sustainability

Article

Strength and Water Absorption of Sustainable Concrete Produced with Recycled Basaltic Concrete Aggregates and Powder

Ibrahim Sharaky [1,*], Usama Issa [1], Mamdooh Alwetaishi [1], Ahmed Abdelhafiz [1], Amal Shamseldin [1], Mohammed Al-Surf [2], Mosleh Al-Harthi [3] and Ashraf Balabel [4]

[1] Civil Engineering Department, College of Engineering, Taif University, P.O. Box 11099, Taif 21099, Saudi Arabia; u.issa@tu.edu.sa (U.I.); m.alwetaishi@tu.edu.sa (M.A.); a.abdelhafiz@tu.edu.sa (A.A.); ashamseldin@tu.edu.sa (A.S.)
[2] U.S. Green Building Council and Green Business Certification Inc., Jeddah 23525, Saudi Arabia; malsurf@gbci.org
[3] Electrical Engineering Department, College of Engineering, Taif University, P.O. Box 11099, Taif 21099, Saudi Arabia; m.harthi@tu.edu.sa
[4] Mechanical Engineering Department, College of Engineering, Taif University, P.O. Box 11099, Taif 21099, Saudi Arabia; a.balabel@tu.edu.sa
* Correspondence: i.sharaky@tu.edu.sa

Abstract: In this study, the recycled concrete aggregates and powder (RCA and RCP) prepared from basaltic concrete waste were used to replace the natural aggregate (NA) and cement, respectively. The NA (coarse and fine) was replaced by the recycled aggregates with five percentages (0%, 20%, 40%, 60% and 80%). Consequently, the cement was replaced by the RCP with four percentages (0%, 5%, 10% and 20%). Cubes with 100 mm edge length were prepared for all tests. The compressive and tensile strengths (f_{cu} and f_{tu}) and water absorption (WA) were investigated for all mixes at different ages. Partial substitution of NA with recycled aggregate reduced the compressive strength with different percentages depending on the type and source of recycled aggregate. After 28 days, the maximum reduction in f_{cu} value was 9.8% and 9.4% for mixtures with coarse RCA and fine RCA (FRCA), respectively. After 56 days, the mixes with 40% FRCA reached almost the same f_{cu} value as the control mix (M0, 99.5%). Consequently, the compressive strengths of the mixes with 10% RCA at 28 and 56 days were 99.3 and 95.2%, respectively, compared to those of M0. The mixes integrated FRCA and RCP showed higher tensile strengths than the M0 at 56 d with a very small reduction at 28 d (max = 3.4%). Moreover, the f_{cu} and f_{tu} values increased for the late test ages, while the WA decreased.

Keywords: basalt; recycled concrete aggregate; concrete properties; recycled natural basalt; recycled concrete powder

Citation: Sharaky, I.; Issa, U.; Alwetaishi, M.; Abdelhafiz, A.; Shamseldin, A.; Al-Surf, M.; Al-Harthi, M.; Balabel, A. Strength and Water Absorption of Sustainable Concrete Produced with Recycled Basaltic Concrete Aggregates and Powder. *Sustainability* **2021**, *13*, 6277. https://doi.org/10.3390/su13116277

Academic Editors: Fausto Minelli, Enzo Martinelli and Luca Facconi

Received: 14 April 2021
Accepted: 25 May 2021
Published: 2 June 2021

1. Introduction

Nowadays, a lot of attention is paid to the sustainable disposal of construction waste and its management, as it decreases the cost of disposal and reduces the environmental impact (EI) [1]. The construction industry has caused high environmental impacts worldwide as it demands excessive extraction of raw materials. Sand and gravel are the highest materials that are used on Earth next to water in contrast, and their natural regeneration rates are significantly lower than their usages as was specified by the United Nations Environment Programme. Natural aggregates of about 45 billion tons were extracted in 2017 and they are estimated to rise to 66 billion tons in 2025. Moreover, about 40 billion tons/year from aggregates were consumed in the cement product industries worldwide [2–4]. Furthermore, the European Statistical Office reported that about 923 billion tons/year of industrial wastes are produced from the construction works. The wastes generated from the construction industry are more than 33% of all wastes produced in the EU, of which about 90% could be reused as recycled materials. In 2018, about 10.93% of the consumed aggregate in Europe came from secondary sources (artificial, recycled, filled). More countries tried to increase their recycling rates of construction and demolition waste (C and DW) to replace the natural aggregate [2,5]. The extraction of recycled aggregates should be an essential part of the economy. The benefits of using recycled aggregates are reducing landfill space and energy of extracting raw materials, reducing greenhouse gases, preserving the natural resources, and achieving environmental sustainability [6].

Green concrete can meet structural function and service life with higher durability and strength than normal concrete (NC). It can be used to construct comfortable and suitable residential buildings for people [7]. Green concrete reduces the biological impact on the environment (environmentally friendly concrete material) either during the manufacturing process or use [8]. There are several modes of production, such as recycled aggregate concrete (RAC), fly ash concrete (FAC), and circular economy concrete (CEC) [9]. In the previous ways of making green concrete, urban construction waste is used as recycled aggregate while the fly ash (FA) as industrial waste is completely consumed. Green concrete can save resources of natural material, reduce spaces, save energy consumption, and reduce soil pollution [9]. Waste clay bricks (WCBF) are also used as a fine aggregate with various replacement ratios to produce recycled brick concrete (RBC) [10]. Increasing the WCBF replacement ratios decreased the density and compressive strength (f_{cu}) of RBC mainly with increasing water amount. Up to 50% WCBF replacement and without additional water, the properties of RBC (density, split tensile strength (f_{tu}), elastic modulus (E), and f_{cu}) were comparable to NC. Moreover, the use of untreated coal waste particles as concrete aggregate with an appropriate replacement ratio reduces the environmental impact of untreated coal waste and improves the mechanical properties of concrete by about (3–8%) [11].

The effects of ground granulated blast furnace slag (GGBFS) on the properties of recycled concrete (RCA) are also summarized [12–14]. Poured concrete with 50% RCA and 30% GGBFS showed comparable mechanical properties to the concrete with natural aggregate (NAC) [12]. The RCA concretes are usually used in road substructure because of the lower mechanical properties, higher WA and porosity f RCA compared to the NAC [15–17]. Consequently, the reduction in the mechanical performance of RCA concretes compared to NC is also reported in [18–20]. The reduction in the mechanical performance of RCA compared to NC is also presented in [15–17]. Concrete with 100% RCA showed 24% lower compressive strength compared to NAC [12]. In contrast, concrete containing up to 30% RCA as NA replacement can achieve the targeted NAC strength [17]. To achieve the sustainability of construction materials and international consensus, RCA should be used to produce new concrete, however, they show higher WA and weakness of interfacial transition zones (ITZs) that could reduce their mechanical properties compared to NAC [21–28]. The attached cement mortar to RCA surfaces affected their physical properties [15,29]. Consequently, the attached or adhered mortar quantity is also modified with the crushing procedure. Moreover, RCA has a lower density and higher WA than NA because of the adhered mortar. Furthermore, the adhered mortar with un-hydrated cement could modify crack propagation and concrete properties [30–32]. Thus, the concrete mechanical properties (compressive and tensile strengths) reduced as the RCA% in the mix increased [33–35].

Fly ash, cenosphere fly ash (CFA) and sintered fly ash are used to produce sustainable concrete as substitutes for cement, fine aggregate and coarse aggregate, respectively [36,37]. Moreover, several studies confirmed that the use of RCA in concrete has a positive effect on EI and cost [38–40]. In [38], the use of 30% and 100% RCA reduced the EI by up to 8% and 23%, respectively. Similarly, in [41], using 30% RCA and 100% RCA instead of NAC in concrete resulted in net cost benefits of 9 and 28%, respectively. Moreover, the environmental and cost impacts were reduced by 50.8 and 68.1% when waste concrete was used to produce RAC concrete [42]. Conversely, the use of 50%RCA was found to be the optimum percentage in terms of EI and cost efficiency [43], while in [44], the appropriate RCA percentage was 80%.

The effect of fine RCA (FRCA) on concrete strengths has been studied [2,38,45–50]. For concrete with 25% FRCA and 100% FRCA, the compressive strength decreased by 15% and 30% respectively, compared to NAC, while the shrinkage increased [45]. Consequently, an admixture of FRCA in concrete decreases its compressive strength and increases shrinkage compared to NAC [46]. Moreover, increasing the proportion of foundry sand (FS) and recycled fine aggregate (RFA) up to 100% resulted in a decrease in compressive strength [51]. In contrast, RFCA had no effect on concrete strength when the FRCA was added by less than 30% [38]. The method of FRCA production affected the properties and integrated concrete [48]. Conversely, the WA, and chloride penetration of concrete with integrated FRCA increased, while its carburization resistance decreased when FRCA was added [47]. The cement mortars grouted with FRCA exhibited a reduction in their compressive and flexural strengths with increasing FRCA content [49,50].

Concrete strength cast with 20% recycled glass sand (RGS) gained its design strength after 7 days. Concrete strength decreased slightly with increasing RGS content. The same previous effects of RGS on flexural and tensile strength were also reported, with f_{tu}/f_{cu}% ranging from 8% to 11% [52]. In addition, the use of individual plastic (PA), rubber (RA) and glass (GA) to partially replace the fine NA showed different effects on concrete strengths [53]. Except for 15% GA, all mixes showed a reduction in compressive strength compared to NAC. The PA concrete showed the highest strength reduction (about 50% for 30% PA) compared to NAC [53]. The same trends were observed for tensile strength as the mixes integrated 30% PA and 30% RA (f_{tu} reduction was 27% and 35%, respectively) [53]. The basalt powder can reduce the EI and improve the concrete properties [54,55]. Consequently, in [56,57], the basalt aggregate and basalt powder had an almost similar composition to Ordinary Portland Cement (OPC) and silica fume (SF). Although the waste glass had pozzolanic or cementitious properties, only part of those wastes can be used as cement replacement SCM as it can be reused to produce new glass [58–60]. Among the several types of glasses, soda-lime glasses are the most public type [61]. It also contains around 73% SiO_2, 10% CaO, and 13% Na_2O that makes it pozzolanic SCM that can be used in concrete [61]. The basalt powder can reduce the IE during the basalt extraction and can also be used to improve the concrete properties [54]. Additionally, in [56,57], the basalt aggregate and basalt powder had a near-similar composition as OPC and SF.

Several theoretical models have been used to evaluate the RAC mechanical properties. In [62], most of these available theoretical models were reported. The reported available models are not rather accurate [62]. For this reason, new mathematical approaches were developed to evaluate the RCA mechanical properties [62]. The proposed model could predict the RAC mechanical properties with higher accuracy and simpler formulae than the available existing models [62].

The above review shows that the use of recycled components obtained from concrete previously cast with basalt is still limited, especially for FRCA and recycled concrete powder (RCP). In this study, the coarse RCA (CRCA) produced from the basaltic concrete waste (CRCA) was used to replace the coarse NA with five percentages (0%, 20%, 40%, 60% and 80%). Consequently, the FRNA was used to partially replace the fine NA with five percentages (0%, 20%, 40%, 60% and 80%). Conversely, the RCP was used to replace the cement with four percentages (0%, 5%, 10% and 20%). Cubes with 100 mm edge length were cast, cured, and tested to obtain the concrete strengths and WA after different curing times (7, 28 and 56 days). The results obtained were also discussed and compared with those of NAC.

2. Research Significance

The use of concrete waste as a recycled aggregate is popular to produce new concrete. In contrast, the use of concrete waste powder as a cement substitute is still limited. Although the basaltic concrete waste has a pozzolanic effect, the use of this waste as a substitute for aggregate and cement is still limited. In this study, the use of basaltic concrete waste as a substitute for natural aggregates with low and high content was investigated. In addition, the use of basaltic concrete powder, that had pozzolanic activity, to replace cement and produce sustainable/green concrete was also investigated.

3. Experimental Work

3.1. Material Properties

3.1.1. Natural Aggregates

The crushed basalt (Figure 1a) and natural sand (Figure 1b) were the coarse and fine aggregates used for the control mixtures. The maximum nominal size (MNS) of the basalt gravel used in this experimental program was 12.5 mm. The natural sand had a fineness modulus of 3.2. The grading curves of the sand and basalt were in accordance with the limits of ASTM C33 [63] (Figure 2a). The physical properties of crushed basalt (coarse NA) and natural sand are listed in Table 1.

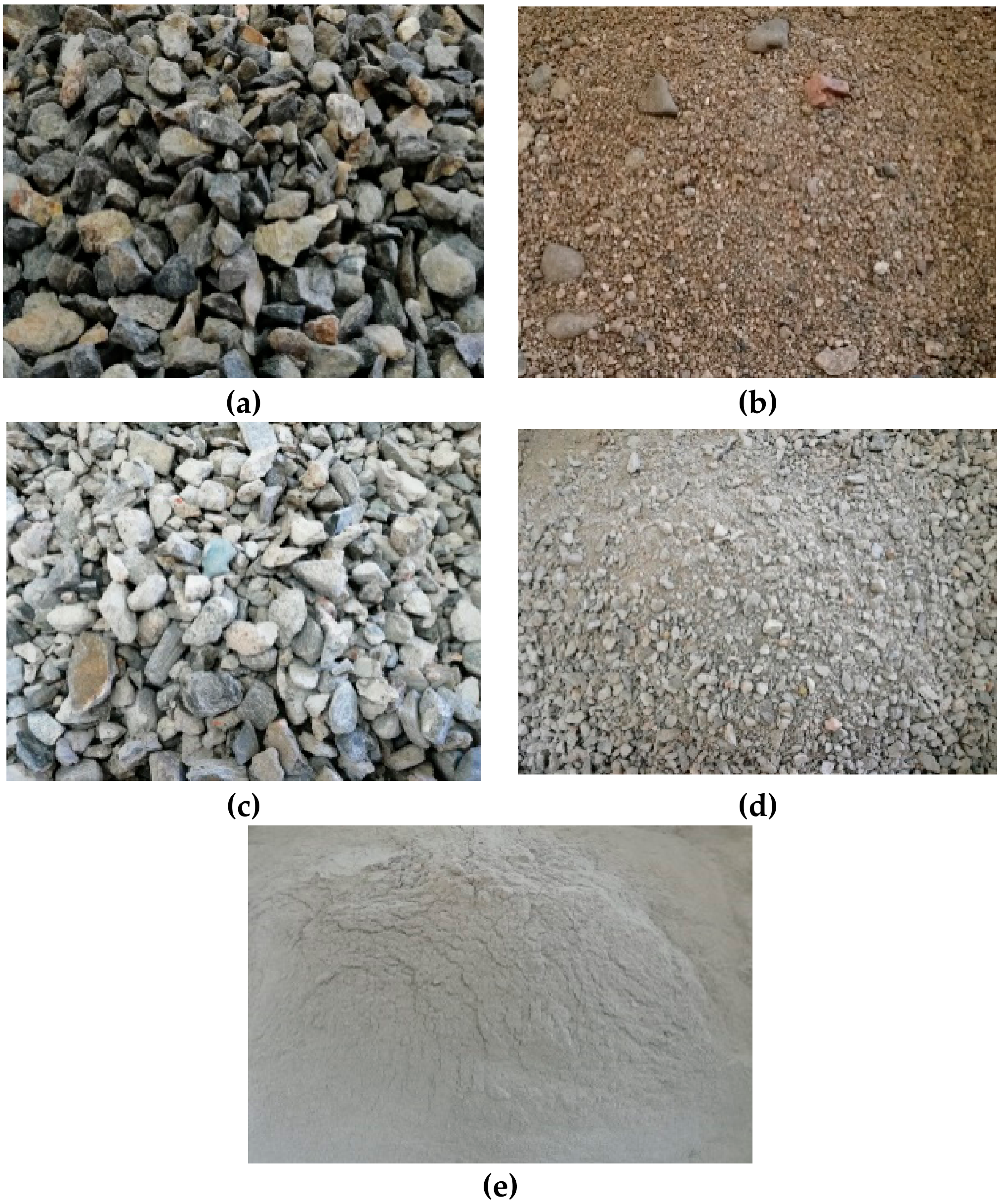


Figure 1. The aggregate and waste materials used in this study. (**a**) Natural basalt aggregate; (**b**) Natural sand; (**c**) CRCA; (**d**) FRCA; (**e**) RCP.

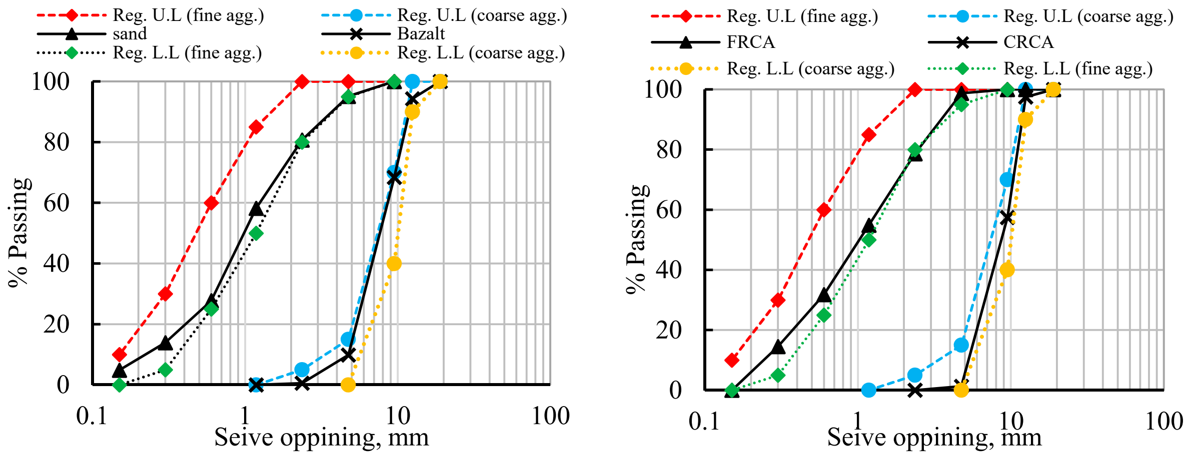


Figure 2. Sieve analysis for the natural and recycled aggregates. (**a**) NA; (**b**) RCA and RNA.

Table 1. Physical properties of natural and recycled aggregate.

Physical Properties	Coarse NA	CRCA	Natural Sand	FRCA
Apparent specific gravity (kg/m^3)	2.95	2.76	2.71	2.64
Bulk specific gravity (SSD) (gr/cm^3)	2.86	2.57	2.28	2.15
Bulk specific gravity (GD) (gr/cm^3)	2.81	2.46	2.03	1.86
Water absorption (%)	1.77	4.32	10.96	13.82
Moisture content (%)	0.93	1.25	2.73	2.37

3.1.2. Recycled Concrete Aggregates

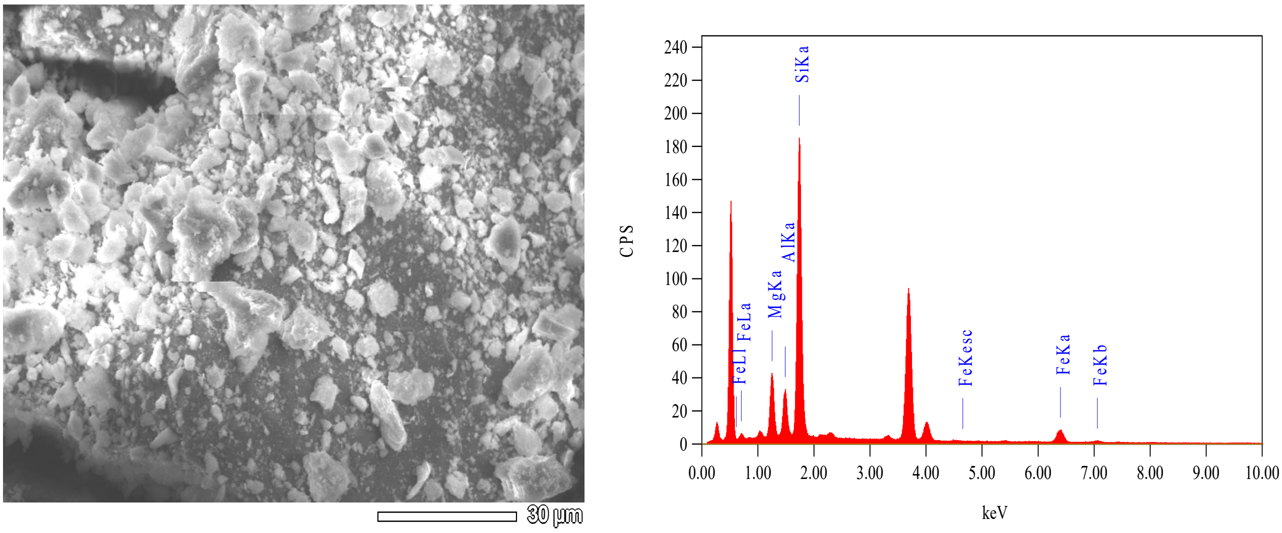
The recycled basaltic concrete is taken from old concrete cubes and cylinders that were tested in the lab five to six years ago for previous research projects and kept outside the lab as wastes. The old cubes and cylinders were manually crushed then put in a crushing machine to obtain RCA, FRCA and powder. The concrete strength of the old concrete ranged from 33 MPa to 39 MPa. The CRCA and FRCA obtained from the basalt concrete are shown in Figure 1c,d, respectively. The standard sieves were used to separate the basaltic concrete wastes (BCWs) into CRCA, FRCA and RCP. The CRCA remaining on sieve No. 4 (sieve opening = 4.75 mm) was used as a replacement for the coarse NA. The MNS of the CRCA used in this experimental program was adjusted to correspond to 12.5 mm. The selected MNS (12.5 mm) was adopted to minimize the negative effects of the FRCA compared to other larger sizes (19 and 25 mm) on the durability and strength of the concrete [64]. Consequently, the FRCA that passed the No. 4 sieve and remained on the No. 100 sieve (sieve opening = 150 microns) were used to replace the fine NA (sand). The fineness modulus of the FRCA was also equal to 3.2. The particle size distribution curves of the CRCA and FRCA were adjusted to comply with the limits of ASTM C33 [63] (Figure 2b). The physical properties of CRCA and FRCA are listed in Table 1.

3.1.3. Recycled Concrete Powder

The RCP passed from sieve No. 100 during sieve analysis of BCWs is shown in Figure 1e. The RCP was analyzed by scanning electron microscope (SEM and EDS) to find its chemical components. The obtained chemical components from EDS analysis are listed in Table 2, while the photos of EDS and SEM are shown in Figure 3a,b, respectively.

Table 2. The chemical compositions of OPC and RCP.

Item	SiO_2	CaO	AL_2O_3	Fe_2O_3	MgO	SO_3	LOI
OPC	21.28	64.64	5.60	3.42	2.06	2.12	0.88
RCP	66.23	-	9.61	11.84	12.32	-	-



(**a**) (**b**)

Figure 3. RCP components. (**a**) SEM; (**b**) EDS.

3.1.4. Cement

The OPC produced locally in one of the Cement Factories in KSA was used for all concrete mixes. The chemical composition of this cement as provided by the supplier is also given in Table 2.

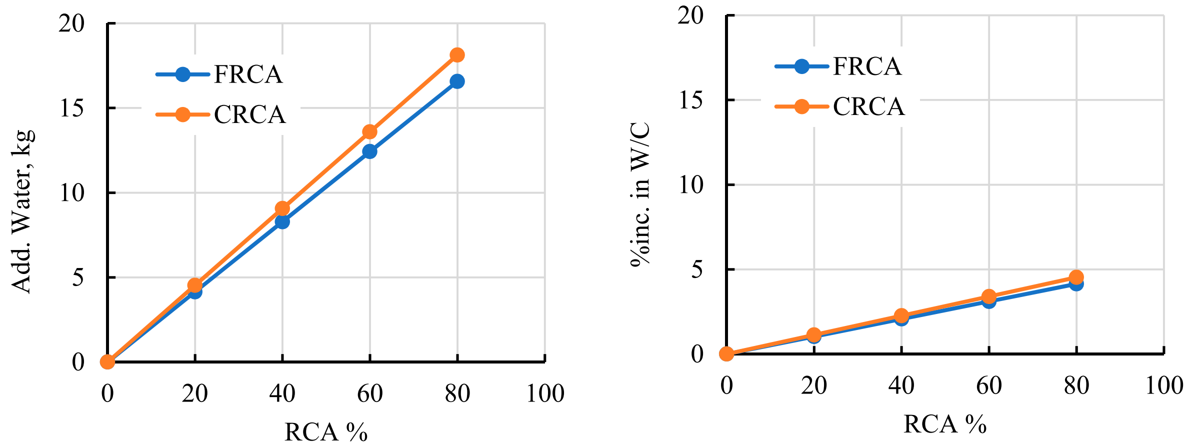
3.2. Validation of the Material Chemical Composition as Natural Pozzolana

The chemical properties of the basaltic concrete powder are shown in Table 1. The chemical composition of RCP is underlain by silica (SiO_2). ASTM C618 recommends a sum of SiO_2, Fe_2O_3, and Al_2O_3 greater than 70% for the chemical composition requirements of natural pozzolana. According to Table 2, the sum of SiO_2, Fe_2O_3, and Al_2O_3 for RCP (87.68%) meets the ASTM C618 requirements for natural pozzolana. Therefore, the utilization of RCA as fine and coarse aggregate and RCP as a waste powder in the hydration process can help to produce sustainable concrete based on basalt waste.

3.3. Mix Proportions and Mixing Procedure

In this work, a control mix (M0) was designated according to the ACI specification [65] to obtain 35 MPa cylindrical concrete strength at 28 days. The M0 mix was designated to keep a slump of 50–80 mm and mechanical compaction was used. The CRCA and FRCA gradings were adopted to be like that for NA. The W/C ratio for M0 was adopted to be 0.5. For mixes with recycled aggregate, the recycled aggregate was used to partially replaced the natural aggregate by weight. All the aspects remained unchanged to study the effects of replacing this recycled aggregate with their different physical properties on the concrete mechanical properties and water absorption. Most previous studies neglected the humidity and water absorption when designing the concrete mixes with or without recycled materials [18,51–53]. The mix M0 was prepared, and its slump was obtained. The slump of M0 mix achieved the required slump with neglecting the humidity and water content of the aggregates. For mixes incorporating RCA, the additional water required for each mix to keep the same consistency of M0 mix was calculated and added during mixing (Figure 4a).

The mix (M0) consisted of natural sand, natural basalt and OPC with weight percentages of 643, 1016 and 400 kg/m^3 respectively (Table 3). The effect of the CRCA and FRCA on the W/C is also shown in Figure 4b. In order to produce sustainable concrete, eleven mixes (M1 to M11) were prepared in which the natural concrete constituents (aggregates and cement) were replaced by the recycled waste materials in different proportions. For the mixes M1-M4, the CRCA was used to replace the coarse NA with five percentages (0%, 20%, 40%, 60% and 80%, respectively). For mixtures M5-M8, natural sand was replaced with FRCA at five percentages (0%, 20%, 40%, 60%, and 80%, respectively). In addition, for mixes M9-M11, OPC was replaced with RCP at four percentages (0%, 5%, 10%, and 20%, respectively). Full details of the mix proportions for all mixes are summarized in Table 3. The aggregates and cement were dry mixed in the concrete mixer for 1 min. The RCP (if any) was then added and dry mixed for another 1 min. Then, the water was added gradually, and mixing was completed for another 2 min. The concrete mixtures were poured into 100 × 100 × 100 mm^3 cubes. The cubes were de-moulded after 24 h and cured in a water tank until the test age (7, 28, and 56 days).



(**a**) (**b**)

Figure 4. The relation between RCA% and (**a**) extra water; (**b**) % increase in W/C ratio.

Table 3. Concrete mixture proportion for 1 m^3.

Group	Mix ID	Recycled Aggregate (%)	RCP (%)	Aggregates (kg)				Water (kg)	Cement (kg)
				Natural Sand	Natural Basalt	FRCA	CRCA		
Control	M0	0	0	643	1016	0	0	200	400
CRCA	M1	20	0	643	812.8	0	203.2	200	400
	M2	40	0	643	609.6	0	406.4	200	400
	M3	60	0	643	406.4	0	609.6	200	400
	M4	80	0	643	203.2	0	812.8		
FRCA	M5	20	0	514.5	1016	128.6	0	200	400
	M6	40	0	385.9	1016	257.3	0	200	400
	M7	60	0	257.3	1016	385.9	0	200	400
	M8	80	0	128.6	1016	514.5	0	200	400
RCP	M9	0	5	643	1016	0	0	200	380
	M10	0	10	643	1016	0	0	200	360
	M11	0	20	643	1016	0	0	200	320

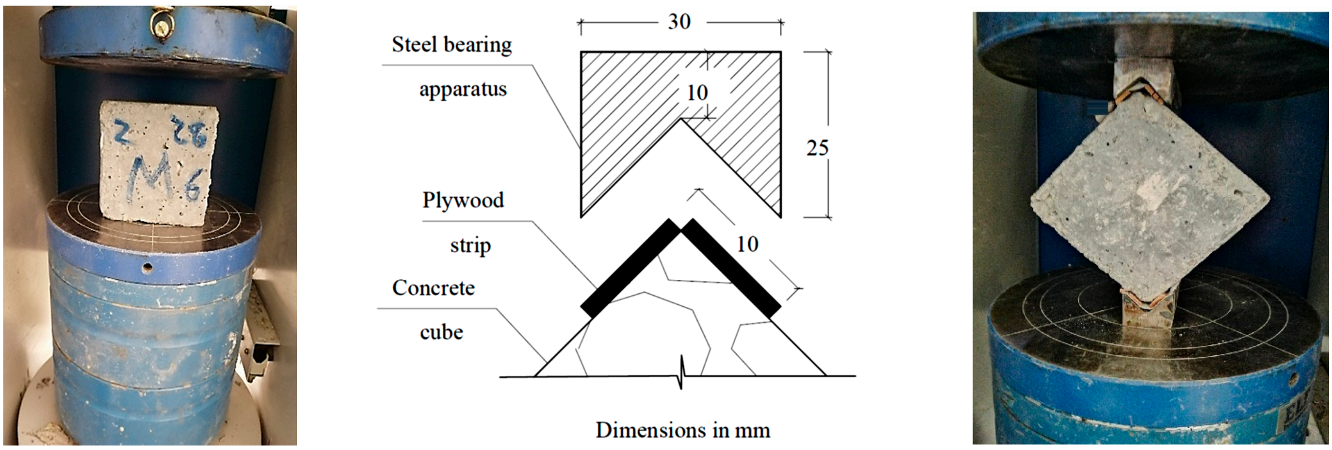
3.4. Test Method

To evaluate the compressive strengths of all mixes, the 100-mm cube specimens were compression tested at 7, 28, and 56 days according to BS EN 12390-3 [66]. At each age, the results of three tested cubes were averaged to obtain the compressive strength (f_{cu}). The concrete tensile strengths (f_{tu}) at 28 and 56 d were also obtained from the diagonal splitting test for the cubes with 100 mm edge length, as shown in Figure 5 and Equation (1) [67].

$$\sigma_{max} = \frac{2P}{\pi bd}\left[\left(1-\beta^2\right)^{\frac{5}{3}} - 0.0115\right] \quad (1)$$

where b and d are the width and diagonal length of the cube, and P is the maximum compressive load. In this study, the value of β is equal to 0.15. At each age, the results of three tested cubes were averaged to obtain the tensile strength (f_{tu}). The compression testing machine with a maximum capacity of 2000 tons was used to test the cubes in compression and in tension at a loading rate of 4 and 3 kN/s, respectively. Water absorption (*WA*) is one of the well-known concrete durability factors [47,68,69]. Moreover, *WA* of concrete was considered as a measure for resistance against carbonation and chloride migration [70]. *WA* was obtained according to ASTM C642 [71] to compare the durability of the mixes after 28 and 56 days. First, the concrete specimens (3 cubes at each age) were dried at a temperature (T) of 100–110 °C for more than 24 h to find the oven-dried mass (A) in grams. Subsequently, the samples were engrossed in water at T ≈ 21 °C for more than 48 h, then the surface-dried samples were weighed in grams (*B*), and then *WA* was calculated according to Equation (2).

$$WA\ \% = \left[\frac{(B-A)}{A}\right] \times 100 \quad (2)$$



(**a**) (**b**)

Figure 5. Details of the compression and diagonal cube splitting tests. (**a**) Compression test; (**b**) Details of diagonal cube splitting test.

4. Results and Discussions

4.1. Concrete Compressive Strength

The cubic concrete strengths (f_{cu}) at 7, 28, and 56 days of age ($f_{cu,7}$, $f_{cu,28}$, and $f_{cu,56}$, respectively) are shown in Table 4. The reduction values of concrete strength at 7, 28, and 56 days (μ_7, μ_{28}, and μ_{56}) due to partial replacement of natural basalt, sand and cement by the recycled waste are also presented in Table 4. The percentage increase in $f_{cu,28}$ compared to $f_{cu,7}$ ($\mu_{28/7}$) and $f_{cu,56}$ compared to $f_{cu,28}$ ($\mu_{56/28}$) for all the tested mixes are also presented in Table 4. The effect of recycled waste on compressive strengths is discussed in the following sections. The percentage compressive strength decreases at each curing time ($\mu_{cu,date}$%) is calculated using Equation (3).

$$\mu_{cu,date}\% = \frac{f_{cu,date}(R) - f_{cu,date}(N)}{f_{cu,date}(N)} \times 100 \quad (3)$$

where $f_{cu,date}$ (R) and $f_{cu,date}$ (N) are the compressive strengths of the mixtures that integrate waste and the control mixture, respectively.

Table 4. The concrete compressive strength for all mixes at 7, 28 and 56 d.

Group	Mix ID	Specimen No.	$f_{cu,7}$ MPa	Mean (σ_μ) MPa	μ_7 %	$f_{cu,28}$ MPa	Mean (σ_μ) MPa	μ_{28} %	$f_{cu,56}$ MPa	Mean (σ_μ) MPa	μ_{56} %	$\mu_{28/7}$ %	$\mu_{56/28}$ %
Control	M0	1	35.60	34.07 (±1.34)	0.0	43.50	43.60 (±0.10)	0.0	52.48	50.02 (±2.72)	0.0	27.98	14.7
		2	33.10			43.70			50.48				
		3	33.50			43.60			47.10				
CRCA	M1	1	28.10	28.17 (±1.00)	17.3	38.50	39.33 (±0.80)	9.80	44.93	44.82 (±0.27)	10.4	39.64	13.9
		2	27.20			39.40			44.51				
		3	29.20			39.69			45.01				
	M2	1	27.70	29.33 (±1.20)	13.9	39.87	39.65 (±0.24)	9.10	45.81	45.33 (±0.80)	9.40	35.18	14.3
		2	30.10			39.40			45.78				
		3	28.80			39.69			44.40				
	M3	1	28.70	30.40 (±1.61)	10.8	41.00	40.30 (±0.72)	7.60	46.60	45.47 (±0.99)	9.10	32.58	12.8
		2	30.60			39.57			45.00				
		3	31.90			40.34			44.80				
	M4	1	28.20	28.37 (±1.26)	16.7	37.48	37.86 (±0.87)	13.2	40.35	40.86 (±0.66)	18.3	33.47	7.90
		2	29.70			38.85			40.98				
		3	27.20			37.25			40.25				
FRCA	M5	1	30.60	29.81 (±0.80)	12.5	40.54	39.81 (±1.22)	8.70	42.83	44.53 (±0.00)	11.0	33.57	11.8
		2	29.00			40.50			45.54				
		3	29.82			38.40			45.22				
	M6	1	29.80	29.01 (±0.80)	14.8	39.63	39.50 (±0.21)	9.40	47.86	49.78 (±0.00)	0.50	36.14	26.0
		2	28.20			39.61			54.71				
		3	29.04			39.26			46.49				
	M7	1	32.50	33.73 (±1.20)	1.0	40.64	41.60 (±2.46)	4.60	46.49	45.25 (±1.28)	9.50	23.33	8.80
		2	34.90			44.40			43.93				
		3	33.80			39.77			45.32				
	M8	1	32.40	32.30 (±0.10)	5.2	39.98	40.09 (±0.57)	8.10	45.71	45.04 (±1.32)	10.0	24.11	12.4
		2	32.30			40.70			43.52				
		3	32.20			39.58			45.89				
RCP	M9	1	32.02	32.01 (±0.06)	6.0	38.73	38.80 (±0.50)	11.0	44.60	44.81 (±0.55)	10.4	21.20	6.70
		2	31.95			39.33			45.44				
		3	32.07			38.34			44.40				
	M10	1	22.34	22.93 (±0.84)	32.7	43.39	43.30 (±0.32)	0.70	46.90	47.61 (±0.67)	4.80	88.81	3.70
		2	23.90			43.57			48.24				
		3	22.56			42.94			47.70				
	M11	1	22.89	21.57 (±1.24)	36.7	39.70	38.27 (±2.32)	12.2	41.20	42.43 (±1.07)	15.2	77.39	11.4
		2	20.42			39.52			43.00				
		3	21.41			35.59			43.10				

$\mu_{Tc}\% = \frac{f_{cu,Tc}(any\ mix)}{f_{cu,Tc}(Mix0)} \times 100$ where Tc = 7, 28, and 56 days.

4.1.1. Effect of the CRCA

For all mixes, the compressive strength increased with increasing curing age (Figure 6a). Comparing the strengths obtained at 7 and 56 days with those obtained at 28 days, they showed higher rates of strength increase when Tc was increased from 7 to 28 days than when Tc was increased from 28 to 56 days. This may be due to the higher cement hydration rates during the first 28 days compared to the late days.

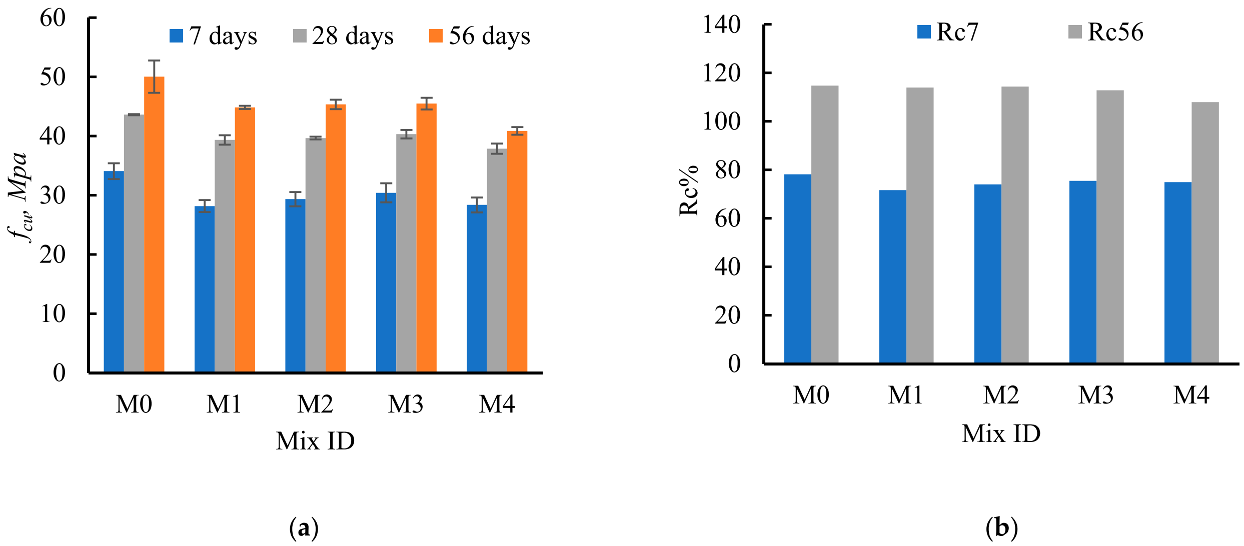


Figure 6. Effect of the CRCA%. (**a**) Concrete compressive strength; (**b**) The compressive strength ratio (Rc%).

The increase in strengths with increasing curing age was also related to CRCA%. When Tc increased from 7 to 28 days, the strength increased by 27.8%, 39.6%, 35.2, 32.5 and 33.4% for M0 to M4, respectively, illustrating the influence of CRCA% on early cement hydration. Consequently, the strength increased with increasing Tc from 28 to 56 d by 14.7%, 13.9%, 14.3%, 12.8% and 7.9% for M0 to M4, respectively. The low increase in strength at 56 days for the mixes integrating CRCA% than that of M0 ensured the effect of crushed concrete and its voids on the absorption of water required to complete cement hydration. The replacement of coarse NA with CRCA generally reduced the concrete strength. The CRCA are made of recycled basalt, and crushed concrete, which had a high void ratio compared to NA, and can affect concrete strength and cement hydration in addition to the powder. Strength reduction was strongly influenced by CRCA% and curing age. After 7 days, the strength reduction (μ_7%) is 17.3%, 13.9%, 10.8%, and 16.7% for mixtures with CRCA content of 20%, 40%, 60%, and 80%, respectively (mean (μ) = 14.8% and standard deviation (σ_μ) = ±2.6%). Subsequently, after 28 days, the strength reduction (μ28%) is 9.8%, 8.7%, 6.9% and 12.2% for mixes with CRCA content of 20%, 40%, 60% and 80%, respectively (μ = 9.9% and σ_μ = ±2.05%). Moreover, the strength reduction (μ56%) after 56 days is 10.4%, 9.4%, 9.1%, and 18.3% for mixes with CRCA content of 20%, 40%, 60% and 80%, respectively (μ = 11.8% and σ_μ = ±3.8%). These reductions were due to the CRCA defects that negatively affected their interfacial transition zones (ITZs)). These weak ITZs led to the propagation of the concrete cracks and reduced the strength values [72–77]. The lowest values of μ7, μ28 and μ56 are 10.8%, 6.9% and 9.1%, respectively (M3, CRCA = 60%). The mixtures with CRCA (M1-M4) experienced higher differences between $\mu_{28/7}$ and $\mu_{56/28}$ compared to M0 (Table 4). These observations summarize the weak ITZs between the cement paste and CRCA (C- CRCA) besides the CRCA voids. At Tc = 28 days, C-CRCA bond may be enhanced by the hydration of the RCP surrounding CRCA (RCP has a pozzolanic effect as mentioned earlier).

To assess the CRCA effects on the strength gained at 7 and 56 days compared to that at 28 days, the Rc7 (f_{cu7}/f_{cu28}) and Rc56 (f_{cu56}/f_{cu28}) were calculated (Figure 6b). From the figure, the Rc7 decreased for mixed integrated CRCA compared to M0. The values of Rc7% are 78.1%, 71.6%, 74%, 75.4%, and 74.9% for CRCA% of 0%, 20%, 40%, 60%, and 80%, respectively. Moreover, the values of R56% are 114.7%, 113.9%, 114.3%, 112.8% and 107.9% for the CRCA% of 0%, 20%, 40%, 60% and 80%, respectively. The comparison of the R7 and R56 values of M0 with those of M1–M5 highlights the small effects of CRCA% on the Rc7 and Rc56 values of concrete especially for M3. It is evident from [11,78] that the concrete strength decreased sharply when the coal waste and RCA aggregates replaced NA. Moreover, in [78] a strength reduction of about 26–32% was reported when the RCA aggregates replaced NA. Furthermore, compressive strength reduction of lower than 40% was observed when RAC was incorporated [79]. When the NA was replaced by RCA of 25–50%, the compressive strength reduction was 2–3% depending on the RCA source while when the RCA replacement was more than 50%, the reduction was 15–23% [22]. Based on the above results, basaltic CRCA could be considered as a good substitute for the coarse NA to produce sustainable concrete and reduces the environmental impact and cost of concrete production.

4.1.2. Effect of the FRCA

The effect of FRCA on concrete strength was also investigated (Figure 7). With increasing Tc, the strength increased for all mixes with FRCA (Figure 7a), although the trend was different from the CRCA mixes. The increase in strengths with increasing curing age was also related to the FRCA content. When Tc increased from 7 to 28 days, the strength increased by 33.57%, 36.14%, 23.33% and 24.11% for M5 to M8, respectively, highlighting the influence of CRCA% on early cement hydration. Consequently, the strength increased by 11.8%, 26%, 8.8% and 12.4% for M5 to M8, respectively, when Tc was increased from 28 to 56 days. Replacing sand with FRCA generally decreased the concrete strength. At 7 days, when FRCA replaced sand at 20%, 40%, 60% and 80%, the strength reduction was 12.5%, 14.8%, 1.0% and 5.2%, respectively (Mean (μ) = 8.38% and Standared deviasion (σ_μ) = ±5.5%). Conversely, the strength reduction for 28 d (μ28) was 8.7%, 9.4%, 4.6% and 8.1% when FRCA was added to 20%, 40%, 60% and 80%, respectively (μ = 7.68% and σ_μ = ±1.58%). Moreover, the strength reduction (μ56) after 56 days was 11.0%, 0.50%, 9.5% and 10.0% when FRCA was added at 20%, 40%, 60% and 80%, respectively (μ = 5.75% and σ_μ = ±4.22%). The mixes with integrated FRCA experience less reduction in concrete strength than those with integrated CRCA. This may be due to the pozzolanic effect of FRCA and its low voids. The lowest values of μ_7 and μ_{28} were 1.0 and 4.6% (M7, FRCA = 60%), respectively, while the lowest value of μ_{56} was 0.50% (M6, FRCA = 40%).

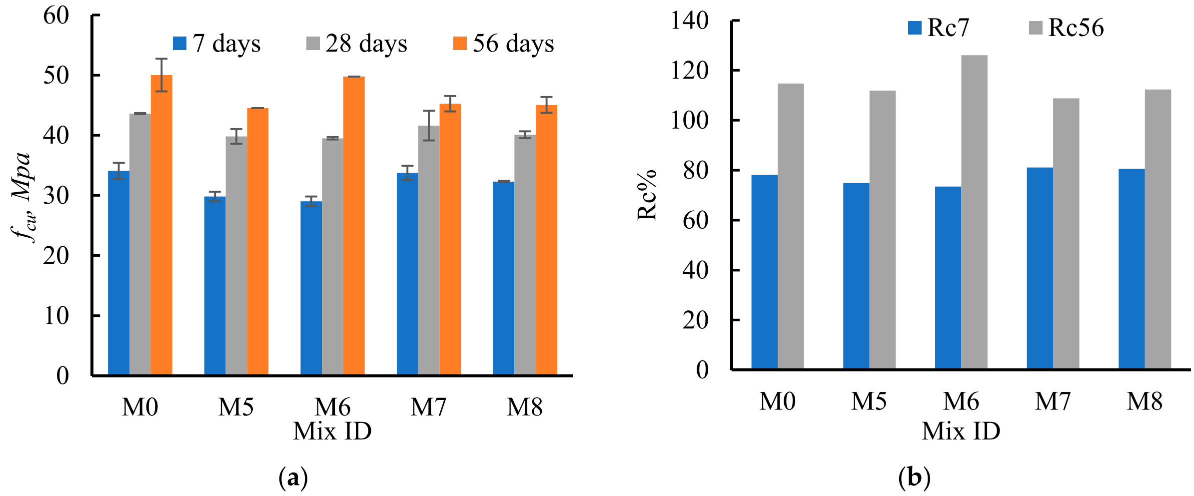


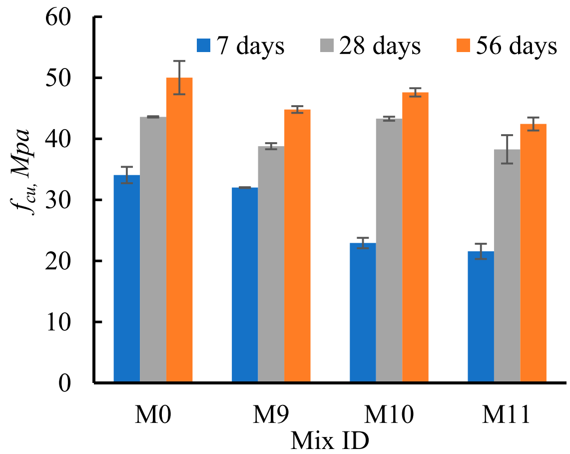
Figure 7. Effect of the FRCA%. (**a**) Concrete compressive strength; (**b**) The compressive strength ratio (Rc%).

The effect of FRCA on the strength gained at 7 and 56 days compared to that at 28 days (Rc7% and Rc56%) was calculated (Figure 7b). The figure shows that the Rc7 values were 78.1%, 74.9%, 73.5%, 81.1% and 80.6% when the FRCA was integrated by 0%, 20%, 40%, 60% and 80%, respectively (μ = 77.6% and σ_μ = ±3.03%). Moreover, the Rc56 values were 114.7%, 111.8%, 126.0%, 108.8% and 112.4% when the FRCA was added by 0%, 20%, 40%, 60% and 80%, respectively (μ = 114.7% and σ_μ = ±5.95%). M6 showed the highest Rc56 value, highlighting the pozzolanic effect of FRCA, which can maintain almost the same M0 strength (99.5%). The incorporation of FRCA into the concrete to replace the natural sand was more efficient than the RA and PA to restore the NAC strength [53]. The previous research studies [35,78] have shown that concrete with RCA has a higher pore structure than concrete with NA. When RCA (coarse and fine) replaced NA, a decrease in strength of about 26–32% was observed in [77] and the same finding was highlighted in [80]. The above observations underlined the suitability of FRCA to produce sustainable concrete with high FRCA replacement ratios.

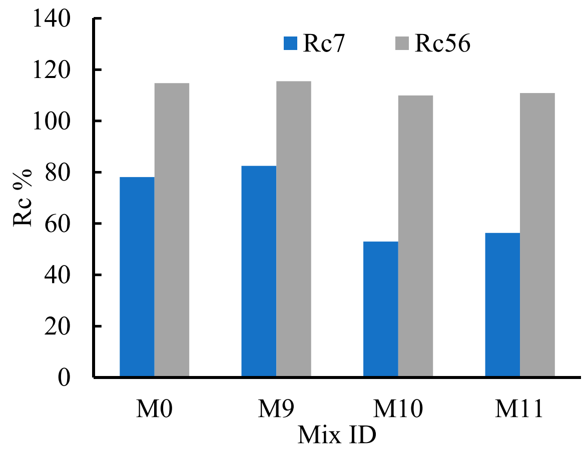
4.1.3. Effect of the RCP

To produce green/sustainable concrete, the RCP was used to partially replace the cement component. The cement was partially substituted by 0%, 5%, 10% and 20% RCP. From Figure 8, the strength increased with increasing Tc value irrespective of the RCP content. When the Tc was increased from 7 to 28 days, the strength increased by 21.20%, 88.81% and 77.39% when the RCP was added with 5%, 10% and 20%, respectively. When the Tc was increased from 28 to 56 days, the strength increased by 6.7%, 3.7% and 11.4% when the RCP was added with 5%, 10% and 20%, respectively. The use of RCP as a replacement material for cement decreased the compressive strength by different percentages depending on the Tc and RCP percentage. After 7 d, the strength decreased by 6.0%, 32.7%, and 36.7% when 5%, 10%, and 20% RCP were added, respectively (μ = 25.12% and $\sigma_\mu = \pm$13.6%).

The use of RCP as a replacement material for cement decreased the compressive strength by different percentages depending on Tc and RCP%. After 7 days, the strength decreased by 6.0%, 32.7% and 36.7% (μ = 25.12% and $\sigma_\mu = \pm$13.6%) when 5%, 10% and 20% RCP were added, respectively. Conversely, the strength decreased by 11.0, 0.7 and 12.2% after 28 days when RCP was added by 5%, 10% and 20%, respectively (μ = 7.97% and $\sigma_\mu = \pm$5.17%). In addition, the attained strength decreased by 10.4%, 4.80% and 15.2% when RCP was integrated by 5%, 10% and 20%, respectively (μ = 10.13% and $\sigma_\mu = \pm$4.95%). The small reduction in strength for mixes with RCP (M9–M11) compared to M0, especially after 28 and 56 days, may be due to the late hydration of RCP. These results assured the pozzolanic effects of RCP, which covered about 99.3% and 95.2% of M0 strength after 28 and 56 days, respectively (RCP = 10%). Moreover, M9 achieved the lowest strength reduction after 7 d (6.0%) with an almost similar difference between μ28/7 and μ56/28 (Table 4). To compare the effect of RCP% on the obtained strength after 7 and 56 d compared to that after 28 d, the Rc7 and Rc56 were calculated (Figure 8b). From the figure, Rc7 was equal to 78.1%, 82.5%, 53% and 56.4% when the RCP was added by 0%, 5%, 10% and 20%, respectively (μ = 67.5% and $\sigma_\mu = \pm$12.97%). Moreover, the Rc56 was equal to 114.7%, 115.5%, 110.0% and 110.9% when the RCP was added by 0%, 5%, 10% and 20%, respectively (μ = 112.8% and $\sigma_\mu = \pm$2.38%). From all the above, basaltic RCP could be considered as a good substitute for cement to produce green/sustainable concrete, reduce environmental impact and produce concrete with low cost. As reported in [80–82], the replacement of cement with SF (5–25%) increases the concrete strength when the recommended superplasticizers are added. The reported and obtained results encourage the use of superplasticizers with the RCP that can regulate their hydration and increase the concrete strength as they have the SF effects on the concrete.



(**a**)



(**b**)

Figure 8. Effect of the fine RCP%. (**a**) Concrete compressive strength; (**b**) The compressive strength ratio (Rc%).

4.2. Concrete Tensile Strength

The cubic diagonal tensile strengths (f_{tu}) at ages 28 and 56 days ($f_{tu,28}$ and $f_{tu,56}$, respectively) are reported in Table 5 and Figures 9–11. Table 5 shows the increases and decreases in f_{tu} at 28 and 56 days ($\mu_{t,28}$ and $\mu_{t,56}$, respectively) as a result of the partial replacement of natural basalt, sand, and cement by CRCA, FRCA, and RCP. The percentage increase in $f_{tu,56}$ compared to $f_{tu,28}$ ($\mu_{t56/28}$) for all tested mixes was also calculated. In addition, the effect of waste concrete components on $f_{tu,28}/f_{cu,28}$ and $f_{tu,56}/f_{cu,56}$% was also adopted. The increased/decreased (I/d) percentage in f_{tu} ($\mu_{t,date}$%) at each curing time can be calculated using Equation (4).

$$\mu_{t,date}\% = \frac{f_{tu,date}(R) - f_{tu,date}(N)}{f_{tu,date}(N)} \times 100 \tag{4}$$

where $f_{tu,date}(R)$ and $f_{tu,date}(N)$ are the concrete tensile strengths for mixes with recycled components and that with NA, respectively.

Table 5. The concrete tensile strength for all mixes at 28 and 56 ages.

Group	Mix ID	Specimen No.	$f_{tu,28}$ MPa	Mean ($\sigma\mu$) MPa	μ_{t28}%	$f_{tu,56}$ MPa	Mean ($\sigma\mu$) MPa	μ_{t56} %	$\mu_{t56/28}$ %	$f_{tu,28}/f_{cu,28}$ %	$f_{tu,56}/f_{cu,56}$ %
Control	M0	1 2 3	3.48 3.58 3.51	3.52 (±0.05)	0.00	3.92 3.88 3.87	3.89 (±0.03)	0.00	10.45	8.08	7.78
CRCA	M1	1 2 3	3.45 3.37 3.39	3.40 (±0.04)	−3.42	3.86 3.53 3.69	3.69 (±0.16)	−5.02	8.61	8.65	8.24
	M2	1 2 3	3.51 3.31 3.47	3.43 (±0.10)	−2.63	3.56 3.57 3.65	3.59 (±0.05)	−7.60	4.81	8.65	7.93
	M3	1 2 3	3.54 3.39 3.49	3.47 (±0.08)	−1.40	3.82 4.32 3.77	3.97 (±0.31)	1.98	14.24	8.62	8.73
	M4	1 2 3	3.40 3.49 3.38	3.42 (±0.06)	−2.88	3.43 3.49 3.47	3.47 (±0.03)	−10.90	1.33	9.03	8.48

Table 5. *Cont.*

Group	Mix ID	Specimen No.	$f_{tu,28}$ MPa	Mean ($\sigma\mu$) MPa	μ_{t28}%	$f_{tu,56}$ MPa	Mean ($\sigma\mu$) MPa	μ_{t56} %	$\mu_{t56/28}$ %	$f_{tu,28}/f_{cu,28}$ %	$f_{tu,56}/f_{cu,56}$ %
FRCA	M5	1 2 3	3.66 3.29 3.38	3.44 (±0.20)	−2.24	4.00 3.78 3.78	3.85 (±0.13)	0.26	13.27	8.65	8.76
	M6	1 2 3	3.27 3.34 3.65	3.42 (±0.20)	−2.88	3.87 4.24 4.05	4.05 (±0.18)	5.40	19.78	8.67	8.24
	M7	1 2 3	3.67 3.61 3.70	3.66 (±0.04)	3.87	4.25 3.96 3.96	4.06 (±0.17)	5.40	12.08	8.79	9.06
	M8	1 2 3	3.21 3.95 3.73	3.63 (±0.36)	3.05	4.20 3.86 3.96	4.01 (±0.17)	3.09	10.49	9.05	8.90
RCP	M9	1 2 3	3.88 3.66 3.74	3.76 (±0.11)	6.81	4.02 3.99 4.03	4.01 (±0.03)	3.09	6.68	9.69	8.95
	M10	1 2 3	3.90 3.58 3.79	3.76 (±0.16)	6.81	3.88 3.97 3.83	3.90 (±0.07)	0.26	3.72	8.68	8.19
	M11	1 2 3	3.24 3.47 3.54	3.42 (±0.16)	−2.92	3.87 3.85 3.70	3.81 (±0.09)	−2.05	11.44	8.93	8.98

$\mu_{tTc}\% = \frac{f_{tu,Tc}(any\ mix)}{f_{tu,Tc}(Mix0)} \times 100$ where Tc = 7, 28 and 56 days.

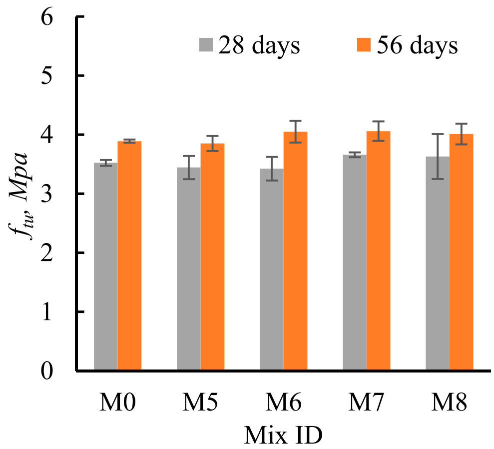


Figure 9. Effect of the CRCA% on the concrete tensile strength.

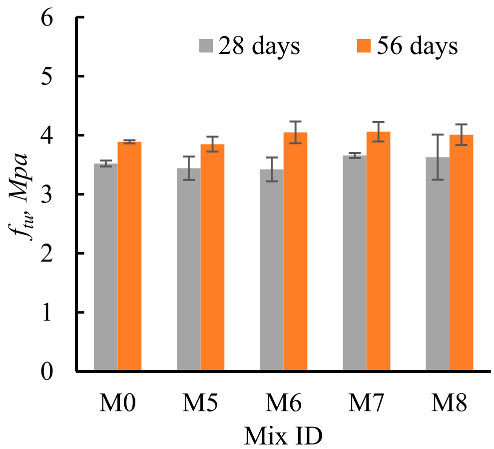
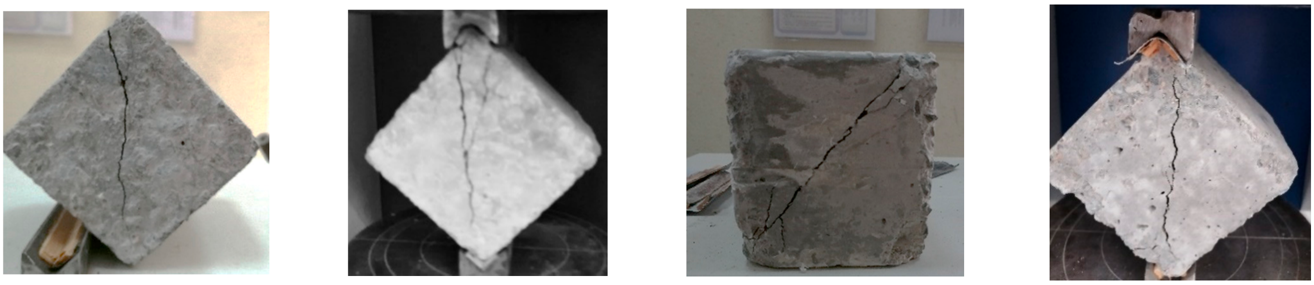


Figure 10. Effect of the FRCA on the concrete tensile strength.



(**a**) (**b**) (**c**) (**d**)

Figure 11. Tensile diagonal failure for some cubes at 28 and 56 d. (**a**) Mix1 at 56 d; (**b**) Mix4 at 28 d; (**c**) Mix5 at 56 d; (**d**) Mix6 at 28 d.

4.2.1. Effect of CRCA

Concrete tensile strength was slightly affected by CRCA% and curing time. Increasing the Tc from 28 to 56 days increased the tensile strength at all CRCA% (Figure 9). The maximum value of increase in f_{tu} was for M3 (CRCA = 60%, $\mu_{t56/28}$ = 14.24%). In contrast, the tensile strength decreased with the addition of CRCA compared to mix M0, except for M3 at 56 d (μ_{t56} = 1.98%). The diagonal strength reduced by −3.42%, −2.63%, −1.4% and −2.88% after 28 days, while it reduced by −5.02%, −7.60%, 1.98% and −10.9% after 56 days when CRCA was added by 20%, 40%, 60% and 80%, respectively. M4 (CRCA = 80%) experienced the highest reduction in diagonal strength (μ_{t56} = −10.90%, Table 4). Although the voids in the CRCA negatively affected the tensile strength, the amount of RCP attached to the CRCA could help to reduce the effects of the voids as it produced more gel when hydrated. The comparison of $f_{tu,28}/f_{cu,28}$% and $f_{tu,56}/f_{cu,56}$% for the mixtures integrating CRCA with those of M0 ensured the lower effect of CRCA on tensile strength than on compressive strength. The pozzolanic effect of RCP can improve the bond between concrete particles when it contains much basalt powder. In contrast, the CRCA with little basalt powder can interfere with cement hydration by absorbing the hydration water and increasing the voids in the concrete. In addition, the mixes with integrated CRCA had more ITZs than those with NA, which contributed to the detachment of fracture surfaces under tensile loading. In addition, the higher porosity of CRCA concretes resulted in high lateral dilatation compared to concretes with NA, which led to a drastic reduction in compressive strength. The same poor effects of CRCA on compressive strength as on tensile strength were reported in [72,83,84]. Moreover, a tensile strength reduction of about 26–32% was found in [78] when RCA (coarse and fine) was added to replace NA. From the above, the low effect of CRCA makes it a good sustainable replacement material for NA to produce green concrete with low cost and environmental impact with lower tensile strength reduction (μ_{t28} = 3.42% (M1) and μ_{t28} = 10.9% (M4)).

4.2.2. Effect of FRCA

The FRCA was implemented to replace the natural sand in five percentages (0%, 20%, 40%, 60%, and 80%). The concrete diagonal strength was dependent on the FRCA percentage and curing time. Increasing Tc from 28 to 56 d increased the diagonal strength at all FRCA% (Figure 10) with a maximum enhancement value of 19.78% (M6, FRCA = 40%). Consequently, the diagonal strength of the mixtures with integrated FRCA was higher than that of M0 at 28 and 56 days, except for M5 and M6 at 28 days (Figure 9). After 56 days, diagonal strength increased by 0.26%, 5.40%, 5.40%, and 3.09% when FRCA was added by 20%, 40%, 60%, and 80%, respectively. Moreover, the highest reduction in diagonal strength compared to M0 was equal to −2.88% after 28 days (M6, Table 5). The diagonal strength may depend on the availability of RCP attached to the FRCA. In addition, the fine basalt aggregates may act as microfibers that help to suppress the internal macrocracks and increase the diagonal strength values.

Comparing the $f_{tu,28}/f_{cu,28}$% and $f_{tu,56}/f_{cu,56}$% for the mixes containing the FRCA with those of M0, the significant effect of the FRCA on the diagonal strength was greater than that on the compressive strength. The pozzolanic effect of RCP can improve the bond between concrete particles. The failure of the cubes followed the diagonal failure characteristics (Figure 11), as reported in [67]. Finally, the FRCA trivially diminished the f_{cu} values while amplified the f_{tu} values. The previous results and comparisons encouraged the use of recycled aggregates as a substitute material for the NA to produce green concrete.

In contrast to the effect of RA and PA, the incorporation of FRCA into concrete increased f_{tu} values compared to NAC [53].

4.2.3. Effect of the RCP

To emphasize the pozzolanic effect of RCP on concrete properties, the tensile strength of mixes integrating RCP was tested (Figure 12). From Figure 12, the diagonal strength for the mixes integrating RCP increased with increasing curing time regardless of the RCP content. When Tc was increased from 28 to 56 days, the diagonal strength increased by 6.68%, 3.72% and 11.44% when RCP was added by 5%, 10% and 20%, respectively. This could be due to the hydration of the remaining un-hydrated cement and the late hydration of the basalt fines and powder. Consequently, replacing the cement with 5% and 10% RCP increased the 28 days tensile strength by 6.81% and 6.81%, respectively, while the 56 days tensile strength increased by 3.09 and 0.26%, respectively, compared to M0. In contrast, for mixes integrating 20% RCP, the tensile strength at 28 and 56 days decreased by −2.92% and −2.05%, respectively, compared to that of M0. Conversely, the $f_{tu,28}/f_{cu,28}$% and $f_{tu,56}/f_{cu,56}$% increased with the incorporation of RCP compared to M0. The pozzolanic effect of RCP may enhance the bond between concrete particles. The results are in agreement with those in [35] which stated that the effect of RCA can be controlled by careful selection during concrete production. In fact, the loss or increase of tensile strength was dependent on the type, size, quantity, and quality of RCA.

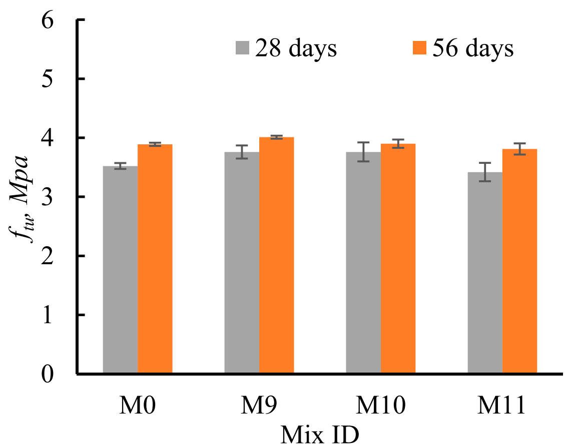


Figure 12. Effect of the RCP% on the concrete tensile strength.

4.3. Water Absorption

To examine the effect of CRCA, FRCA and RCP on concrete durability, the water absorption (WA) was calculated for all concrete mixes after 28 and 56 days (Figure 13). In general, all mixes had lower WA values after 56 days than their WA values after 28 days, except for mixes M2, M7, and M8 (Figure 13). This is because of the excessive hydration of the cement, which increased the C-S-H gel and decreased the voids. In addition, the WA values at the same Tc were dependent on the type and percentages of recycled materials. The WA of mixtures M1–M4 (with integrated CRCA) increased with increasing CRCA content at 28 d (Figure 13a). Similar effects of CRCA content on WA values were observed after 56 days for the same mixtures except for M2. The WA of mixtures M1-M4 was higher than that of mixture M0 (Figure 13a). This may be due to the high void content of

CRCA as it involves crushed mortar. The previous observations were previously reported in [85–87]. Similarly, at 28 and 56 d, mixtures M5–M8 had higher WA values than those of M0 (Figure 13b). Among the mixtures integrating FRCA, both mixtures M6 (FRCA = 40%) and M7 (FRCA = 60%) experienced the lowest WA values at 56 and 28 days, respectively. The WA of the mixes with FRCA may depend on the amount of crushed concrete and the hydration of the fines incorporated in the FRCA. Conversely, cement preplacement with 5% and 10% RCP had a small effect on WA values at 28 and 56 d, while increasing RCP to 20% increased WA (Figure 13c). When RCP replaced cement up to 10%, the effect of RCP on cement hydration was negligible and RCP could store almost the same C-S-H gel as cement, while increasing RCP to 20% may disturb cement hydration and affect the production of C-S-H gel in the mix.

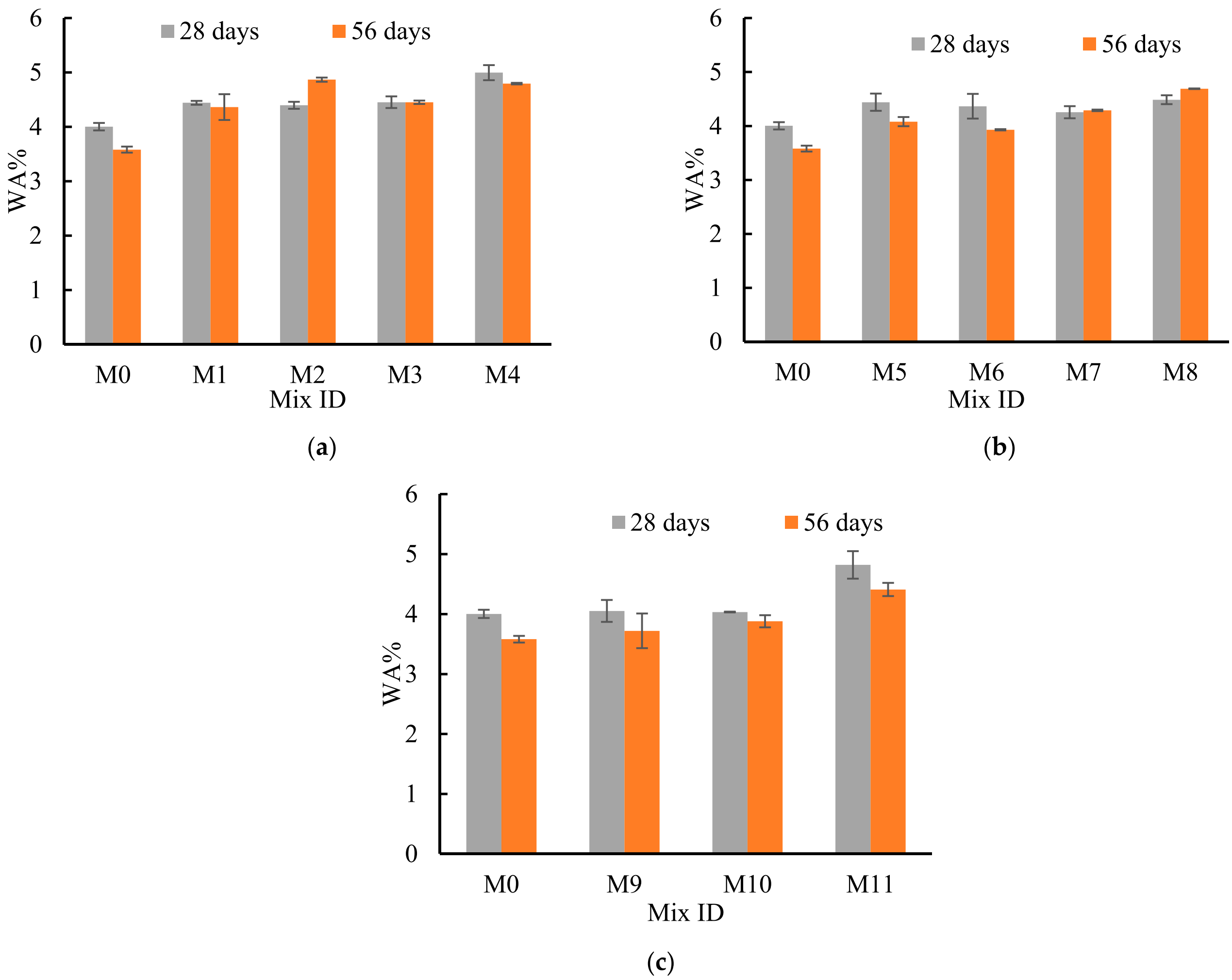


Figure 13. Effect of recycled concrete component on the WA %. (**a**) CRCA; (**b**) FRCA; (**c**) RCP.

5. Theoretical and Experimental Comparisons

The proposed model reported in [62] was used to predict the RAC compressive and tensile strength. The relationship between the theoretical findings and the obtained experimental results is shown in Figure 14. The theoretical compressive and tensile strength were evaluated using Equations (5) and (6), respectively as follows.

$$f'_{c,\ cube} = \frac{28.97 - 4.71 \times r^{1.69}}{\left(w_{eff}/c\right)^{0.63}} \tag{5}$$

$$f_{st} = \frac{2.12 - 0.31 \times r^{0.22}}{\left(w_{eff}/c\right)^{0.63}} \quad (6)$$

The model can predict with good accuracy the compressive and tensile strength of the RAC as shown in Figure 14.

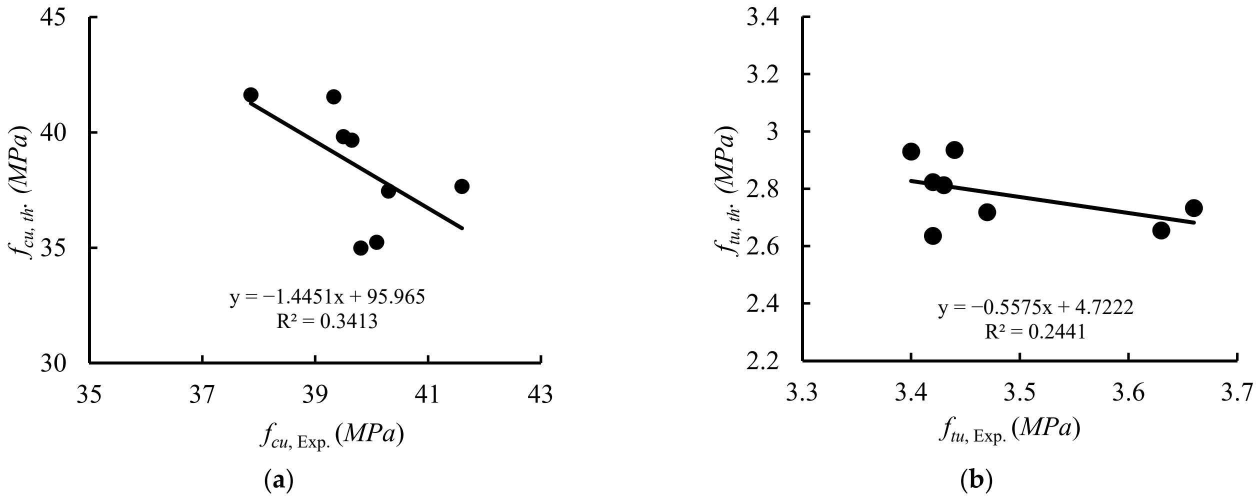


Figure 14. Experimental and theoretical comparison. (**a**) Compressive strength; (**b**) Tensile strength.

6. Conclusions

The strength and durability of green concrete produced with recycled basaltic concrete aggregates and powder were investigated. The effect of RCA, FRNA and RCP as substitutes for the concrete constituents (NA and cement) on the strength and durability of concrete was evaluated experimentally at different test ages. The conclusions obtained are given as follows:

- With increasing curing time, concrete compressive and tensile strengths increased regardless of the concrete components (with or without recycled materials). The concrete strength increased with increasing Tc from 7 to 28 days with a higher percentage than increasing Tc from 28 to 56 days. This may be because of the higher hydration rate of the cement during the first 28 days compared to the later days.
- Partial substitution of recycled aggregate for NA reduced concrete strength with varying percentages depending on the size and source of recycled aggregate, especially after 56 days. After 28 days, the maximum reduction in concrete strength when CRCA or FRCA was incorporated up to 80% was 7.6% and 4.6%, respectively, while the maximum reduction in strength was 13.2% and 9.4% for mixtures with CRCA and FRCA, respectively. After 56 days, the mixes with 40% FRCA achieved almost the same M0 compressive strength (99.5%).
- Increasing RCP from 5 to 10% enhanced the concrete strength at 28 and 56 days due to late hydration of RCP. After 28 days, the concrete strength was about 89% and 99.3% of the strength of M0, while the strength after 56 days was 89.6 and 95.2% of the strength of M0 when the RCP replaced the cement by 5% and 10%, respectively. The maximum strength reduction was 12.2% and 15.2% compared to M0 after 28 and 56 days, respectively, when the RCP = 20%.
- Compared to the M0 mixtures, the tensile strength increased or decreased depending on the proportion and type of recycled material and the curing time. After 56 days, the tensile strength augmented by 1.98%, 5.40% and 17.2% (maximum values) when the cement was substituted by CRCA, FRCA, and RCP, respectively.
- Generally, the values of WA decreased with increasing Tc from 28 to 56 days. The mixes in which coarse RCA was incorporated showed higher WA values than those of

M0. Consequently, WA decreased for mixes integrated FRCA and RCP compared to that of integrated CRCA.

- The obtained results and comparisons encourage the use of recycled aggregates and powders as a substitute material for NA and cement to produce sustainable/green concrete.
- The recycled aggregates could obtain nearly the same mechanical properties of mixes with natural aggregate. Conversely, the use of RCP to replace cement also reduces the cost and CO_2 emission from the cement production process. So, the use of recycled aggregates and powder to replace the natural aggregate and cement, respectively could be considered an efficient method to lower the structures' cost, their impact on the environment, and improves their sustainability.
- The transportation costs of natural aggregate and other construction materials have significant effects on the economic analysis. The use of recycled aggregate in rebuilding, demolition and retrofitting of structures could be very effective as the source of the old concrete is near to the construction site.

Author Contributions: Conceptualization, I.S. and M.A.; Data curation, I.S., U.I., A.A. and M.A.-H.; Formal analysis, I.S., U.I., M.A., A.A., A.S., M.A.-S., M.A.-H. and A.B.; Investigation, I.S., U.I., M.A., A.S., M.A.-S., M.A.-H. and A.B.; Methodology, I.S., U.I., M.A., A.A., A.S. and A.B.; Project administration, U.I. and A.B.; Resources, I.S., U.I., M.A., A.A., A.S., M.A.-S. and M.A.-H.; Visualization, A.A. and A.B.; Writing—review & editing, M.A., M.A.-S. and M.A.-H. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by the Deanship of Scientific Research, Taif University, Saudi Arabia, (Research project number 1-441-108).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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

References

1. Xuan, D.; Poon, C.S.; Zheng, W. Management and sustainable utilization of processing wastes from ready-mixed concrete plants in construction: A review. *Resour. Conserv. Recycl.* **2018**, *136*, 238–247. [CrossRef]
2. Martínez-García, R.; de Rojas, M.I.S.; Del Pozo, J.M.M.; Fraile-Fernández, F.J.; Juan-Valdés, A. Evaluation of mechanical characteristics of cement mortar with fine recycled concrete aggregates (FRCA). *Sustainability* **2021**, *13*, 414. [CrossRef]
3. Pacheco-Torgal, F. High tech startup creation for energy efficient built environment. *Renew. Sustain. Energy Rev.* **2017**, *71*, 618–629. [CrossRef]
4. Tam, V.W.Y.; Soomro, M.; Evangelista, A.C.J. A review of recycled aggregate in concrete applications (2000–2017). *Constr. Build. Mater.* **2018**, *172*, 272–292. [CrossRef]
5. Ginga, C.P.; Ongpeng, J.M.C.; Daly, M.K.M. Circular economy on construction and demolition waste: A literature review on material recovery and production. *Materials* **2020**, *13*, 2970. [CrossRef] [PubMed]
6. Yu, B.; Wang, J.; Li, J.; Lu, W.; Li, C.Z.; Xu, X. Quantifying the potential of recycling demolition waste generated from urban renewal: A case study in Shenzhen, China. *J. Clean. Prod.* **2020**, *247*. [CrossRef]
7. Turk, J.; Cotič, Z.; Mladenovič, A.; Šajna, A. Environmental evaluation of green concretes versus conventional concrete by means of LCA. *Waste Manag.* **2015**. [CrossRef]
8. Liew, K.M.; Sojobi, A.O.; Zhang, L.W. Green concrete: Prospects and challenges. *Constr. Build. Mater.* **2017**. [CrossRef]
9. Zhao, Y.; Yu, M.; Xiang, Y.; Kong, F.; Li, L. A sustainability comparison between green concretes and traditional concrete using an emergy ternary diagram. *J. Clean. Prod.* **2020**, *256*, 120421. [CrossRef]
10. Dang, J.; Zhao, J. Influence of waste clay bricks as fine aggregate on the mechanical and microstructural properties of concrete. *Constr. Build. Mater.* **2019**, *228*, 116757. [CrossRef]
11. Karimaei, M.; Dabbaghi, F.; Sadeghi-Nik, A.; Dehestani, M. Mechanical performance of green concrete produced with untreated coal waste aggregates. *Constr. Build. Mater.* **2020**, *233*, 117264. [CrossRef]
12. Çakir, O. Experimental analysis of properties of recycled coarse aggregate (RCA) concrete with mineral additives. *Constr. Build. Mater.* **2014**. [CrossRef]
13. Majhi, R.K.; Nayak, A.N.; Mukharjee, B.B. Development of sustainable concrete using recycled coarse aggregate and ground granulated blast furnace slag. *Constr. Build. Mater.* **2018**. [CrossRef]

14. Majhi, R.K.; Nayak, A.N. Bond, durability and microstructural characteristics of ground granulated blast furnace slag based recycled aggregate concrete. *Constr. Build. Mater.* **2019**. [CrossRef]
15. De Juan, M.S.; Gutiérrez, P.A. Study on the influence of attached mortar content on the properties of recycled concrete aggregate. *Constr. Build. Mater.* **2009**. [CrossRef]
16. Casuccio, M.; Torrijos, M.C.; Giaccio, G.; Zerbino, R. Failure mechanism of recycled aggregate concrete. *Constr. Build. Mater.* **2008**. [CrossRef]
17. Corinaldesi, V. Mechanical and elastic behaviour of concretes made of recycled-concrete coarse aggregates. *Constr. Build. Mater.* **2010**. [CrossRef]
18. Pani, L.; Francesconi, L.; Rombi, J.; Mistretta, F.; Sassu, M.; Stochino, F. Effect of parent concrete on the performance of recycled aggregate concrete. *Sustainability* **2020**, *12*, 9399. [CrossRef]
19. Tabsh, S.W.; Abdelfatah, A.S. Influence of recycled concrete aggregates on strength properties of concrete. *Constr. Build. Mater.* **2009**. [CrossRef]
20. Malešev, M.; Radonjanin, V.; Marinković, S. Recycled concrete as aggregate for structural concrete production. *Sustainability* **2010**, *2*, 1204–1225. [CrossRef]
21. Rao, A.; Jha, K.N.; Misra, S. Use of aggregates from recycled construction and demolition waste in concrete. *Resour. Conserv. Recycl.* **2007**. [CrossRef]
22. Wagih, A.M.; El-Karmoty, H.Z.; Ebid, M.; Okba, S.H. Recycled construction and demolition concrete waste as aggregate for structural concrete. *HBRC J.* **2013**. [CrossRef]
23. Etxeberria, M.; Vázquez, E.; Marí, A.; Barra, M. Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. *Cem. Concr. Res.* **2007**. [CrossRef]
24. Zhang, W.; Ingham, J.M. Using Recycled Concrete Aggregates in New Zealand Ready-Mix Concrete Production. *J. Mater. Civ. Eng.* **2010**. [CrossRef]
25. Behera, M.; Bhattacharyya, S.K.; Minocha, A.K.; Deoliya, R.; Maiti, S. Recycled aggregate from C&D waste & its use in concrete—A breakthrough towards sustainability in construction sector: A review. *Constr. Build. Mater.* **2014**. [CrossRef]
26. Yang, H.; Qin, Y.; Liao, Y.; Chen, W. Shear behavior of recycled aggregate concrete after exposure to high temperatures. *Constr. Build. Mater.* **2016**. [CrossRef]
27. Otsuki, N.; Miyazato, S.; Yodsudjai, W. Influence of Recycled Aggregate on Interfacial Transition Zone, Strength, Chloride Penetration and Carbonation of Concrete. *J. Mater. Civ. Eng.* **2003**. [CrossRef]
28. Etxeberria, M.; Vázquez, E.; Marí, A. Microstructure analysis of hardened recycled aggregate concrete. *Mag. Concr. Res.* **2006**. [CrossRef]
29. Etxeberria, M.; Mari, A.R.; Vazquez, E. Recycled aggregate concrete as structural material. *Mater. Struct. Constr.* **2007**, *40*, 529–541. [CrossRef]
30. Li, W.; Long, C.; Tam, V.W.Y.; Poon, C.; Hui, W. Effects of nano-particles on failure process and microstructural properties of recycled aggregate concrete. *Constr. Build. Mater.* **2017**, *142*, 42–50. [CrossRef]
31. Katz, A. Properties of concrete made with recycled aggregate from partially hydrated old concrete. *Cem. Concr. Res.* **2003**, *33*, 703–711. [CrossRef]
32. Li, W.; Luo, Z.; Sun, Z.; Hu, Y.; Duan, W.H. Numerical modelling of plastic–damage response and crack propagation in RAC under uniaxial loading. *Mag. Concr. Res.* **2018**, *70*, 459–472. [CrossRef]
33. Silva, R.V.; de Brito, J.; Dhir, R.K. Establishing a relationship between modulus of elasticity and compressive strength of recycled aggregate concrete. *J. Clean. Prod.* **2016**, *112*, 2171–2186. [CrossRef]
34. Silva, R.V.; De Brito, J.; Dhir, R.K. The influence of the use of recycled aggregates on the compressive strength of concrete: A review. *Eur. J. Environ. Civ. Eng.* **2014**. [CrossRef]
35. Silva, R.V.; De Brito, J.; Dhir, R.K. Tensile strength behaviour of recycled aggregate concrete. *Constr. Build. Mater.* **2015**, *83*, 108–118. [CrossRef]
36. Majhi, R.K.; Nayak, A.N. Properties of Concrete Incorporating Coal Fly Ash and Coal Bottom Ash. *J. Inst. Eng. Ser. A* **2019**. [CrossRef]
37. Satpathy, H.P.; Patel, S.K.; Nayak, A.N. Development of sustainable lightweight concrete using fly ash cenosphere and sintered fly ash aggregate. *Constr. Build. Mater.* **2019**. [CrossRef]
38. Evangelista, L.; de Brito, J. Mechanical behaviour of concrete made with fine recycled concrete aggregates. *Cem. Concr. Compos.* **2007**. [CrossRef]
39. Flower, D.J.M.; Sanjayan, J.G. Green house gas emissions due to concrete manufacture. *Int. J. Life Cycle Assess.* **2007**. [CrossRef]
40. Estanqueiro, B.; Dinis Silvestre, J.; de Brito, J.; Duarte Pinheiro, M. Environmental life cycle assessment of coarse natural and recycled aggregates for concrete. *Eur. J. Environ. Civ. Eng.* **2018**. [CrossRef]
41. Mah, C.M.; Fujiwara, T.; Ho, C.S. Life cycle assessment and life cycle costing toward eco-efficiency concrete waste management in Malaysia. *J. Clean. Prod.* **2018**. [CrossRef]
42. Wijayasundara, M.; Mendis, P.; Crawford, R.H. Net incremental indirect external benefit of manufacturing recycled aggregate concrete. *Waste Manag.* **2018**. [CrossRef] [PubMed]
43. Marinković, S.; Radonjanin, V.; Malešev, M.; Ignjatović, I. Comparative environmental assessment of natural and recycled aggregate concrete. *Waste Manag.* **2010**. [CrossRef] [PubMed]

44. Braga, A. *Comparative Analysis of the Life Cycle Assessment of Conventional and Recycled Aggregate Concrete*; Instituto Superior Tecnico—University of Lisbon: Lisbon, Portugal, 2015. (In Portuguese)
45. Khatib, J.M. Properties of concrete incorporating fine recycled aggregate. *Cem. Concr. Res.* **2005**. [CrossRef]
46. Kou, S.C.; Poon, C.S. Properties of concrete prepared with crushed fine stone, furnace bottom ash and fine recycled aggregate as fine aggregates. *Constr. Build. Mater.* **2009**. [CrossRef]
47. Evangelista, L.; de Brito, J. Durability performance of concrete made with fine recycled concrete aggregates. *Cem. Concr. Compos.* **2010**. [CrossRef]
48. Fan, C.C.; Huang, R.; Hwang, H.; Chao, S.J. Properties of concrete incorporating fine recycled aggregates from crushed concrete wastes. *Constr. Build. Mater.* **2016**. [CrossRef]
49. Dapena, E.; Alaejos, P.; Lobet, A.; Pérez, D. Effect of Recycled Sand Content on Characteristics of Mortars and Concretes. *J. Mater. Civ. Eng.* **2011**. [CrossRef]
50. Zhao, Z.; Remond, S.; Damidot, D.; Xu, W. Influence of fine recycled concrete aggregates on the properties of mortars. *Constr. Build. Mater.* **2015**. [CrossRef]
51. Gholampour, A.; Zheng, J.; Ozbakkaloglu, T. Development of waste-based concretes containing foundry sand, recycled fine aggregate, ground granulated blast furnace slag and fly ash. *Constr. Build. Mater.* **2021**, *267*, 121004. [CrossRef]
52. Tamanna, N.; Tuladhar, R.; Sivakugan, N. Performance of recycled waste glass sand as partial replacement of sand in concrete. *Constr. Build. Mater.* **2020**, *239*, 117804. [CrossRef]
53. Steyn, Z.C.; Babafemi, A.J.; Fataar, H.; Combrinck, R. Concrete containing waste recycled glass, plastic and rubber as sand replacement. *Constr. Build. Mater.* **2021**, *269*, 121242. [CrossRef]
54. Uncik, S.; Kmecova, V. The effect of basalt powder on the properties of cement composites. *Procedia Eng.* **2013**, *65*, 51–56. [CrossRef]
55. Ren, P.; Li, B.; Yu, J.-G.; Ling, T.-C. Utilization of recycled concrete fines and powders to produce alkali-activated slag concrete blocks. *J. Clean. Prod.* **2020**. [CrossRef]
56. Shahrour, N.; Allouzi, R. Shear behavior of captive- and short- column effects using different basalt aggregate contents. *J. Build. Eng.* **2020**, *32*, 101508. [CrossRef]
57. Kurańska, M.; Barczewski, M.; Uram, K.; Lewandowski, K.; Prociak, A.; Michałowski, S. Basalt waste management in the production of highly effective porous polyurethane composites for thermal insulating applications. *Polym. Test.* **2019**, *76*, 90–100. [CrossRef]
58. Ashish, D.K.; Verma, S.K. Determination of optimum mixture design method for self-compacting concrete: Validation of method with experimental results. *Constr. Build. Mater.* **2019**. [CrossRef]
59. Jani, Y.; Hogland, W. Waste glass in the production of cement and concrete—A review. *J. Environ. Chem. Eng.* **2014**. [CrossRef]
60. Zaidi, K.A.; Ram, S.; Gautam, M.K. Utilisation of glass powder in high strength copper slag concrete. *Adv. Concr. Constr.* **2017**. [CrossRef]
61. Chen, G.; Lee, H.; Young, K.L.; Yue, P.L.; Wong, A.; Tao, T.; Choi, K.K. Glass recycling in cement production-an innovative approach. *Waste Manag.* **2002**. [CrossRef]
62. Xu, J.; Zhao, X.; Yu, Y.; Xie, T.; Yang, G.; Xue, J. Parametric sensitivity analysis and modelling of mechanical properties of normal- and high-strength recycled aggregate concrete using grey theory, multiple nonlinear regression and artificial neural networks. *Constr. Build. Mater.* **2019**, *211*, 479–491. [CrossRef]
63. ASTM International. *ASTM C33 Standard Specification for Concrete Aggregates*; ASTM International: West Conshohocken, PA, USA, 2010.
64. Ghorbani, S.; Sharifi, S.; Ghorbani, S.; Tam, V.W.; de Brito, J.; Kurda, R. Effect of crushed concrete waste's maximum size as partial replacement of natural coarse aggregate on the mechanical and durability properties of concrete. *Resour. Conserv. Recycl.* **2019**. [CrossRef]
65. American Concrete Institute. *ACI 211.1 Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI 211.1-91)*; American Concrete Institute: Farmington Hills, MI, USA, 2002.
66. British Standards Institution. *BS EN 12390-3:2009 Testing Hardened Concrete, Part 3: Compressive Strength of Test Specimens*; British Standards Institution: London, UK, 2009.
67. Ince, R. Determination of concrete fracture parameters based on peak-load method with diagonal split-tension cubes. *Eng. Fract. Mech.* **2012**. [CrossRef]
68. Zhang, S.P.; Zong, L. Evaluation of relationship between water absorption and durability of concrete materials. *Adv. Mater. Sci. Eng.* **2014**, *2014*. [CrossRef]
69. Gupta, N.; Gupta, A.; Saxena, K.K.; Shukla, A.; Goyal, S.K. Mechanical and durability properties of geopolymer concrete composite at varying superplasticizer dosage. *Mater. Today Proc.* **2020**. [CrossRef]
70. De Schutter, G.; Audenaert, K. Evaluation of water absorption of concrete as a measure for resistance against carbonation and chloride migration. *Mater. Struct. Constr.* **2004**, *37*, 591–596. [CrossRef]
71. ASTM International. *ASTM C642-13 Standard Test Method for Density, Absorption, and Voids in Hardened Concrete*; ASTM International: West Conshohocken, PA, USA, 2013.
72. Ali, B.; Qureshi, L.A. Durability of recycled aggregate concrete modified with sugarcane molasses. *Constr. Build. Mater.* **2019**. [CrossRef]

73. Ali, B.; Qureshi, L.A. Influence of glass fibers on mechanical and durability performance of concrete with recycled aggregates. *Constr. Build. Mater.* **2019**. [CrossRef]
74. Kou, S.C.; Poon, C.S.; Agrela, F. Comparisons of natural and recycled aggregate concretes prepared with the addition of different mineral admixtures. *Cem. Concr. Compos.* **2011**. [CrossRef]
75. Koushkbaghi, M.; Kazemi, M.J.; Mosavi, H.; Mohseni, E. Acid resistance and durability properties of steel fiber-reinforced concrete incorporating rice husk ash and recycled aggregate. *Constr. Build. Mater.* **2019**. [CrossRef]
76. Xiao, J.; Li, W.; Sun, Z.; Lange, D.A.; Shah, S.P. Properties of interfacial transition zones in recycled aggregate concrete tested by nanoindentation. *Cem. Concr. Compos.* **2013**. [CrossRef]
77. Wang, H.L.; Wang, J.J.; Sun, X.Y.; Jin, W.L. Improving performance of recycled aggregate concrete with superfine pozzolanic powders. *J. Cent. South Univ.* **2013**. [CrossRef]
78. Gorjinia, A.; Shafigh, P.; Moghimi, M.; Bin, H. The role of 0–2 mm fine recycled concrete aggregate on the compressive and splitting tensile strengths of recycled concrete aggregate concrete. *J. Mater.* **2014**, *64*, 345–354. [CrossRef]
79. Rahman, I.A. Assessment of Recycled Aggregate Concrete. *Mod. Appl. Sci.* **2009**, *3*, 47–54.
80. Pedro, D.; de Brito, J.; Evangelista, L. Evaluation of high-performance concrete with recycled aggregates: Use of densified silica fume as cement replacement. *Constr. Build. Mater.* **2017**. [CrossRef]
81. Wu, Z.; Shi, C.; Khayat, K.H. Influence of silica fume content on microstructure development and bond to steel fiber in ultra-high strength cement-based materials (UHSC). *Cem. Concr. Compos.* **2016**. [CrossRef]
82. Karthikeyan, B.; Dhinakaran, G. Influence of ultrafine TiO2 and silica fume on performance of unreinforced and fiber reinforced concrete. *Constr. Build. Mater.* **2018**. [CrossRef]
83. Hossain, F.M.Z.; Shahjalal, M.; Islam, K.; Tiznobaik, M.; Alam, M.S. Mechanical properties of recycled aggregate concrete containing crumb rubber and polypropylene fiber. *Constr. Build. Mater.* **2019**, *225*, 983–996. [CrossRef]
84. Ahmadi, M.; Farzin, S.; Hassani, A.; Motamedi, M. Mechanical properties of the concrete containing recycled fibers and aggregates. *Constr. Build. Mater.* **2017**, *144*, 392–398. [CrossRef]
85. Das, C.S.; Dey, T.; Dandapat, R.; Mukharjee, B.B.; Kumar, J. Performance evaluation of polypropylene fibre reinforced recycled aggregate concrete. *Constr. Build. Mater.* **2018**, *189*, 649–659. [CrossRef]
86. Lima, C.; Caggiano, A.; Faella, C.; Martinelli, E.; Pepe, M.; Realfonzo, R. Physical properties and mechanical behaviour of concrete made with recycled aggregates and fly ash. *Constr. Build. Mater.* **2013**, *47*, 547–559. [CrossRef]
87. Somna, R.; Jaturapitakkul, C.; Amde, A.M. Effect of ground fly ash and ground bagasse ash on the durability of recycled aggregate concrete. *Cem. Concr. Compos.* **2012**, *34*, 848–854. [CrossRef]