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Experimental Study on the Physical and Mechanical Characteristics of Roller Compacted Concrete Made with Recycled Aggregates

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Abstract: A huge volume of waste is generated by natural and human-made disasters and by rapid urbanization that leads to the demolition of structures reaching the end of their service life. Using recycled aggregates in concrete producing reduces environmental pollution by decreasing the disposal of this waste material in landfills and preserving unreasonable exploitation of natural resources. This manuscript presents the results of an experimental program aiming to study the effect of recycled aggregates on the physical and the mechanical properties of roller compacted concrete (RCC). A Dreux–Gorisse mix design method together with the modified proctor test were adopted to prepare a reference mixture with natural aggregates with three derived mixtures where coarse aggregates were replaced by 50%, 70%, and 100% of recycled aggregates. The physical properties of RCC were evaluated by means of water absorption and gas permeability tests while the mechanical properties were evaluated using compressive, tensile splitting and 3-point flexural tests. The results of physical tests showed that both water absorption ability and gas permeability increase proportionally with the replacement ratios. The results of the mechanical tests showed that the compressive strength class was approximately constant for all developed mixtures at the age of 28 days. For a substitution ratio of 100%, a drop in the compressive strength of only 6% was recorded. The reduction in the tensile and flexural strength was more pronounced than the compressive strength and was about 10% for the mixture of 100% recycled aggregates. It was found that the strength increases with time, and it can be estimated at any age using the analytical models adopted for conventional hydraulic concretes. Based on the obtained results, it was concluded that recycled aggregates up to 50% don't negatively affect the physical and mechanical properties of RCC.

Keywords: roller compacted concrete; recycled aggregates; water absorption; permeability; mechanical properties



Citation: Kheirbek, A.; Ibrahim, A.; Asaad, M.; Wardeh, G. Experimental Study on the Physical and Mechanical Characteristics of Roller Compacted Concrete Made with Recycled Aggregates. *Infrastructures* **2022**, *7*, 54. <https://doi.org/10.3390/infrastructures7040054>

Academic Editor: Kevin Paine

Received: 8 March 2022

Accepted: 7 April 2022

Published: 8 April 2022

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1. Introduction

Recycled aggregates (RA) represent a sustainable alternative to natural aggregates (NA) due to its availability in huge volume. This availability is related to urbanization and industrial activities which require the demolition of existing structures, or related to natural and human made disasters [1]. Construction and demolition waste (CDW) left in landfills imposes serious environmental problems and its valorization has become a socio-economic necessity in an innovative circular economy approach [2–4].

Aggregates resulting from the deconstruction of civil engineering structures have demonstrated their ability to replace natural aggregates in structural concrete. Recycled concrete aggregates mainly differ from natural aggregates in that the presence of the old cement mortar remains attached to the natural grains [5]. Indeed, the volume of the old

cement paste present in recycled concrete aggregates varies according to their origin [5] as well as the method of recycling [6]. The old cement mortar causes the decline in the characteristics of recycled aggregates compared to natural ones. The density of recycled aggregates is generally lower than that of natural aggregates due to the low density of the mortar adhering to recycled grains [7]. Moreover, water absorption capacity is higher for recycled aggregates [8]. The presence of the attached mortar reduces the impact and wear resistances of recycled aggregates which are characterized by means of Los Angeles test [5,9]. Natural aggregate concrete (NAC) formulation approaches remain applicable for the formulation of concrete incorporating recycled aggregates (RAC). The exhaustive works carried out in the literature over the past two decades have shown that it is quite possible to formulate concrete based on recycled aggregates with mechanical properties comparable to the properties of concrete from natural aggregates [10–12].

Roller compacted concrete (RCC) is a special type of concrete made with the same ingredients of conventional structural concrete which are the cement, water, coarse aggregates and sand but it is more dry with practically zero slump and it is compacted using vibratory rollers [13,14]. RCC is used for the construction of dams, pavements, stations, low-volume roads and parking lots, aircraft parking areas, and many other infrastructure applications [14,15].

RCC mixtures typically have a lower volume of cementitious materials, coarse aggregates, and water than conventional concrete mixes and a higher volume of fine aggregates, which fill the air voids in the pavement system. The fine aggregates in RCC are more packed than in conventional concrete which provides a high friction (aggregate interlock) between the particles and contributes to the pavement's initial load carrying capacity [14]. The consistency of RCC mixtures is evaluated through the Vebe test [16,17] by measuring the Vebe time which defined as the vibration time necessary until the appearance of mortar ring in the specimen [16]. A Vebe time ranged between 15 and 20 s is recommended for RCC according to standard ACI 309.5R-00 [15] for compaction in four to six passes with a dual-drum, 9 tonne (10 ton) vibratory roller while it is between 45 and 60 s in pavement application according to Chhorn et al. [17]. The constancy may be improved by increasing the volume of fines the diameter of which is less than 75 μm to supplement the cementitious paste volume and reduce internal voids between aggregate particles. [15]. The performance of RCC depends on the compaction quality [15]. The RCC mixture must be stiff enough to support the compactor weight and wet enough to allow a homogenous distribution of the ingredients without segregation [13,15]. The strength development in RCC is due to the consolidation (also called compaction) process plus the hydration process unlike conventional concretes which harden as a result of the chemical process of cement hydration [13,15,17]. Thereby, as a result, the RCC develops interesting mechanical properties at early age while a conventional concrete is still in the plastic state [14].

The ease of RCC compaction and placement depends on the size of used aggregates [14,15]. The nominal maximum size aggregate (NMSA) affects the ease of compaction due to the tendency of large aggregate to segregate from the drier. The addition of fines whose diameter is lower than 75 μm reduced the internal voids between aggregate particles, enhances the compactness of the granular skeleton and improve handling and compactability of the mixture while reducing the segregation susceptibility [15].

The valorization of recycled aggregates in RCCs has attracted the attention of researchers around the world [18–20]. Debieb et al. [18] studied the performance of roller compacted concrete with recycled aggregates. They concluded that the strength of RCC containing only crushed concrete is acceptable as compared to RCC made with natural aggregates. However, the mechanical and durability performances depend on the quality of aggregates. Hosseinnézhad et al. [19] conducted an experimental study on the mechanical properties of roller compacted concrete containing recycled concrete aggregate. The results showed a reduction in the compressive strength for substitution ratios higher than 25%. Fardin et al. [20] found that recycled aggregates can be used as a coarse aggregate in producing RCC but not with large substitution percentages.

The main objective of the present research is to study the effect of replacement ratios of natural aggregates by recycled ones on the strength and the physical properties of roller compacted concrete with a particular emphasis on the development of strength at early age.

2. Materials and Methods

2.1. Materials

Ordinary Portland cement CEMI 32.5 N with a density of 3.1 was used in this investigation. Two crushed natural sands in the size fractions 0.075/10 mm and 0.075/2 mm were used with a natural coarse gravel 4/20 mm. The recycled aggregates were produced in laboratory from rubbles collected from a demolition site located at the north of Latakia in Syria. The collected rubble was sorted manually then crushed using a hammer. A mixture of 60% old concrete, 20% of ceramic waste, and 20% of cinder block was prepared before introducing in a laboratory automatic crusher. These percentages were adopted after visiting many landfills in Syria and sorting waste on site.

After the mechanical operation, only coarse aggregates of 20 mm maximum size were selected. The physical properties of all aggregates are given in Table 1 and the particle size distribution is depicted in Figure 1.

Table 1. Physical properties of aggregates.

	Density (kg/m ³)	LA Coefficient (%)	W _A (%)	Sand Equivalent (%)
Recycled concrete	2504	31.9	4.3	-
Ceramic and tiles	2346	38.7	6.4	-
Cinder block	2327	68.3	8.2	-
Recycled aggregate mixture (RCA)	2447	35.5	4.8	-
Natural fine sand (NFS)	2525	-	-	70.4
Natural coarse sand (NCS)	2700	-	-	84.4
Natural coarse gravel (NCA)	2775	19.2	0.8	-

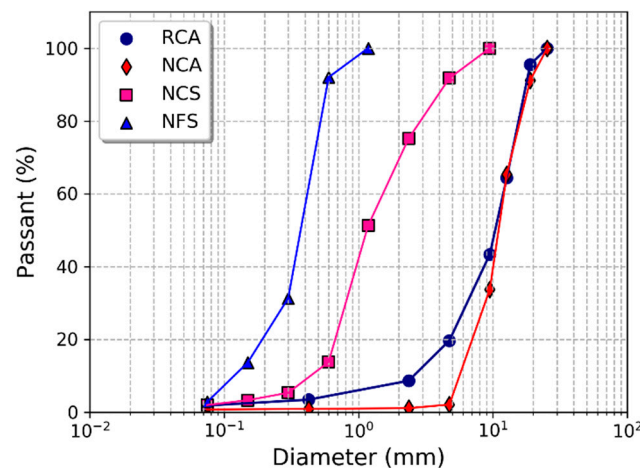


Figure 1. Particles size distribution of used aggregates.

2.2. Mix Proportions

Concrete mixtures were designed according to Dreux–Gorisse [21] method without admixtures. The modified Proctor test based on ASTM D 1557 [22] was also carried out as an additional procedure to accurately determine the maximum dry density values that correspond to the optimal water ratio. This procedure is related to the specificity of RCC and the high sensitivity of its properties to the moisture content. From the reference mixture, three mixtures were derived by substituting the coarse natural graven by 50%, 70%, and 100% of recycled coarse gravel. The mixtures are named, respectively, RCC50, RCC70, and RCC100.

For all the mixtures, the cement content was fixed at 250 kg/m³ and the air content of was estimated equals to 20 L taking into account the maximum aggregates size. The granular skeleton was also optimized for each formulation to achieve the maximum compactness. Concerning the water content, it was optimized through two steps. The first step consists in finding the water to cement ratio (W/C), called theoretical by means of Bolomey’s equation:

$$f_{cm} = Gf'_c \left(\frac{C}{W + A} - 0.5 \right) \tag{1}$$

where f_{cm} is the target compressive strength at the age of 28 days. It was fixed equal to 20 MPa in the present work. G is a coefficient related to the nature of aggregates. A value of 0.45 was adopted in this work. f'_c is the nominal cement strength which was taken equal to 32.5 MPa.

The second step of the water content optimization consists in performing the modified proctor test to find the optimal water content allowing to reach the maximum density. Finally, the adopted content was the average of two values. The mixing operations consisted of mixing the dry ingredients first then adding the water gradually. After that, continuing the mixing for supplementary two minutes.

The mix proportions of all concretes are recapitulated in Table 2 with the density and the Vebe time measured at the fresh state. It can be observed that the density decreases while the Vebe time increases with the replacement ratio of recycled aggregates. One reason to explain the increase in the Vebe time is the absorption of a part of the total water by the recycled aggregates used in the dry state.

Table 2. Mix proportions pf roller compacted concrete mixtures.

Component (kg/m ³)	RCC0	RCC50	RCC70	RCC100
Cement	250	250	250	250
Water	142.8	143.1	142.2	144.5
Natural fine sand (NFS)	329	281	249	248
Natural coarse sand (NCS)	486	415	368	366
Natural coarse gravel (NCA)	1239	682	435	-
Recycled coarse aggregate (RCA)	-	601	895	1275
Water to cement ratio (W/C)	0.57	0.57	0.57	0.58
Density (kg/m ³)	2543.4 ± 4.2	2519.1 ± 3.8	2456.4 ± 8	2438.6 ± 7.4
Vebe time (s)	19	21	23	26

2.3. Experimental Tests

Test specimens were prepared by firstly placing the molds on a vibrating table. The fresh concrete was filled into the molds by layers of approximately 5 cm. At the same time as the vibration, each layer received 50 strikes using a metal rod 25 mm in diameter.

Compression tests were conducted on 15 × 15 × 15 cm³ cubic specimens using a servo-hydraulic machine with a loading rate of 1 MPa/s. Splitting tensile tests were carried out using the same machine and the same loading rate on 15 × 30 cm² cylindrical specimens. The flexural tests were carried out on prismatic specimens 10 × 10 × 50 cm³ by means of a servo -hydraulic machine with a loading rate of 2 MPa/min.

Physical properties were characterized through water absorption and gas permeability tests. Permeability tests were carried out on 15 cm in diameter and 5 cm thick discs cut from the central part of 15 × 30 cylinders by means of a CEMBUREAU permeameter with a constant pressure of 2 bars. Based on Darcy’s law, the effective permeability when the flow is assumed to be laminar and unidirectional is described by the following equation:

$$K = \frac{2\mu L Q_s P_s}{A(P_e^2 - P_s^2)} \tag{2}$$

where L (m) is the sample thickness, A (m^2) is the section subjected to flow, P_e (Pa) is the upstream absolute pressure, and P_s is the downstream absolute pressure. μ (Pa.s) is the dynamic viscosity of fluid, while Q_s (m^3/s) is the volumetric gas flow.

Water absorption tests were conducted under atmospheric pressure on cubes of dimensions $10 \times 10 \times 10 \text{ cm}^3$. The tested specimens were immersed in water until saturation, identified by mass stabilization, then were dried in an oven at $105 \text{ }^\circ\text{C}$ until the dry mass was reached. The water absorption was calculated by the following equation:

$$W_A(\%) = \frac{M_{sat} - M_{dry}}{M_{dry}} \times 100 \tag{3}$$

where M_{sat} (kg) is the saturated mass and M_{dry} (kg) the dry mass.

For the repeatability of the results, each test was done at least five times.

3. Results

3.1. Physical Properties

The results of water absorption and gas permeability are shown in Figure 2. It can be observed that the two properties increase when the recycled aggregates percentage increases. These results are in agreement with many experimental studies in the literature [23–25] and are explained by the presence of the attached mortar to the natural grains. The microstructure of recycled concrete is generally more porous than natural concrete and the higher is the substitution ratio the higher is the porosity.

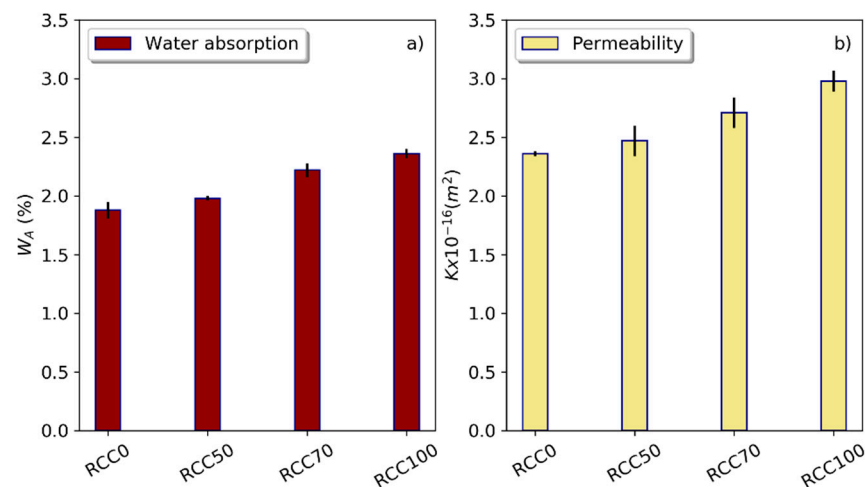


Figure 2. Physical properties, (a) water absorption, (b) gas permeability.

The increase in water absorption is 5% for a replacement ratio of 50%, while it reaches 18% and 25% when the substitution is 70% and 100%, respectively. The increase in permeability is of the same order of magnitude and reaches 4%, 15%, and 24% for RCC50, RCC70, and RCC100, respectively.

Based on the results obtained, linear relationships were found between the water absorption and the replacement ratio as well as the permeability and the replacement with good correlation coefficients (Equations (4) and (5)).

$$W_A(\%) = 4.41 \times 10^{-3}RCA + 1.88, \quad R^2 = 0.89 \tag{4}$$

$$K(\times 10^{-16} \text{ m}^2) = 5.29 \times 10^{-3}RCA + 2.363, \quad R^2 = 0.85 \tag{5}$$

3.2. Mechanical Properties

Figure 3a represents the compressive strength at 1, 3, 7, 14, and 28 days for all the concretes. At all the ages, it was found that the strength of concrete incorporating recycled

aggregates remains comparable to that of the reference concrete RCC0. The compressive strength of the RCC50 mixture is approximately 3% higher than RCC0 while that of RCC100 mixture is 6% lower than RCC0. Moreover, the strength of RCC70 mixture is identical to the resistance of the reference concrete. All studied mixtures developed a cubic compressive strength higher than 30 MPa at the age of 28 days and the replacement of natural aggregates by recycled ones did not affect the compressive strength. The conservation of the compressive strength is due to the presence of fines in the recycled aggregates where the passing across the sieve of 0.075 mm in the present study is about 1.8%. The fines play the role of filler which, after the compaction process, enhance the compactness of the solid skeleton and enhance the interlocking between aggregates. Moreover, the compaction process enhances the interfacial transition zone (ITZ) between the aggregates and the surrounding cement paste. The fines, hence, compensate the effect of recycled aggregates processing a lower quality than natural aggregates.

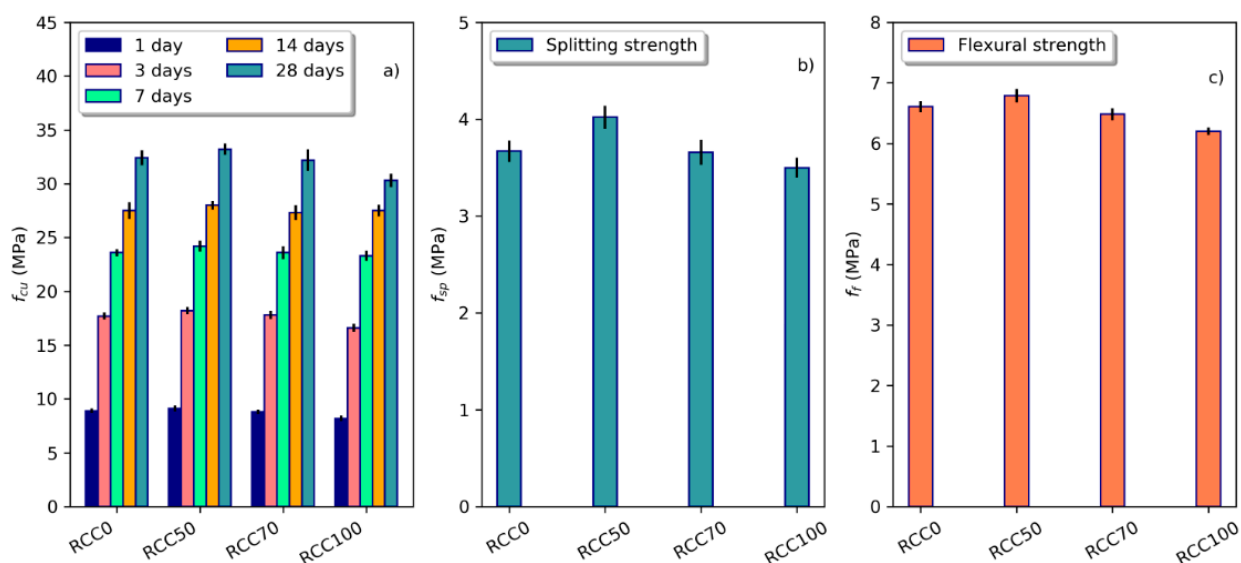


Figure 3. Mechanical properties: (a) compressive strength, (b) splitting tensile strength, (c) flexural strength.

The evolution of the splitting tensile strength and the flexural strength at the age of 28 days as a function of the substitution ratio is illustrated in Figure 3b,c. The evolution of these two strengths is identical except that the flexural strength is higher than the splitting strength, taking into account the size effect [26]. The variation of the tensile strength as a function of replacement ratio follows that of the compressive strength where the strength of RCC50 is about 10% higher than RCC0 while the strength of RCC100 is approximately 10% lower than the strength RCC0. The strengths of RCC70 and RCC0 remain, however, identical.

The development of the compressive strength with time is depicted in Figure 4a–d in addition to the predictive models of EC2 [27] and Baron and Oliver [28] initially developed for conventional hydraulic concrete.

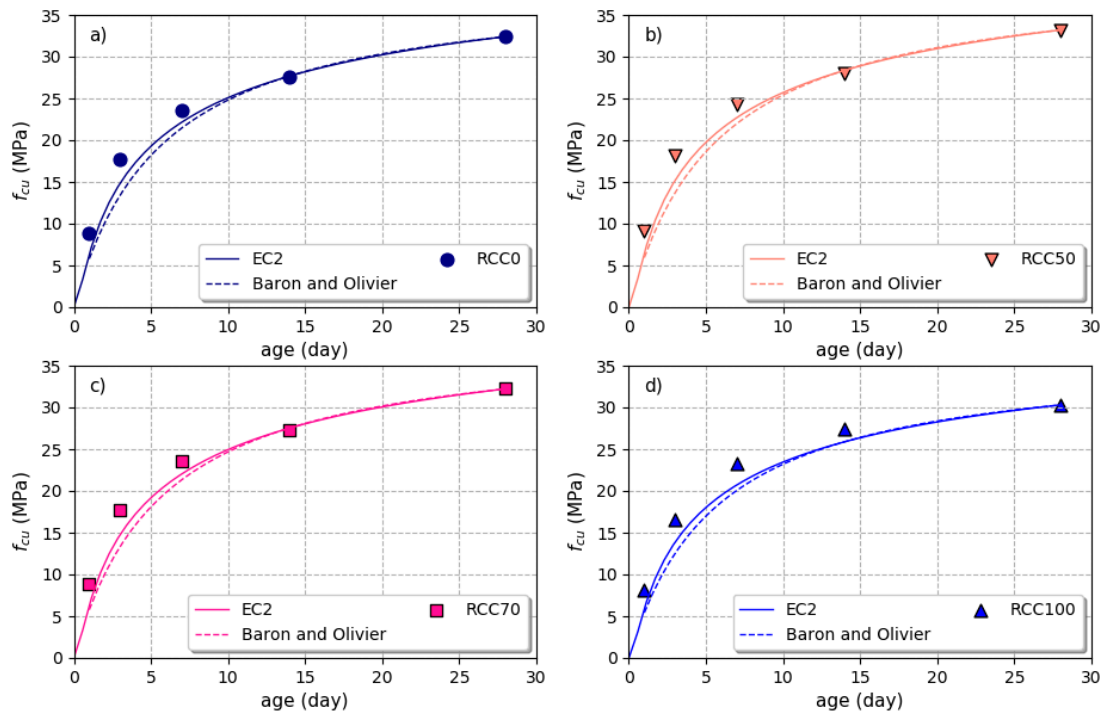


Figure 4. Development of the compressive strength over time, (a) RCC0, (b) RCC50, (c) RCC70, (d) RCC100.

According to the EC2 [27] the compressive strength at an age of t days, called $f_{cu}(t)$, can be estimated using expressions 6 and 7.

$$f_{cu}(t) = \beta_{cc}(t)f_{cu} \tag{6}$$

With

$$\beta_{cc}(t) = \exp \left\{ s \left[1 - \left(\frac{28}{t} \right)^{\frac{1}{2}} \right] \right\} \tag{7}$$

where f_{cu} is the mean compressive strength at 28 days, $\beta_{cc}(t)$ is a coefficient which depends on the age of the concrete t , and s is a coefficient which depends on the type of cement and taken equal to 0.38 for cement of the normal class.

According to Baron and Olivier [28], the compressive strength at the age t can be predicted using the following expression:

$$f_{cu}(t) = \frac{f_{cu}}{AF} \tag{8}$$

where AF is the aging factor which can be calculated using Equation (9).

$$AF = \frac{R_d(t - 28) + 28}{t} \tag{9}$$

with R_d a coefficient depending on the type of cement and taken equal to 0.83 for the class N.

The curves in Figure 4 show that Baron’s model underestimates resistance at a young age, while the model of EC2 is more suitable to predict the development of the compressive strength with time. From the 14th day, the two models come together.

In order to quantify the validity of each model, the correlation factor, R^2 , was calculated according to the following equation [29]:

$$R^2 = 1 - \frac{SSE}{SST} \tag{10}$$

where $SSE = \sum (f_{cu,exp} - f_{cu,cal})^2$ the sum of squares of error and $SST = \sum (f_{cu,exp} - \overline{f_{cu,exp}})^2$ the deviation of the experimental results, named $f_{cu,exp}$, from the mean $\overline{f_{cu,exp}}$.

The correlation factors are summarized in Table 3, where it can be noticed that the agreement with the experimental results is good for both models. However, the values of R^2 are more important for the EC2. The validity of EC2 model, which is initially proposed for natural aggregate concrete, was confirmed without any modification to predict the development of concrete strength of hydraulic recycled aggregates concretes [30] and may be extended to predict the strength evolution of RCC.

Table 3. Correlation factors between experimental results and prediction models.

Prediction Model	RCC0	RCC50	RCC70	RCC100
EC2	$R^2 = 0.95$	$R^2 = 0.95$	$R^2 = 0.94$	$R^2 = 0.93$
Baron and Olivier	$R^2 = 0.90$	$R^2 = 0.9$	$R^2 = 0.89$	$R^2 = 0.88$

The relationships between compressive strength at the age of 28 days and the physical properties are shown in Figure 5. The compressive strength increases with the density (Figure 5a) while it is inversely proportional to the water absorption (Figure 5b) and the permeability (Figure 5c). Based on the experimental evidence, the linear models depicted on the subfigures were established.

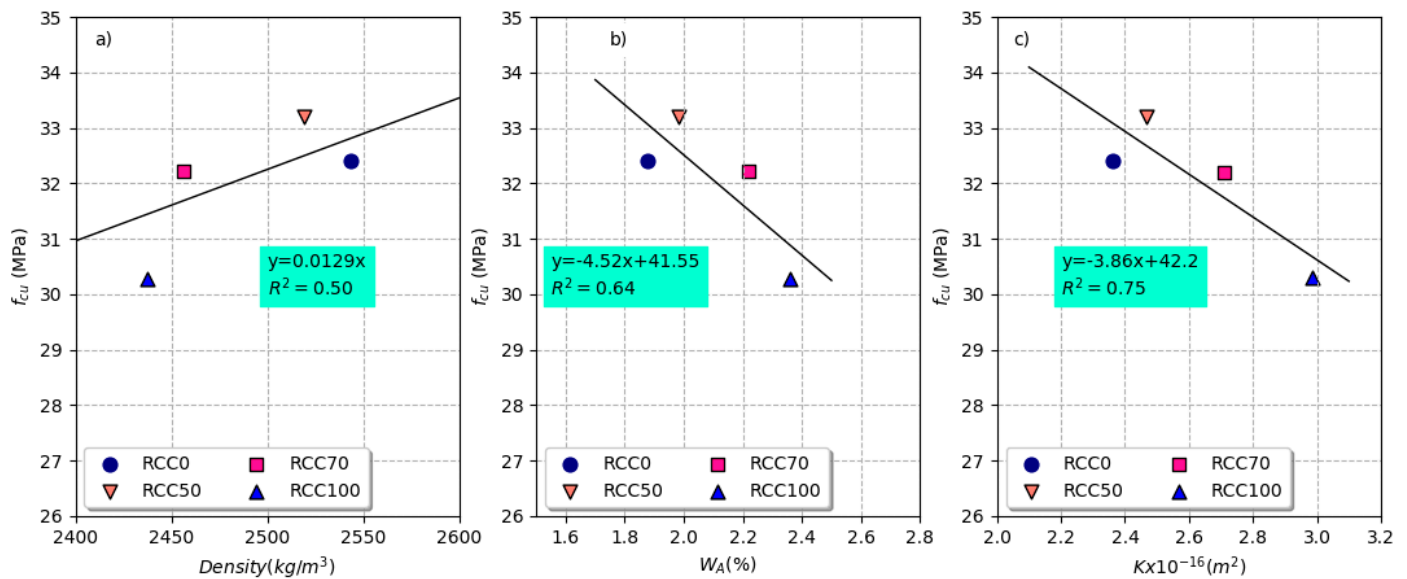


Figure 5. The compressive strength versus (a) the density, (b) water absorption, and (c) permeability.

Figure 6 illustrates the variation of the splitting tensile strength with the compressive strength at 28 days (Figure 6a) and the replacement ratio (Figure 6b). The splitting tensile strength is linearly proportional to the compressive strength while its variation is nonlinear with the substitution ratio.

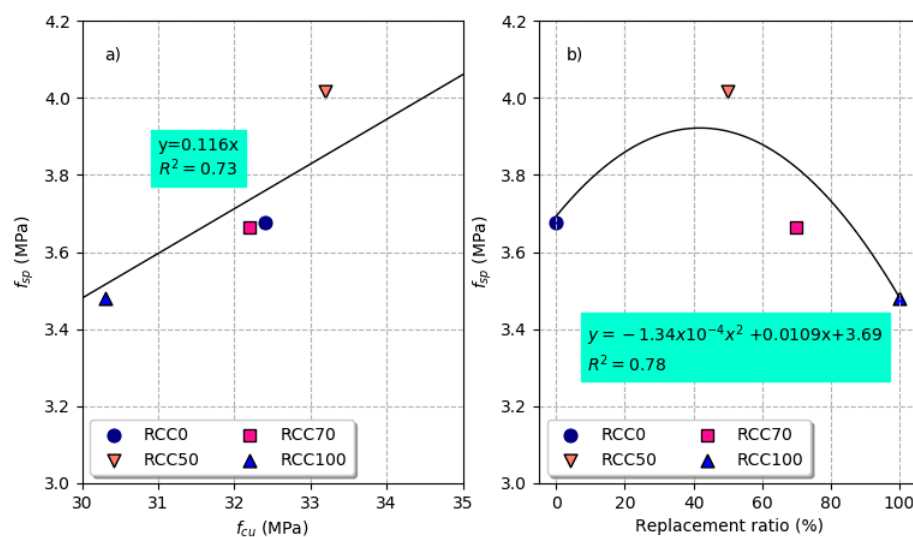


Figure 6. Splitting tensile strength versus (a) compressive strength and (b) replacement ratio.

4. Conclusions

The paper aimed to study the effect of recycled aggregates on the physical and mechanical properties of roller compacted concrete containing recycled aggregate with incorporation ratios of 50%, 70%, and 100% replacement ratios.

Based on the obtained results the following conclusions can be withdrawn:

- The introduction of recycled aggregates in RCC mixtures induces an increase in the water absorption and gas permeability accompanied by a decrease in concrete density;
- Coarse recycled aggregates concrete can be introduced in RCC mixtures up to 100% without significantly altering the compressive strength. The decrease in mechanical properties for all percentage ratios remains very slight as compared to the reference concrete;
- The substitution of natural aggregates by recycled ones does not affect the development of strength over time. The compressive strength at any age can be estimated using analytical models developed for hydraulic concrete with natural aggregates;
- The introduction of recycled aggregates induces a reduction in the splitting and flexural tensile strength when the substitution ratio is 100%;
- The decrease in mechanical properties is a consequence of the increase in physical properties (absorption and permeability). Linear relationships describing the experimental finding were established with good correlation factors.

Author Contributions: Conceptualization, formal analysis, investigation, and test performing, A.I.; supervision and validation of test results, A.K. and M.A.; review and editing the original manuscript, G.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no funding.

Conflicts of Interest: The authors declare no conflict of interest.

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