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Effect of Aggregate Type and Specimen Configuration on Concrete Compressive Strength

Sherif Yehia *, Akmal Abdelfatah and Doaa Mansour

Civil Engineering Department, American University of Sharjah (AUS), Sharjah PO Box 26666, UAE; akmal@aus.edu (A.A.); g00045494@alumni.aus.edu (D.M.)

* Correspondence: syehia@aus.edu

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Abstract: In this paper, concrete mixes utilizing two sizes of natural aggregate and two sources of lightweight and recycled aggregates were used to investigate the effect of aggregate type and specimen size and shape on the compressive strength of concrete. In addition, samples from ready-mix concrete producers with different strengths were evaluated using standard size cylinders and cubes. Results were obtained on the 7th, 28th, and 90th day. In addition, flexural strength, split tension, and modulus of elasticity were evaluated on the 28th and 90th day. Statistical analyses were conducted to examine the significance of the difference between the compressive strength values for each two mixes using tests of hypotheses. Moreover, other mechanical properties as a function of compressive strength were discussed and compared to those predicated by the American Concrete Institute (ACI) specifications. Results indicate specimen shape has a noticeable effect on the compressive strength as the Cylinder/Cube ratio on the 90th day was ranging between 0.781 and 0.929. The concrete compressive strength and modulus of elasticity were significantly affected by the aggregate type. The flexural strength and split tensile strength were less affected by the aggregate type, which was also confirmed by the values predicted with the ACI equations.

Keywords: aggregate type; specimen shape; specimen size; compressive strength; concrete mechanical properties

1. Introduction

Concrete compressive strength (f_c') provides an indication about the ability of a specific mix to resist axial compression loads. Traditionally, axial compression test utilizes standard cubes and cylinders to determine f_c' and became the most commonly used test in the construction industry. In addition, other mechanical properties could be predicted as a function of f_c' and design codes and standards for concrete structures consider the concrete compressive strength as the main indicator of the concrete resistance to loading. Concrete compressive strength is greatly affected by cement content, water-to-cement ratio (w/c), and aggregate size and type. Other factors, summarized in Table 1, influence the test results or indirectly affect the concrete compressive strength [1–16].

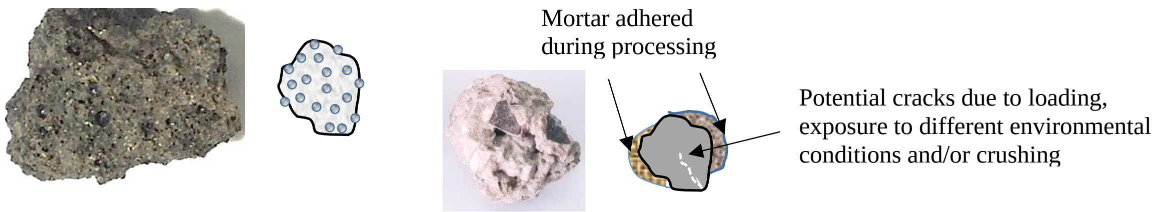
Table 1. Factors affecting compressive strength of concrete [1–16].

Factors Affecting Compressive Strength	Comments
Type of cement	Different concrete applications according to exposure conditions might require cement with specific properties. Five basic types of Portland cement are commonly used in the construction industry. A blend of cement and cementitious materials is also available in the market. The main bonding material and responsible for strength.
Supplementary Cementitious materials	Used to reduce heat of hydration, to improve workability and durability depending on the materials. They also ensure quality of concrete during the stages of mixing, transporting, placing, and curing in adverse weather conditions.
Water/cement ratio (w/c)	A low water/cement ratio increases resistance to weathering, provides a good bond between successive concrete layers. Excess water increases the porosity and permeability of the concrete and reduces strength.
Aggregate	Concrete strength is affected by the strength, surface texture, grading, and maximum size of the aggregate.
Mixing water	Impurities in the mixing water might affect concrete set time, strength, and long-term durability. It is generally thought that the pH of water should be between 6.0 and 8.0.
Curing	Moisture during curing: prolonged moist curing leads to the highest concrete strength. 3- and 7-day moist curing period will lead to 60% and 80% of the strength of the continuously cured concrete.
	Temperature during curing: increasing curing temperature while preventing moisture loss leads to an increase in the rate of hydration and, consequently, the rate of strength development. In cold weather, if concrete freezes soon after it has been placed will have a severe strength loss.
Age of concrete	Concrete gains strength with age.
Maturity of concrete	It indicates the progress of hydration and it is the relationship between strength gain, time, and concrete temperature.
Rate of loading	The axial compressive strength is reduced by about 75% of the standard test strength under slow rates of loading. Whereas, at high rates of loading, the strength increases, reaching 115% of the standard strength tests.
Specimen shape and size	Cube specimen generally gives more strength than that of cylinder specimen. Moreover, increasing the specimen size decreases the compressive strength.
Admixtures	Air-entraining admixtures increase resistance to freeze and thaw cycles by adding a stable bubble of air which might lead to a reduction of compressive strength. However, target compressive strength could be achieved by careful mix proportioning and reduced w/c ratio.
	Using superplasticizers can improve the strength, marginally, when using recycled aggregates or GGBFS. For self-compacting concrete, the use of superplasticizers has a slight effect on the concrete strength and that effect is more apparent in the early stages.

As shown in Table 1, several factors might influence the strength of concrete, especially aggregate since it represents about 40–60% per volume of any concrete mix. In general, for the same cementitious materials, w/c ratio and curing conditions, aggregate strength, texture, absorption, size, and gradation affect the failure mechanism of the concrete, which in turn affects the compressive strength. Failure of concrete depends mainly on three factors: bond strength between the aggregate and the cement paste, strength of the cement paste, and strength of the aggregate.

1.1. Effect of Aggregate Type on Compressive Strength

In general, compressive strength of normal weight aggregates depends on the strength of the parent rock that ranges from 35 MPa to 350 MPa [1]. Aggregate strength influences the production of high-strength concrete (HSC). Such mixes have high strength of the paste and the bond between aggregate and cement is improved. Accordingly, cracks may extend through the aggregate under loading, which makes use of the full strength of the aggregate and hence affects the concrete strength. However, for normal strength concrete, bond strength between the aggregate and the cement paste is affected by the physical properties of the aggregate, which in turn influences the concrete compressive strength. Therefore, failure tends to occur in the cement paste and in the interfacial zone between aggregate particles and the paste, before happening in the aggregate [7]. Other aggregate types, lightweight and recycled aggregates, and their effect on compressive strength of concrete are summarized in Table 2 [17–28]. Lightweight and recycled aggregates usually have lower strength and higher absorption than that of natural aggregate. High porosity of lightweight aggregate leads to less strength and high absorption, while recycled aggregate properties are affected by processing, previous loading, and exposure conditions, as illustrated in Figure 1. Compressive strength of concrete prepared with lightweight aggregate is affected by aggregate strength, w/c ratio, surface texture, mechanical interlock, and bond with the cement paste. In addition, variation in absorption capacities leads to formation of interfacial transition zones (ITZ), which have different microstructure. However, mixing procedure and the use of supplementary materials improve the ITZ and the concrete compressive strength. Similarly, concrete strength produced utilizing recycled aggregate is affected by the previous factors, in addition to the percentage of recycled aggregate used in the mix.



(**a**) Lightweight aggregate. Aggregate size 4–14mm

(**b**) Recycled aggregate. Aggregate size 4–8 mm

Figure 1. Schematic of lightweight and recycled aggregate particles.

The effect of petrographic characteristics of aggregates on the quality of concrete has been considered by References [29,30]. It was evident that concrete strength is significantly affected by the mineralogy and microstructure of the coarse aggregates. In addition, the aggregate strength and mechanical properties are influenced by the secondary products of serpentinites and andesites.

1.2. Effect of Aggregate Size and Shape

Aggregate gradation (size distribution), shape (flat, elongated aggregate, round), and texture (rough and smooth) have different effects on the mechanical properties according to concrete type being prepared Normal Strength Concrete (NSC), High Strength Concrete (HSC), Lightweight Concrete (LWC), and Recycled Aggregate Concrete (RAC). Several research efforts evaluated the effect of aggregate size and shape on the mechanical properties of concrete are summarized in Table 3 [6,7,31–34]. Aggregate size and shape can affect the cement-aggregate bond strength; for example, large aggregate size creates high stress concentration in the cement paste, leading to increased cracking; therefore, small aggregate size is recommended for HSC. Similar recommendation is suggested for LWC to avoid crushing of big size aggregates while loading.

Table 2. The effect of aggregate type on concrete compressive strength [13,17–28].

References	Aggregate Used in the Study	Effect on Strength (Compressive and Modulus of Elasticity)	Comments
Chi et al. [17]	Three types of LWA	Both compressive strength and elastic modulus were affected by the aggregate type and decreased with an increase in w/c ratio.	Different concrete strength, Portland cement, w/c ratio 0.3, 0.4, and 0.5
Wasserman and Bentur [18]	Fly ash LWA	Concrete strength does not depend only on the aggregate strength but affected by other characteristics such as its rough surface, porosity, and pozzolanic nature.	Portland cement, w/c ratio 0.4
Lo and Cui [19]	LWA	Porous surface of LWA improved the interfacial bond between aggregate and cement paste, resulting in better interlocking. Development of initial strength was much higher in LWC than in NWC.	Portland cement, w/c ratio 0.36
Topçu, and Uygunoğlu [20]	Normal crushed limestone and three types of LWA	Compressive strength increased with w/c decrease. Replacement of natural aggregate with LWA cause decrease in modulus of elasticity. Pumice is a useful aggregate for production of SCLC with high interlocking in ITZ and high compressive strength.	Different concrete strength. Portland cement, w/c ratio 0.36, 0.4, 0.43, 0.46, and 0.48
Tabsh and Abdelfatah [13]	RA	Concrete strength is affected by the source of the recycled aggregate. In addition, bond strength is affected by the quantity and the shape of the old cement mortar adhered on the aggregate surface.	
Poon and Lam [21]	Natural crushed aggregate and three types of RCA	Compressive strength increased when aggregate/cement ratio decreased. Using RCA instead of NCA reduced density and strength. The compressive strength was directly proportional to strength of the blended aggregate	
Seo and Choi [22]	RCA	The amount of the used recycled aggregate has a remarkable effect on the compressive strength. If amount of old cement mortar is about 10%, the mortar can improve the bond quality.	Portland cement
Xiao et al. [23]	Natural and RCA	Both compressive strength and modulus of elasticity reduced as the RCA percentage increased.	
Tsounami et al. [24]	Natural and RCA	For RCA replacement percentage higher than 25%, compressive strength reduces as replacement percentage increases.	Portland cement
Katz [25]	RCA	Concrete with 100% recycled aggregate was weaker than that of the natural aggregate, and about 25% reduction of the compressive strength was observed.	Portland cement
McNeil et al. [26]	RCA	RCA is less dense, more porous, and has higher water absorption than NCA due to the residual adhered mortar on RCA, which weakens the interfacial zone and reduces both compressive strength and modulus of elasticity.	

Table 2. *Cont.*

References	Aggregate Used in the Study	Effect on Strength (Compressive and Modulus of Elasticity)	Comments
Wardeh et al. [27]	Recycled gravel with 30%, 65%, and 100% replacement ratio.	The use of recycled aggregate up to 30% caused a 14% reduction in the compressive strength, while increasing the replacement ratio had increased the cement content, causing an increase in the compressive strength that counterbalances the negative effect of the recycled aggregate.	C35, CEM I CALCIA 52.5 N CE CP2 NF cement, w/c ratio 0.5–0.52
Choi et al. [28]	RA	Enhancing the ITZ help suppress the occurrence of microcracks and improve the mechanical performance of the aggregate, resulting in improved strength, permeability, and durability of concrete.	Normal strength concrete, Portland cement, w/c ratio 0.55

Table 3. The effect of aggregate size and shape on concrete compressive strength [6,7,31–34].

References	Aggregate Used in the Study	Cementitious Materials (Mineral Admixtures)	Effect on Strength (Compressive and Modulus of Elasticity)	Comments
Loannides and Mills [7]	Natural aggregate with different sizes	Air entraining admixtures	Smaller aggregates tended to shear under loading while larger aggregate was more prone to pull out.	Normal strength concrete Portland cement w/c ratio 0.5
Rocco and Elices [31,32]	Mullite aggregate with different sizes		Fracture energy increased with increasing the aggregate size and not affected significantly by the aggregate shape. Modulus of elasticity decreased as the aggregate size increased. Using crushed aggregates (with strong matrix-aggregate interfaces) showed higher modulus of elasticity than that while using spherical ones of the same size.	Normal strength concrete Portland cement w/c ratio 0.42, 0.7
Ajamu and Ige [33]	Aggregate with different sizes		Compressive strength increased as the aggregate size increase from 13mm to 19mm.	Normal strength concrete Portland cement w/c ratio 0.65
Meddah et al. [34]	Aggregate with different size and distribution	HRWRA	Compressive strength increased as the aggregate size increased in normal strength concrete. While in HSC, Compressive strength increased with decreasing the aggregate size. Increasing coarse aggregate content in NSC enhanced the compressive strength, while in HSC there is an optimum content. Effect of aggregate content and particle size is more significant in HSC than NSC.	Normal and High-strength concrete w/c ratio 0.58, 0.4
Yaqub and Bukhari [6]	Aggregate with different sizes		Smaller aggregate sizes exhibited higher compressive strength in the case of HSC.	High-strength concrete Portland cement w/c ratio 0.23–0.35

1.3. Effect of Specimen Configuration

Cylinders (100 × 200 mm, 150 × 300 mm) and cubes (100 × 100 × 100 mm, 150 × 150 × 150 mm) are commonly used to monitor compressive strength of concrete. The variation in concrete compressive strength due to shape and size might be attributed to variability in aggregate physical properties, different friction between concrete surfaces and loading platen, and variation of crack propagation and localized failure zone. Localization of the damage in a certain zone is affected by the slenderness of the sample and the boundary restraint between the loading platens and the specimen [12,35,36]. For cylinder specimens, it is expected that compressive strength should not be affected by the sample size as long as the ratio of height to maximum lateral dimension (h/d) is maintained 2:1 [37]. However, several studies [9,10,38,39] showed that compressive strength of small-size cylinders is slightly higher than that obtained using the 150/300 mm cylinders. This is due to the smaller contact area between the specimen surface and steel platen of the testing machine, which results in lower friction-based shear forces. Smaller specimens are also denser as they have less number of micro-cracks and defects, which strengthen their compressive strength. The effect of specimen shape on concrete compressive strength is, however, recognized in the difference between cylinder and cube strength. The concrete nominal strength (f_c') has a great effect on the specimen shape factor. It positively correlates with the cylinder/cube strength ratio as it is found that increasing the concrete strength decreases the specimen shape effect [40]. European standard (ENV 206:1990) and (BS 1881: Part 120) specifications [41,42] recommend a 0.8 ratio for the cylinder/cube strength and this ratio reaches 1.0 as concrete strength increases. Several studies showed that it is considerably hard to adopt a simple ratio for the cylinder/cube strength [40,43–51]. Compressive strength of concrete utilizing lightweight (LWA) and recycled aggregate (RA) are significantly affected by the size and aspect ratio of specimens due to the decrease in the concrete unit weight. This also could be attributed to poor crack distribution and localized failure zone due to the deteriorated aggregate interlock, which causes further decrease in the compressive strength with the increase of the specimen size [1,35].

In this study, effect of aggregate type and specimens' configuration on compressive strength of concrete is investigated. The aggregate type includes natural aggregate, recycled aggregate, and lightweight aggregate. The specimens' configuration includes two sizes for cubes and cylinders. The lab tests were conducted at 7, 28, and 90 days. Tests were conducted according to the American Society for Testing and Materials (ASTM) specifications and British Standards (BS). In addition, statistical analyses were conducted to examine the significance of the difference between the compressive strength values for each two mixes using tests of hypotheses.

1.4. Research Significance

Due to the depletion of and increased demand for natural resources, several natural aggregates were introduced to the construction industry. Therefore, one of the authors' goals is to evaluate the quality of the natural aggregates and compare the results to the previous well-established facts. In addition, another goal was to evaluate the suitability of the recycled and lightweight aggregates available in the market to produce concrete comparable to that produced by natural aggregate, hence, establish a base for comparison with concrete produced with natural aggregate.

2. Experimental Program

The main objective of the experimental program is to investigate the effect of aggregate type and specimen size and shape on the concrete compressive strength. In addition, correlation between compressive strength and aggregate strength is examined. The experimental program focuses on the evaluation of samples prepared in the laboratory utilizing six aggregate types, in addition to samples of five concrete strength (C45_1 (Ready mix 1-1), C75 (Ready mix 1-2), C45_2 (Ready mix 2-1), C60 (Ready mix 2-2), and C80 (Ready mix 2-3)) collected from ready-mix producers in Dubai and Sharjah, UAE. The use of the ready-mix concrete is considered to validate the results obtained based on the mixes prepared in the laboratory while conducting this research. Laboratory samples were prepared twice to ensure consistency and to account for variability of aggregate properties, especially recycled aggregate. The evaluation criteria included compressive strength of standard size cylinders and cubes, modulus of elasticity, flexural strength, and split tensile strength. Testing was conducted according to ASTM specifications [52–58].

2.1. Materials

All mixes prepared in the laboratory have Ordinary Portland cement type I (SG = 3.15), silica fume (SG = 2.2), Ground Granulated Blast-Furnace Slag "GGBS" (SG = 2.85), and tap water. In addition, normal weight dune sand (particle size 100% passing 0.6 mm, SG 2.60) and coarse sand (maximum particle size 4.75 mm, SG 2.60) were used as fine aggregates. Six types of coarse aggregate (Figure 2) were used to produce the concrete mixes in the lab: 10 mm and 20 mm sizes limestone (10 mm Nat., 20 mm Nat.), sintered pulverized–fuel ash (LWA_1) and pumice (LWA_2) lightweight aggregates with aggregate size 4 to 8 mm, and recycled aggregate (RCA_1, RCA_2) from two sources with size 4–14 mm. In addition, several mechanical and physical properties of the coarse aggregates were evaluated and summarized in Table 4. Detailed investigation of the aggregate properties has been reported in previous research [59,60]. In addition, all ready-mix producers' mixes used a mix of 10 mm and 20 mm natural aggregates, cement, GGBS, silica fume, fine sand, and w/cm = 0.39.

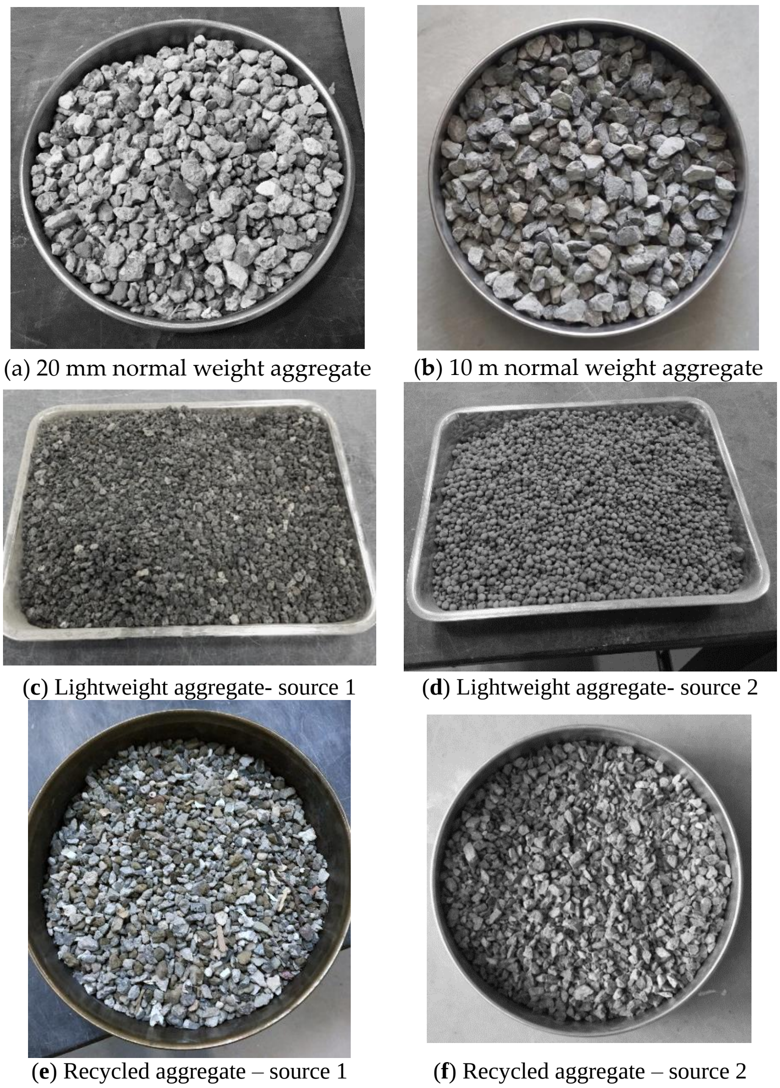


Figure 2. Coarse aggregate used in the investigation.

Table 4. Summary of the coarse aggregate properties.

Physical Property / Aggregate Type	Absorption %	Bulk Dry Sp. Gr.*	Moisture Content%	LA Abrasion		
				Grade B %	Grade C %	Grade D %
Natural Aggregate	0.65	2.685	0.558	22.38		
Sintered pulverized–fuel ash	24.32	1.336	0.564			25.97
Pumice	12.6	1.605	0.604			27.27
Recycled Aggregate - 1	3.94	2.36	0.719	35	31	
Recycled Aggregate - 2	3.35	2.47	0.84	24.97		

* Bulk Dry Specific Gravity.

Los Angeles abrasion: results from the Los Angeles (LA) abrasion test could be used as an indicator of aggregate strength and a relative measure of resistance to crushing under a gradually applied compressive load. A high LA abrasion number reflects a larger portion of crushed aggregates (fine) compared to the original mass. However, in case of recycled aggregate, high LA values could be attributed to the mortar adhered to the aggregate during crushing of recycled concrete. In general, aggregate's composition, texture, and structure affect its strength [1]; therefore, it is recommended to evaluate the aggregate performance in concrete samples to have a better indication of its strength.

Absorption: lightweight and recycled aggregates from both sources have high absorption capacity than that of the NWA. Therefore, the LWA and RCA were pre-wet 15 min prior to mixing with part of the mixing water (about 15% of the LWA aggregate weight and 5% of the RCA aggregate weight) to compensate for the high absorption capacity and to avoid impact on short-term workability. In addition, about 5% of the cement and cementitious materials weight were added during the pre-wet time to enhance the bond strength between the aggregate and the cement paste [59,60].

2.2. Mix Proportioning

All mixes prepared in the lab were proportioned using the absolute volume method and were based on a normal weight self-consolidated concrete mix [61] with a target strength of 70 MPa. Volume fractions, Table 5, for all materials and w/c ratio were the same for all mixes prepared in the laboratory; however, weights of course aggregates were adjusted to account for the difference in specific gravities. The total volumetric fraction of the cement and supplementary cementitious materials was 16%. A low cement content (8%) per volume was selected as an approach to achieve eco-friendly concrete mixes. The volume fraction of the GGBS (6%) and silica fume (2%) are the commonly used ratios by the ready-mix producers. In addition, the w/c ratio was selected to achieve the target strength and durability requirements [61].

Table 5. Mix proportioning.

Material	Absolute Volume
Cement	0.08
GGBS	0.06
Silica fume	0.02
water	0.18
Coarse aggregate	0.33
FA (1/2 dune and 1/2 crushed)	0.33
Total Volume	1

2.3. Testing Program

Cylinders 100 × 200 mm (4 × 8 in.) (Cy_1), 150 × 300 mm (6 × 12 in.) (Cy_2) and cubes 100 × 100 × 100 mm (4 × 4 × 4 in.) (Cu_1) and 150 × 150 × 150 mm (6 × 6 × 6 in.) (Cu_2) were prepared from each mix to evaluate the compressive strength development. In addition, flexural, splitting tensile strength, and modulus of elasticity were evaluated at 28- and 90-day for all mixes except mix LWA_1. There was not enough material from LWA_1 to produce all samples, and the source was not available in the market. Therefore, only samples for compressive strength evaluation, for LWA_1, were prepared and included in the related discussions. All samples were cured using wet burlaps for three days and were left to dry in ambient room temperature. Table 6 summarizes the tests, number of samples, sample size, age at testing, and specifications followed during testing.

Table 6. Summary of the experimental investigation.

Test	Test Specifications	Specimen Size (mm)	No. of Specimens Per Test	Testing Events (day)
Compressive strength	ASTM C39/C39M-17 [37]	150 × 300 cylinder 100 × 200 cylinder 150 × 150 × 150 cube 100 × 100 × 100 cube	2 cylinders* 2 cylinders* 2 cubes* 2 cubes*	7th, 28th and 90th
Modulus of Elasticity	ASTM C469/C469M-14 [58]	150 × 300 cylinder	1 cylinder	28th and 90th
Splitting tensile strength	ASTM C496/C496M-11 [56]	150 × 300 cylinder	2 cylinders	28th and 90th
Flexural strength	ASTM C78/C78M-16 [57]	100 × 100 × 500 beam	2 beams	28th and 90th

* Two sets of samples were prepared for a total of 4 samples of each cube/cylinder.

3. Results

3.1. Compressive Strength

Table 7 provides a summary of the compressive strength results for different concrete mixes at 7-, 28- and 90-day. In addition, Figures 3 and 4 show the average compressive strength for cube and cylinder specimens, respectively. The results show that generally the compressive strength for all the concrete mixes increased with age, as expected. The cube specimen of the natural concrete mixes gave 75% of its target strength (70 MPa) on the 7-day, 97% on the 28-day, and exceeded it on the 90-day. Both the lightweight aggregate and recycled aggregate concrete mixes resulted in 15–20% lower compressive strength than that of the natural mixes in the 7-, 28-, and 90-day due to the lower aggregate strength. Cylinder specimen exhibited lower strength than that of the cube as a result of the specimen shape effect. In addition, sample failure modes of cubes and cylinders from all mixes are shown in Figure 5. In addition, failure modes of other samples are illustrated in Annex A. These failure modes indicate the variability of the aggregate-cement bond strength, which is affected by the aggregate type. Similar results were reported by References [13,16,19,62,63]. Nonetheless, the lightweight and recycled aggregates showed improved bond strength due to the addition of cementitious materials during the pre-wet process before mixing, which was discussed elsewhere by References [59,60].

Table 7. Summary of compressive strength for different concrete mixes at 7th, 28th, and 90th day.

Test Date / Mixes	7-day				28-day				90-day			
	Cy_1	Cy_2	Cu_1	Cu_2	Cy_1	Cy_2	Cu_1	Cu_2	Cy_1	Cy_2	Cu_1	Cu_2
10mm Natural	46.06	40.9	52.1	52.83	63.31	56.05	59.47	67.93	63.01	58.35	64.07	79.13
20mm Natural	59.67	48.8	61.97	58.31	65.19	65.65	67.6	72.63	72.68	54.16	76.55	77.01
LWA_1	44.9	43.2	43.49	49.2	53.54	42.4	52.89	60.92	54.67	50.25	57.37	61.65
LWA_2	38.47	41.15	37.78	45.1	47.65	46.4	52.28	60.57	51.69	43.76	52.94	59.57
RCA_1	44.89	41.15	51.4	48.44	52.34	51.4	52.72	60.93	56.9	60.46	57.49	66.4
RCA_2	45.56	38.35	45.98	54.97	54.56	53.1	60.52	66.63	59.82	48.8	66.56	69.6
Ready mix 1-1	35	31.3	43.7	45	36.57	35.75	44.43	52.2	37.66	37.05	55.6	56.59
Ready mix 1-2	48.17	53.1	60.66	59.32	58.98	57.85	62.51	68.13	58.09	57.7	67.61	76.83
Ready mix 2-1	43.61	41.87	46.39	47.91	50.49	49	54.35	59.11	54.28	49.3	59	61
Ready mix 2-2	53.08	48.55	49.49	54.07	58.23	57.85	58.7	66.4	60.47	55.5	55.76	62.35
Ready mix 2-3	64.4	65.14	63.19	64.64	67.91	82.8	75.74	83.19	78.49	80.89	81.11	86.47

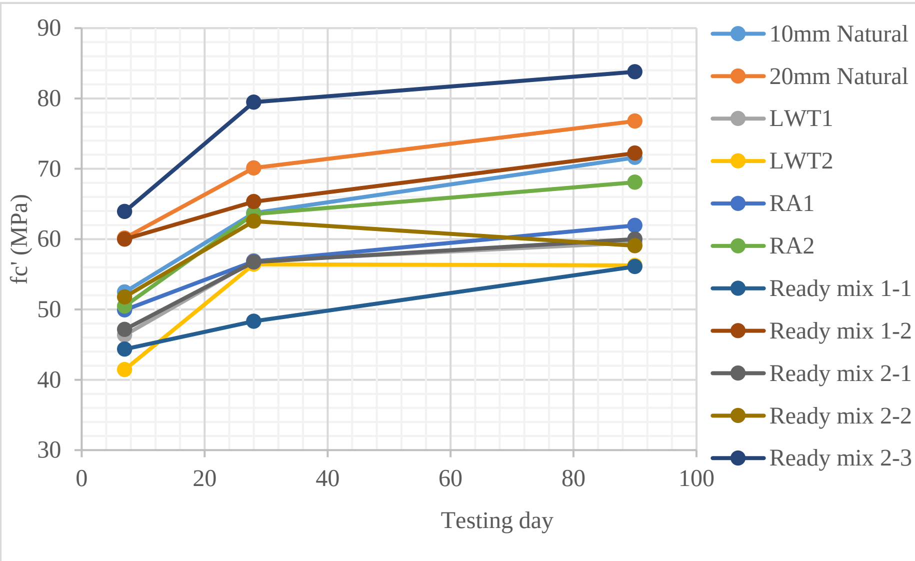


Figure 3. Average cube compressive strength.

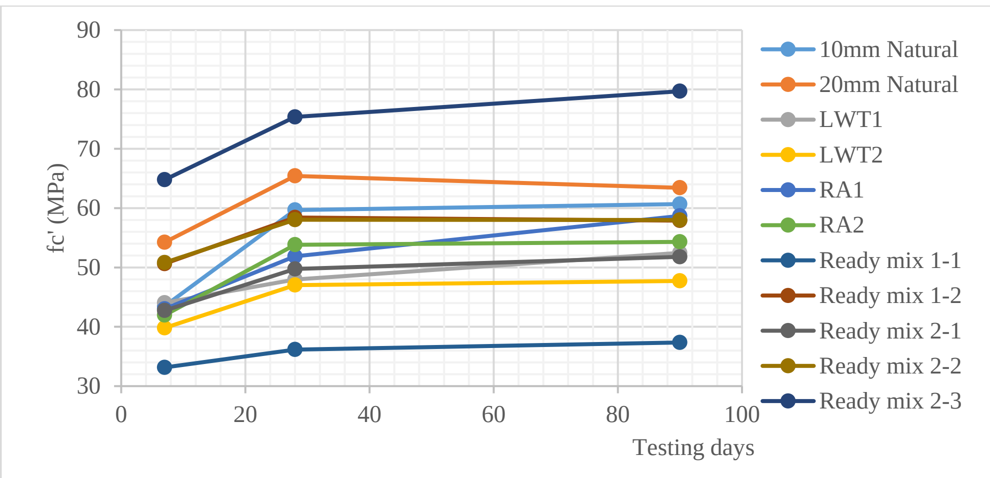


Figure 4. Average cylinder compressive strength.

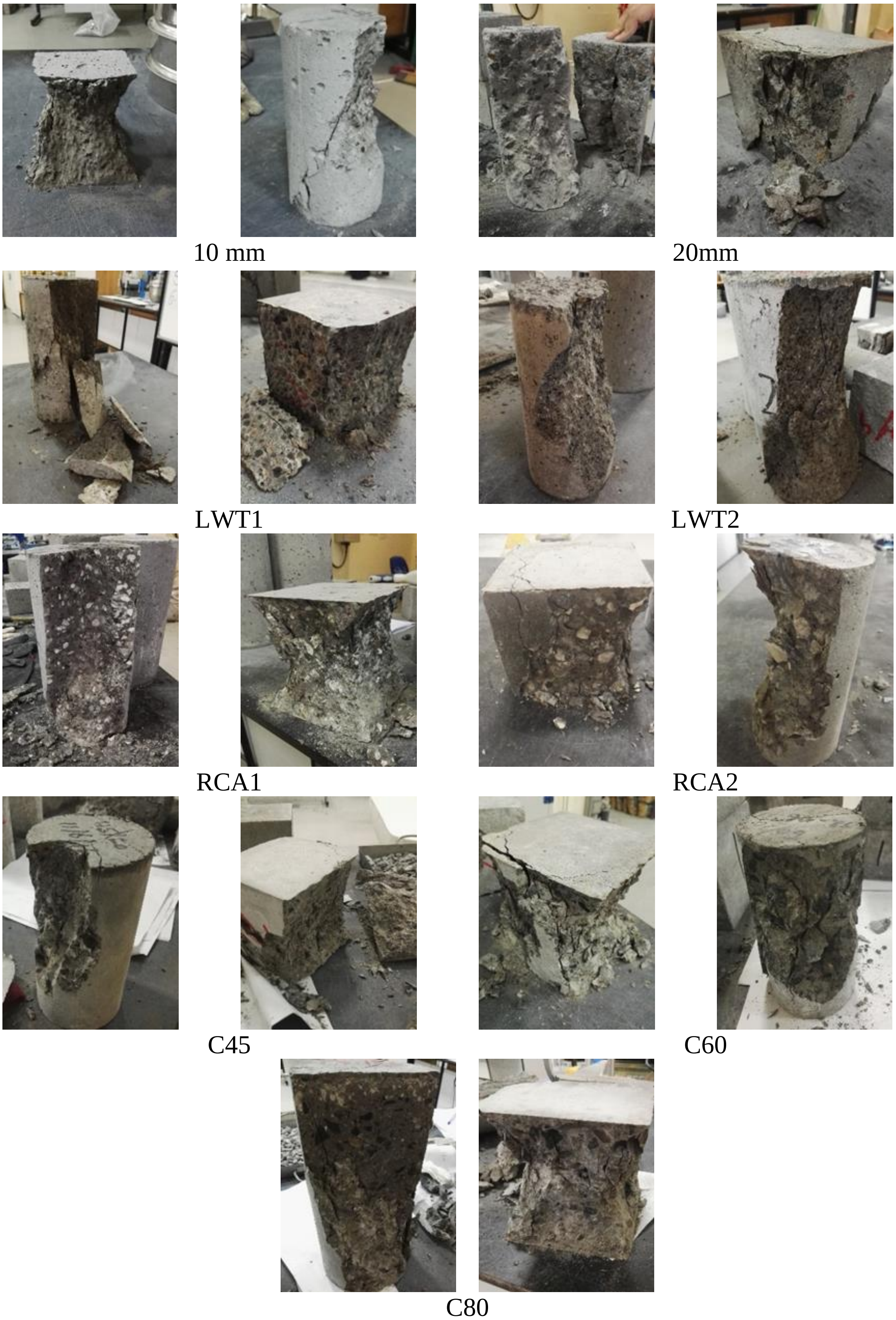


Figure 5. Failure modes of cube and cylinder specimens from all mixes.

3.2. Modulus of Elasticity, Split Strength, and Flexure Strength Results

Figures 6–8 summarize the test results of modulus of elasticity, split tensile strength, and flexure strength for all mixes except mix LWA_1. The results were significantly affected by the aggregate type. Moreover, the modulus of elasticity and flexural strength test results for all the concrete mixes had increased from 28-day to 90-day, as shown in Figures 6 and 8. The modulus of elasticity was less than that of the natural aggregate and ready-mix concrete by about 25% (for RCA) and 40% (for the LWA). However, the results of split tensile strength test indicate a significant variation among different concrete mixes as illustrated in Figure 7. This could be attributed to variation of the aggregate-cement bond properties, which are greatly influenced by the aggregate type [19,39,64,65]. It should be noted that the results in Figures 6–8 are based on two (for modulus of elasticity) or four (for split test) specimens only. Therefore, the results are considered preliminary results.

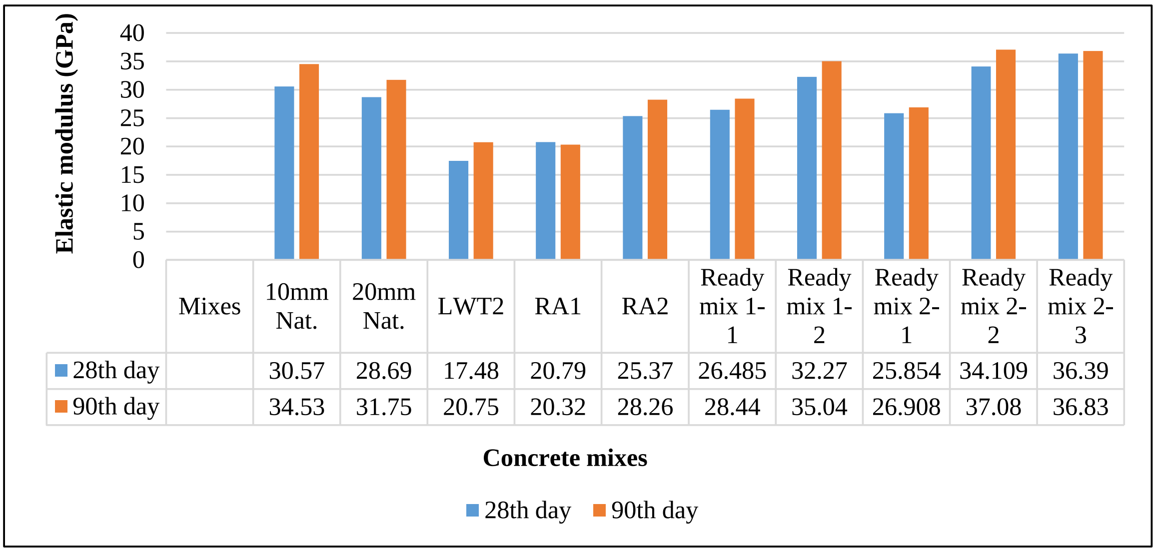


Figure 6. Elastic modulus for different concrete mixes at 28- and 90-day.

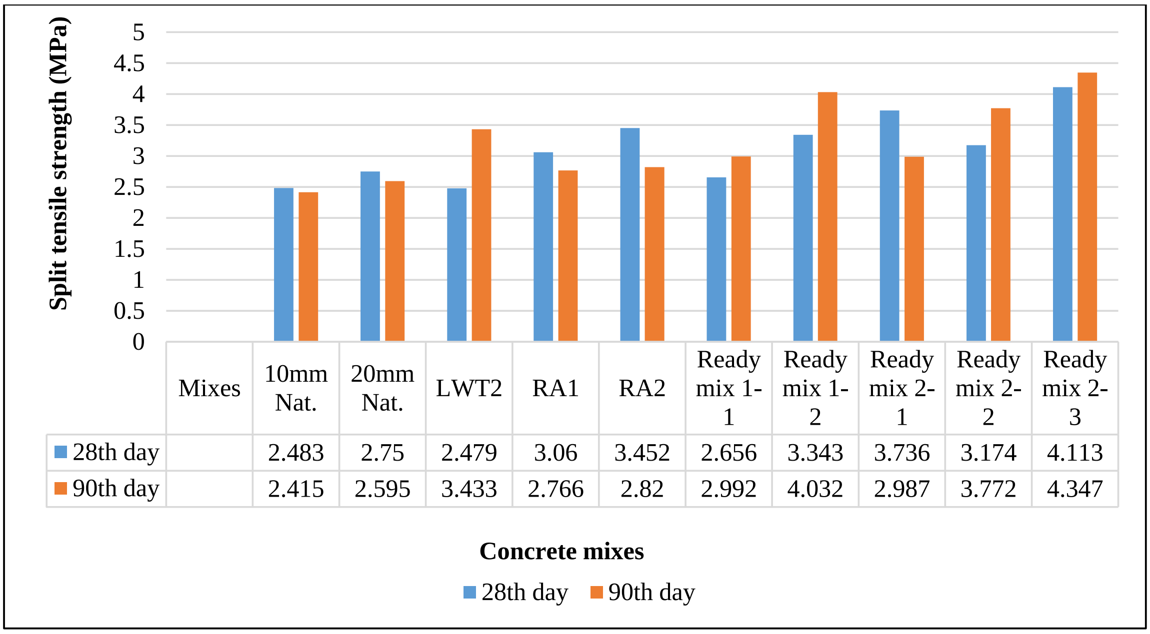


Figure 7. Split strength for different concrete mixes at 28- and 90-day.

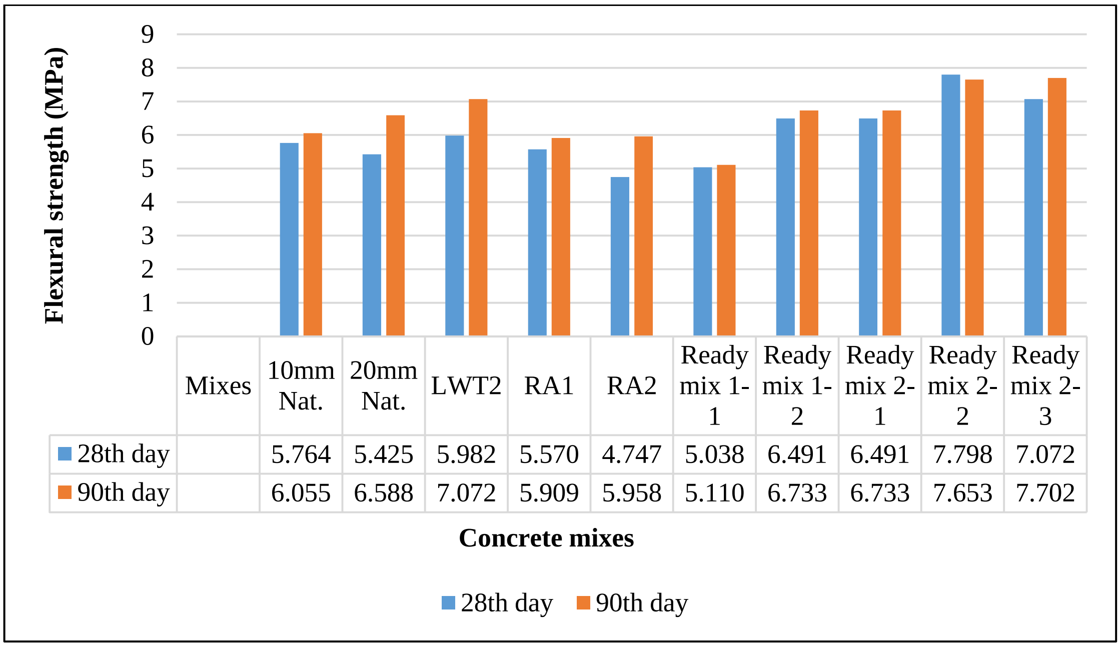


Figure 8. Flexure strength for different concrete mixes at 28- and 90-day.

4. Discussion

To evaluate the effect of sample configuration (size and shape) and aggregate strength on the concrete compressive strength, t-pooled statistical analysis was conducted on the test results. For a specific sample configuration and testing date, most of the results reported in Table 7 are average of four samples. The results for the same sample size, ratios between f'_c at 7-day and 28-day, f'_c at 90-day and 28-day, f'_c at 7-, 28-, and 90-day and the target compressive strength, and average shape factor (ratio between the cylinder and cube compressive strength values) at 7-, 28-, and 90-day are summarized in Table 8. The results indicated that there was a continuous hydration and formation of C-S-H, which is reflected by the strength gain, and most of the ratios for Cy_1, Cy_2, Cu_1, and Cu_2 specimens for different mixes were less than 1 for 7- to 28-day ratio. Previous studies [16,59,60] conclude that the natural concrete mixes typically achieve 0.7-0.8 of the 28-day strength in the first 7 days. On the other hand, most of the ratios are more than 1 for 90- to 28-day ratio. This highlights the importance of long-term evaluation especially for lightweight and recycled aggregate concrete, which is also in agreement with the recommendations for concrete with GGBS, lightweight, and recycled aggregate concrete [15,19,60]. Some scattered results in Table 8 show lower compressive strength for the 90-day than the 28-day, especially for Cy_2 specimen; nonetheless, the majority of the results indicate higher strength, which is similar to results reported in the literature [31,32,44]. Table 9 illustrates a summary of the ratio between the cylinder and cube strength from the literature and from the current study.

4.1. Shape Factor Analysis

Aggregate type, target strength, and sample configuration (cylinder or cube) and sample size might affect the compressive strength values of the concrete mixes and the shape factor (the ratio of cylinder to cube compressive strength). Therefore, statistical analysis was conducted to examine the effect of these parameters on the shape factor.

Table 8. Summary of compressive strength ratios.

Test Date / Mixes	Ratio between 7th /28th- Day Compressive Strength				Ratio between 90th /28th-Day Compressive Strength				Cu_2/TS Ratios			Average Cy/Cu Ratio		
									7th	28th	90th	7th	28th	90th
	Cy_1	Cy_2	Cu_1	Cu_2	Cy_1	Cy_2	Cu_1	Cu_2	Cu_2/T_S	Cu_2/T_S	Cu_2/T_S	Cy/Cu	Cy/Cu	Cy/Cu
10 mm Natural	0.73	0.73	0.88	0.78	1.00	1.04	1.08	1.16	0.75	0.97	1.13	0.839	0.922	0.839
20 mm Natural	0.92	0.74	0.92	0.80	1.11	0.82	1.13	1.06	0.83	1.04	1.10	0.925	0.925	0.866
LWA_1	0.84	1.02	0.82	0.81	1.02	1.19	1.08	1.01	0.70	0.87	0.88	0.946	0.806	0.878
LWA_2	0.81	0.89	0.72	0.74	1.08	0.94	1.01	0.98	0.64	0.87	0.85	0.957	0.829	0.818
RCA_1	0.86	0.80	0.97	0.80	1.09	1.18	1.09	1.09	0.69	0.87	0.95	0.872	0.934	0.929
RCA_2	0.84	0.72	0.76	0.83	1.10	0.92	1.10	1.04	0.79	0.95	0.99	0.855	0.836	0.781
Ready mix C45_1	0.96	0.88	0.98	0.86	1.03	1.04	1.25	1.08	1.00	1.16	1.25	0.747	0.748	0.666
Ready mix C75	0.82	0.92	0.97	0.87	0.98	1.00	1.08	1.13	0.79	0.91	1.02	0.844	0.894	0.802
Ready mix C45_2	0.86	0.85	0.85	0.81	1.08	1.01	1.09	1.03	1.06	1.31	1.35	0.906	0.877	0.863
Ready mix C60	0.91	0.84	0.84	0.81	1.04	0.96	0.95	0.94	0.90	1.11	1.04	0.981	0.928	0.982
Ready mix C80	0.95	0.79	0.83	0.78	1.16	0.98	1.07	1.04	0.81	1.04	1.08	1.013	0.948	0.951

Cy_1: cylinder 4x8 in, Cy_2: cylinder: 6x12 in, Cu_1: cube 4x4x4 in, Cu_2: cube 6x6x6 in, TS – Target Strength.

Table 9. Summary of cylinder vs. cube strength ratios from the literature compared to the current study. [43,45–51].

Reference	Average cylinder/cube Ratio	Remarks
Cormack [43]	0.87	Study focused on high-strength concrete. Few data were generated for f_c'<41 MPa
Evans [45]	0.77–0.96	Lower-strength concrete had generally lower cylinder/cube strength ratios
Sigvaldason [46]	0.71–0.77 0.76–0.84	Segregating concrete Non-segregating concrete
Gyengo [47]	0.65–0.84	Variation due to changing coarseness of aggregate grading
Gonnerman [48]	0.85–0.88	Tests performed using standard cylinders and 6″ and 8″ cubes
Plowman, Smith, and Sheriff [49]	0.74 0.64	Water-cured specimens Air-cured specimens In both cases, portions of steel bars were embedded in cylinder specimens
Raju and Basavarajaiah [50]	0.61 0.51	Using 150 mm cubes Using 100 mm cubes
Lasisi et al. [51]	0.67–0.76 0.55–0.86	Landcrete specimens (small agg. From lateric soil) Concrete specimens
Current study	0.66–0.98 0.82–0.88 0.78–0.93	Normal and high-strength concrete. Lightweight aggregate concrete. Recycled aggregate concrete.

4.1.1. Effect of Aggregate Type on Shape Factor

The statistical testing was conducted to compare the compressive strength of the 6-inch and the 4-inch standard specimen sizes for the same specimen shape (cube and cylinder) and concrete mix. Testing was conducted for available "n1 = n2 = 4" samples of results and was carried out for the compressive strength at 7-, 28- and 90-day. The result of this test showed that the majority of the compared standard specimen sizes gave equal compressive strength, which indicates a negligible effect of using different standard sizes on the concrete compressive strength. Accordingly, the data for the cube and cylinder have been combined (having a size of 8 samples). The average concrete compressive strength is calculated as the trimmed average of 6 samples (after excluding the highest and the lowest value). The specimen shape factors "C_y/C_u" for six concrete mixes were compared using the t-pooled hypothesis testing, for a 95% confidence level, to investigate the effect of aggregate type on the shape factor. Table 10 shows the summary of the hypothesis testing results for the shape factors at 90-day, which is considered to represent the long-term performance of the concrete. It should be noted that the limit for "t" is ±2.228. The results shown in Table 9 indicate that the aggregate type has a significant effect on the shape factor and the following observations were concluded: (i) there is no significant difference in the shape factor values when comparing natural and lightweight aggregates. However, there was a significant difference between the two types of lightweight aggregates, which was confirmed by Reference [59]; (ii) recycled aggregate concrete mixes show a statistically significant difference in the shape factors when compared to other types of aggregate. This can be attributed to the fact that the recycled aggregate properties cannot be controlled due to the high variability of their sources even in the same batch, which may have different quality and strength [13,21,59,66].

Table 10. Summary of hypothesis testing results for Cy/Cu at 90-day.

Mixes	t-Value					
	10 mm Nat.	**20 mm Nat.**	**LWA_1**	**LWA_2**	RCA_1	RCA_2
10 mm Nat.		0.860	1.301	−0.652	3.104	−1.808
20 mm Nat.			0.534	−2.087	3.130	−3.531
LWA_1				−2.971	3.108	−4.525
LWA_2					5.989	−1.640
RCA_1						−7.393
RCA_2						

4.1.2. Effect of Concrete Target Strength on Shape Factor

A summary of calculated specimen shape factors Cy_1/Cu_1 and Cy_2/Cu_2 of the five ready-mix concrete with different target strengths at 7-, 28-, and 90-day are shown in Table 11. The results for samples collected from the same ready-mix producer show that, in general, when increasing the target strength level of the concrete mix, the specimen shape factor increased. Similar results were reported by other researchers [12,40].

Table 11. Summary of Cy_1/Cu_1 and Cy_2/Cu_2 ratios at 7-, 28-, and 90-day.

Test Date / Mixes	7-day		28-day		90-day	
	Cy_1/Cu_1	**Cy_2/Cu_2**	**Cy_1/Cu_1**	**Cy_2/Cu_2**	**Cy_1/Cu_1**	**Cy_2/Cu_2**
Ready mix 1-1 (45 MPa)	0.80	0.70	0.82	0.68	0.68	0.65
Ready mix 1-2 (75 MPa)	0.79	0.90	0.94	0.85	0.86	0.75
Ready mix 2-1 (45 MPa)	0.94	0.87	0.93	0.83	0.92	0.81
Ready mix 2-2 (60 MPa)	1.07	0.90	0.99	0.87	1.08	0.89
Ready mix 2-3 (80 MPa)	1.02	1.01	0.90	1.00	0.97	0.94

4.2. Effect of Aggregate Type on Concrete Compressive Strength Analysis

Compressive strength of six concrete mixes was compared using the pooled t-test method to investigate the effect of the aggregate type on the concrete strength. Table 12 summarizes the t-pooled analysis for each specimen shape "Cy and Cu" at 90-day. For the cylinder specimen, Table 12, the results showed that compressive strength was affected by both the aggregate type and specimen shape. To investigate the aggregate type effect separately, the 90-day specimen shape factors were applied to the compressive strength of the cylinders and then re-compared using the t-pooled testing method. Results in Table 12 show that generally the concrete compressive strength was highly affected by the aggregate type. The following observations were concluded:

Table 12. Summary of **t** pooled analysis results at 90-day.

t-Value	**Cy of Six Concrete Mixes**						**Cu of Six Concrete Mixes**						**Adjusted Cy of Six Concrete Mixes**					
Mixes	**10 mm Nat.**	**20 mm Nat.**	**LWA_1**	**LWA_2**	**RCA_1**	**RCA_2**	**10 mm Nat.**	**20 mm Nat.**	**LWA_1**	**LWA_2**	**RCA_1**	**RCA_2**	**10 mm Nat.**	**20 mm Nat.**	LWA_1	LWA_2	RCA_1	RCA_2
10 mm Nat.		0.880	−4.079	−4.263	−3.837	−0.616		1.346	−3.065	−4.773	−1.138	−2.040		0.736	−3.390	−4.060	−2.677	−0.705
20 mm Nat.			−3.247	−3.510	−2.899	−1.188			−3.075	−4.175	−1.941	−2.511			−3.663	−4.217	−3.067	−1.404
LWA_1				−0.581	0.865	2.534				−1.717	2.056	0.623				−0.800	0.894	3.199
LWA_2					1.412	2.866					3.814	2.175					1.711	4.018
RCA_1						2.072						-1.153						2.340
RCA_2																		

(1) For normal strength concrete, changing the aggregate size did not affect the concrete compressive strength when using natural aggregate, similar findings were reported by References [7,34].

(2) Both lightweight and RCA_1 mixes show less compressive strength than the two natural concrete mixes. This is attributed to their lower aggregate strength. This conclusion is compatible with the results reported by previous research [13,27], which conclude that compressive strength has decreased with replacing the natural aggregate with recycled aggregate.

(3) The RCA_2 mix resulted in an equivalent compressive strength to those of the natural concrete mixes for both cylinder and cube specimens, which matches their corresponding aggregate strength and similarly gives higher compressive strength than those of the lightweight aggregate mixes.

(4) In accordance with the higher strength shown by the RCA_2 than RCA_1, its concrete mix exhibited a slightly higher compressive strength than that of RCA_1 concrete mix in the cube specimen and an equivalent strength in the cylinder case. This difference could be attributed to the variation of the recycled aggregate sources even within the same batch, which may have different properties and strength.

4.3. Correlation between Aggregate Strength and Concrete Compressive Strength

Regression analysis was conducted to investigate the relationship between the aggregate strength of the six types considered in this study represented with their weight loss percentage that resulted from the LA abrasion test, and their concrete mixes' trimmed average of the equivalent compressive strength. Analysis was done for both cylinder and cube specimens' compressive strength at 28-day. The results indicate a good correlation between the aggregate strength and their concrete mix compressive strength. The R^2 values, for a second-order equation, was around 0.60 for the cylinder and cube compressive strength, as shown in Figure 9. These results refer to the great role played by the aggregate type in affecting the concrete compressive strength. This contradicted with several previous studies [67–71] that estimate concrete compressive strength based on the water-cement ratio and ignoring the effect of aggregate type/strength in their models. Findings from the current study are in agreement with other studies [6,9,17,44,62–64] that aggregate type should be considered while predicting the concrete compressive strength.

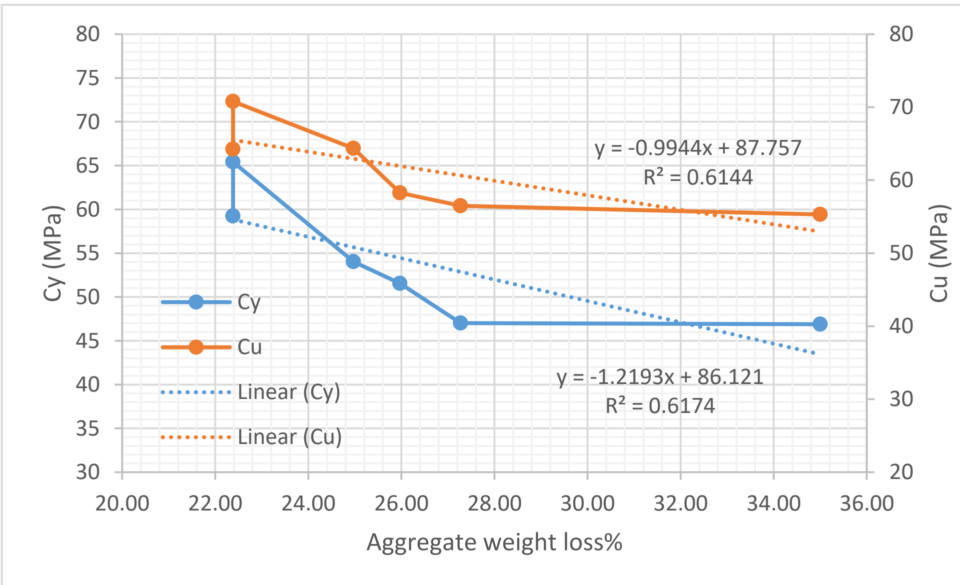


Figure 9. Correlation between compressive strength and aggregate strength.

4.4. Comparing Test Results to ACI Standards

ACI363R-10 [72] and ACI318-19 [73], Equations (1) to (6) [72,73], utilize cylinder compressive strength to predict other mechanical properties.

$$\text{Modulus of elasticity } E = 3320\sqrt{f_c'} + 6900 \text{ for } f_c' \text{ 21 MPa } < f_c' < 83 \text{ MPa} \quad (1)$$

$$E = 4700\sqrt{f_c'} \quad (2)$$

$$\text{Split tensile strength } f_{spt} = 0.59\sqrt{f_c'} \text{ for } f_c' \text{ 21 MPa } < f_c' < 83 \text{ MPa} \quad (3)$$

$$f_{spt} = 0.56\sqrt{f_c'} \quad (4)$$

$$\text{flexural strength } f_r = 0.94\sqrt{f_c'} \text{ for } f_c' \text{ 21 MPa } < f_c' < 83 \text{ MPa} \quad (5)$$

$$f_r = 0.62\,\lambda\sqrt{f_c'} \quad (6)$$

where,

f_c' is the cylinder Cy_2 compressive strength at 28-day in MPa.
λ is a reduction factor to account for aggregate type. $\lambda = 0.85$ for sand lightweight concrete.

In the current study, modulus of elasticity, split tensile strength, and flexural strength were calculated using equations from Reference [72] for natural aggregates and equations from Reference [73] for lightweight and recycled aggregate concrete mixes. The main goal of the comparison is to check the applicability of using ACI equations to predict the mechanical properties of concrete with different aggregate types. Table 13 summarizes the comparison of the calculated and tested values for the modulus of elasticity, the flexure strength, and the split strength. It is observed that the tested modulus of elasticity for the ready mixes and the mixes with natural aggregate ranged between 0.85 and 1.06 of the calculated values according to ACI equations. However, in the case of lightweight and recycled aggregates, the ACI equations overestimated the modulus of elasticity, which indicates unsuitability of these equations with RCA and LWA samples. Values from the tested samples were much lower than their standard predicted values, which were in the range of 0.55 to 0.74 of the calculated values. Lightweight aggregate and recycled aggregate samples require more curing time, which might affect the test results at 28 days, as discussed earlier in the paper.

The tested split tensile strength for the majority of the concrete mixes is lower than the standard predicted value, especially for the 10mm and 20mm concrete mixes. This indicates weak bond strength, resulting in an early failure in the lateral direction. In addition, ready-mix concrete mixes have resulted in tested flexural strength that is comparable to the calculated values (ratio of 0.83 to 1.09). The natural aggregates resulted in a lower flexure strength than the calculated values. The pumice lightweight aggregate and recycled aggregate concrete mixes exhibited higher flexural strength than those predicted, especially for the pumice lightweight aggregate concrete mix. This could be a result of its small size and rough surface, which increased the interlocking between aggregate and the cement paste and the special presoaking procedure followed for both lightweight and recycled aggregate concrete mixes, which enhanced the bond in the ITZ.

Table 14 summarizes some of the results of the modulus of elasticity, split strength, and flexural strength from the literature and the current study results, which came compatible with each other. Variation in values is attributed to the different types of aggregate used and the strength level targeted in those studies.

Table 13. Summary of calculated and tested values.

Mix	Modulus of Elasticity (GPa)			Split Strength (MPa)			Flexure Strength (MPa)		
	Calculated	Tested	Ratio+	Calculated	Tested	Ratio+	Calculated	Tested	Ratio+
10 mm Nat.	31.76	30.57	0.96	4.42	2.48	0.56	7.04	5.76	0.82
20 mm Nat.	33.80	28.69	0.85	4.78	2.75	0.58	7.62	5.43	0.71
LWA2	32.02	17.48	0.55	3.81	2.48	0.65	3.59*	5.98	1.67
RCA1	33.70	20.79	0.62	4.01	3.06	0.76	4.45	5.57	1.25
RCA2	34.25	25.37	0.74	4.08	3.45	0.85	4.52	4.75	1.05
Ready mix 1-1	26.75	26.49	0.99	3.53	2.66	0.75	5.62	5.04	0.90
Ready mix 1-2	32.15	32.27	1.00	4.49	3.34	0.74	7.15	6.49	0.91
Ready mix 2-1	30.14	25.85	0.86	4.13	3.74	0.90	6.58	6.49	0.99
Ready mix 2-2	32.15	34.11	1.06	4.49	3.17	0.71	7.15	7.80	1.09
Ready mix 2-3	37.11	36.39	0.98	5.37	4.11	0.77	8.55	7.07	0.83

*λ factor of 0.85 was adopted to account for the aggregate type; + Ratio = tested/calculated.

Table 14. Results of mechanical properties from literature and the current study results. [13,20,21,25–28,33,34,62,63,74–80].

Reference	Flexural Strength (MPa)	Split Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Remarks
Topcu and Uygunoglu [20]		3.7–3.9 1.6–1.7	33–39 17–18	Natural aggregate concrete. Lightweight aggregate concrete.
Tabsh and Abdelfatah [13]		4 2.9–4		Natural aggregate concrete. Recycled aggregate concrete.
Poon and Lam [21]		3–4.2		Normal and high-strength concrete.
Katz [25]	5.4	3.1	11.3	Recycled aggregate concrete.
McNeil et al. [26]	10.2 8.9–9.7	3.3 2.7–3		Natural aggregate concrete. 15%, 30%, and 50% RCA.
Beshr et al. [62]		2.4–4	21–28	High-strength concrete.
Beushausen and Dittmer [63]	2.66–2.93	3.74–4.35	27.03–44.81	High-strength concrete.
Kilic et al. [74]	5.2–17.3			High-strength concrete.
Wu et al. [75]		5–5.3	31–39.5	w/c = 0.44.
Zhou et al. [76]			18.6–51.3	High-performance concrete.
Ozturan and Cecen [77]	4.7–5.3	3.9–5.2		Normal and high-strength concrete.
Aitcin and Mehta [78]			31.7–37.9	High-strength concrete.
Ezeldin and Aitcin [79]	7.4–9.2			High-strength concrete.
Sengul et al. [80]		2.59–3.88 4.44–8.14	25.3—38 36.3–51.1	Normal strength concrete. High-strength concrete.
Ajamu and Ige [33]	4.4-4.93			Normal concrete with different aggregate sizes.
Meddah et al. [34]			28.5–37	Normal and high-strength concrete.
Wardeh et al. [27]	4.9 3.95–4.75	3.6 3–3.3	39.5 30–36	Natural aggregate concrete. 300%, 65%, and 100% RCA.
Choi et al. [28]		1.8–2.5		Recycled aggregate concrete.
Current study	5.5–7.8 6 4.75–5.57	2.5–4.11 2.5 3–3.5	28–36 17.5 21–25	Normal and high-strength concrete. Lightweight aggregate concrete. Recycled aggregate concrete.

5. Conclusions

This paper presents a preliminary experimental investigation of the effect of specimen configuration and aggregate type on the concrete compressive strength. Six concrete mixes with different aggregate types were cast and tested for compressive strength, elastic modulus, splitting tensile strength, and flexural strength. In addition, samples from five ready-mix concrete were collected from two producers and were evaluated for the same mechanical properties. Two specimen shapes, cylinder and cube, were used with 100 × 200 mm (4 × 8 in.) and 150 × 300 mm (6 × 12 in.) sizes. Compressive strength was evaluated on the 7-, 28- and 90-day, while the elastic modulus, split tensile strength, and flexural strength were evaluated on the 28- and 90-day. The results from the current study are based on a small number of samples, however, the following could be concluded from the findings:

For the same cementitious materials, w/c ratio and curing conditions, compressive strength of the recycled and lightweight aggregate concrete was about 15–20% lower than that of natural aggregate and ready-mix concrete mixes. The modulus of elasticity was less than that of the natural aggregate and ready-mix concrete by about 25% (for RCA) and 40% for the LWA. These lower values can be attributed to the fact that these aggregates have lower strength than natural aggregates.

For all the concrete mixes in the study, the concrete compressive strength shows significant correlation with the aggregate strength (with an R2 of 0.61). Both flexural and split tensile strengths were less affected by the aggregate type than the compressive strength and elastic modulus.

The specimen size and aggregate unit weight effect on compressive strength is negligible regardless of the specimen shape and the aggregate type. In addition, for normal strength concrete and for the aggregate gradation used in the study (10 mm and 20 mm), aggregate size has no effect on the concrete compressive strength.

The cylinder/cube ratio ranged between 0.781 and 0.929 for the 90-day, which is in agreement with previous research. Using different types of aggregate in concrete mixes resulted in a cylinder/cube ratio influenced by the aggregate strength and, in turn, was affected by the specimen shape.

Based on the preliminary results obtained in this research, it seems that ACI equations [72,73] overestimated modulus of elasticity and split tensile strength values for LWC and RAC, which indicates inapplicability of such equations for lightweight and recycled concrete.

The presoaking procedure followed during mixing of lightweight and recycled concrete enhanced the ITZ, which was reflected by the improved bond, interlocking with the cement paste and better flexural performance. In this study, pumice lightweight aggregate and recycled aggregate concrete mixes exhibited higher flexural strength than those predicted by the ACI standard [69,70].

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References

1. Neville, A.M. *Properties of Concrete*; Addison Wesley Longman: London, UK, 1995.
2. MacGregor, J.G.; Wight, J.K. *Reinforced Concrete: Mechanics and Design*; Prentice-Hall: Singapore, 2016.

3. Mamlouk, M.S.; Zaniewski, J. *Materials for Civil and Construction Engineers*, 3rd ed.; Pearson Education, Inc.: Upper Saddle River, NJ, USA, 2016.
4. Nikbin, I.M.; Beygi, M.H.; Kazemi, M.T.; Vaseghi, J.A.; Rabbanifar, S.; Rahmani, E.; Rahimi, S. A comprehensive investigation into the effect of water to cement ratio and powder content on mechanical properties of self-compacting concrete. *Constr. Build. Mater.* **2014**, *57*, 69–80. [CrossRef]
5. Toutanji, H.; Delatte, N.; Aggoun, S.; Duval, R.; Danson, A. Effect of supplementary cementitious materials on the compressive strength and durability of short-term cured concrete. *Cem. Concr. Res.* **2004**, *34*, 311–319. [CrossRef]
6. Yaqub, M.; Bukhari, I. Effect of size of coarse aggregate on compressive strength of high strength concrete. In Proceedings of the 31st Conference Our World in Concrete & Structures, Singapore, 16–17 August 2006.
7. Loannides, A.M.; Mills, J.C. *Effect of Larger Sized Coarse Aggregates on Mechanical Properties of Portland Cement Concrete Pavements and Structures*; FHWA/OH-2006/10A; Ohio Department of Transportation Office of Research and Development: Columbus, OH, USA, 2006.
8. Prem, P.R.; Bharatkumar, B.H.; Iyer, N.R. Influence of curing regimes on compressive strength of ultra high performance concrete. *Sadhana* **2013**, *38*, 1421–1431. [CrossRef]
9. Del Viso, J.; Carmona, J.R.; Ruiz, G. Shape and size effects on the compressive strength of high-strength concrete. *Cem. Concr. Res.* **2008**, *38*, 386–395. [CrossRef]
10. Yi, S.-T.; Yang, E.I.; Choi, J.-C. Effect of specimen sizes, specimen shapes, and placement directions on compressive strength of concrete. *Nucl. Eng. Des.* **2006**, *236*, 115–127. [CrossRef]
11. Tokyay, M.; Ozdemir, M. Specimen shape and size effect on the compressive strength of higher strength concrete. *Cem. Concr. Res.* **1997**, *27*, 1281–1289. [CrossRef]
12. Abd, M.K.; Habeeb, Z.D. Effect of specimen size and shape on compressive strength of self-compacting concrete. *Diyala J. Eng. Sci.* **2014**, *7*, 17–29.
13. Tabsh, S.W.; Abdelfatah, A.S. Influence of recycled concrete aggregates on strength properties of concrete. *Constr. Build. Mater.* **2009**, *23*, 1163–1167. [CrossRef]
14. Sharma, R. Effect of wastes and admixtures on compressive strength of concrete. *J. Eng. Des. Technol.* **2020**. [CrossRef]
15. Zhang, S.Y.; Fan, Y.F.; Li, N.N. The Effect of Superplasticizer on Strength and Chloride Permeability of Concrete Containing GGBFS. *Adv. Mater. Res.* **2013**, *804*, 12–16. [CrossRef]
16. Mardani-Aghabaglou, A.; Tuyan, M.; Yılmaz, G.; Arıöz, Ö.; Ramyar, K.; Yilmaz, G. Effect of different types of superplasticizer on fresh, rheological and strength properties of self-consolidating concrete. *Constr. Build. Mater.* **2013**, *47*, 1020–1025. [CrossRef]
17. Chi, J.; Huang, R.; Yang, C.; Chang, J. Effect of aggregate properties on the strength and stiffness of lightweight concrete. *Cem. Concr. Compos.* **2003**, *25*, 197–205. [CrossRef]
18. Wasserman, R.; Bentur, A. Effect of lightweight fly ash aggregate microstructure on the strength of concretes. *Cem. Concr. Res.* **1997**, *27*, 525–537. [CrossRef]
19. Lo, Y.T.; Cui, H. Effect of porous lightweight aggregate on strength of concrete. *Mater. Lett.* **2004**, *58*, 916–919. [CrossRef]
20. Topçu, I.B.; Uygunoğlu, T. Effect of aggregate type on properties of hardened self-consolidating lightweight concrete (SCLC). *Constr. Build. Mater.* **2010**, *24*, 1286–1295. [CrossRef]
21. Poon, C.S.; Lam, C.S. The effect of aggregate-to-cement ratio and types of aggregates on the properties of pre-cast concrete blocks. *Cem. Concr. Compos.* **2008**, *30*, 283–289. [CrossRef]
22. Seo, D.; Choi, H. Effects of the old cement mortar attached to the recycled aggregate surface on the bond characteristics between aggregate and cement mortar. *Constr. Build. Mater.* **2014**, *59*, 72–77. [CrossRef]
23. Xiao, J.; Li, W.; Fan, Y.; Huang, X. An overview of study on recycled aggregate concrete in China (1996–2011). *Constr. Build. Mater.* **2012**, *31*, 364–383. [CrossRef]
24. Tsoumani, A.A.; Matikas, T.E.; Barkoula, N.M. Influence of Recycled Aggregates on Compressive Strength of Concrete. In Proceedings of the 2nd International Conference on Sustainable Solid Waste Management, Athens, Greece, 12–14 June 2014.
25. Katz, A. Properties of concrete made with recycled aggregate from partially hydrated old concrete. *Cem. Concr. Res.* **2003**, *33*, 703–711. [CrossRef]
26. McNeil, K.; Thomas, H.; Kang, K. Recycled Concrete Aggregates: A Review. *Int. J. Concr. Struct. Mater.* **2013**, *7*, 61–69. [CrossRef]

27. Wardeh, G.; Ghorbel, E.; Gomart, H. Mix Design and Properties of Recycled Aggregate Concretes: Applicability of Eurocode 2. *Int. J. Concr. Struct. Mater.* **2014**, *9*, 1–20. [CrossRef]
28. Choi, H.; Choi, H.; Lim, M.; Inoue, M.; Kitagaki, R.; Noguchi, T. Evaluation on the Mechanical Performance of Low-Quality Recycled Aggregate Through Interface Enhancement Between Cement Matrix and Coarse Aggregate by Surface Modification Technology. *Int. J. Concr. Struct. Mater.* **2016**, *10*, 87–97. [CrossRef]
29. Petrounias, P.; Giannakopoulou, P.P.; Rogkala, A.; Stamatis, P.M.; Tsikouras, B.; Papoulis, D.; Lampropoulou, P.; Hatzipanagiotou, K. The Influence of Alteration of Aggregates on the Quality of the Concrete: A Case Study from Serpentinites and Andesites from Central Macedonia (North Greece). *Geosciences* **2018**, *8*, 115. [CrossRef]
30. Petrounias, P.; Giannakopoulou, P.P.; Rogkala, A.; Stamatis, P.M.; Lampropoulou, P.; Tsikouras, B.; Hatzipanagiotou, K. The Effect of Petrographic Characteristics and Physico-Mechanical Properties of Aggregates on the Quality of Concrete. *Minerals* **2018**, *8*, 577. [CrossRef]
31. Elices, M.; Rocco, C. Effect of aggregate size on the fracture and mechanical properties of a simple concrete. *Eng. Fract. Mech.* **2008**, *75*, 3839–3851. [CrossRef]
32. Rocco, C.; Elices, M. Effect of aggregate shape on the mechanical properties of a simple concrete. *Eng. Fract. Mech.* **2009**, *76*, 286–298. [CrossRef]
33. Ajamu, S.O.; Ige, J.A. Effect of Coarse Aggregate Size on the Compressive Strength and the Flexural Strength of Concrete Beam. *J. Eng. Res. Appl.* **2015**, *5*, 67–75.
34. Meddah, M.S.; Zitouni, S.; Belâabes, S. Effect of content and particle size distribution of coarse aggregate on the compressive strength of concrete. *Constr. Build. Mater.* **2010**, *24*, 505–512. [CrossRef]
35. Sim, J.-I.; Yang, K.-H.; Kim, H.-Y.; Choi, B.-J. Size and shape effects on compressive strength of lightweight concrete. *Constr. Build. Mater.* **2013**, *38*, 854–864. [CrossRef]
36. Van Mier, J.G.M. Strain-Softening of Concrete under Multiaxial Loading Conditions. Ph.D. Thesis, Eindhoven University of Technology, Eindhoven, The Netherlands, 1986.
37. ASTM Standards. *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*; Annual Book of ASTM Standards (ASTM C39–01); American Society for Testing and Materials: Philadelphia, PA, USA, 2001.
38. Yazıcı, Ş.; Sezer, G.I. The effect of cylindrical specimen size on the compressive strength of concrete. *Build. Environ.* **2007**, *42*, 2417–2420. [CrossRef]
39. Kampmann, R.; Roddenberry, M.; Ping, W.V. Contribution of Specimen Surface Friction to Size Effect and Rupture Behavior of Concrete. *ACI Mate. J.* **2013**, *110*, 169–176.
40. Elwell, D.J.; Fu, G. *Compression Testing of Concrete: Cylinders vs. Cubes*; New York State Department of Transportation, State Campus: Albany, NY, USA, 1995; Report FHWA/NY/SR-95/119.
41. BS 1881: Part 120 Method of Determination of the Compressive Strength of Concrete Core. *Mag. Concr. Res.* **1983**, *27*, 161–170.
42. ENV 206. *Concrete: Performance, Production, Placing, and Compliance Criteria*; European Standard: London, UK, 1990; ISBN 0-580-20943-1.
43. Cormack, H.W. *Notes on Cubes Versus Cylinders*; New Zealand Engineering: Wellington, New Zealand, 1956; Volume 11, pp. 98–99.
44. De Brito, J.; Kurda, R.; Da Silva, P.R. Can We Truly Predict the Compressive Strength of Concrete without Knowing the Properties of Aggregates? *Appl. Sci.* **2018**, *8*, 1095. [CrossRef]
45. Evans, R.H.; Abeles, P.W.; E Reynolds, C.; Konyi, K.H.; Squire, R.H. Correspondence. the Plastic Theories for the Ultimate Strength of Reinforced Concrete Beams. *J. Inst. Civ. Eng.* **1944**, *22*, 383–398. [CrossRef]
46. Sigvaldason, O.T. The influence of testing machine characteristics upon the cube and cylinder strength of concrete. *Mag. Concr. Res.* **1966**, *18*, 197–206. [CrossRef]
47. Gyengo, T. Effect of Type of Test Specimen and Gradation of Aggregate on Compressive Strength of Concrete. *J. Am. Concr. Inst.* **1938**, *34*, 269–282.
48. Gonnerman, H.F. Effect of Size and Shape of Test Specimen on Compressive Strength of Concrete. In *Proceedings of ASTM*; ASTM International: West Conshohocken, PA, USA, 1925; Volume 25, pp. 237–250.
49. Plowman, J.M.; Smith, W.F.; Sheriff, T. *Cores, Cubes, and the Specified Strength of Concrete*; The Institution of Structural Engineer: London, UK, 1974; Volume 52, pp. 421–426.
50. Raju, N.K.; Basavarajaiah, B.S. Experimental Investigations on Prismatic Control Specimens for Compressive, Flexural, and Tensile Strength of Concrete. *J. Inst. Eng. (India) Civil Eng. Div.* **1976**, *56*, 254–257.

51. Lasisi, F.; Osunade, J.A.; Olorunniwo, A. Strength Characteristics of Cube and Cylinder Specimens of Laterized Concrete. *West Indian J. Eng.* **1987**, *12*, 50–59.
52. ASTM C33–01. *Standard Specification for Concrete Aggregates*; ASTM International: West Conshohocken, PA, USA, 2002.
53. ASTM C136/C136M-14. *Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates*; ASTM International: West Conshohocken, PA, USA, 2014.
54. ASTM C127–15. *Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate*; ASTM International: West Conshohocken, PA, USA, 2015.
55. ASTM C131/C131M-14. *Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine*; ASTM International: West Conshohocken, PA, USA, 2006.
56. ASTM C496/C496M-11. *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens*; ASTM International: West Conshohocken, PA, USA, 2004.
57. ASTM C78/C78M-16. *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)*; ASTM International: West Conshohocken, PA, USA, 2016.
58. ASTM C469/C469M-14. *Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression*; ASTM International: West Conshohocken, PA, USA, 2014.
59. Yehia, S.; Helal, K.; Abusharkh, A.; Zaher, A.; Istaitiyeh, H. Strength and Durability Evaluation of Recycled Aggregate Concrete. *Int. J. Concr. Struct. Mater.* **2015**, *9*, 219–239. [CrossRef]
60. Yehia, S.; Alhamaydeh, M.; Farrag, S. High-Strength Lightweight SCC Matrix with Partial Normal-Weight Coarse-Aggregate Replacement: Strength and Durability Evaluations. *J. Mater. Civ. Eng.* **2014**, *26*, 04014086. [CrossRef]
61. Yehia, S.; Abudayyeh, O.; Bhusan, B.; Maurovich, M.; Zalt, A. Self-Consolidating Concrete Mixture with Local Materials: Proportioning and Evaluation. *Mater. Sci. Res. J.* **2009**, *3*, 41–64.
62. Beshr, H.; Almusallam, A.; Maslehuddin, M. Effect of coarse aggregate quality on the mechanical properties of high strength concrete. *Constr. Build. Mater.* **2003**, *17*, 97–103. [CrossRef]
63. Beushausen, H.; Dittmer, T. The influence of aggregate type on the strength and elastic modulus of high strength concrete. *Constr. Build. Mater.* **2015**, *74*, 132–139. [CrossRef]
64. Jones, R.; Kaplan, M.F. The effect of coarse aggregate on the mode of failure of concrete in compression and flexure. *Mag. Concr. Res.* **1957**, *9*, 89–94. [CrossRef]
65. Zimbelmann, R. A contribution to the problem of cement-aggregate bond. *Cem. Concr. Res.* **1985**, *15*, 801–808. [CrossRef]
66. Yehia, S.; Abdelfatah, A. Examining the Variability of Recycled Concrete Aggregate Properties. In Proceedings of the International Conference on Civil, Architecture and Sustainable Development, London, UK, 1–2 December 2016.
67. Feret, R. *On the Compactness of Hydraulic Mortars (in French–Sur la compacité des mortiers hydrauliques)*; C. Dunod: Paris, France, 1892.
68. Abrams, L.D. *Properties of Concrete*, 3rd ed.; Pitman Publishing Ltd.: London, UK, 1919.
69. Powers, T.; Brownyard, T. *Studies of the Physical Properties of Hardened Portland Cement Paste*; American Concrete Institute (ACI): Farmington Hills, MI, USA, 1946; Volume 18, pp. 669–712.
70. Popovics, S.; Ujhelyi, J. Contribution to the concrete strength versus water-cement ratio relationship. *J. Mater. Civ. Eng.* **2008**, *20*, 459–463. [CrossRef]
71. Behnood, A.; Behnood, V.; Gharehveran, M.M.; Alyamaç, K. Prediction of the compressive strength of normal and high-performance concretes using M5P model tree algorithm. *Constr. Build. Mater.* **2017**, *142*, 199–207. [CrossRef]
72. ACI363R-10. *Report on High-Strength Concrete. Farmington Hills*; American Concrete Institute: Farmington Hills, MI, USA, 2010.
73. ACI318–19. *Building Code Requirements for Structural Concrete. Farmington Hills*; American Concrete Institute: Farmington Hills, MI, USA, 2019.
74. Kılıç, A.; Atiş, C.; Teymen, A.; Karahan, O.; Özcan, F.; Bilim, C.; Ozdemir, M.; Kılıç, A. The influence of aggregate type on the strength and abrasion resistance of high strength concrete. *Cem. Concr. Compos.* **2008**, *30*, 290–296. [CrossRef]
75. Wu, K.-R.; Chen, B.; Yao, W.; Zhang, N. Effect of coarse aggregate type on mechanical properties of high-performance concrete. *Cem. Concr. Res.* **2001**, *31*, 1421–1425. [CrossRef]

76. Zhou, F.; Lydon, F.; Barr, B. Effect of coarse aggregate on elastic modulus and compressive strength of high performance concrete. *Cem. Concr. Res.* **1995**, *25*, 177–186. [CrossRef]
77. Özturan, T.; Çeçen, C. Effect of coarse aggregate type on mechanical properties of concretes with different strengths. *Cem. Concr. Res.* **1997**, *27*, 165–170. [CrossRef]
78. Aitcin, P.C.; Mehta, P.K. Effect of Coarse Aggregate Characteristics on Mechanical Properties of High-Strength Concrete. *ACI Mater. J.* **1998**, *95*, 252–261.
79. Mehta, P.; Ezeldin, A.; Aitcin, P.-C. Effect of Coarse Aggregate on the Behavior of Normal and High-Strength Concretes. *Cem. Concr. Aggreg.* **1991**, *13*, 121–124. [CrossRef]
80. Sengul, O.; Tasdemir, C.; Mehmet Ali Tasdemir, M.A. Influence of Aggregate Type on Mechanical Behavior of Normal and High Strength Concretes. *ACI Mater. J.* **2002**, *99*, 528–533.