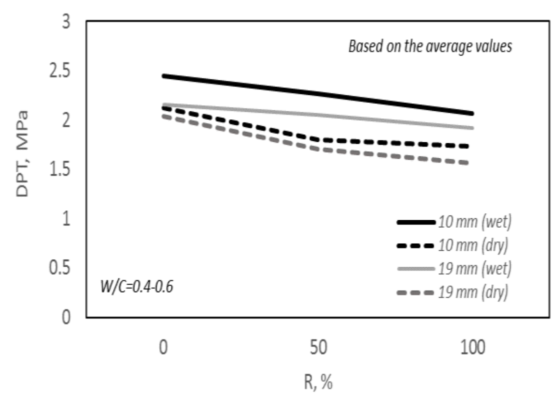


Fig. 18. Variation of DPT results with respect to R for different aggregate sizes and curing conditions.

3.2.2. Statistical analysis

The major goal in statistical analysis is forming a structure of statistical models capable of reflecting significant aspects related to the aim of investigation with some degrees of realism. The goal of regression analysis is determining mathematical models that explicate the relationships that may exist between variables [29]. In this section, a linear equation is provided for prediction of DPT results as a function of influencing parameters, such as W/C ratio, maximum size of coarse aggregate (MSCA), replacement level of RCA ,and curing conditions. Namely, the specimens involving these parameters were regarded as explanatory (independent) variables and DPT value was regarded as response (dependent) variable. It can be stated that in dealing with a large number of independent variables, it is important to derive the best combination of these variables in order to predict dependent variable. So, DPT may be expected to be reasonably related to the aforementioned variables by the following type of equation:

$$\varphi\left(\frac{W}{C}, MAS, Curing, RCA, DPT\right) = 0 \qquad (1)$$

The response variable y may be related to k regressor variables. The model $y = \beta_0 + \sum_{1}^{k} \beta_i x_i + \varepsilon$ is named as a multiple linear regression model with k regressor variables. The model explains a hyperplane in k-dimensional space of the regressor variables. The least squares method is commonly used to estimate regression coefficients, $\beta_i, i = 0,1,...,k$, in a multiple linear regression model [29]. SPSS (statistical package for the social sciences) software was utilized for model definition.

Table 3 presents the results regarding significance of regression coefficients in DPT estimation. Also, standardized regression coefficients, Beta, t-value (at the 95% confidence level), and Sig (p)-value were indicated.

The effect of each predictor variable, in which a high absolute t-value and small p-value (< 0.05) are observed, can be defined by t and Sig. (p) values. Predictor variables with p-value of less than 0.05 at 95% confidence level are considered to be important in model.

Table 3. Significance of regression coefficients.

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig. (p)
		B	Std. Error	Beta		
1	(constant)	2.820	0.103		27.308	0.00
	MAS	-0.18	0.003	-0.314	-5.765	0.00
	Curing	0.325	0.029	0.613	11.279	0.00
	Wtoc	-1.083	0.176	-0.334	-6.140	0.00
	RCA	-0.004	0.000	-0.568	-10.438	0.00

a. Dependent Variable: DPtest

As mentioned above, according to Table 3, all the variables were significantly effective and should be considered in the final equation to estimate the DPT results. This result was previously and implicitly confirmed in experimental parametric analysis.

In general, coefficient of determination between the measured and predicted values is a good indicator to check prediction performance of the model. Higher value of R^2 means that there is a good correlation between the experimentally measured values and the predicted values using the developed models. As the number of independent variables is increased, R^2 will be greater. Therefore, R^2 should be adjusted (R^2_{adj}).These error estimation parameters, on the basis of model performance are presented in Table 4. Statistical evaluation of the results proved the accuracy gained by the proposed relationships so that, around 91% of variation in response value can be described by the fitted model.

Table 4. Determined coefficients in the developed linear regression model.

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.953	0.908	0.896	0.08644

a. Predictors: (Constant), RCA, WtoC, Curing, MAS

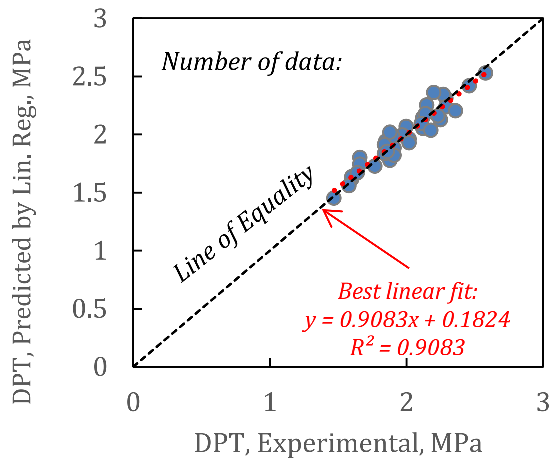


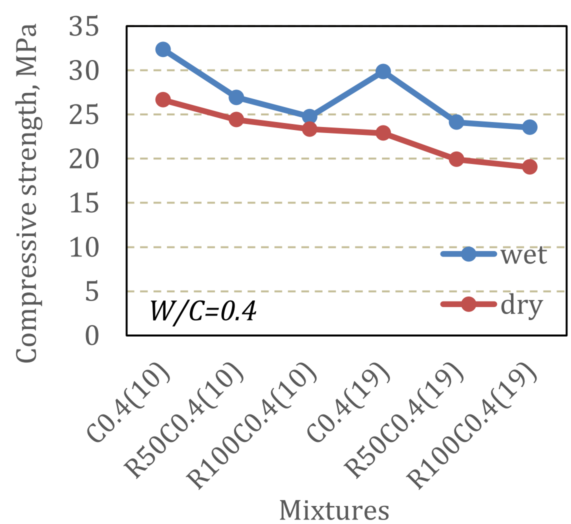
Fig. 19. Performance of linear regression model on estimation of DPT results.

Fig.19 presents good accuracy of the linear regression model, demonstrating reliability of the defined model for estimation of DPT results. As can be seen, a large part of the real and predicted values are generally close and congregated near the line of equality.

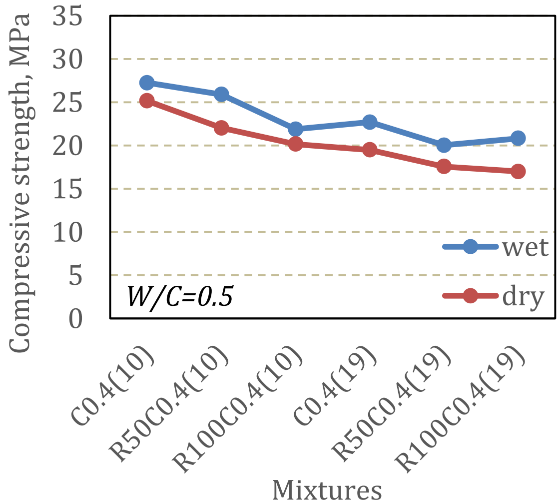
3.3. Discussion on other mechanical properties

3.3.1. Compressive strength

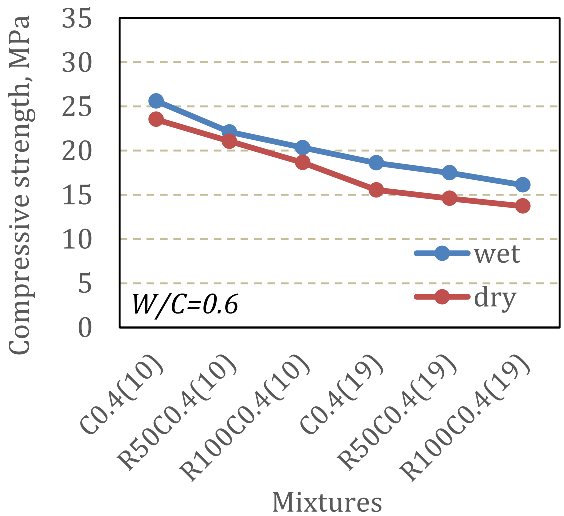
Fig.20 shows the curves regarding compressive strength variations of different mixtures with respect to maximum RCA sizes, replacement levels of RCA (0, 50, and 100) ,and types of curing conditions at different W/C ratios. As can be observed, compressive strength values were diminished by increasing replacement level of RCA and aggregate size, independent of curing condition and W/C ratio. However, the results showed that the difference in compressive strength values for two curing conditions has a tendency to decline by increasing W/C ratio. In other words, the results were less sensitive to curing condition by increasing W/C ratio. So that, the difference in results for specimen C0.4 (10) was obtained as 5.72 and 2.07 MPa for W/C ratios of 0.4 and 0.6, respectively. Corresponding values were found to be 6.93 and 3.05 MPa for 19 mm of aggregate size, respectively. Hansen [6] reported that compressive strength of the recycled aggregate concrete was significantly influenced by W/C ratio of the initial recycled concrete and consequently, W/C ratio of the recycled aggregate, while other effective parameters were assumed to be constant. This may be due to the fact that reduction of W/C ratio in the presence of the recycled aggregates results in an increase in the specific gravity of the concrete, which may lead to the increase in the strength, modulus of elasticity, and other mechanical properties of the concrete [2].



(a)



(b)

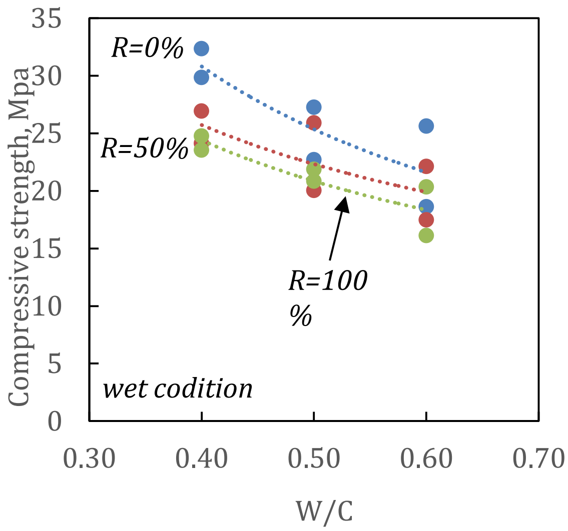


(c)

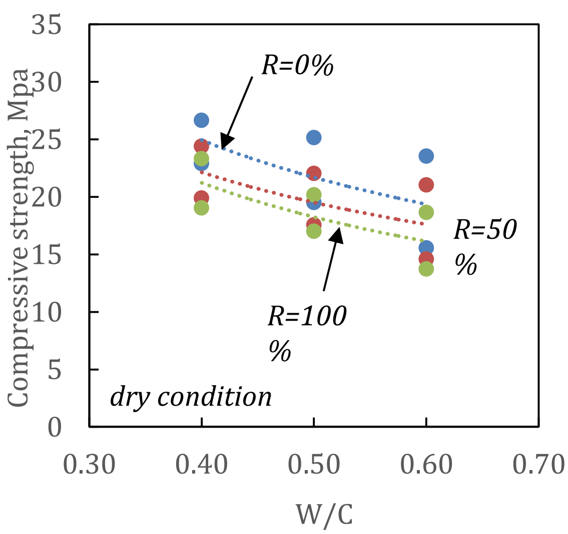
Fig 20. Changes in compressive strength for different mixtures in two types of curing conditions for (a) W/C=0.4, (b) W/C=0.5 (c) W/C=0.6.

Fig.21 presents variations of compressive strength at different W/C ratios in wet and dry curing conditions for different replacement levels of RCA, regardless of the effect of maximum RCA size. As shown in Fig.21, the effect of R had a tendency to decline for higher values of W/C ratio. So that, the trend of graphs revealed less difference at W/C = 0.6 than W/C = 0.4. This result is more evident for wet curing condition. It can also be noted that at replacement level of R=50%, changes in compressive strength results were not noticeable. However, confirmation of this finding requires further study and investigation of more relative proportions. These results are in line with the previous studies. Xiao et al., [31] studied the use of the recycled coarse aggregates in ratios up to 100% and found that in replacement ratios up to 30%, reduction in compressive strength was not significant compared to natural aggregate concretes. Also, Limbochiya et al., [32] showed that the specimens made by replacing up to 30% of RCA had similar strengths for W/C ratios greater than 0.25.

According to the figure, mean compressive strength of the specimens containing 0% of RCA was 31 and 23% higher than those containing 100% of RCA at W/C=0.4 and W/C=0.6 in wet curing condition, respectively. Corresponding values in dry curing condition were approximately 16 and 21%, respectively. Sasanipour and Aslani [8] found that increasing replacement level of RCA resulted in a decrease in compressive strength while its effect on reduction of tensile strength was found to be insignificant. Froudinstou-Yannas [33] stated that the mixtures containing 100% of RCA showed about 76% of compressive strength compared to natural aggregate concretes. Furthermore, Majhi et al., [34] indicated that the decrease in the compressive strength of concrete containing 100% of RCA on 7, 28, and 90 days was equal to 43.6, 36.5 ,and 25.5%, respectively, compared to compressive strength of the control concrete mixture on corresponding days in the presence of 60% ground granulated blast furnace slag. According to the literature [35], this is probably because of high porosity of the recycled coarse aggregates and poor bonding of the previous cementitious layer on the recycled aggregates to new paste, ultimately leading to a weaker ITZ and bonding of the recycled aggregate/paste compared to the concretes made by natural aggregates (R=0).



(a)



(b)

Fig. 21. Compressive strength variations with respect to W/C ratios in (a) wet and (b) dry curing conditions for different values of R.

Fig.22 demonstrates the variation trends of compressive strength results according to W/C ratios in different curing conditions and maximum sizes of RCA, irrespective of replacement level of RCA. Compressive strength of the specimens containing 10 mm RCA was found to be higher than that of 19 mm RCA, as observed for both curing conditions. Also, in accordance with the above mentioned trend, the difference in compressive strength results of the specimens in dry and wet curing conditions tended to decrease by increasing W/C ratio, for each size of the recycled coarse aggregate. However, this was more prominent in the mixtures containing 10 mm RCA. So that, compressive strength in wet and dry curing conditions was found to be 1.07 and 1.2 for mixtures containing 10 and 19 mm RCA, respectively, based on the overall trend of changes.

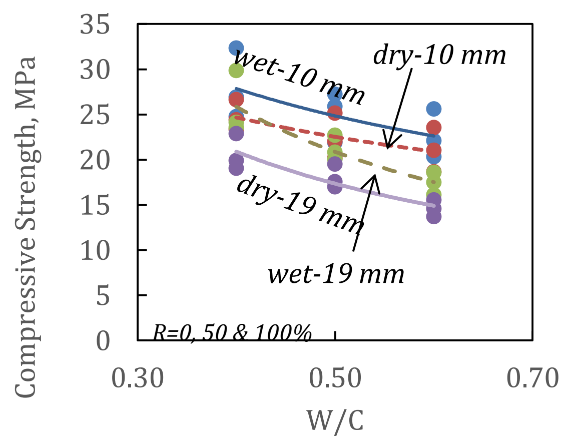


Fig. 22. Compressive strength variations with respect to W/C ratio for different curing conditions and maximum sizes of the recycled coarse aggregate.

3.3.1. Modulus of elasticity

Fig.23 shows the significant relationship between compressive strength results of RCA concretes and their modulus of elasticity. It is noteworthy that the results were obtained regardless of curing conditions, maximum aggregate sizes, and W/C ratios. Interestingly, values of modulus of elasticity obtained for 50 and 100% of RCA were closely related. In other words, it can be claimed that there is no significant change in the relationship between modulus of elasticity and compressive strength for RCA replacement levels greater than 50% in the specimens. Concerning this, Zhao and Duan [36] stated that modulus of elasticity of RCA concrete was lower than that of normal concrete, and this phenomenon was attributed to the influence of weakness of RCA in ITZ. They stated that the recycled aggregates not only have higher porosity and lower density than natural aggregates, but also they inherently have micro-cracks. Therefore, these phenomena could be the main reason for lower modulus of elasticity of RACs.

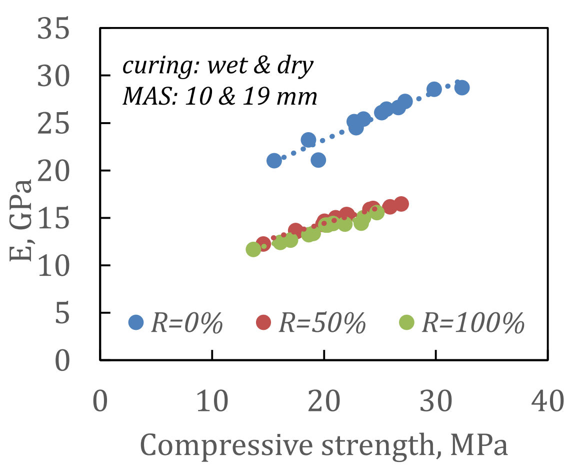


Fig. 23. Relationship between compressive strength results of RC and modulus of elasticity for different replacement levels of RCA.

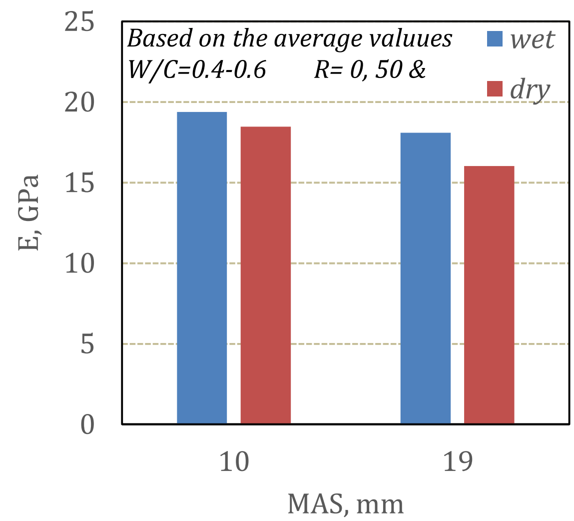


Fig. 24. The effect of the recycled coarse aggregate size on modulus of elasticity.

Fig.24 shows the results regarding the effect of maximum RCA size on modulus of elasticity for two types of curing conditions. It seems that this parameter can also play an important role in quantitative evaluation of modulus of elasticity of RCA concretes. This effect was also found to be more intense in the mixtures containing 19 mm RCA, as the difference between mean values in dry and wet curing conditions was obtained as 5 and 13.1% for maximum aggregate sizes of 10 and 19 mm, respectively.

4. Conclusion

In this study, a variety of concrete tensile testing methods including direct tensile, splitting tensile strength, and DPT tests were used to evaluate tensile strength of the RCA concretes. Also, compressive strength and modulus of elasticity of the mixtures were obtained. Variations of the experiments and their relationships were studied in terms of different effective variables. In addition, statistical analysis of the variables was performed for more thorough assessment of DPT results and significance of effective parameters was also evaluated. The following conclusions can be drawn from results of this investigation:

- DPT results were verified by direct tensile and splitting tensile strength tests on the specimens and proximity of DPT results with those of direct tensile strength test was observed. The results were more similar in dry curing condition.

- Mean values of DPT in the specimens were 18.91 and 11.82% higher than direct tensile strength test in wet and dry curing conditions, respectively, indicating importance of curing condition factor as a significant parameter.

- Correlation coefficient of the DPT, based on a single variable equation was lower than two other test methods showing the need for considering all the effective variables in this test.

- Increasing W/C ratio diminished the results of DPT. This reduction rate was equal to 13.8 and 7.2% for dry and wet curing conditions, respectively.

- In wet curing condition, mean values of splitting tensile, DPT, and direct tensile strength tests in the specimens containing 19mm RCA were 11.61, 10.06, and 9.44% higher than those containing 10mm RCA, respectively. Corresponding values in dry curing condition were equal to 14.96, 6.18, and 9.69%, respectively.

-Based on the results, increasing replacement level of RCA led to reduction in DPT results, which was more intense in wet curing condition. For R=50% and a maximum RCA size of 10 mm in wet curing condition, the increment in mean values of splitting tensile strength test compared to DPT and direct tensile strength tests was equal to 16 and 47%, respectively. Corresponding values for 19 mm RCA were equal to 15 and 43%, respectively.

- Compressive strength was diminished by increasing replacement level of RCA and aggregate size, independent of curing condition and W/C ratio. In wet curing condition, mean compressive strength of the specimens containing 0% of RCA was 31 and 23% higher than those containing 100% of RCA at W/C=0.4 and W/C=0.6, respectively. Corresponding values in dry curing condition were equal to 16 and 21%, respectively.

-The results indicated that increasing the maximum RCA size can make the mixtures more sensitive to curing condition. The difference between mean values in dry and wet curing conditions was obtained as 5 and 13.1% for maximum RCA sizes of 10 and 19 mm, respectively.

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