Mechanical properties of roller compacted concrete containing recycled concrete aggregate

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Abstract
The compressive strength, splitting tensile strength, pulse velocity and drop weight impact resistance of roller compacted concrete (RCC) mixtures containing recycled concrete aggregate (RCA) were investigated. The cement contents of the RCC mixtures were chosen as 150, 200 and 250 kg/m^3. In addition to the control mixtures containing no RCA, 25, 50, 75 and 100 wt% of the crushed limestone aggregate was replaced with RCA. In this way, 15 RCC mixtures were prepared. The water content of RCC mixtures was determined by the maximum density method. The results showed that increasing the amount of recycled aggregate decreased the mechanical properties of the concrete. However, up to 25% replacement level, recycled aggregate had not a significant detrimental effect on the properties of RCC. Besides, the detrimental effect of RCA substitution was more pronounced in leaner mixtures and reduced by increasing the cement content of the RCC.

Keywords: roller compacted concrete, recycled aggregate, cement dosages, optimum water content, mechanical properties.

Introduction

In recent years, urban renewal programs in Turkey implemented huge concrete waste. Using these wastes as recycled aggregate in roller compacted concrete (RCC) is one of the possibilities to reduce the difficulties arises from their deposition. As a result of the demolition of old structures, large volume concrete waste is emerging and large field is needed to store them. Due to the increase of environmental awareness, the concrete waste storage is a major problem in large cities of Turkey. One of the main purposes in the protection of natural life is the recovery and utilization of waste in a way that reduces the use of natural resources. Metal-based construction wastes are easily distinguished and recycled. On the other hand, concrete wastes are poured into agricultural areas or storage areas as rubble and stored. It is possible to separate these wastes from other construction wastes and to be broken into aggregate. Re-use of this type of recycled concrete waste aggregate in concrete production will reduce the environmental damage of these wastes and the consumption of natural aggregate. The decrease or depletion of natural resources over time, the distance of existing resources from their usage areas increases the interest in recycling of construction waste. The fact that most of the buildings that have been demolished or will be demolished during the urban transformation process are reinforced concrete, will allow the waste to be obtained from these to be used instead of aggregate in concrete. Therefore, it is also very important to encourage the use of such recycled concrete aggregates in the production of low strength concrete like RCCs to use them in road concrete.

The rapid urbanization and increased population made cause rapid consumption of natural resources and reduce their sustainability. Therefore, waste materials recycling is very important in terms of the preservation of the natural resources. Now a days, in order to reduce the above mentioned distress waste aggregates recycled from old concrete or old asphalt concrete mixtures are used in concrete in some countries (Gürer, 2004). The effect of recycled asphalt concrete aggregate and waste rubber particles on the properties of RCC have been studied by many researchers (Courard et. al., 2010; Fakhri, 2016; LaHucik et al. 2017; Meddah et. al., 2014; Modarres et. al., 2014; Settari et. al., 2015). Besides, there are various studies on the effect of coarse recycled concrete aggregate (RCA) on the properties of conventional portland cement concrete. It was found that replacement of natural coarse aggregate with RCA at levels up to 30 wt% had no significant detrimental effect on the strength of concrete. However, beyond 30 wt% replacement level, a considerable reduction in the strength of RCA-bearing mixtures, compared to that of the control mixture, was reported (Peng et. al., 2013; Muscalu et. al., 2011; Rao et. al., 2011; Etxeberria et. al., 2007; Paul et. al., 2013; Sonawane et. al., 2013).

Debieb et. al. (2009), produced RCA from laboratory made 40 MPa strength concrete containing crushed limestone aggregate having 20 mm maximum size (D_{max}) and an average specific gravity around 2.7. The RCA thus produced, had a 20 mm D_{max}, an average specific gravity of 2.3 and absorption capacity of 9.2%, 4.9% and 6% for 0/4, 4/14 and 14/20 mm, size fractions, respectively. RCC mixtures having a cement content of 250 kg/m^3 were prepared either with natural crushed limestone aggregate or 100% replacement of natural aggregate with RCA. The w/c ratio of the control mixture (0.38), was somewhat higher than that of the RCA-bearing mixture (0.32). In spite of having a lower w/c ratio, RCA-containing mixture showed 30%, 56% and 32% lower compressive strength, splitting tensile strength and modulus of elasticity, respectively, compared to those of the control mixture (Debieb et. al., 2009).

Lopez-Uceda et. al. (2016), investigated the mechanical properties of RCC containing RCA obtained from a construction and demolition waste plant. The RCA had an SSD density of 2.51 g/cm^3, water absorption of 4.69% and maximum particle size of 31.5 mm. Four series of RCC mixtures having 110, 175, 250 and 350 kg/m^3 cement contents were prepared. In addition to the control mixture containing no RCA, 50 and 100 vol% of the coarse natural aggregate was replaced with coarse RCA. For a given workability, the water requirement of RCA-bearing mixtures was found to increase by increasing RCA substitution level, reaching to around 122% that of the control mixture. Depending on the cement content, the 28-day compressive strength of RCC mixtures was found to be in the range of 5.4 to 34.5 MPa. The corresponding range for flexural strength was 1.0 to 5.4 MPa. The RCA-bearing mixtures were reported to have a higher rate of compressive strength development beyond 28 days than the corresponding control mixtures. Compared to that of the control mixtures, the average reduction in 28-day splitting tensile strength was in the range of 8-15% in 50% RCA-bearing (RCA50) mixtures and 13-27% in 100% RCA-containing (RCA100) mixtures. The corresponding values for the reduction in 28-day flexural strength were around 18% and 24%, respectively; which were very close to the average reduction in 28-day elastic moduli values upon RCA substitution (19% for RCA50 and 28% for RCA100 mixtures) (Lopez-Uceda et. al., 2016).

Jalilifar et. al. (2020) investigated the durability of concrete containing coarse recycled concrete aggregate as well as silica-fume and natural zeolite. For this purpose, four series of RCC mixtures were prepared. In these mixtures 0%, 25%, 50%, and 100 wt.% of natural coarse aggregate (NCA's) were replaced with RCA. Besides, cement replaced with 5%, 10%, and 15 wt.% silica fume or 10%, 20%, and 30 wt.% of zeolite. The 28-day compressive strength, water absorption by immersion, water suction, and rapid chloride ion penetration properties were investigated. The water absorption and water suction of the mixtures increased by increasing coarse RCA level. The RCC mixture containing 10% silica fume showed the highest compressive strength. Besides, RCC`s incorporating natural zeolite had higher water absorption than that of silica fume-bearing mixtures. The RCC mixture containing 25% RCA and 10% silica fume showed the lowest chloride ion penetration depth (Jalilifar et. al., 2020).

In this study, the mechanical properties of 15 RCC mixtures containing 150, 200 and 250 kg/m^3 cement as well as 25, 50, 75 and 100% coarse recycled aggregate (replaced with crushed limestone coarse aggregate) were investigated.

Materials

In the experimental study, a CEM II/A-M (P-L) 42.5R cement was used. The chemical composition, physical properties and compressive strength of the cement are given in Table 1.

Table 1. Chemical composition, physical and mechanical properties of cement. (Self-Elaboration).

Chemical composition	(%)
SiO_2	21.68
Al_2O_3	6.43
Fe_2O_3	2.43
CaO	57.99
MgO	1.36
Na_2O	0.36
K_2O	1.08
SO_3	2.987
Loss on ignition	5.18
Cl	0.0095
Insoluble residue	7.83
Free CaO	0.83
Physical properties	(%)
Specific gravity	3.12
Blaine specific surface (cm^2/g)	4535
Initial setting time (min.)	175
Final setting time (min.)	225
Compressive strength (MPa)	(%)
1-day	14.4
2-day	26.7
7-day	39.3
28-day	47.0

Aggregate

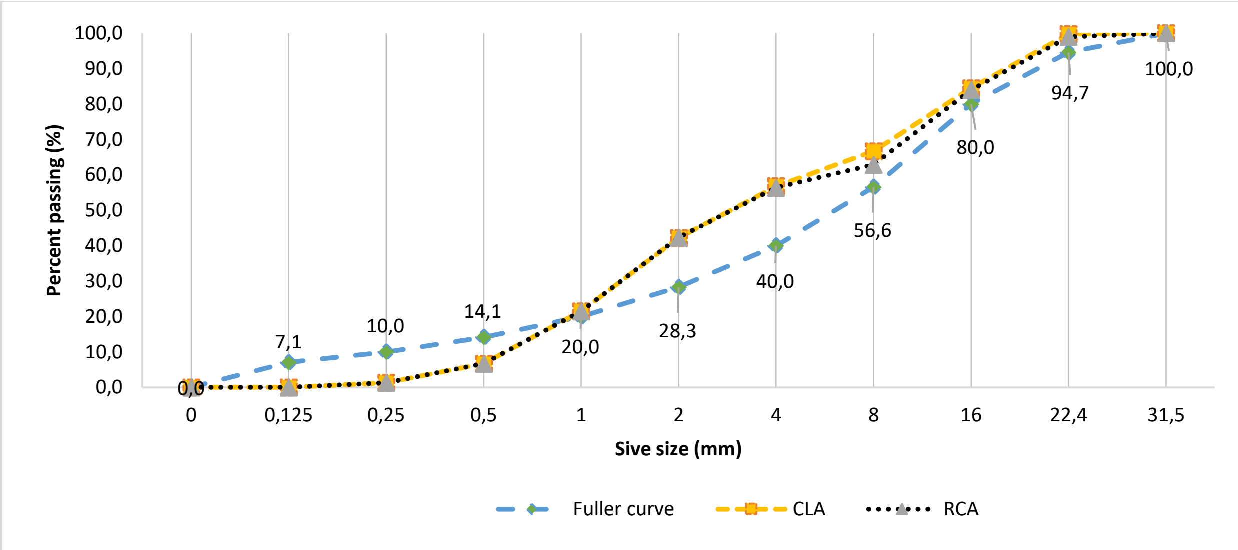
Two types of aggregates were used as coarse aggregate in this investigation. Crushed coarse limestone aggregate (CLA) was used in the control mixtures. In the test mixtures 25, 50, 75 and 100 wt% of the coarse CLA was replaced with coarse RCA. The fine aggregate in all of the mixtures was crushed limestone. The physical properties of CLA and RCA are shown in Table 2.

Table 2. Physical properties of coarse and fine aggregates. (Self-Elaboration).

Properties of aggregates	LCA			RCA	
	0-5 mm	5-15 mm	15-25 mm	5-15 mm	15-25 mm
Dry rodded unit weight (kg/m^3)	1889	1573	1548	1368	1308
Loose unit weight (kg/m^3)	1673	1480	1466	1215	1196
SSD balk specific gravity	2.654	2.676	2.711	2.446	2.44
Water absorption capacity (%)	0.92	0.30	0.23	4.88	5.04

The RCA were prepared by crushing waste concrete laboratory specimens having compressive strengths in the range of 20-50 MPa using a jaw crusher. The RCA was screened it into 5/15 and 15/25 mm size fractions. Gradations of the combined CLA and RCA as well as the Fuller curve are shown in Figure 1.

Figure 1. Gradation curve of CLA, RCA and Fuller curve. (Self-Elaboration).



Sample preparation

The water content of RCC mixtures was determined by the maximum density method in accordance with ACI 207.5R.89 (ACI 207.5R.89, 1988). For this purpose, mixtures with at least four different water contents were prepared. The mixes were placed in three layers in 150/300 mm cylinder molds. Each layer was compacted for 15-20 seconds at around 20 J impact energy level using a 10.1 kg vibrating hummer equipped with a 5 kg tamping plate in accordance with ASTM C 1435. During the compaction of the top layer, an additional collar was used to obtain a smooth surface. The samples were designated by their cement content and RCA replacement level. For example, RCC150/100 indicates a mixture having 150 kg/m^3 cement, in which 100% of the CLA is replaced with RCA.

The wet unit weights of the compacted RCC samples were measured according to ASTM C 138 standard. The actual mix proportions, adjusted by taking into consideration the measured unit weights of fresh RCC mixtures are given in Table 3. A total of 15 RCC mixtures, including 3 control mixtures containing no RCA were prepared. The relation between dry unit weight and water content of RCC150/0 and RCC150/50 mixtures are shown in Figures 2. The same procedure was applied to the other mixtures to determine their maximum dry density and optimum water content. The specimens were demolded after 24 h and cured in 22 ± 2 ºC water until testing. As it can be observed from Table 3, the optimum water content and consequently the w/c ratio of the mixtures increased by increasing RCA substitution level. Meanwhile, a gradual reduction occurred in the unit weight of RCC mixtures upon increasing RCA replacement level. The increasing in w/c ratio upon RCA inclusion became more pronounced by increasing cement content of the mixtures.

Figure 2. Relation between dry unit weight and water content of 150/0 and 150/50 mixture. (Self-Elaboration).

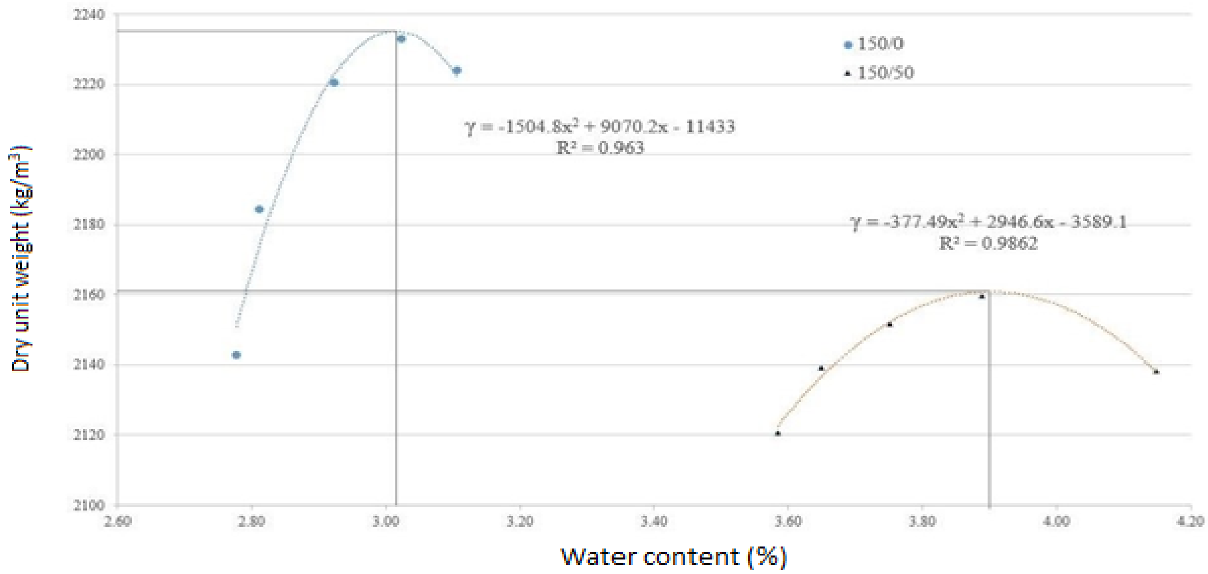


Table 3. The actual mix proportion of the RCC. (Self-Elaboration).

Mixtures	Optimum water content (%)*	W/C ratio	Materials, kg/m^3						UW, kg/m^3	
			cement	water	CLA 0-5 mm	CLA 5-15 mm	CLA 15-25 mm	RCA 5-25 mm	wet	dry
RCC150/0	3.01	0.42	144	60.2	1302	472	472	0	2450	2235
RCC150/25	3.37	0.42	144	60.6	1281	348	348	232	2412	2187
RCC150/50	3.93	0.47	144	67.1	1261	228	228	457	2386	2147
RCC150/75	4.60	0.47	143	67.5	1235	112	112	671	2340	2128
RCC150/100	5.84	0.48	142	68.6	1219	0	0	882	2312	2123
RCC200/0	4.17	0.42	197	83.0	1276	462	462	0	2480	2280
RCC200/25	4.35	0.42	197	83.3	1258	342	342	228	2450	2241
RCC200/50	5.18	0.47	196	92.0	1229	223	223	445	2408	2202
RCC200/75	5.93	0.48	196	93.0	1212	110	110	658	2379	2188
RCC200/100	6.89	0.50	195	98.5	1187	0	0	860	2341	2168
RCC250/0	4.61	0.42	249	105.4	1233	446	446	0	2480	2344
RCC250/25	5.48	0.44	249	108.5	1214	330	330	220	2450	2276
RCC250/50	6.31	0.48	248	117.6	1180	214	214	427	2399	2257
RCC250/75	7.04	0.50	247	123.3	1154	104	104	627	2360	2247
RCC250/100	8.14	0.53	247	129.9	1132	0	0	820	2328	2222

*percent by weight of the mixture.

Test procedures

The strength tests were applied on 150 × 300 mm cylinder specimens (EN 12390-3, 2010; EN 12390-6, 2010) and drop weight impact was applied on 150 × 64 mm cylinder specimens, cut from 150 × 300 mm cylinders (ACI Committee 544, 1988). The toughness values were calculated by dividing fracture energy ($mghN_f$) of the specimens into the volume of specimens. Here, m is the dropping mass (kg), g is gravitational acceleration (9.8 m/s^2), h is height (m) from which the weight is dropped and N_f is number of drops. The ultrasonic pulse velocity (UPV) values of 28-day, 90-day and 180-day old 150 × 300 mm cylinder specimens were determined in accordance with the ASTM C 597 standard (ASTM C 597, 2002). The dynamic elastic modulus of concrete was calculated by the following equation [Neville, 2010; Philleo, 1955):

$$E_d=\gamma c^2 \frac{(1+\upsilon)(1-2\upsilon)}{(1-\upsilon)\times 1000} \quad (1)$$

where E_d is the dynamic elastic modulus of concrete (GPa), γ the hardened concrete density (kg/m^3), c the UPV (km/s) and υ is the Poisson's ratio (assumed as 0.2 for all of the mixtures).

Test results and discussion

The compressive and split tensile strength as well as drop weight impact test results of RCC mixtures are given in Figure 3 and Figure 4 as well as in Table 4. Besides, 95% confidence intervals of relationship between 90-day compressive strength and dry unit weight of RCC mixtures are shown in Figure 5.

Figure 3. Compressive strength of RCC mixtures. (Self-Elaboration).

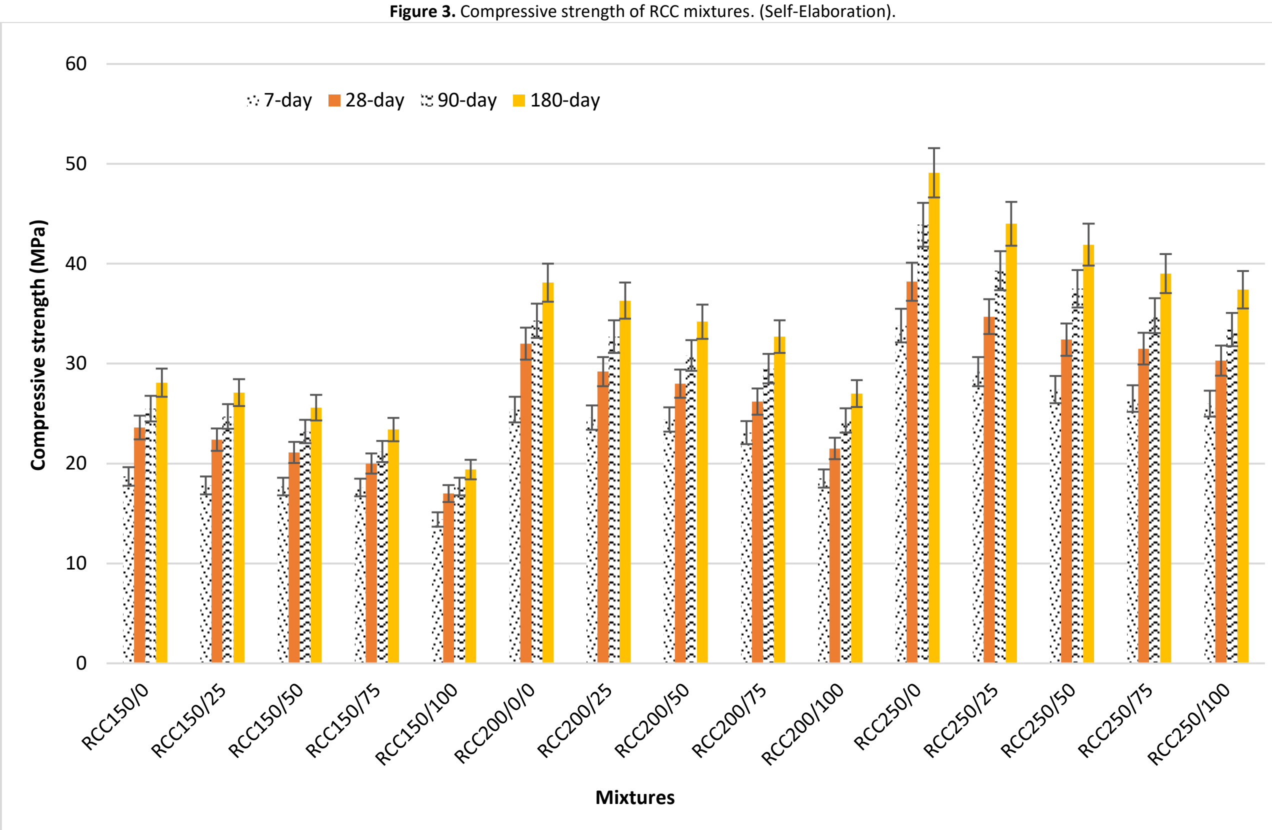
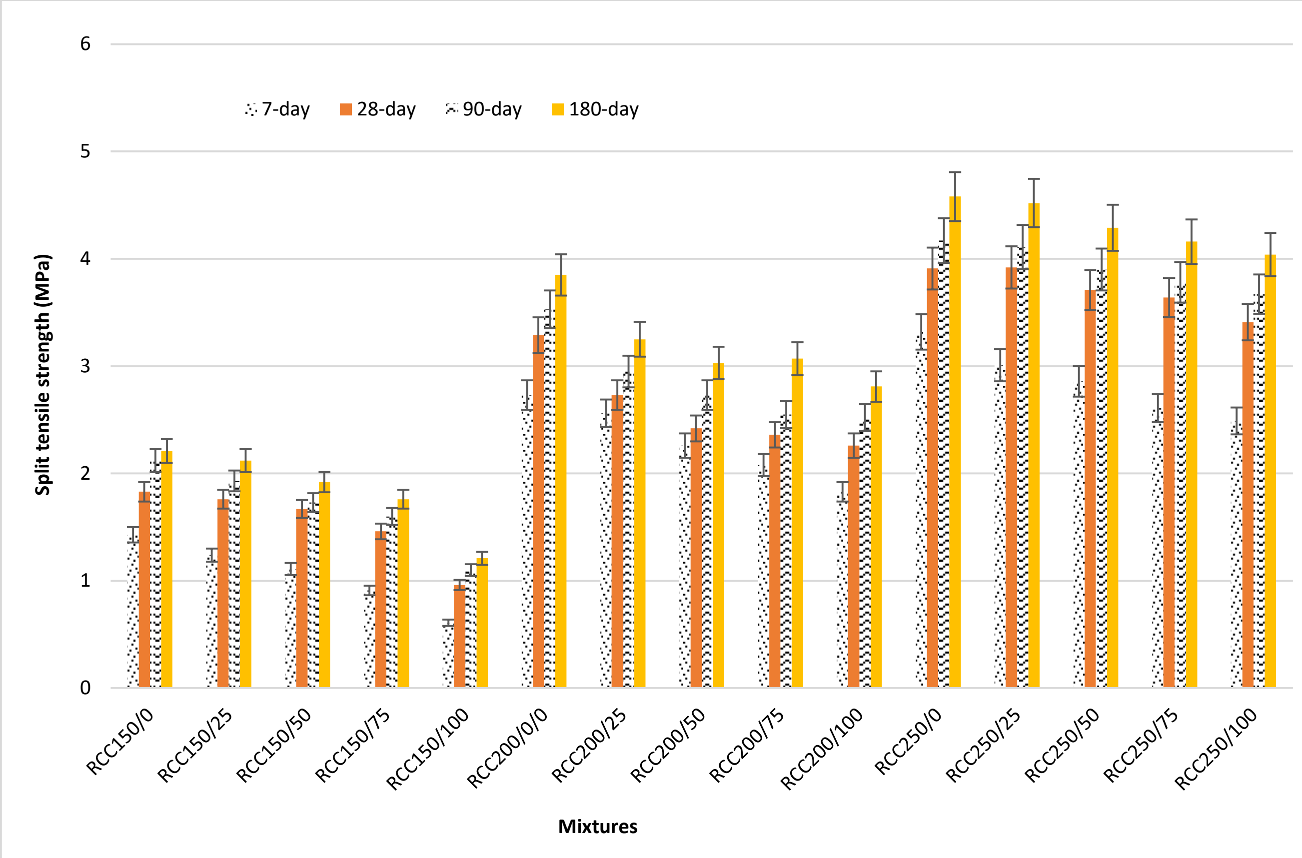


Figure 4. Splitting tensile strength of RCC mixtures. (Self-Elaboration).

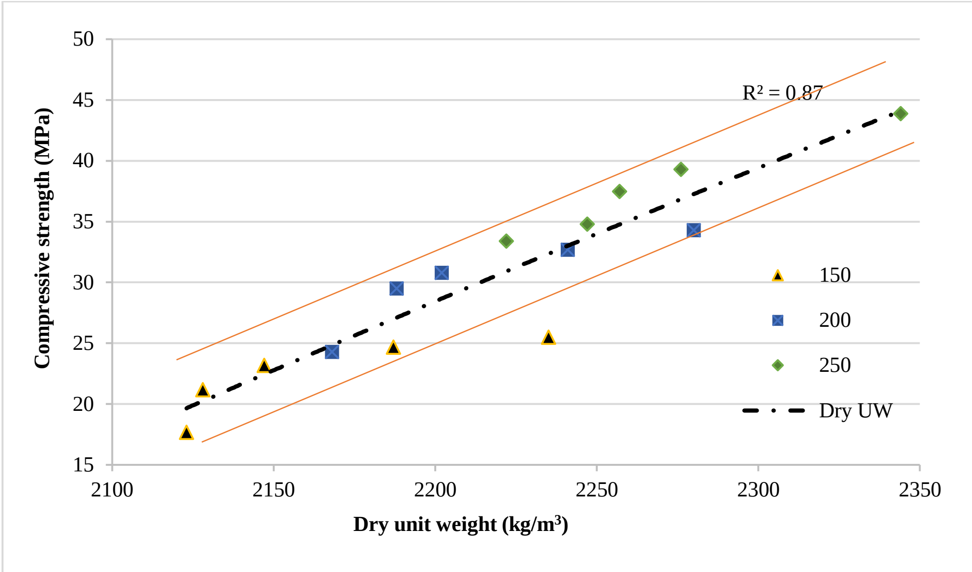


As it can be seen from the results, the minimum strength values at all ages in every cement content belongs to the mixtures that contain 100% RCA. Irrespective of cement content, the strength of RCC mixtures reduced upon replacement of CLA with RCA. The effect increased by increasing RCA replacement level. The reduction in strength upon RCA inclusion is in part due to the higher w/c ratio of RCA-bearing mixtures and in part due to the presence of porous and weak old mortar adhered on the surface of RCA particles which may cause a weak bond strength between aggregate and new matrix compared to that of the LCA.

Table 4. Drop weight impact test results. (Self-Elaboration).

Mixture	28-day		90-day		180-day	
	N_f	Toughness (N.mm/mm^3)	N_f	Toughness (N.mm/mm^3)	N_f	Toughness (N.mm/mm^3)
RCC150/0	25	0.44	28	0.49	29	0.51
RCC150/25	21	0.37	24	0.42	24	0.42
RCC150/50	21	0.37	23	0.40	23	0.40
RCC150/75	18	0.32	20	0.35	21	0.37
RCC150/100	15	0.26	17	0.30	18	0.32
RCC200/0/0	32	0.56	35	0.62	37	0.65
RCC200/25	31	0.54	33	0.58	36	0.63
RCC200/50	31	0.54	34	0.60	36	0.63
RCC200/75	26	0.46	29	0.51	30	0.53
RCC200/100	23	0.40	25	0.44	27	0.47
RCC250/0	51	0.90	55	0.97	57	1.00
RCC250/25	48	0.84	54	0.95	55	0.97
RCC250/50	46	0.81	49	0.86	51	0.90
RCC250/75	40	0.70	46	0.81	47	0.83
RCC250/100	37	0.65	39	0.69	41	0.72

Figure 5. 95% confidence intervals of relationship between 90-day compressive strength and dry unit weight of RCC. (Self-Elaboration).



The splitting tensile strength / compressive strength ratio of RCC mixtures with 150 kg/m^3 cement content (i.e. RCC150/0, RCC150/25, RCC150/50, RCC150/75, and RCC150/100) were found to be 7.9%, 7.6%, 7.3%, 6.9% and 5.6%. The corresponding values for the mixture containing 200 and 250 kg/m^3 cement were in the range of 10.4% to 8.9% and 10.7% to 9.7%, respectively. The relationship between compressive strength, split tensile strength and toughness of the mixtures are plotted in Fig. 6, 7, 8 and 9. As it can be seen from the figures good correlations with coefficient of correlation (R^2) values ranging from 0.92 to 0.96 were found between compressive strength, splitting tensile strength and toughness of the RCC mixtures.

Figure 6. Relationship between compressive and split tensile strength of RCC mixtures. (Self-Elaboration).

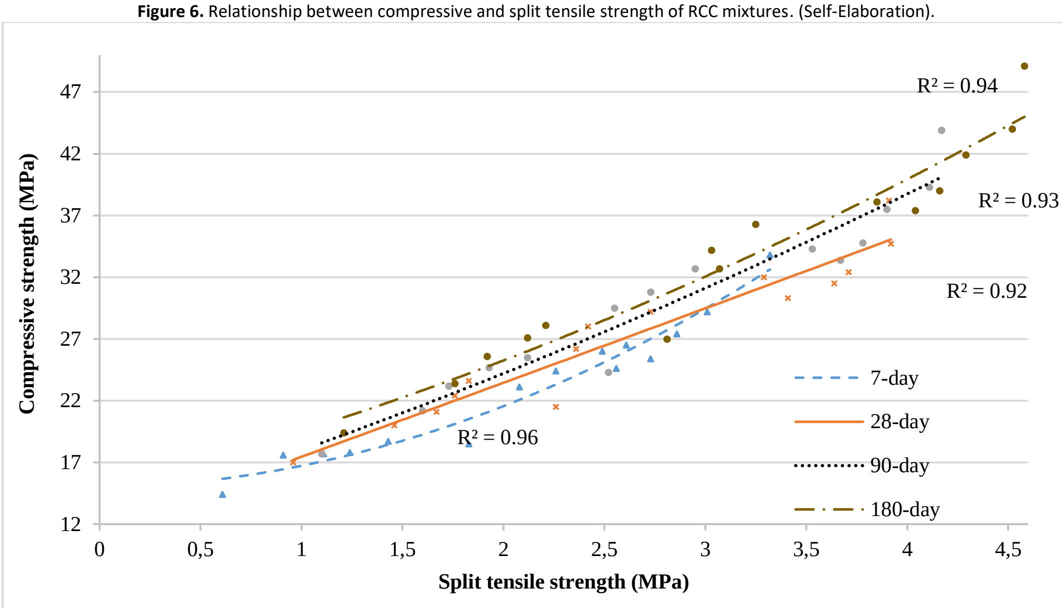


Figure 7. Compressive strength- toughness relationship of RCC mixtures. (Self-Elaboration).

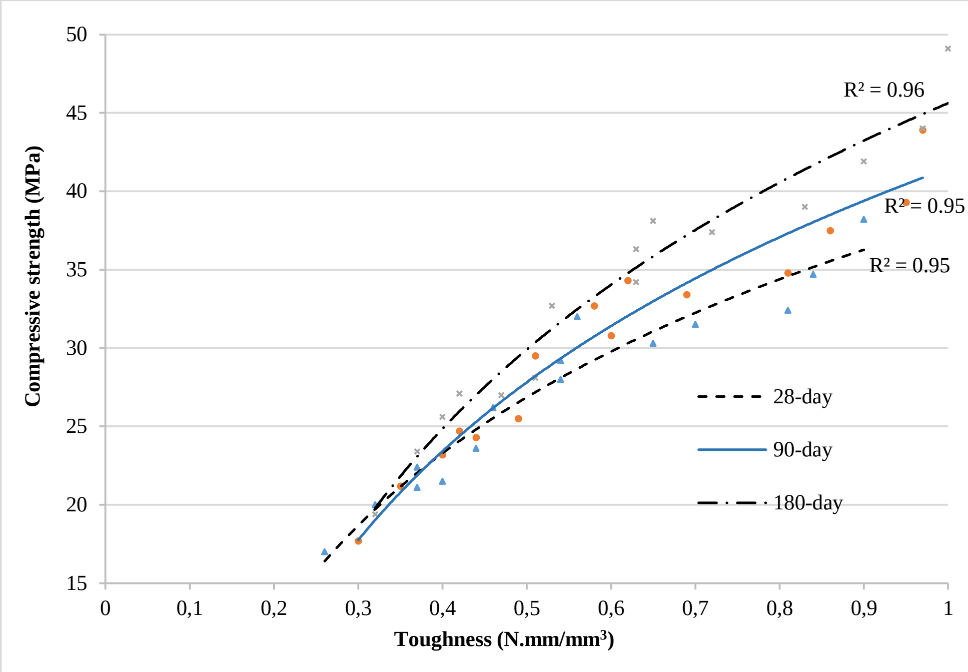


Figure 8. Relationship between split tensile strength and toughness of RCC mixtures. (Self-Elaboration).

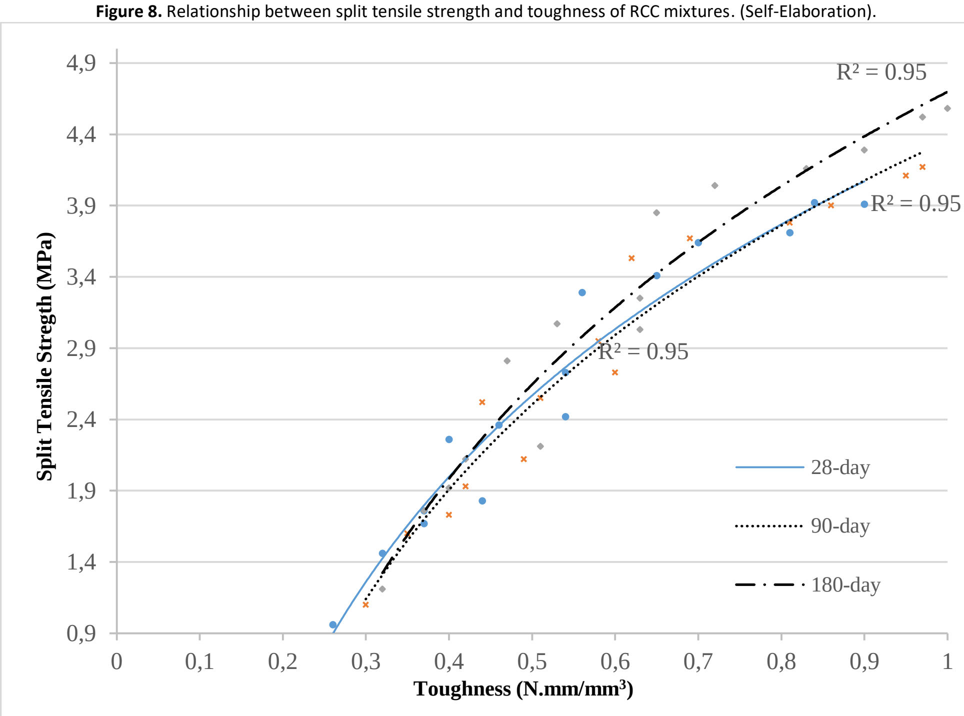
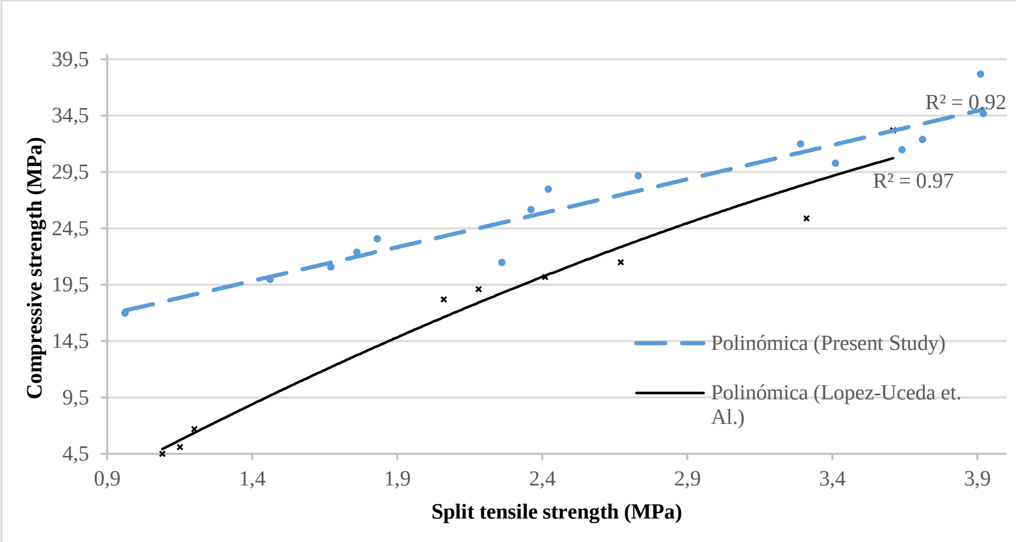


Figure 9. Comparison of the relationship between 28-day compressive - 28-day split tensile strength of RCC obtained in the present study and the study of Lopez-Uceda et. al. (2018).



The average 28-day compressive strength /180-day compressive strength ratios for RCC mixtures containing 150, 200 and 250 kg/m^3 cement are around 0.84, 0.81 and 0.79, respectively. It is possible to say that the compressive strength development beyond 28-day in RCC mixtures is more pronounced in leaner mixtures. The fact seems to be arisen, to some extent, from lower w/c ratio of the leaner mixtures compared to the corresponding richer ones.

As it can be seen from Figure 3 increasing the cement content of the mixture from 150 to 250 kg/m^3 improved the 180-day compressive strength of the control mixture by 75%. The corresponding value for RCC mixtures containing 25, 50 and 75% RCA was around 65%, however, RCC mixture containing 100% RCA showed considerably higher strength increment (93%). The effect of increasing cement content of the mixture from 150 to 250 kg/m^3 was more pronounced on the 180-day splitting tensile strength (Figure 4) than on the 180-day compressive strength. The increase in the 180-day splitting tensile strength in the control mixture upon increasing the cement content (from 150 to 250 kg/m^3) was 107%. The corresponding values for 25, 50, 75 and 100% RCA-bearing mixtures were found to be 113%, 123%, 136% and 234%, respectively. The improvement in either compressive or tensile strength of RCC mixtures containing 100% RCA is interesting. This improvement may be arisen to some extent from higher W/C ratio of RCC 250/100 (0.53) compared to that of RCC 150/100 (0.48); which provides somewhat greater strength gain at later ages. Besides, it seems that the higher cement content is more beneficial in improving the ITZ upon further pozzolanic reaction arisen from the utilization of Portland composite cement. It is well-known that ITZ is the weakest link in concrete mixtures, particularly in RCA-bearing mixtures. This may result in a greater strength improvement at later ages in RCA-bearing mixtures compared to those of the control mixtures.

The 28, 90 and 180-day UPV and dynamic modulus of elasticity of RCC mixtures and the limits specified for UPV values of concrete by Whitehurst (1951) are shown in Table 5 and 6, respectively (Whitehurst, 1951). The relationship between compressive strength and UPV as well as relationship between compressive strength and dynamic modulus of elasticity of RCC mixtures are shown in Figure 10 and 11, respectively.

Table 5. UPV values and dynamic modulus of elasticity of RCC mixtures. (Self-Elaboration).

Mixture	UPV (km/s)			Dynamic modulus of elasticity (GPa)		
	28-day	90-day	180-day	28-day	90-day	180-day
RCC150/0	3.61	3.68	3.71	26.21	27.24	27.69
RCC150/25	3.55	3.58	3.60	24.81	25.23	25.51
RCC150/50	3.5	3.51	3.52	23.67	23.81	23.94
RCC150/75	3.36	3.37	3.39	21.62	21.75	22.01
RCC150/100	3.24	3.26	3.26	20.06	20.31	20.31
RCC200/0/0	4.05	4.06	4.08	33.66	33.82	34.16
RCC200/25	3.82	3.83	3.9	29.43	29.59	30.68
RCC200/50	3.76	3.76	3.76	28.02	28.02	28.02
RCC200/75	3.60	3.64	3.67	25.52	26.09	26.52
RCC200/100	3.51	3.54	3.59	24.04	24.45	25.15
RCC250/0	4.69	4.69	4.70	46.40	46.40	46.60
RCC250/25	4.6	4.61	4.61	43.34	43.53	43.53
RCC250/50	4.49	4.51	4.52	40.95	41.32	41.50
RCC250/75	4.29	4.31	4.39	37.22	37.57	38.97
RCC250/100	4.13	4.16	4.2	34.11	34.61	35.28

Table 6. The limit specified for concrete. (Self-Elaboration).

UPV(km/s)	Concrete quality
> 4.5	strong
3.50 – 4.50	good
3.00 – 3.50	intermediate
2.00 – 3.00	weak
< 2.00	very weak

Figure 10. Relationship between compressive strength and UPV of RCC mixtures. (Self-Elaboration).

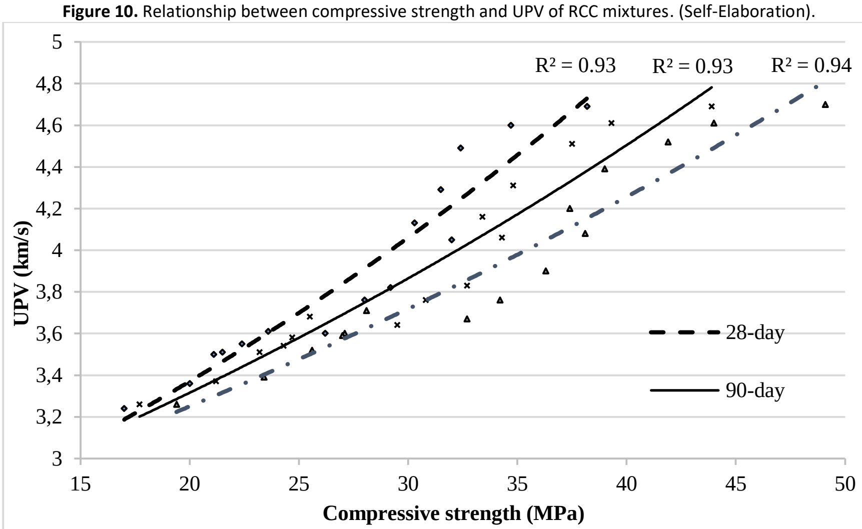


Figure 11. Compressive strength-dynamic modulus of elasticity relationship of RCC mixtures. (Self-Elaboration).

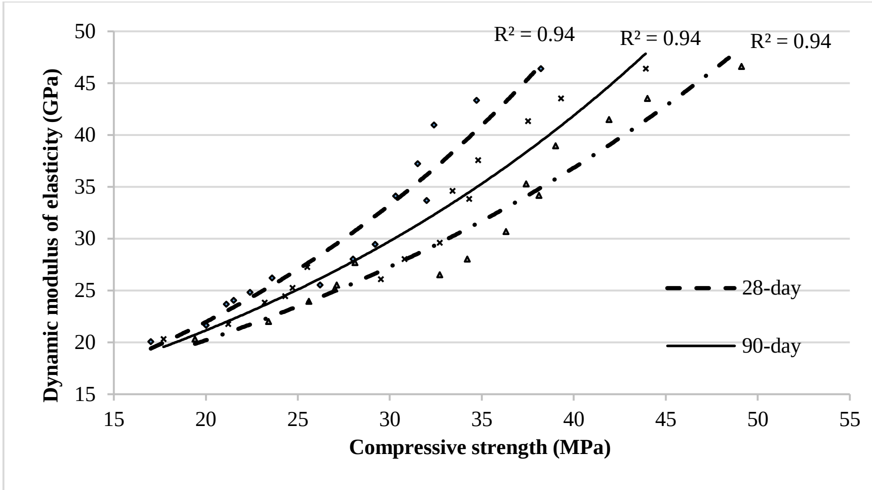


Figure 12. 95% confidence intervals of compressive strength- UPV relationship of RCC mixtures. (Self-Elaboration).

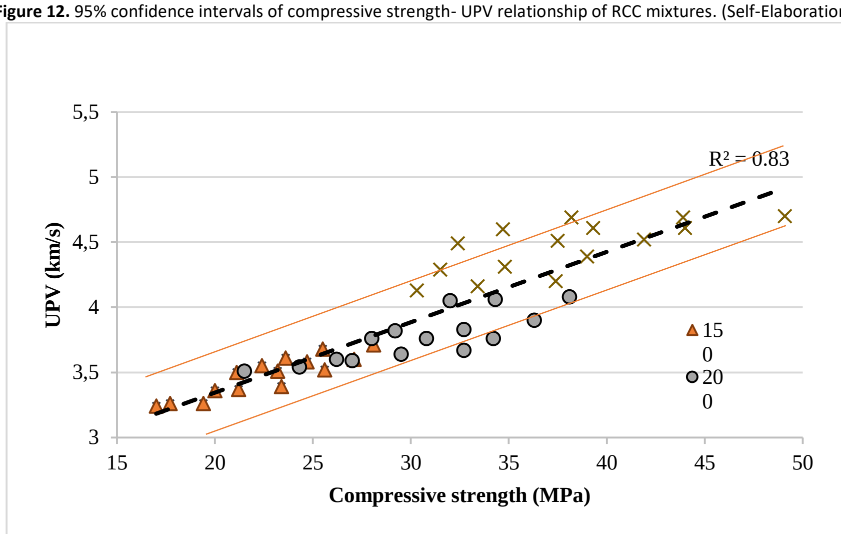
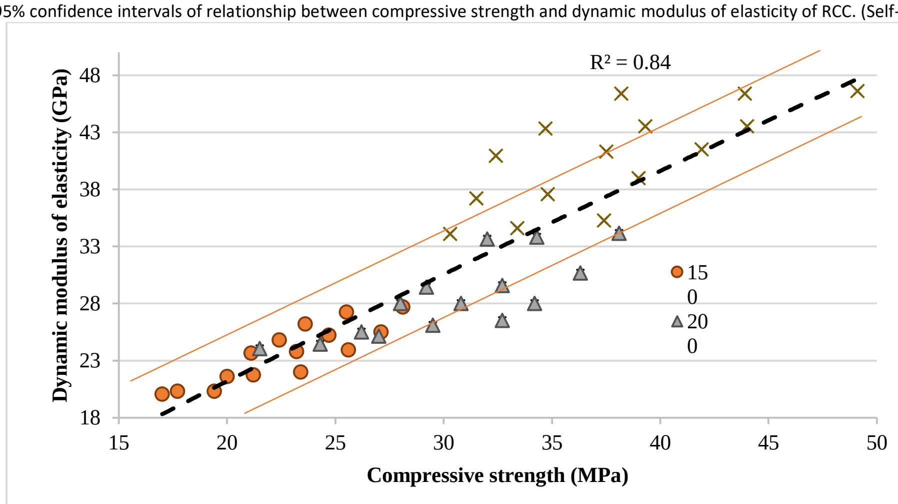


Figure 13. 95% confidence intervals of relationship between compressive strength and dynamic modulus of elasticity of RCC. (Self-Elaboration).



As it can be seen from the results, regardless of the cement content, the minimum UPV and dynamic modulus of elasticity values at all ages belong to the mixtures that contain 100% RCA. Irrespective of cement content, the UPV and dynamic modulus of elasticity values of RCC mixtures reduced upon replacement of CLA with RCA. The effect increased by increasing RCA replacement level. The reduction in UPV and dynamic modulus of elasticity values upon RCA inclusion seems to be arisen from the higher w/c ratio of RCA-bearing mixtures, ITZ characteristics and the presence of porous and weak old mortar adhered on the surface of RCA particles which may cause a weaker bond strength between aggregate and new matrix compared to that of the LCA. As it can be seen from the Figure 10 and 11, good correlations, with coefficient of correlation (R^2) values around 0.94, were found between compressive strength, UPV and dynamic modulus of elasticity of the RCC mixtures. The 95% confidence intervals of relationship between compressive strength and dynamic modulus of elasticity of RCC mixtures are given in Figure 12 and 13.

Conclusion

Based on the materials used and tests applied the following conclusions can be drawn:

- Compared to these of control mixture, the optimum water content and consequently the w/c ratio of the mixtures increased by increasing RCA substitution level. Meanwhile, a gradual reduction occurred in the unit weight of RCC mixtures upon increasing RCA replacement level.
- Replacing of 25% of crushed limestone aggregate with recycled aggregate had not a significant detrimental effect on the mechanical properties of concrete. Besides, the detrimental effect of RCC substitution reduced by increasing the cement content of the mixtures. However, increasing the amount of recycled aggregate beyond 25% decreased the mechanical properties of concrete.
- The strength, UPV and dynamic modulus of elasticity values of RCC mixtures reduced upon replacement of CLA with RCA. The effect increased by increasing RCA replacement level.
- The splitting tensile strength, UPV and dynamic modulus of elasticity developments beyond 28 days in RCC mixtures are more pronounced in richer mixtures. The fact seems to be arisen in part from higher w/c ratio and in part from the higher pozzolanic reactions in hydrated cement paste.

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