EFFECT OF AGGREGATE TYPE AND SPECIMEN CONFIGURATION ON CONCRETE COMPRESSIVE STRENGTH

by

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Abstract

Cement content, water-to-cement ratio (w/c), aggregate size and type, specimen size and shape, loading rate, and curing are some factors that affect the concrete compressive strength.

This study focuses on the effect of aggregate type and specimen configuration on the compressive strength of concrete. Six concrete mixes utilizing 10 mm and 20 mm natural, LAYTAG and Pumice lightweight, and recycled aggregate from two sources, "Bee'ah and Jabal Ali", were used to investigate the effect of these two factors. In addition, samples from ready-mix concrete producers with different strengths "C45, C75, C60, and C80" were evaluated for the compressive strength using standard size cylinders and cubes. Strength development was monitored 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 estimate the relationships among the variables considered in the investigation. Moreover, other mechanical properties as a function of compressive strength were discussed and compared to those predicated by the ACI specification. Results indicate that standard specimen size has a negligible effect on the concrete compressive strength; whereas, specimen shape had 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. Other mechanical properties, such as 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.

Search Terms: Aggregate Type, Specimen Shape, Specimen Size, Compressive Strength, Concrete Mechanical Properties.

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Chapter 1: Introduction

1.1 Problem Statement

In the civil engineering practice, compressive strength is the most important mechanical properties of concrete due to its importance for design and its simplicity for testing procedures. It has been also used as an indicator for other concrete mechanical properties such as tensile strength and modulus of elasticity which related to it via empirical formulas. Concrete compressive strength is affected by several factors. The most important factors affecting the concrete compressive strength are highlighted below:

1. Water/cement ratio (w/c): a low water/cement ratio reduces the porosity of the hardened concrete and thus increases the number of interlocking solids which provides a good bond between successive concrete layers and increases strength. It also increases resistance to weathering. On the other hand, excess water increases the porosity and permeability which tends to reduce concrete strength [1, 2].
2. Type of cement: different concrete applications require cement with specific properties. Five basic types of Portland cement are used. These are normal, modified with supplementary with cementitious materials, low heat of hydration, high early strength, and sulfate resisting [1].
3. Supplementary cementatious materials: commonly used to achieve economy, to reduce heat of hydration, improve workability, and increase strength depending on the materials. They also ensure the quality of concrete during the stages of mixing, transporting, placing, and curing in adverse weather conditions [1, 3].
4. Aggregate: concrete compressive strength is affected by aggregate strength, surface texture, grading and maximum size. Normal strength concrete made with high strength aggregates fails due to mortar cracking, more than failing by aggregate particles crushing. The stress strain curves of such concretes tend to have an appreciable declining branch after reaching the maximum stress. In cases where aggregate failure precedes mortar cracking, failure tends to occur abruptly with a very steep declining branch [1, 4, and 5].
5. Mixing water: impurities in the mixing water can affect concrete set time, strength, and durability. It is generally thought that pH of water should be between 6.0 and 8.0 [1, 6].

6. Moisture conditions during curing: pro-longed moist curing leads to the highest concrete strength. 3rd and 7th day moist curing period will lead to 60% and 80% of the strength of the continuously cured concrete [1, 7].
7. Temperature conditions during curing: increasing curing temperature increases the rate of hydration and consequently increases the rate of strength development. Concrete that freezes soon after it has been placed will have a severe strength loss [1, 7].
8. Age of concrete: concrete gains strength with age as long as loading and environmental conditions are meeting the design requirements [1].
9. Maturity of concrete: it is the summation of the product of the difference between the curing temperature and the threshold temperature, and the time the concrete has cured at that temperature [1].
10. Rate of loading: during testing, under very slow rates of loading, the axial compressive strength is reduced to about 75% of the standard test strength. Whereas, at high rates of loading, the strength increases and reaching 115% of the standard test strength [1, 8].
11. Specimen configurations: cylinder specimen generally gives lower compressive strength than the cube specimen. For the same aspect ratio, increasing the specimen size might decrease the compressive strength of the concrete, especially in the cubic shape [1, 9-13].

Several studies consider the specimen size and type effect on compressive strength of normal and high strength concrete, light weight aggregate concrete and recycled aggregate concrete; however, most studies are focused on a specific concrete type and no comparison was found to establish the effect of aggregate type on the specimen size and shape factors. Moreover, limited numbers of studies explored the effect of specimen configuration on compressive strength of both light weight and recycled aggregate concrete types, which indicates that more research is required.

This study focuses on investigating the effect of aggregate type, and specimen size and shape on the compressive strength of concrete mixes.

1.2 Significance of the Thesis

This study helps engineers to better understand the aggregate effect on concrete compressive strength and to predict compressive strength of lightweight, and recycled aggregate concrete in terms of those of natural concrete. A correction factors between specimen configuration and aggregate type is proposed to help predict the concrete compressive strength for different aggregate types.

1.3 Objectives of Study

This study investigates the specimen shape and size factors for three different types of concrete; normal concrete, light weight aggregate concrete, and recycled aggregate concrete. It then compares the findings in order to study the effect of aggregate type on concrete compressive strength with respect to the size and shape factors of those specimens.

In order to achieve the above mentioned goals, six concrete mixes utilizing 10mm and 20mm natural aggregate, LAYTAG and Pumice lightweight aggregate and two sources of recycled aggregate were evaluated for the compressive strength. They were evaluated using cylinders and cubes of different sizes. Strength development was monitored on the 7th, 28th and 90th day. In addition, flexural strength, split tension, and modulus of elasticity were evaluated.

Statistical analyses were conducted to estimate the following:

1. The relationship between the aggregate type and the cylinder/cube ratio to investigate the aggregate type effect on the specimen shape factor.
2. The relationship between the compressive strength of specimens of two standard sizes for the same concrete mix and same specimen shape to investigate the effect of specimen size on the concrete compressive strength.
3. The relationship between the aggregate type and the compressive strength for the same specimen shape and size to investigate the effect of aggregate type on the concrete compressive strength.

Moreover, other mechanical properties, as a function of compressive strength, were discussed and compared to those predicated by the ACI specifications.

1.4 Thesis Structure

This study mainly investigates the effect of aggregate type and specimen configuration on the concrete compressive strength. This is presented through the following chapters:

- ***Chapter 1: Introduction***: provides discussion of the problem statement and the need for this study. Presents the objectives of the current study.

- ***Chapter 2: Background***: presents a survey of the previous studies and related literatures.
- ***Chapter 3: Experimental Program***: explains all the experimental work done, such as casting mixes, preparing samples, curing procedure, and testing methods.
- ***Chapter 4: Summary***: summarizes the results of testing.
- ***Chapter 5: Statistical Analyses and Discussion***: is done for results presented in the chapter 4 and a detailed discussion is provided for the results.
- ***Chapter 6: Conclusions***: summarizes the final outcomes of the experimental results and suggests recommendations for future research.

Chapter 2: Background

This chapter presents available studies found in the literature on the effect of aggregate type, size, and the specimen configuration on the compressive strength of different concrete types.

2.1 Aggregate Type and Size Effect

2.1.1 Aggregate type. For the same cementitious materials, w/c and curing conditions for concrete, aggregate type and size are the most important factors affecting the concrete compressive strength as aggregate represents about 60-70% per volume of any concrete mixtures. Using aggregate of large sizes leads to a low surface to volume ratio and weak aggregate-cement paste bond which decreases the compressive strength of the concrete mix. Aggregate type affects the failure mechanism of the concrete mix which in turn affects the compressive strength. Failure of concrete strength depends mainly on three factors: the strength of the aggregate, the strength of the cement paste, and the bond strength between the aggregate and the cement paste. Different aggregate types have varying properties, which leads to different failure mechanisms.

Loannides et al. [5] studied the effect of coarse aggregate on concrete mechanical properties and state that concrete strength mainly depends on three factors: aggregate strength, cement paste strength, and bond between the aggregate and the cement paste. They explain that, for concrete with normal weight aggregate, aggregate strength is generally higher than that of the cement paste and the bond between the aggregate and the cement paste. Thus, failure tends to occur in the cement paste and in the interfacial zone between aggregate particles and the paste, before happening in the aggregate.

For lightweight concrete, aggregate strength is lower than both the cement paste strength and the bond strength between the aggregate and the cement paste; therefore, failure starts in the aggregate particles before and during cracks formation in the cement paste. Chen and Wang [14] and Zimbelmann [15] explain that the strength of bond depends on three different factors: 1) the mechanical keying of the hydration products of cement with the rough surface of the aggregate, 2) the epitaxial growth of hydration products at some aggregate surfaces, and 3) the physical-chemical bond between the hydrating cement paste and aggregate.

Chi et al. [16] investigated the effect of aggregate properties on the strength and stiffness of lightweight aggregate. They report that the lightweight aggregate is relatively weaker than the normal aggregate and has a high internal porosity, which results in a low apparent specific gravity. Three different types of lightweight aggregate with four volume fractions of 18%, 24%, 30%, and 36% were used for preparing concrete mixes with three different water/cement ratios. Both compressive strength and elastic modulus were tested at 28th day. The results were statistically analyzed and indicate that increasing the water/cement ratio and the aggregate volume fraction has decreased both the compressive strength and the elastic modulus of the mixes. Similarly, increasing the aggregate strength had increased both the compressive strength and the elastic modulus of the mixes prepared with aggregate of volume fractions of 24%, 30%, and 36%. On the other hand, with 18% volume fraction of aggregate, concrete compressive strength and elastic modulus were independent on the aggregate strength but controlled by the cement paste, as shown in Figure 2.1.

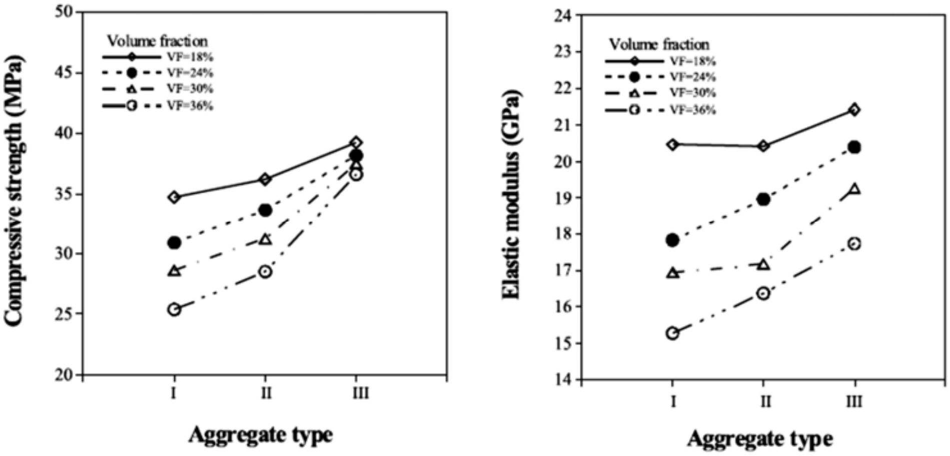


Figure 2.1: Effect of aggregate type on compressive strength and elastic modulus for concrete with various volume fractions [16].

Wasserman et al. [17] studied the effect of lightweight fly ash aggregate microstructure on the strength of concretes. The sintered fly ash lightweight aggregate was modified by heat and polymer treatments to obtain aggregate with different strength, absorption, and pozzolanic activity. The strengths of concretes produced from such aggregates were evaluated and their microstructure was characterized. The study indicates that the mechanical properties of lightweight aggregate concrete cannot be related solely to aggregate strength and effective w/c ratio. Other special characteristics of such aggregates may influence the concrete strength; for instance, the rough surface which leads to mechanical interlocking, water absorption by the porous aggregates, and the pozzolanic nature of the solid comprising the aggregate which leads to chemical bond formation. All of these factors resulted in a different interfacial transition zone than that of the normal aggregate concretes and in different concrete strengths.

Lo et al. [18] investigated the effect of porous lightweight aggregate on the concrete strength. They studied the microstructure of interfacial zone (IZ) of one type of lightweight aggregate concrete. The researchers explain that dense IZ resulted in a good bond between the aggregate and the matrix, which resulted in good performance characteristics for the concrete. For normal weight concrete, wall effect occurred at the surface of the normal weight aggregate, and the IZ was porous with 50-100 μm width. For lightweight concrete, the IZ has higher porosity which attributes to the formation of large crystalline products, like calcium hydroxide crystals, which is not continuous and may be parallel, perpendicular, or random which prevented the occurrence of the wall effect on the surface of the lightweight aggregate. Moreover, Lo et al. [18] point out that the initial strength development at the first 7 days for LWC was much higher than for the normal weight concrete specimen (NWC); they related that to the improved interfacial bond of the lightweight aggregate to the cement paste.

A study by Topcu et al. [19] of the effect of aggregate type on properties of hardened self-consolidating lightweight concrete (SCLC) reported different results. Normal crushed limestone was used for producing self-consolidating concrete (SCC), and three coarse lightweight aggregate (LWA) types: pumice, volcanic tuff and diatomite were used for producing SCLC with different water to binder ratios. The interfacial transition zone (ITZ) in SCC was not observed in the SCLC made with pumice and tuff lightweight aggregate due to the rough surface texture of aggregates which increased the interconnection of the lightweight aggregate and the cement matrix, leading to better interlocking. Topcu et al. [19] conclude that the wavy surface of LWA increases the holding of hydrated cement mortar on the aggregate. The ITZ of SCLC with diatomite showed weak bond with no interlocking was observed. They attributed that to the high porous structure of diatomite aggregate which allows for moisture exchange between the partially saturated lightweight aggregate and plastic mortar phase. This leads to the development of thin films of water at the interface between the aggregate and cement paste “wall effect” which prevents the occurrence of the mechanical interlocking. The study indicates that strength development decreases with the increase of the w/b ratio. Furthermore, the replacement of the normal crushed stone with lightweight aggregate decreases the compressive strength of the concrete due to the weakness of the lightweight aggregates.

For recycled aggregate concrete, Tabsh et al. [20] indicate that generally recycled aggregate concrete mixes require more water than natural concrete to maintain the same slump without the use of admixtures. This additional amount of water decreases the quality and strength of the concrete. In addition, the bond between the recycled aggregate surface and cement mortar is affected by the quantity and the growth shape of the old cement mortar on the aggregate surface.

Poon et al. [21] investigated the effect of different aggregate to cement ratio (3 to 6) and types of aggregates (natural crushed aggregate (NCA), recycled crushed aggregate (RCA) and recycled crushed glass (RCG) on the properties of precast concrete blocks. Four series of concrete mixes were prepared using NCA for series I, RCA for series II, RCG for series III, and 50% RCA and 50% RCG for series IV with A/C ratios of 3, 4, and 6 and were casted in 200x100x60 mm blocks. Results indicate that the compressive strength generally decreases when the aggregate to cement (A/C) ratio increases for all concrete mixes with different types of aggregates, as shown in Figure 2.2.

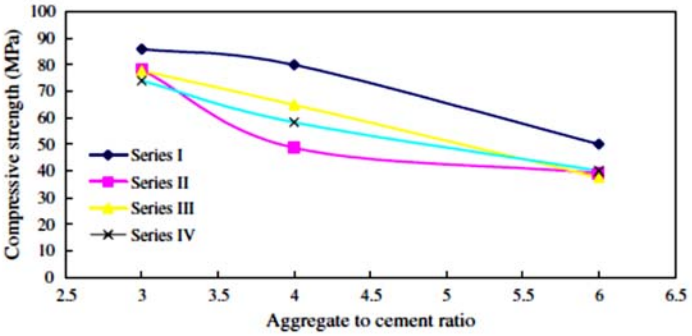


Figure 2.2: Relationship between strength and A/C ratio for concrete mixtures in Series I, II, III, and IV [21].

With A/C ratio equal to 3, the strength of the concrete blocks was mainly dependent on the strength of the cement matrix. For A/C ratio of 4, the blocks strength was found directly proportional to the corresponding aggregate strength (10% fines value as an indication of the crushing strength of the aggregate), as shown in Figure 2.3.

For a high A/C ratio of 6, the concrete blocks showed lower strength as the bonding between the cement matrix and the RCA and RCG became relatively weak.

The strength for the blocks made of natural crushed aggregate was still high; this is probably due to the better strength of the NCA.

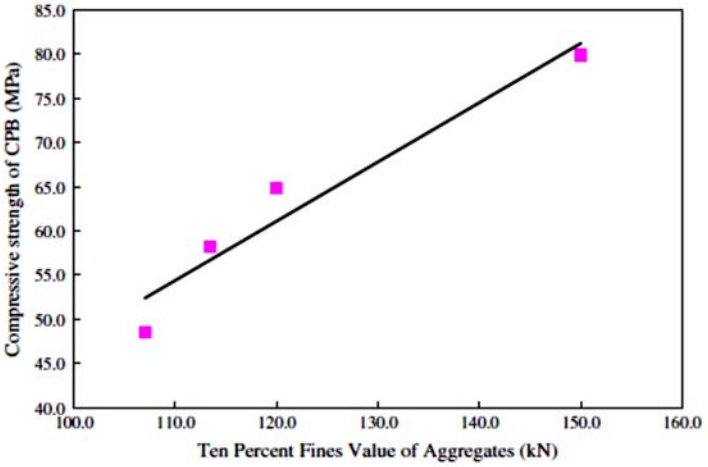


Figure 2.3: Relationship between strength and 10% fines value of concrete mixtures prepared with A/C ratio of 4 in series I, II, III, and IV [21].

In their study, Seo et al. [22] report that the amount of the recycled coarse aggregate has a remarkable effect on the compressive strength of the concrete. Same results were obtained by Xiao et al. [23] and Tsoumani et al. [24] who illustrate the relationship between the recycled coarse aggregate (RCA) replacement percentage % and the relative compressive strength defined as the ratio of the compressive strength of recycled aggregate concrete (RAC) to that of the natural concrete. As shown in Figure 2.4, the concrete compressive strength decreased with the increase in the recycled coarse aggregate (RCA) content, and the compressive strength percentage loss is more significant in a weak concrete than in a stronger one. However, when the recycled coarse aggregate RCA content is less than 25-30%, the influence on the compressive strength is not obvious.

In addition, the amount of the recycled coarse aggregate has a remarkable decreasing effect on the elastic modulus of the concrete, which in turn has an effect on the compressive strength. Another illustration of the relationship between the recycled coarse aggregate (RCA) replacement percentage % and the relative elastic modulus of recycled aggregate concrete (RAC) to that of the conventional concrete is shown in Figure 2.5. The concrete elastic modulus decreased with the increase in the recycled coarse aggregate (RCA) content, and this is attributed to the large amount of old mortar

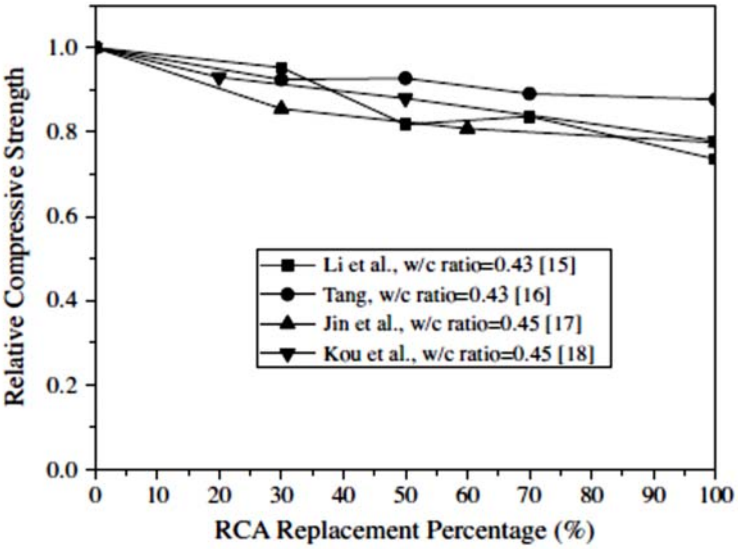


Figure 2.4: Influence of RCA content on compressive strength [23].

with comparatively low modulus of elasticity which was attached to the original aggregate in the recycled aggregate concrete. Decreasing the elastic modulus led to lower compressive strength compared to that of the natural concrete.

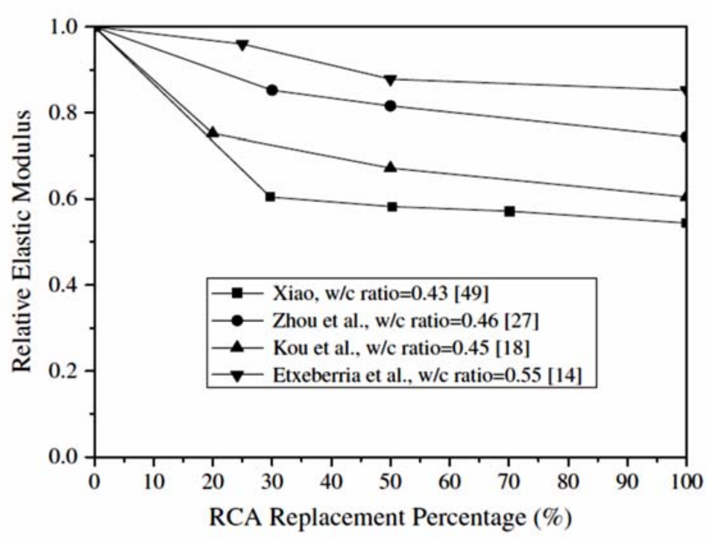


Figure 2.5: Influence of RCA content on elastic modulus [23].

Katz [25] studied the properties of concrete made with 100% recycled aggregate from partially hydrated old concrete. Concrete having a 28th day compressive strength of 28 MPa was crushed at 1st, 3rd and 28th day to be used as an aggregate for new concrete mixes using Ordinary Portland Cement (OPC), and White Portland Cement

(WC). Both of the old concrete used to produce the recycled aggregate, and the new concrete made with recycled aggregate were tested to specify their properties. Katz [25] reports that aggregate with different sizes had different properties with no effect from the crushing age. The crushing age affected the concrete made with it. For example, WC concrete made with aggregate crushed at the age of 3-day showed better properties than those crushed at 1st and 28th day. Nonetheless, OPC concrete made with aggregate crushed at age 1st day showed better properties than those crushed at 3rd and 28th day. The concrete made with OPC gave 18% weaker strength than that made with WC. Using recycled aggregate led to a loss of the strength for both concretes, made with OPC and WC, and this is attributed to the lower strength of the old concrete, and the presence of unhydrated cement in the recycled aggregate, as shown in Figure 2.6.

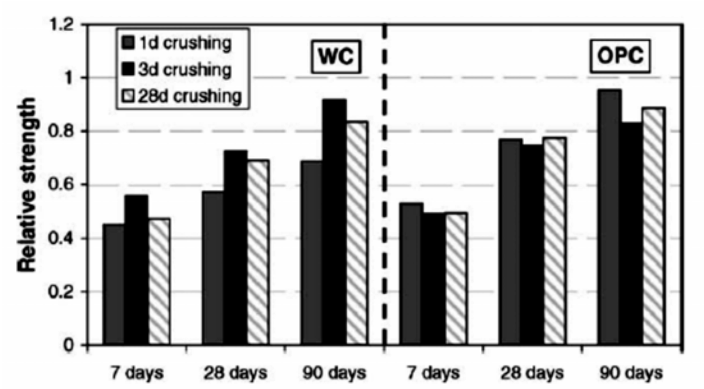


Figure 2.6: The compressive strength of recycled concrete crushed at different ages relative to the reference concrete [25].

McNeil et al. [26] conducted an overview study for recycled aggregates. They state that recycled aggregate is less dense, more porous and has higher water absorption than natural aggregate due to the residual adhered mortar on it which weakens the interfacial zone and the interlocking between the aggregate and the cement paste and results in lower compressive strength. They also report that replacing the natural aggregate with recycled aggregate reduces the modulus of the elasticity caused by the more ductile aggregate.

Beshr et al. [27] conducted a study investigating the effect of aggregate quality on the mechanical properties of high strength concrete. Four types of coarse aggregates with different properties were utilized to prepare the concrete mixes. The four concrete mixes were tested for compressive strength, split tensile strength, and modulus of elasticity at 7th, 28th, 90th, and 180th day. As shown in Figure 2.7, the compressive strength increased with age in all concrete specimens. Similarly, the average rate of strength development was higher at early ages. The compressive strength was found dependent on the aggregate strength rather than the cement or the bond strength; this is attributed to the low w/c ratio and the high cement content which gave more strength to the hardened cement paste. Beshr et al. [27] also report that concrete mixes prepared with weaker aggregate types gave lower compressive strength. Whereas, concrete mixes prepared with aggregate of higher absorption capacity showed a failure within the aggregate since the interface in these concrete specimens is strong due to the good bond between the aggregate and the cement paste.

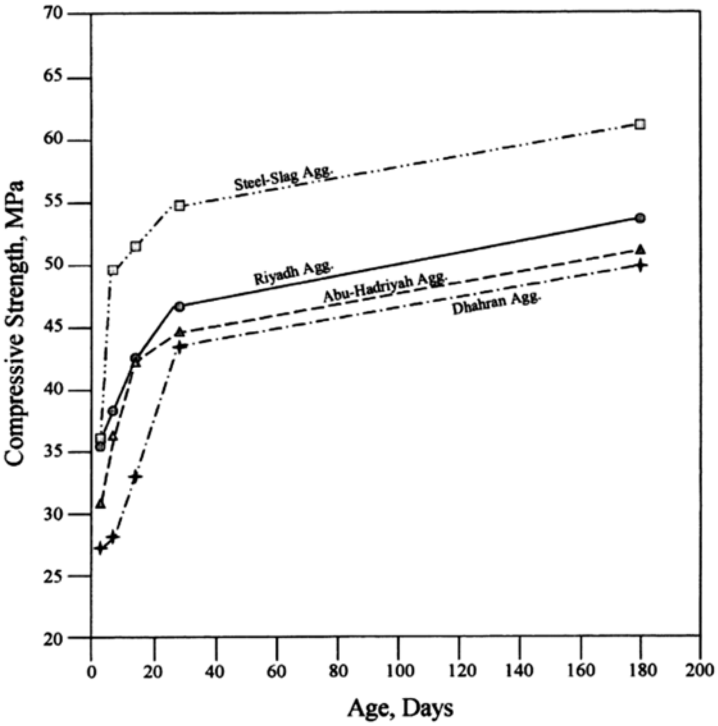


Figure 2.7: Compressive strength development of concrete specimens prepared with the selected aggregates [27].

Contrary to the findings of Beshr et al. [27], a study by Beushausen et al. [28] report that, for higher strength concrete (120 MPa), the effect of aggregate type on compressive strength was less significant. The researchers tested four mixes of different target strengths of 30, 60, 90, and 120 MPa prepared with two different types of aggregate: Andesite and Granite. As shown in Figure 2.8, for all mixes, the Granite concrete gave a higher compressive strength than the Andesite concrete due to the higher elastic modulus of Andesite which resulted in more significant stress concentrations at the interface between the aggregate and the paste, causing an earlier failure. Whereas, for higher strength concrete (120 MPa), the aggregate effect almost disappeared. Beushausen et al. [28] suggest that the stress concentration effect of the stiffer aggregate is partly offset by the increase in compressive strength due to the higher aggregate strength.

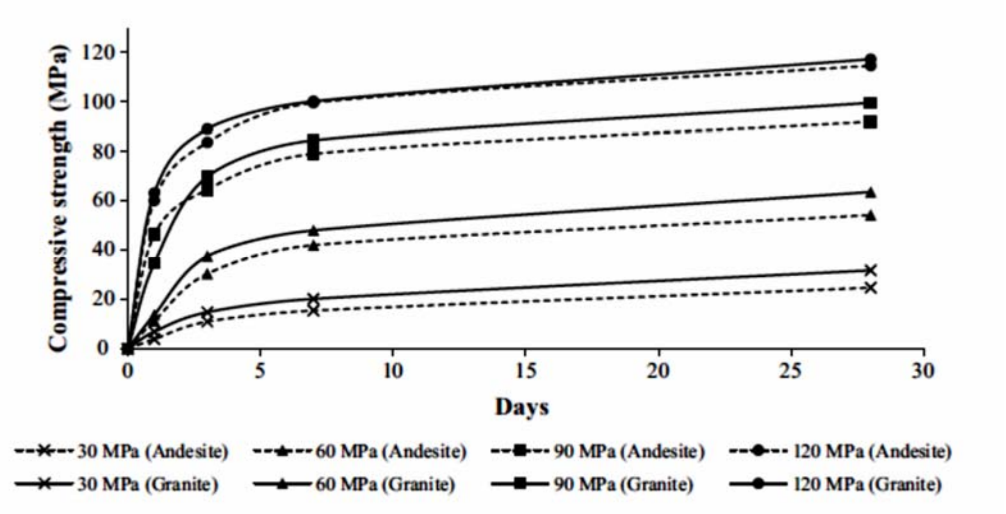


Figure 2.8: Compressive strength development for mixes made using Andesite and Granite aggregate [28].

Another study conducted by Kilic et al. [29] investigates the influence of aggregate type on the strength and abrasion resistance of high strength concrete using five different aggregate types. Results of the study show that aggregate strength, and texture influence the compressive strength and abrasion resistance of the concrete. Increasing the aggregate strength increased the concrete compressive strength and decreased the concrete abrasion. In addition, the researchers did a regression analysis and found a relationship between the aggregate strength and the concrete compressive strength and abrasion, as shown in Figures 2.9 and 2.10.

Wu et al. [30] indicate that the effect of coarse aggregate type is more significant in high strength concrete, which is usually made with a w/c less than 0.4, than in normal strength concrete. In high strength concrete, the strength of the paste and the bond between aggregate-cement is improved; cracks may extend through the aggregate under loading which makes use of the full strength of the aggregate and hence affects the concrete strength.

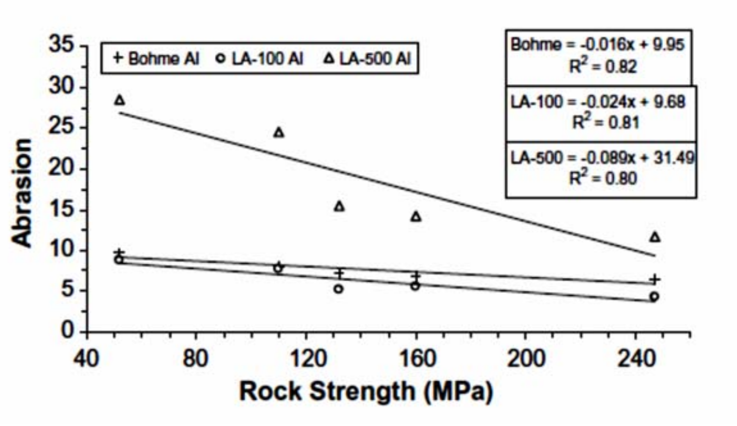


Figure 2.9: The relationship between abrasion of concrete, and rock strength [29].

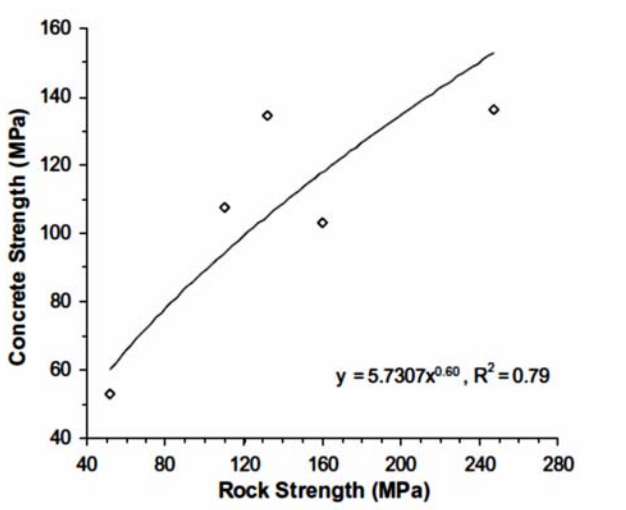


Figure 2.10: The relationship between compressive strength of concrete, and compressive strength of aggregate rock [29].

As shown in Figure 2.11, as w/c is lowered, namely for high strength concrete, the compressive strength increased with the increase in aggregate strength.

Another study by Zhou et al. [31] tested six high-strength concrete mixes made of six different types of aggregates: expanded clay, sintered fly ash, limestone, gravel, glass and steel, and one cement mortar for compressive strength at 7th, 28th and 90th day. As shown in Figure 2.12, concrete containing limestone aggregate showed corresponding 28th day strength to that of the cement mortar mix. Mixes with expanded clay aggregates and sintered fly ash aggregate showed 30% and 80% of the mortar

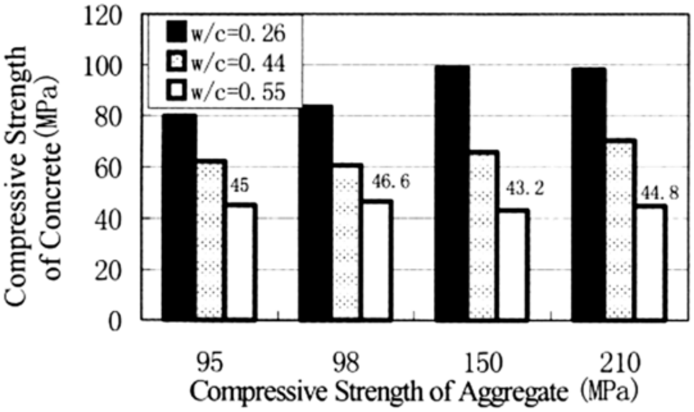


Figure 2.11: The relationship between compressive strength of concrete and aggregates [30].

strength, respectively. They attributed this reduction to the porosity of those aggregate types. Concrete mix with steel showed a small reduction on strength than the mortar strength which may be attributed to the bond strength as cracks passed around the particles. Concrete mix containing glass aggregate showed higher strength than mortar; similarly, cracks were passing through the bond, and small numbers of aggregate were broken.

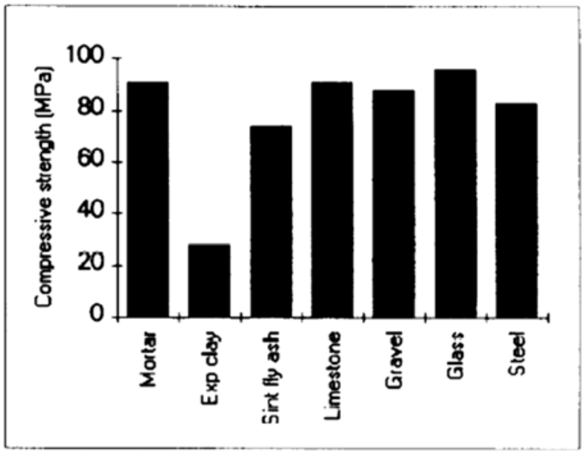


Figure 2.12: Effect of aggregates on compressive strength of concrete (28 day old at test) [31].

Ozturan et al. [32] investigated the effect of coarse aggregate type on mechanical properties of concretes with different strengths. Concrete with 28th day target compressive strengths of 30, 60, and 90 MPa were cast using basalt, limestone, and gravel coarse aggregates. For high strength concrete (>60 MPa), crushed aggregates of basalt and limestone produced around 10 to 20% higher compressive strength than that of the rounded gravel. They attribute this to the lower expected strength of the gravel aggregate and the lower strength of the bond with the matrix due to the round and smooth surface of the gravel particles. For normal strength concrete (30 MPa), the limestone coarse aggregate concrete produced higher compressive strength than both basalt and gravel aggregate concretes. Ozturan et al. [32] attribute this to the formation of some interfacial chemical reactions which improved the bond strength. They conclude that the coarse aggregate type effect is more important in high strength concrete than in normal strength concrete.

Similar results were reported by Kozul et al. [33] who indicate that the high strength concrete mix containing basalt aggregate produced a slightly higher compressive strength, higher flexural strength, and significantly higher fracture energy than that with limestone aggregate. In contrast, in normal strength concrete, basalt produced lower concrete compressive strength and higher fracture energy than lime stone aggregate, and flexural strength was not affected by the aggregate type. The researchers conclude that in both normal and high strength concretes, neither the compressive strength nor the flexural strength was affected by the aggregate size.

Nallathambi et al. [34] studied the effect of specimen and crack sizes, water/cement ratio, and coarse aggregate texture upon fracture toughness of concrete. They report that failure occurs with the extension of the micro-cracks in the aggregate-paste interface leading to the nonlinear behavior which is governed by the size, texture, and angularity of the coarse aggregate. The fracture toughness had increased with increasing the maximum size of the coarse aggregate because of the enhanced resistance to crack growth. Similarly, crushed aggregate showed better bond strength at the aggregate-mortar interface than the rounded aggregate which enhanced the fracture toughness due to the increased surface area and angularity of the aggregate. Nallathambi et al. [34] also point out that the fracture toughness had increased with increasing the specimen depth due to the higher probability of micro-cracks and bond cracks in the fracture zone. In addition, they indicate that fracture toughness decreased significantly with the increase in water/cement ratio.

Another study by Aitcin et al. [35] investigated the effect of coarse aggregate characteristics on mechanical properties of high strength concrete (>80 MPa, 0.275 w/c). Four concrete mixes with different coarse aggregate types (diabase, limestone, granite, and river gravel) were tested for compressive strength and modulus elasticity.

The study shows that both compressive strength and elastic module were affected by the mineralogical characteristics of aggregate. Furthermore, mixes with granite aggregate produced significantly lower compressive strength and elastic moduli than the other mixes. Failure occurred through the aggregate particles, not in the transition zone, and this is attributed to the weak granite aggregate containing laumonite mineral which is unstable in a moist environment. Concrete mix with river gravel showed slightly lower strength than mixes with diabase and limestone. This is attributed to the weakness of the transition zone that appeared in numerous cases of the aggregate cement paste debonding. Both concrete mixes with crushed aggregates from fine-grained diabase and limestone showed more transgranular fracture rather than aggregate cement paste debonding and gave better results for compressive strength and elastic modulus, as shown in Figure 2.13.

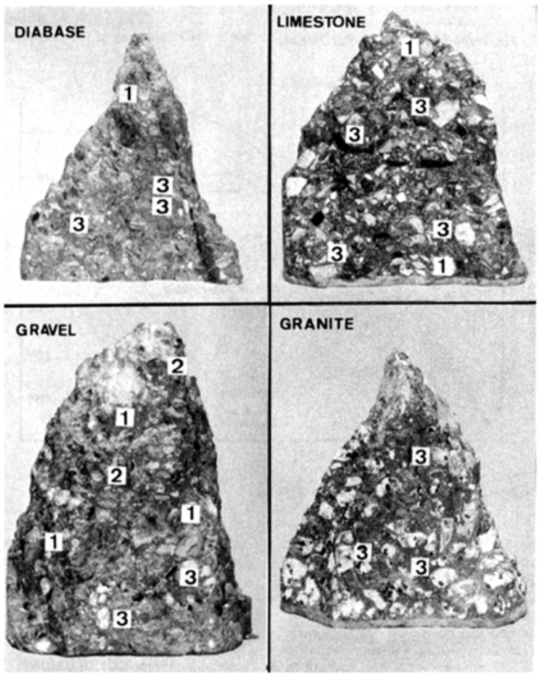


Figure 2.13: Surface of failure specimens: 1) deponding; 2) aggregate print; 3) transgranular fracture [35].

Aitcin et al. [35] also examined the stress-strain plots and found that in both limestone and diabase aggregate mixes, a narrow hysteresis loop occurred, which indicates a strong aggregate and strong transition zone, unlike the gravel and granite aggregate mixes which showed a wide hysteresis loop as an indication of weak aggregate and/or weak transition zone, see Figure 2.14. Similar results were obtained by Jones et al. [36] and Ezeldin et al. [37].

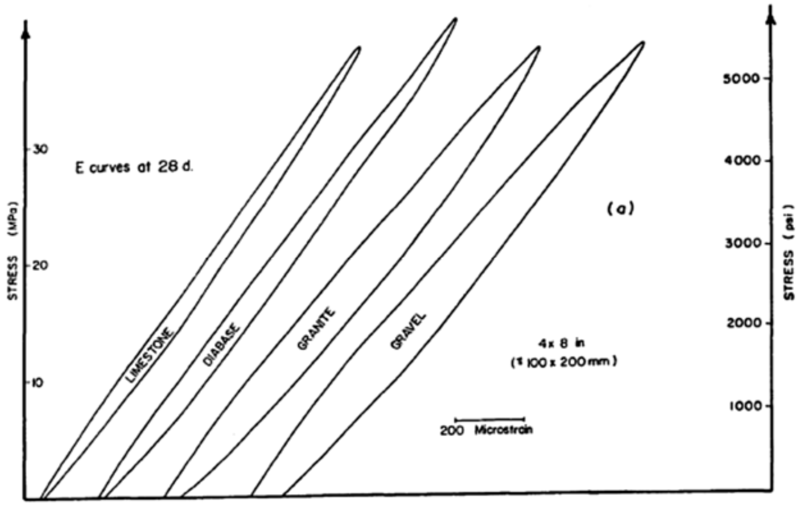


Figure 2.14: Hysteresis loops at 28 days [35].

Similar results were also found by Sengul et al. [38] who studied normal and high-strength concrete mixes with four different aggregate types (Devonian limestone, Triassic lime stone, Sandstone, and Basalt). Normal strength concrete and Triassic aggregate showed the best mechanical properties. Whereas, in high-strength concrete, Basalt showed the highest compressive strength, and the hysteresis loops of Triassic and Devonian limestone were narrower than those of Basalt and Sandstone aggregates.

In the same vein, Mehta et al. [39] studied the effect of aggregate, cement, and mineral admixtures on the microstructure of the transition zone. They investigated two types of concrete mixes with different aggregates (quartz and limestone), and three mineral admixtures (silica fume, fly ash, and granulated blast-furnace slag) which had cured up to three years. They concluded that when concrete is loaded, the micro-cracks form first in the weak transition zone as it showed higher porosity and larger size crystals of hydration products. Using mineral admixtures reduced the weakness in the microstructure of the transition zone by refining the pores and grains, leading to lower porosity.

A number of similar studies on the effect of aggregate type on the concrete compressive strength have been conducted. Sahin et al. [40] indicate that, for an increasing cement content, the increasing strength depends on the type of aggregate used, and the cement content itself. Similarly, Sengul et al. [41] indicate that Basalt aggregate concrete has higher compressive strength than Triassic or Limestone aggregate concretes.

Yasar et al. [42] studied the effect of limestone aggregate type and water-cement ratio on the concrete strength. Their study reports that the concrete strength significantly increased with the decrease in water-cement ratio. They clarified that changing the aggregate size distribution and water-cement ratio affects the compressive strength and tensile strength of the concrete. In the same vein, Torgal et al. [43] studied the effect of aggregate type on the durability and strength of C20/25 strength concrete by testing seven concrete mixes with different coarse aggregate types and one mortar matrix. Their results reflect the major role played by the aggregate size and absorption in concrete performance.

Abdullahi [44] investigated the effect of the aggregate type using three types of coarse aggregate, quartzite, granite, and river gravel on concrete compressive strength. The crushed quartzite produced the highest compressive strength, followed by the river gravel in which the interlock strength was affected by its rounded particles. The lowest strength was recorded for the crushed granite as it contained greater voids which affected the workability of the concrete and provided weaker mortar/aggregate interface.

2.1.2 Aggregate size and shape. Loannides et al. [5] indicate that aggregate size and shape can affect the cement-aggregate bond strength. Larger aggregate size creates larger stress concentrations in the cement paste, leading to increased cracking. In studies by Rocco and Elices [45, 46] who explored the effect of aggregate shape and size on concrete mechanical properties, report that fracture energy increased with the increase in aggregate size while it was not affected significantly by the aggregate shape. However, the modulus of elasticity decreased with the increase in aggregate size. In addition, using crushed aggregates (with strong matrix-aggregate interfaces) showed higher modulus of elasticity than using spherical ones of the same size. The tensile strength showed dependence on neither shape nor size of aggregate.

Ajamu and Ige [47] studied the effect of coarse aggregate size on the compressive strength and flexural strength of concrete beam. They tested concrete cubes and beams with varying aggregate sizes: 9 mm, 13.2 mm, 19 mm, 25 mm, and 37.5 mm at 28th day. The researchers note that compressive strength increased significantly from 13.2 mm to 19 mm aggregate size with the increase in aggregate size. Flexural strength of concrete beam is inversely affected by the increase in aggregate size. Compressive strength is inversely proportional to flexural strength as coarse aggregate size increases when subjected to same conditions, as shown in Figure 2.15.

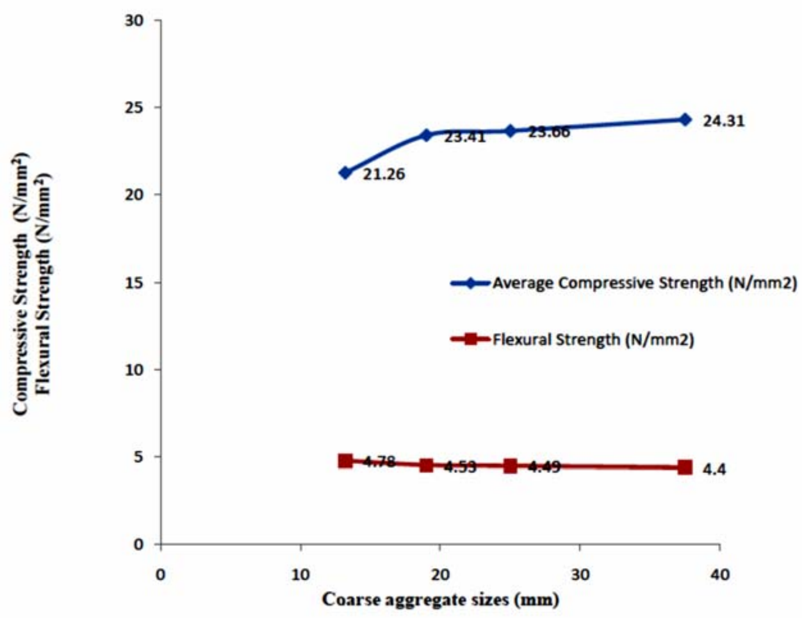


Figure 2.15: Variation of compressive strength and flexural strength with coarse aggregate sizes [47].

Meddah et al. [48] investigated the effect of content and particle size distribution of coarse aggregate on the compressive strength of concrete. They conclude that for normal strength concrete (NSC), the aggregate strength plays a minor role in affecting the mechanical properties which are controlled by the w/c ratio, and the stress transfer between the aggregate and the weak bulk paste through an even weaker transition zone. While for high strength concrete (HSC) with enhanced cement paste and transition zone, the aggregate particles could be the weaker phase, and its strength could have a significant effect on the concrete strength. The researchers report that the compressive strength of the normal strength concrete increased with the increase in the course aggregate size while for high strength concrete, the compressive strength decreased with the increase in coarse aggregate size. In addition, they point out that the content of the coarse aggregate has a significant effect on both the normal and high strength concrete and more significant for HSC than NSC.

Yaqub et al. [4] studied the size effect of coarse aggregate on compressive strength of high strength concrete. Five different sizes of coarse aggregate were used for different trials of mixing of high strength concrete, as follows: 37.5 mm and 25 mm, 25 mm and 20 mm, 20 mm and 10 mm, 10 mm and 5 mm, to investigate the influence of the aggregate size on concrete compressive strength. Results of compressive strength testing for the different mixes indicate that minimum sizes of aggregates used (10 mm and 5 mm) showed higher compressive strength than those of bigger sizes of aggregate. This is due to the low concentration of stress around the small aggregate particles which are caused by the difference between the elastic module of paste and aggregate.

Studying the aggregate shape effect shows that using flat or elongated aggregate particles decreases the contact area between the particles which decreases the potential to resist layering and slippage and thereby decreases the concrete strength. In addition, several studies have shown that crushed stone produces higher strength than rounded aggregate [4, 5].

2.2 Specimen Configuration Effect

The effect of specimen size and shape on compressive strength of concrete specimens has been studied based on fracture mechanics [10]. In fracture mechanism, there is a direct relation between the nucleation and propagation of fracture processes and the failure of the specimen. The effect of shape and size of a specimen appears due to non-scaled aggregate, different frictions between concrete surfaces and loading platen, and the variation of crack propagation and localized failure zone [13]. Cylinder specimens display well-defined fracture patterns as per ASTM C39 [49], as shown in Figure 2.16.

Numerous studies have investigated the specimen size and type factors affecting the strength of natural concrete. Mier [50] explain that the failure in uniaxial compression is due to a localization of the damage in a certain zone. He studied this localization process in compression using a method in which the pre-peak deformation was subtracted from the total deformation of the specimen. RILEM TC 148 “Strain Softening of Concrete” [51, 52] show that two effects interact during localization: the slenderness of the sample, and the boundary restraint between the loading platens and the specimen. In addition, Borges et al. [53] studied the concrete ductility in uniaxial and flexural compression. All of these studies suggest considering the compressive strength test as a structural test because of the dependence of its results on different factors more than the actual mechanical properties, such as the geometry of the specimen, and the boundary conditions like end constraints, feedback signal, or specimen capping [9].

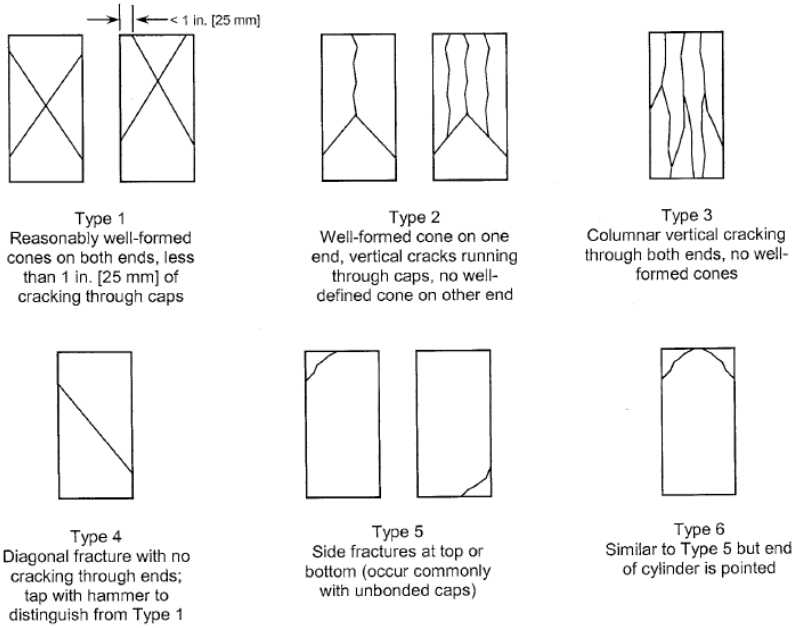


Figure 2.16: Schematic of typical fracture patterns [49]

2.2.1 Specimen size. It is also observed that large specimens are less resistant to stress than smaller ones, and this size effect is less noticeable in cylinders than cubes where the compressive strength decreases by approximately 10% as the specimen size increases [9, 10], as shown in Figure 2.17.

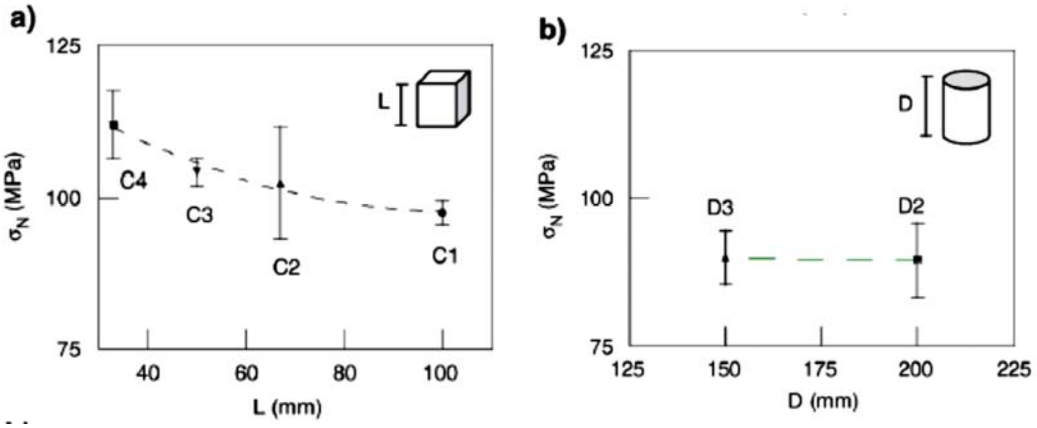


Figure 2.17: Size effect on the peak strength: (a) Cubes; (b) Cylinders [9].

ASTM specified that using standard specimen sizes 150/300 mm and 100/200 mm has no effect on concrete compressive strength. Various studies have been conducted to investigate the effect of using standard specimen sizes on the compressive strength. Yazici et al. [54] and Kampmann et al. [55] had investigated the specimen size effect on the compressive strength of cylindrical concrete specimen. Typical sizes of cylindrical specimen used by standards for determining concrete compressive strength are 150/300 mm, and 100/200 mm. Smaller size is preferred to be used as it is lighter, smaller, consumes less material, and needs smaller area for curing period and low capacity press for testing and lower costs for casting. They indicate that the compressive strength of 100/200 mm cylinder is generally higher than 150/300 mm, and 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. Decreasing the water-cement ratio increased the concrete strength for both specimen sizes, as shown in Figure 2.18.

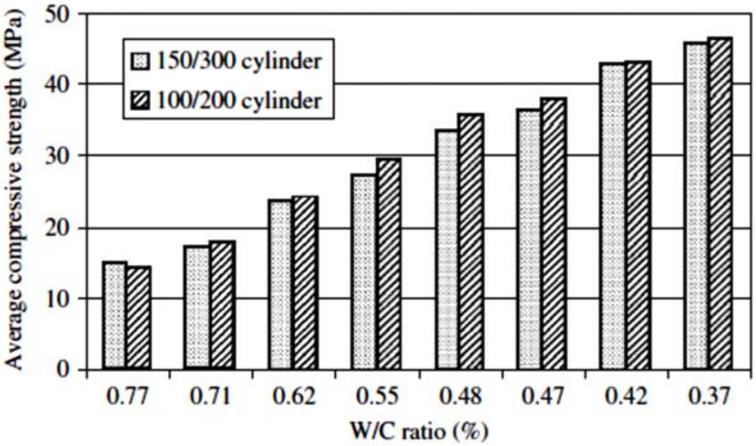


Figure 2.18: Average compressive strength of 150/300 and 100/200 cylinder specimen sizes [54].

2.2.2 Specimen shape. As per several research findings, cylinder specimens generally give less compressive strength than cube specimens. According to BS 1881: Part 120 [56], strength of the cylinder is equal to 0.8 of the cube strength; however, it is considerably hard to get a simple relation between the strength of the specimens with the two shapes.

Viso et al. [9] and Yi et al. [10] studied the effect of specimen size and shape on the concrete compressive strength. They point out that cube specimen gives commonly higher compressive strength than that recorded from a cylinder. This is consistent with the observation of the crack pattern which shows that the extent of cracking throughout the specimen is denser with “lateral sides getting spalled leading to the so called hour glass failure mode” in the cubes than in the cylinders where the failure is a main inclined fracture surface, as shown in Figure 2.19.

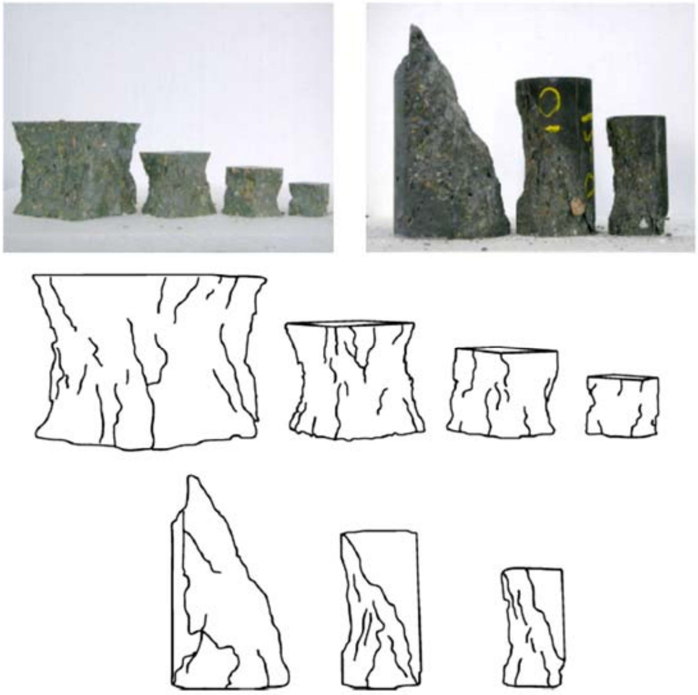


Figure 2.19: Crack pattern for cubes and for cylinders [9].

A study conducted by Abd et al. [12] reports that the cylinder/cube ratio strongly increased with the increase in the concrete compressive strength, and it reached to 1 at strengths of more than (100 MPa). On the other hand, European standard (ENV 206:1990) [57] notes the 0.8 value for the cylinder/cube ratio similar to BS 1881: Part 120 [56].

RILEM (Réunion Internationale des Laboratoires et Experts de Matériaux, systèmes de construction et ouvrages)), which is an international organization of testing laboratories, recommends using cylinders rather than cubes for research purposes because they give a greater uniformity of results as their failure is less affected by the end restraint of the specimen, their strength is less influenced by the used coarse aggregate properties, and the stress distribution on horizontal planes is more uniform than on a cube specimens [12].

Elwell et al. [58] conducted a comparative study on using cylinder vs. cube specimens in compressive strength test. Their study includes the testing procedures, factors affecting the cylinder/cube strength ratio and conversion factors and equations. The cylinder/cube strength ratio is found to be affected by several factors. The most important factors are:

1) Casting, curing, and testing procedures: such as the type of cylinder mold and capping system, and planeness of cube surfaces. The ends of cylinder specimen should be capped while testing because they are usually not plane or parallel enough to mate properly with platens of compression testing machines. In contrast, the sides of cube specimen are always plane and parallel and do not need any capping while testing.

2) Specimen geometry: ratio of height to maximum lateral dimension (h/d) is the most important factor and is inversely related to specimen strength, as shown in Figure 2.20. Other factors are the lateral dimension d alone and specimen volume V [58].

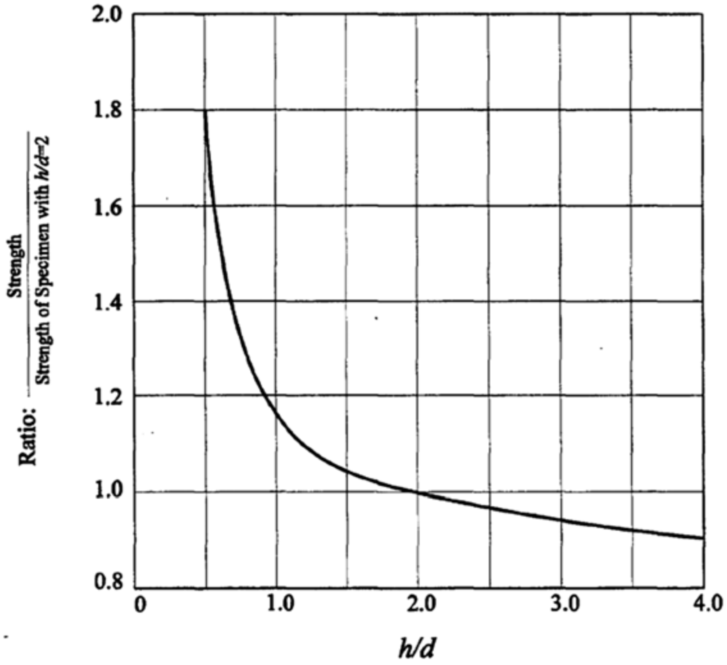


Figure 2.20: General relationship between height/diameter ratio and strength ratio [58].

3) Level of 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 [58].

Yi et al. [10] studied the effect of specimen size on the specimen shape effect for both normal and high strength concrete. They report that the shape effect decreases as the specimen size increases regardless of strength level, and the compressive strength difference between cylinder and cube specimens is more rapidly disappearing for high strength concrete (more than 100 MPa), as shown in Figure 2.21.

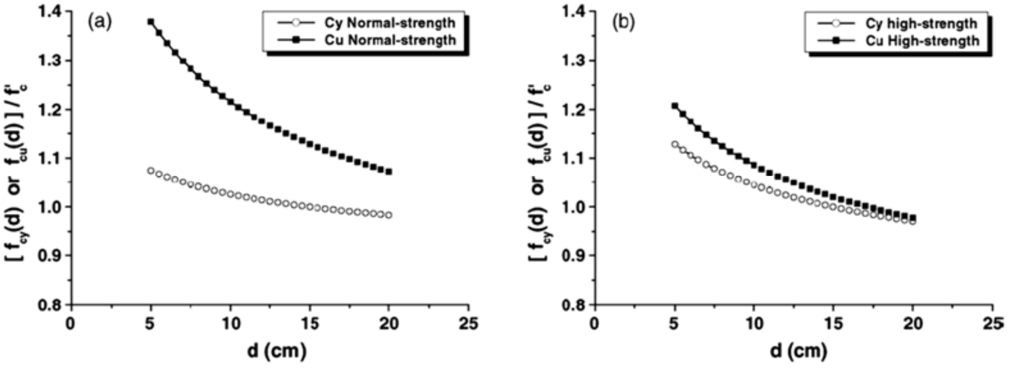


Figure 2.21: Effect of strength level on shape effect of compressive strength: (a) normal-strength concrete; (b) high-strength concrete [10].

4) Direction of loading and machine characteristics: in cylinders, compression loads are applied in the casting direction, so each casting layer occupies an entire cross section and receives total load. However, in cubes, loads are applied perpendicular to the casting direction, so each casting layer receives its portion of the total load from a different part of the platen, and this is related to aggregate segregation and platen fixity [58].

5) Aggregate grading: changing aggregate grading affects cube strength more than cylinder strength due to the wall effect of the higher surface/volume ratio of the cube specimen compared to the cylinder specimen of the same size. Increasing aggregate coarseness negatively correlates with the cylinder/cube strength ratio, see Figure 2.22.

Yi et al. [10] study reports a difficulty in determining empirical conversion relationships and conversion factors between cylinder and cube specimens strength. It suggests that the cylinder/cube strength ratio varies between about 0.65 and 0.9 for 150 x 300 mm (6x12 in.) cylinders and 150 mm (6 in.) cubes, as shown in Table 2.1 [58].

Tokyay et al. [11] also studied the cylinder/cube ratio for four different sizes (75, 100, 150, and 200 mm) for cylinder diameters with aspect ratio of 2.0 and cube sizes. The study reports that, for the smaller specimens (75 and 100 mm), the average cylinder/cube ratio was 1.00; whereas, for larger specimens (150 and 200 mm), it was 0.82.

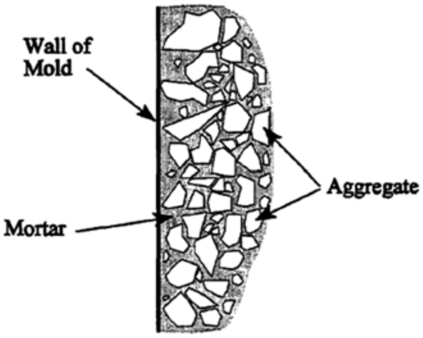


Figure 2.22: Wall effect [58].

Table 2.1: Results of cylinder vs. cube comparative studies [58]

Reference	Average cyl./cube ratio	Remarks
Cormack [59]	0.87	Study focused on high strength concrete. Few data were generated for $f_c'<41$ MPa
Evans [60,61]	0.77-0.96	Lower-strength concrete had generally lower cylinder/cube strength ratios
Sigvaldason [62]	0.71-0.77 0.76-0.84	Segregating concrete Non-segregating concrete
Lysle and Johansen [63]	0.86	
Gyengo [64]	0.65-0.84	Variation due to changing coarseness of aggregate grading
Gonnerman [65]	0.85-0.88	Tests performed using standard cylinders and 6" and 8" cubes
Plowman, Smith, and Sheriff [66]	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 [67]	0.61 0.51	Using 150 mm cubes Using 100 mm cubes
Lasisi, Osunade, and Olorunniwo [68]	0.67-0.76 0.55-0.86	Landcrete specimens (small agg. From lateric soil) Concrete specimens

2.2.3 Specimen shape and size effect on light weight concrete. The compressive strength of the lightweight concrete (LWC) is significantly affected by the size and aspect ratio of specimens. Sim et al. [13] conclude that the size effect is stronger with the decrease in the concrete unit weight, especially with an aspect ratio of 2.0 than 1.0. This is due to the increasing localization of the crack band zone in the LWC specimen and the poor crack distribution than the NWC, which causes further decrease in the compressive strength with the increase of the specimen size, as shown in Figure 2.23.

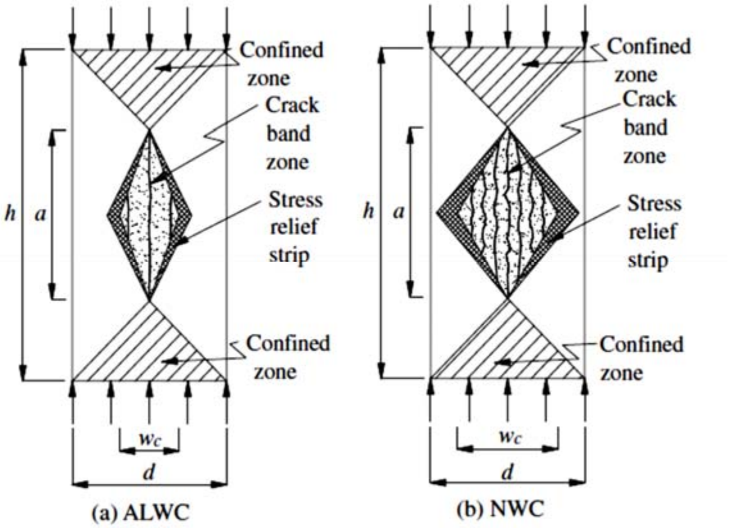


Figure 2.23: Idealized crack band zone in concrete specimens at peak stresses [13].

Neville [60] clarifies that the artificial lightweight aggregate is generally weaker and produces lower cohesion and higher void in the interface with pastes than the normal weight aggregate which increases the number of the cracks propagated in the local failure zone and results again in further decrease in the compressive strength. Furthermore, MacGregor [69] points out that the cracks at the failure plane of the concrete passed through the lightweight aggregate particles. In addition, the compressive strength measured from a cube was found higher than that recorded from a cylinder.

Sim et al. [13] had applied a uni-axial compressive test for both LWC and NWC concrete cylinder specimens with the same size in order to compare the cracks propagation in both materials. They report that, for NWC specimens, the initial cracks were developed at 60-80% peak stress, and by increasing the applied load, the initial cracks slowly propagated upwards and downwards, showing a good crack distribution. The strong aggregate interlock caused a wider crack band zone compared to the LWC.

For LWC specimens, the initial cracks were longitudinally developed at 50-60% peak stress within the mid height of the specimen, and by increasing the applied load, the initial cracks sharply propagated toward the top and bottom surfaces of the specimen. The crack distribution was very poor with a few cracks and more localized failure zone than the NWC specimen due to the deteriorated aggregate interlock. This more localized failure zone is the reason of increasing the specimen size effect on LWC than NWC, see Figure 2.24.

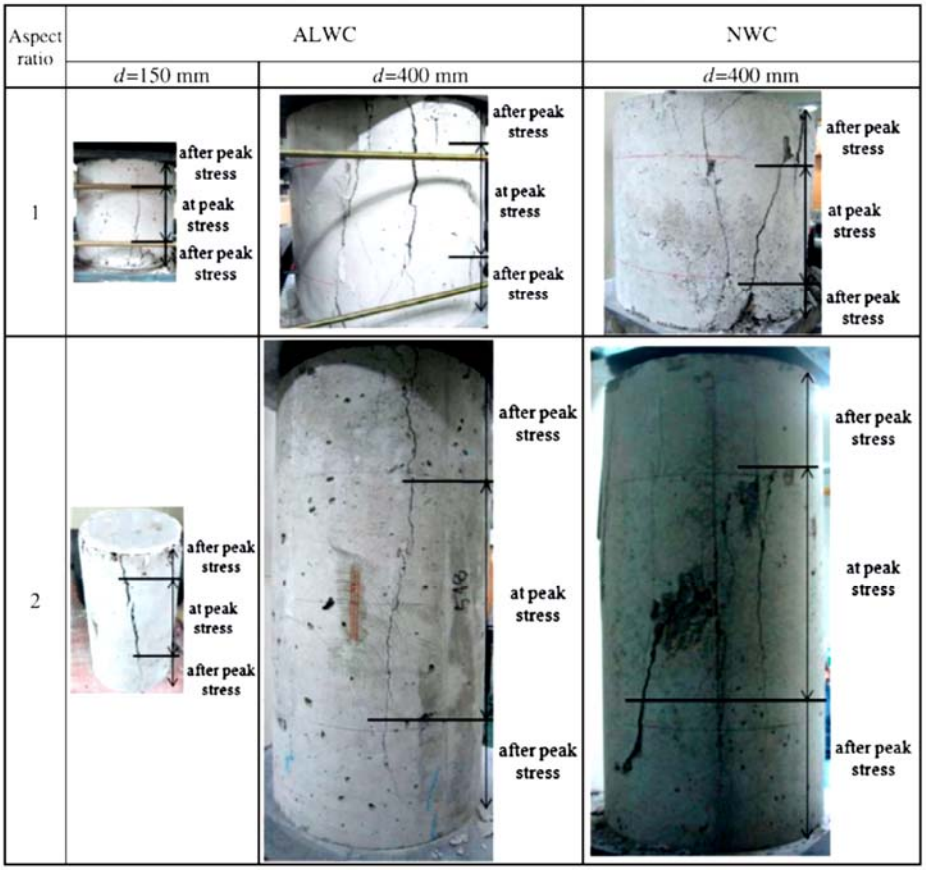


Figure 2.24: Typical propagation and distribution of cracks in cylindrical specimens [13].

Illustrating the relationship between the normalized compressive strength $f'_c(d)/f'_c$ and the unit weight (ρ_c) of the concrete, it is shown that the normalized compressive strength generally increased slightly as the ρ_c increased at the same d, and this increase becomes higher with the increase of d regardless of the specimen shape, as shown in Figure 2.25. Bold symbols indicate specimens with aspect ratio (n_1) equal to 2, while white symbols indicate specimens with n_1 equal to 1.

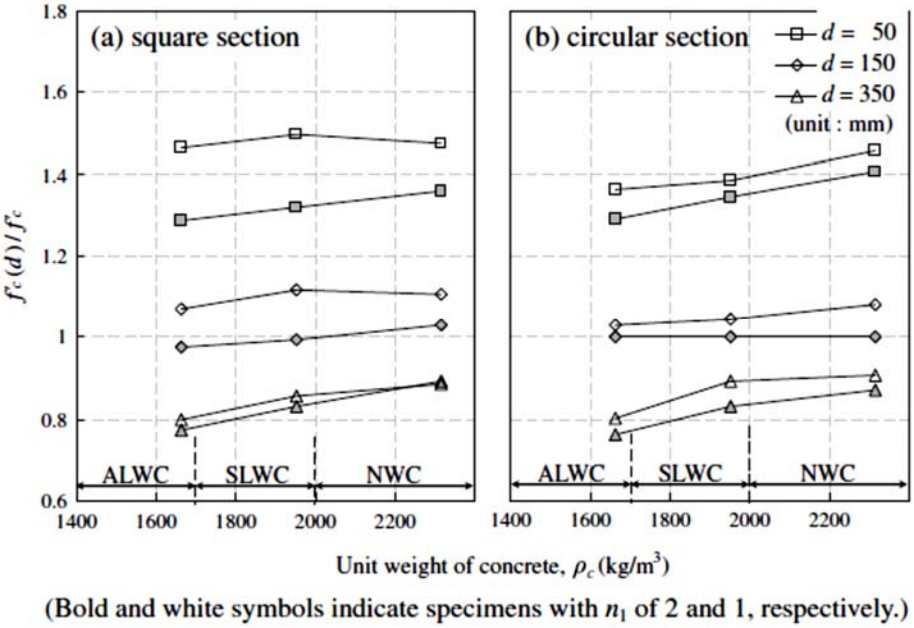


Figure 2.25: Effect of ρ_c on $f'_c(d)/f'_c$ [13].

2.3 Summary

In this chapter, three factors affecting the concrete compressive strength are presented and discussed. Those are: aggregate type, and specimen shape and size.

Research shows that concrete failure depends on aggregate strength, cement paste strength and strength of bond between aggregate and cement paste. For natural concrete, aggregate strength plays a minor role as the aggregate is the strongest phase; whereas, for lightweight aggregate, the weak aggregate causes a reduction in the concrete compressive strength. Nevertheless, a study conducted by Lo et al. [18] indicate that porous surface of lightweight aggregate improves interfacial bond between the aggregate and the cement paste and results in better interlocking and higher compressive strength. The modulus of elasticity also decreases with replacement of natural aggregate with lightweight aggregate.

Using recycled aggregate instead of natural aggregate has also reduced the concrete density and strength as the compressive strength is found directly proportional to the strength of the blended aggregate. Both the compressive strength and the modulus of elasticity decrease as the recycled aggregate replacement percentage increases. Recycled aggregate is less dense, more porous, and has higher water absorption than natural aggregate due to the residual adhered mortar on it which weakens the interfacial zone between aggregate and cement paste and results in lower compressive strength.

High strength concrete is more affected by the aggregate type than normal strength concrete. Compressive strength and elastic modulus are significantly influenced by the mineralogical characteristic of aggregate. For weaker aggregate, failure tends to be a transgranular failure while for stronger aggregate, a combination of aggregate debonding and transgranular failure could occur. Generally, compressive strength increases with a decrease in w/c ratio.

Aggregate shape and size are also reported to have a great effect on both normal strength and high strength concrete. For normal concrete, compressive strength increases and modulus of elasticity decreases with an increase in the aggregate size. On the other hand, for high strength concrete, smaller aggregate sizes produce higher compressive strength. Using crushed aggregates with strong aggregate-matrix interfaces show higher compressive strength and modulus of elasticity than using the smooth spherical ones of the same size.

Specimen shape and size has a great effect on the concrete compressive strength. Cylinder specimens generally produced lower strength than cube specimens as the extent of cracking throughout the specimen is denser in the cubes than in the cylinders. The shape effect decreases as the specimen size increases regardless of the concrete strength level. It is also observed that large specimens are less resistant to stress than smaller ones, and this size effect is less noticeable in cylinders than cubes. This is due to the smaller contact area between 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 its compressive strength. In contrast, a study by Tokyay et al. [11] report that compressive strength of high strength concrete (60 MPa-75 MPa) is not dependent on the specimen size, and using smaller specimen for testing may result in significantly lower apparent strengths than using bigger specimens, especially in cubes. The researchers attribute that to the wall effect, as the quantity of mortar required to fill the space between the particles of the coarse aggregate and the wall of the mold is greater than that necessary in the interior of the mass and hence in excess of the mortar available even in a well-proportioned mix. ASTM specified that using different standard specimen sizes has no effect on the natural concrete compressive strength.

The specimen size affects the lightweight concrete (LWC) more than the normal weight concrete (NWC) due to the increasing localization of the crack band zone in the LWC specimen and the poor crack distribution compared to the NWC specimen, which causes further decrease in the compressive strength with the increase of the specimen size regardless of the specimen shape.

The current study investigates the specimen shape and size effect on the compressive strength of three different types of concrete; normal concrete, light weight aggregate concrete and recycled aggregate concrete. Results are compared in order to study the effect of aggregate type on concrete compressive strength with respect to the size and shape factors of those specimens. Other mechanical properties, such as modulus of elasticity, split tensile strength and flexural strength, are measured and discussed to identify the effect of aggregate type on them.

Chapter 3: Experimental Program

3.1 Introduction

This study aims to investigate the effect of aggregate type, specimen shape, and size on the concrete compressive strength. In addition, correlation between compressive strength and these factors is examined. This chapter presents a detailed explanation of the experimental program conducted to achieve these goals.

The experimental program is divided into three phases: Phase 1 is an evaluation of the aggregate properties used in this study, Phase 2 is an evaluation of compressive strength of two patches of six concrete types and different mechanical properties (compressive strength, modulus of elasticity, flexural strength and split tensile strength) of two strength concrete (C45 and C75) from a ready-mix, and Phase 3 is an evaluation of the mechanical properties (compressive strength, modulus of elasticity, flexural strength and split tensile strength) of one patch of six types of concrete and three concrete strength (C45, C60 and C80) from another ready-mix producer.

A summary of the experimental program conducted in this investigation is shown in Figure 3.1.

3.2 Phase 1: Evaluation of Aggregate Properties

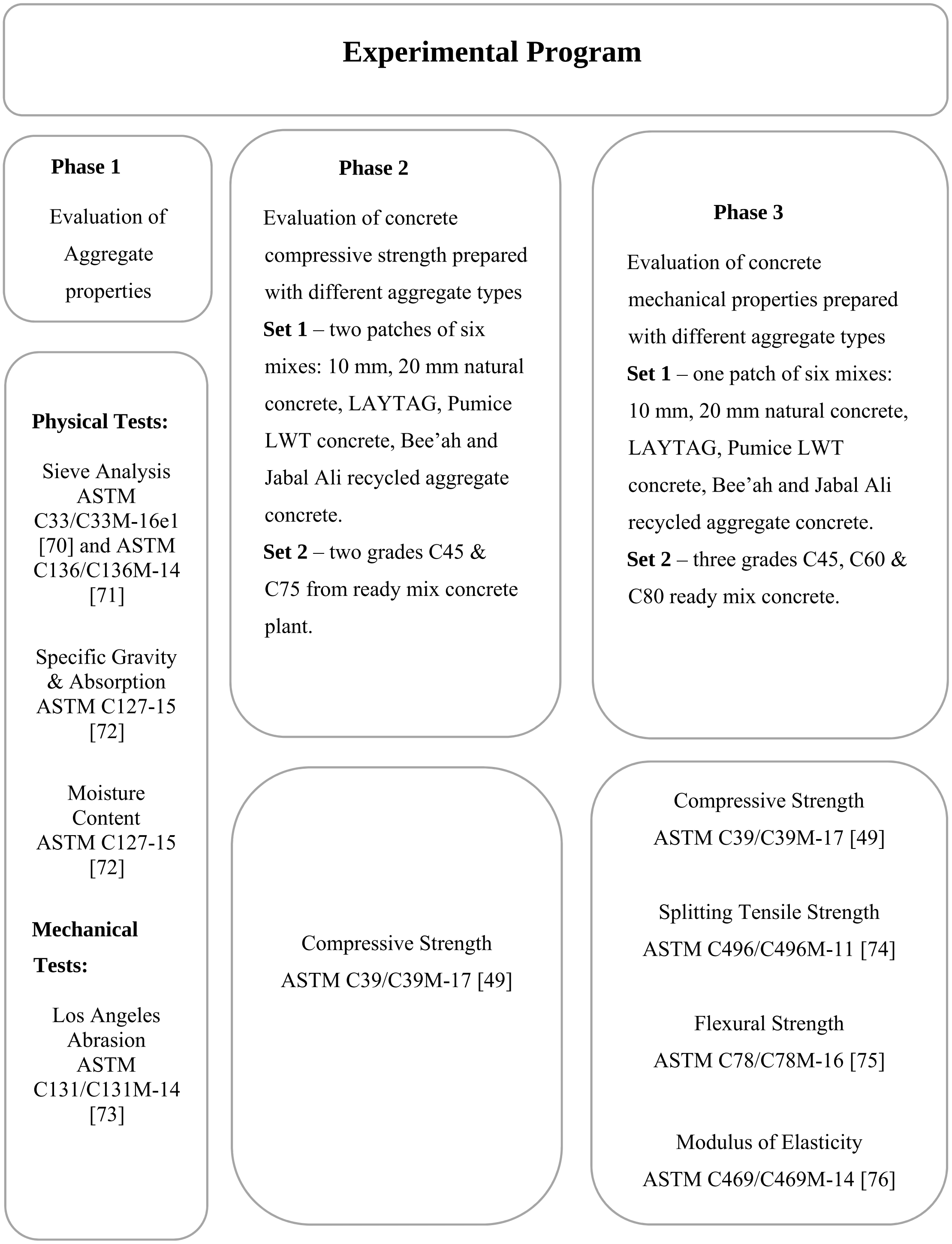
3.2.1 Aggregate samples. This phase deals with the evaluation of the physical and mechanical properties of the six aggregate types used in this study. Samples are collected for 10 mm and 20 mm size natural aggregate, LAYTAG and Pumice lightweight aggregate, and the two recycled aggregates from different sources (Bee'ah and Jabal Ali), as shown in Figure 3.2.

3.2.2 Aggregate testing. Physical properties of coarse aggregate are evaluated by conducting the sieve analysis, moisture content, specific gravity, and water absorption tests. Los Angeles Abrasion test is run for mechanical properties evaluation. All tests are conducted according to ASTM specifications.

3.3 Phase 2: Evaluation of Compressive Strength of Concrete Prepared with Different Aggregate Types

This Phase deals with the evaluation of the compressive strength of concrete made with the aggregate types considered in the investigating. Testing is conducted based on ASTM C39/C39M-17 Standard Test Method for Compressive strength [49]. Two sets of concrete mixes are prepared as following:

Set 1: Two patches of six concrete mixes prepared using the six aggregate types considered in this study.



Experimental Program

Phase 1

Evaluation of Aggregate properties

Physical Tests:

Sieve Analysis ASTM C33/C33M-16e1 [70] and ASTM C136/C136M-14 [71]

Specific Gravity & Absorption ASTM C127-15 [72]

Moisture Content ASTM C127-15 [72]

Mechanical Tests:

Los Angeles Abrasion ASTM C131/C131M-14 [73]

Phase 2

Evaluation of concrete compressive strength prepared with different aggregate types

Set 1 – two patches of six mixes: 10 mm, 20 mm natural concrete, LAYTAG, Pumice LWT concrete, Bee'ah and Jabal Ali recycled aggregate concrete.

Set 2 – two grades C45 & C75 from ready mix concrete plant.

Compressive Strength ASTM C39/C39M-17 [49]

Phase 3

Evaluation of concrete mechanical properties prepared with different aggregate types

Set 1 – one patch of six mixes: 10 mm, 20 mm natural concrete, LAYTAG, Pumice LWT concrete, Bee'ah and Jabal Ali recycled aggregate concrete.

Set 2 – three grades C45, C60 & C80 ready mix concrete.

Compressive Strength ASTM C39/C39M-17 [49]

Splitting Tensile Strength ASTM C496/C496M-11 [74]

Flexural Strength ASTM C78/C78M-16 [75]

Modulus of Elasticity ASTM C469/C469M-14 [76]

Figure 3.1: Summary of the experimental program conducted in this investigation.

20 mm natural aggregate 10 mm natural aggregate

Pumice lightweight aggregate LAYTAG lightweight aggregate

Recycled aggregate - Bee’ah Recycled aggregate - Jabal Ali

Figure 3.2: Aggregate samples.

Set 2: Samples collected for two concrete grades C45 and C75 from ready mix concrete producers.

3.3.1 Set 1: Two patches of six concrete mixes.

- ***Material used.*** Mixes have Ordinary Portland cement type I (SG = 3.15), silica fume (SG = 2.2), Ground Granulated Blast-Furnace Slag “GGBS” (SG = 2.91), and tap water were used for preparing the six concrete mixes. Dune sand (SG = 2.56) and crushed aggregate (SG = 2.51) have been used as fine aggregates. Six types of coarse aggregate were used to produce the concrete mixes in the lab: 10mm and 20mm sizes natural aggregate, LAYTAG and Pumice lightweight aggregate and recycled aggregate from two sources (Bee’ah and Jabal Ali). These six concrete the same water/cement ratio (w/c), the same volume fractions of fine and course aggregates, and cementation materials, refer to mixes design in Appendix A. The weight of the coarse aggregate varies based on the specific gravity of each type.

- ***Mixing.*** A 5 ft^3 concrete mixer was used for mixing. Coarse and fine aggregate were added to the cement, silica fume, and GGBS. In addition, water amount was added during the mixing. Two patches were cast for each concrete mix.

A special procedure was followed for both lightweight and recycled aggregate concrete mixes. Coarse aggregates were per soaked in water (5% of the aggregate weight), cement, silica fume, and GGBS. All aggregates were mixed for 5 minutes and then left for soaking for 30 minutes. This procedure was done to avoid affecting the w/c ratio as lightweight and recycled aggregates showed higher absorption capacity than that of the natural aggregates. The amount of water used for soaking was deducted from the total amount of the mixing water to avoid adding more water which could negatively affect the concrete strength [77, 78].

- ***Casting.*** 100 x 200 mm (4 x 8 in.) cylinders, 150 x 300 mm (6 x 12 in.) cylinders, 100 x 100 x 100 mm (4 x 4 x 4 in.) cubes, and 150 x 150 x 150 mm (6 x 6 x 6 in.) cubes were prepared from each mix. Specimens were covered with plastic for 24 hours and then demolded, labeled and left for curing at room temperature until testing dates, as shown in Figure 3.3.

Figure 3.3: Casted samples.

3.3.2 Set 2: C45 and C75 ready mix concrete mixes.

- ***Sample collection.*** Samples were collected from ready mix concrete producers with two concrete strengths of 45 MPa and 75 MPa. Specimens included cylinders 100 x 200 mm (4 x 8 in.), cylinders 150 x 300 mm (6 x 12 in.), cubes 100 x 100 x 100 mm (4 x 4 x 4 in.), cubes 150 x 150 x 150 mm (6 x 6 x 6 in.) and beams 100 x 100 x 500 mm (4 x 4 x 20 in.). Samples were labeled and left for curing at room temperature until testing dates.

3.3.3 Testing:

- ***Compressive strength.*** Compressive strength testing was done in accordance with ASTM C39/C39M–17 Standard test methods for Compressive Strength [49]. Two 100 x 200 mm (4 x 8 in.) cylinders, two 150 x 300 mm (6 x 12 in.) cylinders, two 100 x 100 x 100 mm (4 x 4 x 4 in.) cubes and two 150 x 150 x 150 mm (6 x 6 x 6 in.) cubes were tested in 7th, 28th and 90th day. Before testing, the weight of each specimen was measured and recorded. The specimens were loaded to failure. When the test was complete, compressive strength data was collected from the machine, and visual observations were documented, as shown in Figure 3.4.
- ***Modulus of elasticity.*** Modulus of Elasticity was tested in accordance with ASTM C 469/C469M-11 standard test method for static modulus of elasticity and Poisson's ratio of concrete in compression [76]. One 150x 300 mm (6 x 12 in.) cylinder was tested in 28th and 90th day. The specimen was tested in uniaxial compression at a constant rate of loading. The specimen was loaded to 40% ultimate compressive strength and then unloaded and reloaded for a second time with the same rate of loading and to the same 40% compressive strength. After unloading the sample, the modulus of elasticity was calculated by plotting the stress-strain curve and calculating its slope.
- ***Flexural strength.*** Flexural strength testing was done in accordance with ASTM C 78/C78M –16 Standard test method for flexural Strength of concrete [75]. Two 4 x 4 x 20 in. beams were tested in 28th and 90th day. Beams were tested using a three-point setup, and the failure load was recorded. Figure 3.5 shows specimens after testing. The flexural strength was calculated using equation (3.1):

$$\text{Flexural Strength} = PL/bd^2 \qquad (3.1)$$

P= load at failure
L= span length
b= width of specimen
d= depth of specimen

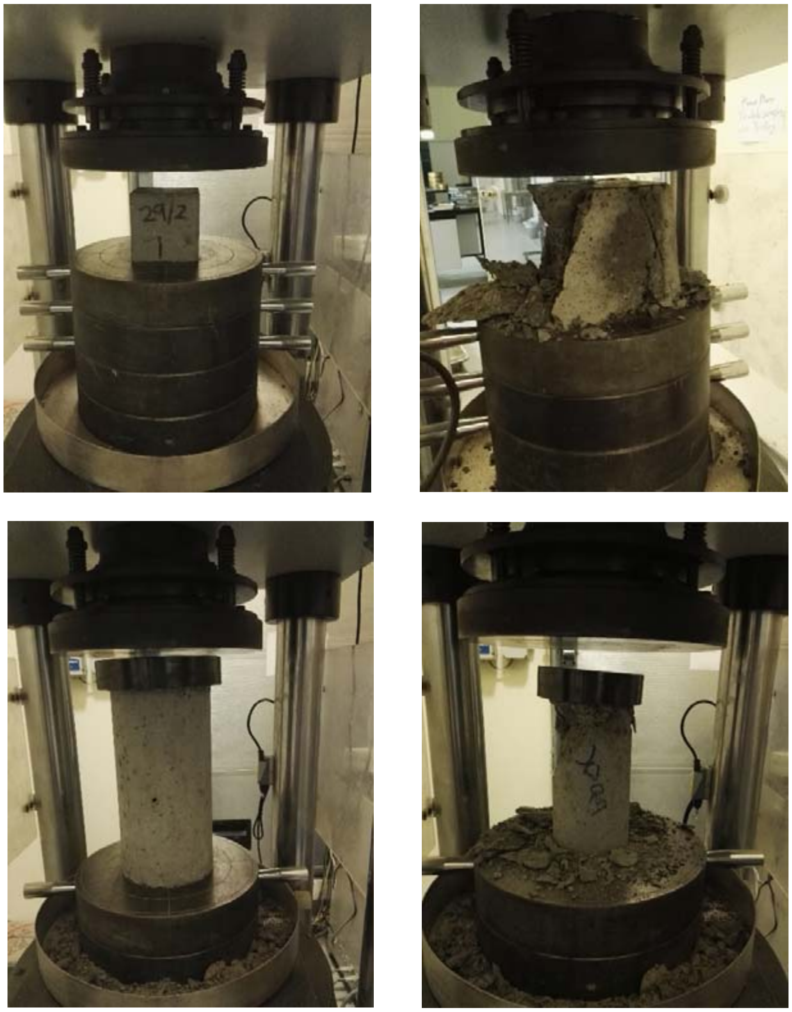


Figure 3.4: Compressive strength test.

- ***Splitting tensile strength.*** Splitting tensile strength testing was done in accordance with ASTM C496 standard test method for splitting tensile strength of cylindrical concrete specimen [74]. Two 150 mm x 300 mm (6 in. x 12 in.) cylinders were tested in 28th and 90th day. The cylinders were subjected to compressive load at a constant rate along the vertical diameter until failure. Failure occurs along the specimen vertical diameter due to tension developed in the transverse direction, as shown in Figure 3.6. The split tensile strength was calculated using equation (3.2):

Figure 3.5: Flexural strength failure.

Figure 3.6: Splitting tensile strength test.

$$\text{Tensile Strength} = 2P/\pi Ld \tag{3.2}$$

P= load at failure

L= length of specimen

d= diameter of specimen

A summary of the tests conducted is presented in Table 3.1.

Table 3.1: Summary of conducted tests

Test	Test specifications	Specimen size (mm)	No. of specimens per test	Test date since casting
Compressive strength	ASTM C39/C39M-17 [49]	150 x 300 cylinder 100 x 200 cylinder 150 x 150 x 150 cube 100 x 100 x 100 cube	2 cylinders 2 cylinders 2 cubes 2 cubes	7th , 28th and 90th day
Modulus of Elasticity	ASTM C469/C469M-14 [76]	150 x 300 cylinder	1 cylinder	28th and 90th day
Splitting tensile strength	ASTM C496/C496M-11 [74]	150 x 300 cylinder	2 cylinders	28th and 90th day
Flexural strength	ASTM C78/C78M-16 [75]	100 x 100 x 500 beam	2 beams	28th and 90th day

3.4 Phase 3: Evaluation of Mechanical Properties of Concrete Prepared with Different Aggregate Types

This Phase deals with the evaluation of the mechanical properties of concrete made with different aggregate types. Those are compressive strength, modulus of elasticity, flexural strength, and split tensile strength. Testing is conducted based on ASTM standards. The following two Sets of concrete mixes were prepared:

Set 1: One patch of six concrete mixes was prepared using the six aggregate types considered in this study.

Set 2: Samples were prepared from three ready mix concrete grades: C45, C60, and C80 from two other ready mix plants.

3.4.1 Set 1: One patch of six concrete mixes

- ***Material used.*** Ordinary Portland cement type I, silica fume, GGBS, and tap water were used for preparing the six concrete mixes. Dune sand and crushed aggregate were used as fine aggregates. Similar to Phase 2, six types of coarse aggregate were used to produce the concrete mixes in the lab: 10 mm and 20 mm sizes natural aggregate, LAYTAG and Pumice lightweight aggregate and recycled aggregate from two sources (Bee’ah and Jabal Ali), which have the same water/cement ratio (w/c), the same volume fractions of fine and course aggregates, and cementation materials, refer to mixes design in Appendix A. Whereas, the weight of the coarse aggregate varies based on the specific gravity of each type.

- ***Mixing.*** A 5 ft^3 concrete mixer was used for mixing. All coarse and fine aggregate, cement, silica fume, and GGBS were mixed. In addition, water amount was added during the mixing.

A special procedure was followed for both lightweight and recycled aggregate concrete mixes similar to Phase 2.

- ***Casting.*** 100 x 200 mm (4 x 8 in.) cylinders, 150 x 300 mm (6 x 12 in.) cylinders, 100 x 100 x 100 mm (4 x 4 x 4 in.) cubes, 150 x 150 x 150 mm (6 x 6 x 6 in.) cubes and 100 x 100 x 500 mm (4 x 4 x 20 in.) beams were prepared from each mix. Specimens were covered with plastic for 24 hours and then demolded, labeled and left for curing at room temperature until testing dates.

3.4.2 Set 2: C45, C60, and C80 ready mix concrete mixes

- ***Sample collection.*** Samples were collected from a ready mix concrete producer different than that in phase 2 with three concrete strengths of 45 MPa, 60 MPa, and 80 MPa. Specimens included cylinders 100 x 200 mm (4 x 8 in.), cylinders 150 x 300 mm (6 x 12 in.), cubes 100 x 100 x 100 mm (4 x 4 x 4 in.), cubes 150 x 150 x 150 mm (6 x 6 x 6 in.) and beams 100 x 100 x 500 mm (4 x 4 x 20 in.). Samples were labeled and left for curing at room temperature until testing dates.

3.4.3 Testing. Compressive strength test was conducted on the 7th, 28th and 90th day. Modulus of elasticity test, flexural strength test, and split tensile strength test were conducted on the 28th and 90th day.

Chapter 4: Results

This chapter reports the results of the evaluation of aggregate properties, compressive strength, modulus of elasticity, flexural strength, and split tensile strength tests. These results were analyzed and discussed in Chapter 5.

Notations used in this chapter are as the following:

- 10 mm Natural: 10 mm natural aggregate concrete.
- 20 mm Natural: 20 mm natural aggregate concrete.
- LWT1: LAYTAG lightweight aggregate concrete.
- LWT2: Pumice Lightweight aggregate concrete.
- RA1: Bee'ah recycled aggregate concrete.
- RA2: Jabal Ali recycled aggregate concrete.
- Ready mix 1-1: C45 grade ready mix concrete casted at phase 2.
- Ready mix 1-2: C75 grade ready mix concrete casted at phase 2.
- Ready mix 2-1: C45 grade ready mix concrete casted at phase 3.
- Ready mix 2-2: C60 grade ready mix concrete casted at phase 3.
- Ready mix 2-3: C80 grade ready mix concrete casted at phase 3.
- Cy1: 4x8 in. cylinder specimen.
- Cy2: 6x12 in. cylinder specimen.
- Cu1: 4x4x4 in. cube specimen.
- Cu2: 6x6x6 in. cube specimen.

4.1 Aggregate Evaluation Results

Results of water absorption and moisture content tests show that the absorption capacity for all lightweight aggregate and recycled aggregate sources is higher than that of the natural aggregate. This was addressed during mixing stage by presoaking the aggregate for 30 minutes before mixing to avoid affecting the w/c content [77, 78]. Water used for soaking was deducted from the total weight of water used during mixing to avoid increasing the amount of water which could negatively affect the concrete strength.

Results of specific gravity test show that the specific gravity of all lightweight aggregate and recycled aggregate sources; is less than that of the natural aggregate which may increase the surface area and reduce concrete workability. Using Ground Granulated Blast-Furnace Slag (GGBS) would help in enhancing the workability.

Results of water absorption, specific gravity, and moisture content tests are presented in Table 4.1.

Table 4.1: Water absorption, specific gravity, and moisture content test results

Aggregate type	Natural	LAYTAG	Pumice	Bee'ah	Jabal Ali
Absorption %	0.648	24.32	12.599	3.94	3.35
Bulk Dry Sp. Gr.	2.685	1.336	1.605	2.36	2.47
Moisture Content%	0.558	0.564	0.604	0.719	0.84

Results of Los Angeles Abrasion test show that the percentage weight loss for all lightweight and recycled aggregate sources is higher than that of the natural aggregate. This indicates lower aggregate strength for recycled and lightweight aggregates. As per ASTM C131/C131-14 [73], the testing procedure accounts for the grade distribution of each aggregate type. Results of LA Abrasion test are shown in Table 4.2.

Table 4.2: LA abrasion test results

Aggregate type	Grade B %	Grade C %	Grade D %
Natural Aggregate	22.38		
LAYTAG Lightweight Aggregate			25.97
Pumice Lightweight Aggregate			27.27
Bee'ah Recycled Aggregate	35	31	
Jabal Ali recycled Aggregate	24.97		

Sieve analysis for Natural aggregate is presented in Figure 4.1, which shows that its grading is located between the upper and lower limits for size no. 56 (25 to 9.5 mm), while both LAYTAG and Pumice lightweight aggregate sieving analyses are shown in Figure 4.2 where their grading are located between the upper and lower limits for size no. 8 (9.5 to 2.36 mm). Figure 4.3 shows the sieve analysis for Bee'ah recycled aggregate grading which is found located between the upper and lower limits for size no. 7 (12.5 to 4.75 mm). Finally Figure 4.4 shows the sieve analysis for Jabal Ali recycled aggregate whose grading is located between the upper and lower limits for size no. 6 (19 to 9.5 mm) [1].

4.2 Compressive Strength Results

Results of compressive strength test 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 7th day, 97% on the 28th day and exceeded it on the 90th day.

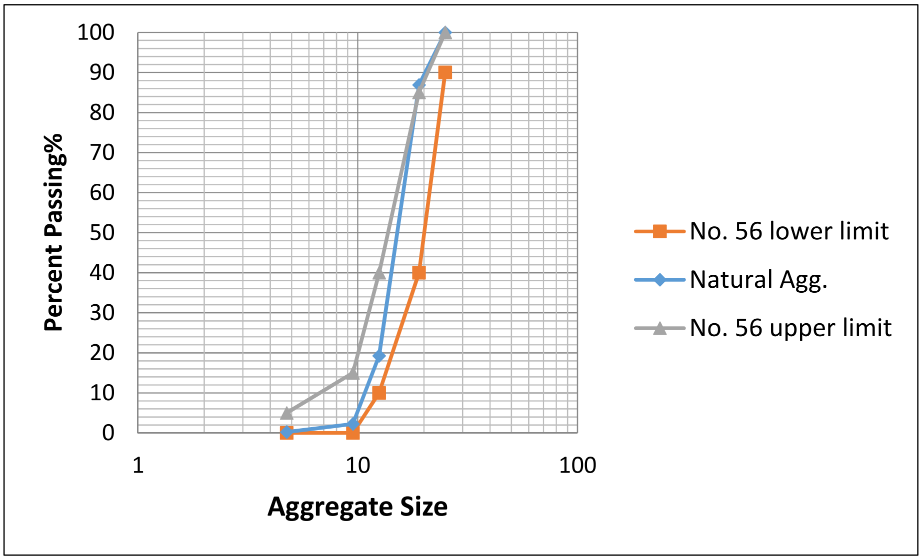


Figure 4.1: Natural aggregate sieve analysis results

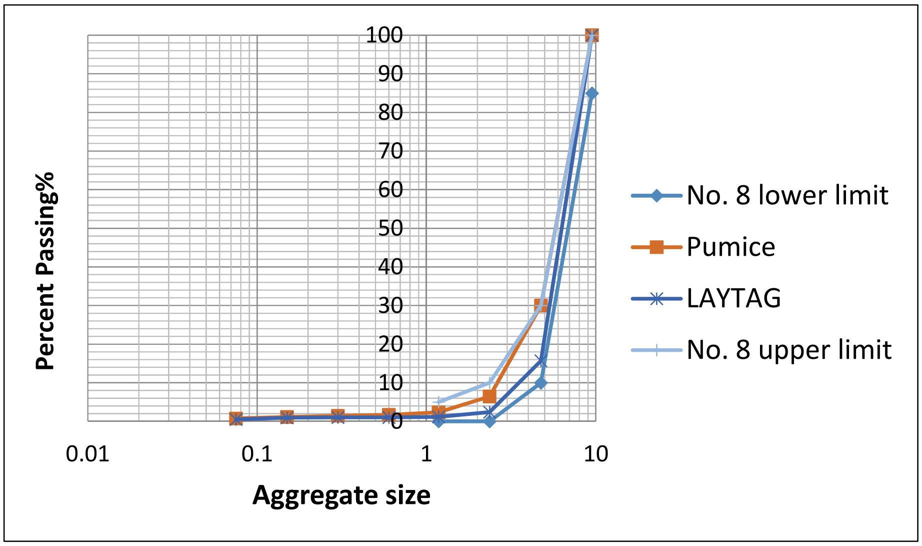


Figure 4.2: LAYTAG and Pumice lightweight aggregate sieve analysis results

Both the lightweight aggregate and recycled aggregate concrete mixes resulted in lower compressive strength than that of the natural mixes in the 7th, 28th, and 90th 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. Summary of compressive strength for different concrete mixes at 7th, 28th and 90th day are shown in Table 4.3.

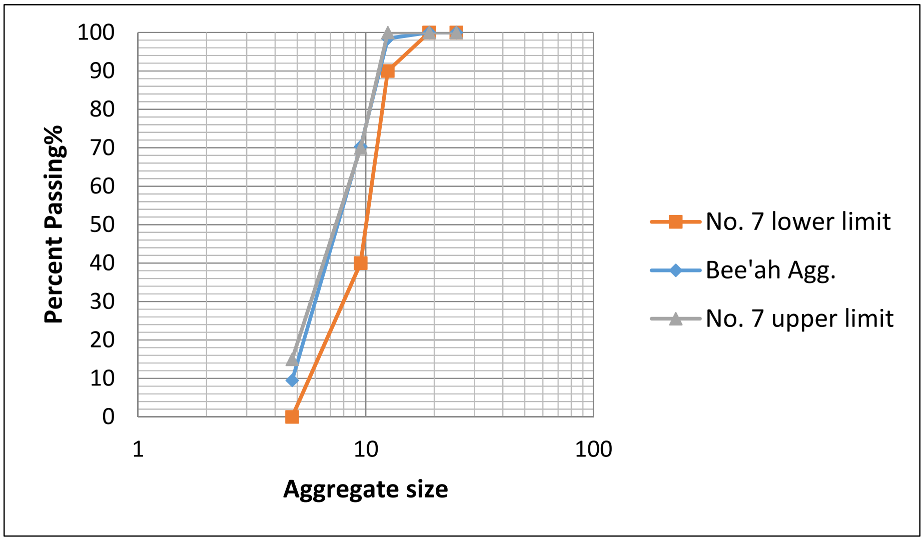


Figure 4.3: Bee’ah recycled aggregate sieve analysis results

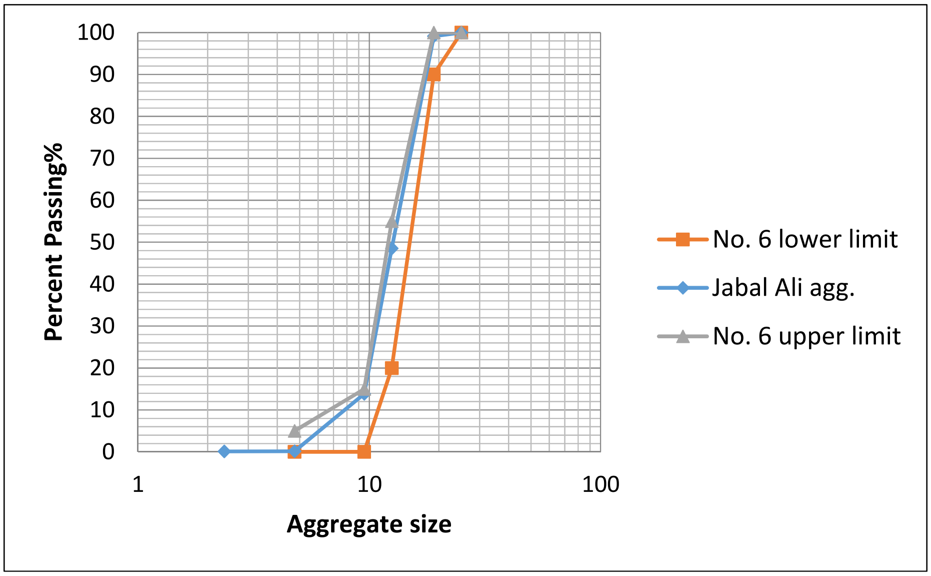


Figure 4.4: Jabal Ali recycled aggregate sieve analysis results

4.3 Modulus of Elasticity Results

Results of modulus of elasticity test show that generally the elastic modulus for all the concrete mixes had increased from 28th day to 90th day and was significantly affected by the aggregate type. A summary of elastic modulus for different concrete mixes at 28th and 90th day is shown in Figure 4.5. Modulus of elasticity test could not be done for LAYTAG aggregate concrete mix because this type of aggregate was not available at Phase 3.

Table 4.3: Summary of compressive strength for different concrete mixes at 7th, 28th and 90th day

Test date	7th day				28th day				90th day			
Mixes	Cy1	Cy2	Cu1	Cu2	Cy1	Cy2	Cu1	Cu2	Cy1	Cy2	Cu1	Cu2
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
LWT1	44.9	43.2	43.49	49.2	53.54	42.4	52.89	60.92	54.67	50.25	57.37	61.65
LWT2	38.47	41.15	37.78	45.1	47.65	46.4	52.28	60.57	51.69	43.76	52.94	59.57
RA1	44.89	41.15	51.4	48.44	52.34	51.4	52.72	60.93	56.9	60.46	57.49	66.4
RA2	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

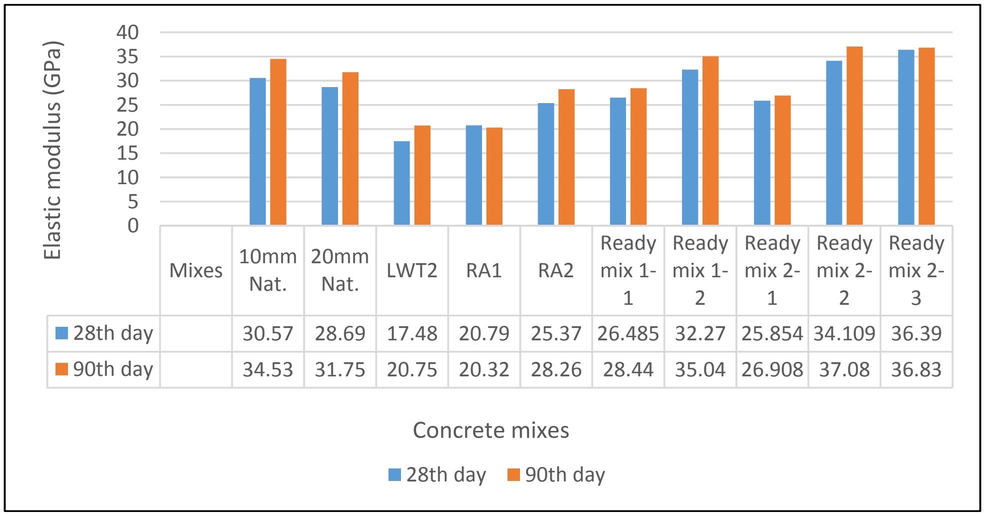


Figure 4.5: Elastic modulus for different concrete mixes at 28th and 90th day.

4.4 Split Tensile Strength Results

Results of split tensile strength test indicate a great variation between different concrete mixes which refers to the big role played by the aggregate type in affecting the splitting tensile strength of the concrete. A summary of split tensile strength for different concrete mixes at 28th and 90th day is shown in Figure 4.6. LAYTAG lightweight aggregate concrete mix was not evaluated for the split tensile strength due to material shortage of this type of aggregate at Phase 3.

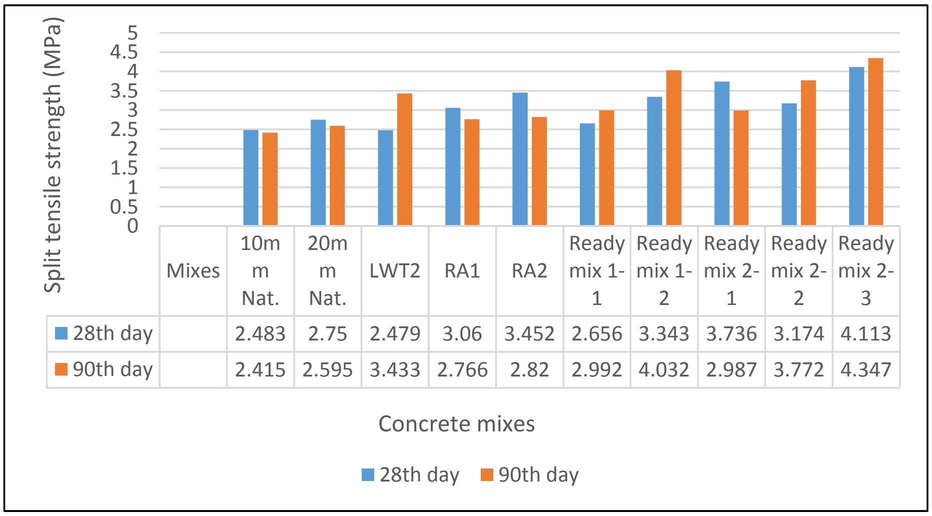


Figure 4.6: Split tensile strength for different concrete mixes at 28th and 90th day.

4.5 Flexural Strength Results

Flexural strength for all concrete mixes had increased values from 28th day to 90th day. Results show that aggregate type had a remarkable effect on the flexural strength. A summary of flexural strength for different concrete mixes at 28th and 90th day is shown in Figure 4.7. Due to material shortage of LAYTAG aggregate at Phase 3, flexural strength could not be evaluated for its concrete mix.

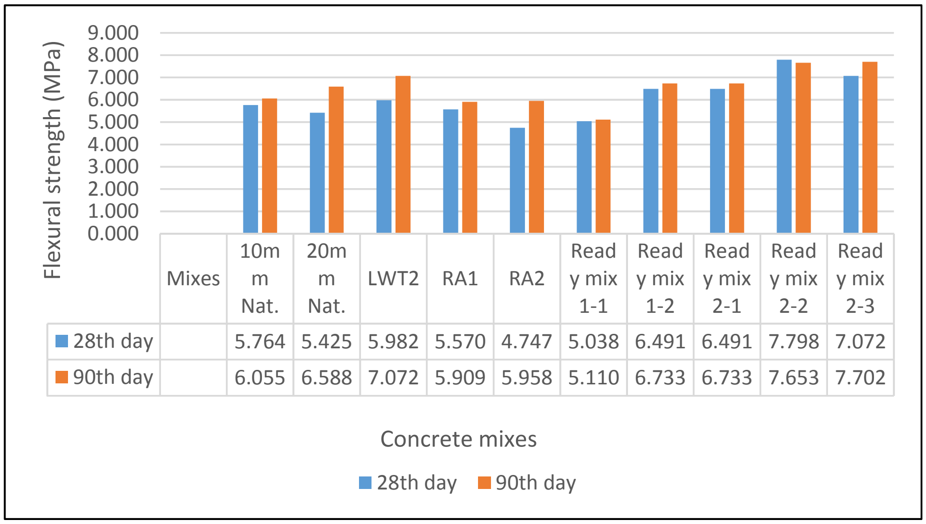


Figure 4.7: Flexural strength for different concrete mixes at 28th and 90th day.

4.6 Summary

In this chapter, a summary of the testing results is presented. Six aggregate types were considered in this study, and their properties were evaluated. Mechanical properties of samples prepared in the laboratory from six concrete mixes and samples prepared at two ready mix concrete producers were evaluated and presented. These are compressive strength, modulus of elasticity, split tensile strength, and flexural strength. Analyses and discussion of all the results are presented in Chapter 5.

Chapter 5: Statistical Analyses and Discussion

This chapter presents the statistical analyses conducted for the results presented in Chapter 4. Analyses were carried out to investigate the effect of aggregate type, and specimen size and shape on the concrete compressive strength. Each analysis principle is explained and illustrated through an example of the calculation for more clarity. Outcomes of the analyses are discussed and compared to conclusions of previous studies from the literature. Testing results for other mechanical properties of concrete such as modulus of elasticity, flexural strength, and split tensile strength are also discussed in order to assess the effect of the aggregate type on them.

Notations used in this chapter are as the following:

- 10 mm Natural, 10 mm Nat.: 10 mm natural aggregate concrete.
- 20 mm Natural, 20 mm Nat.: 20 mm natural aggregate concrete.
- LWT1: LAYTAG lightweight aggregate concrete.
- LWT2: Pumice Lightweight aggregate concrete.
- RA1: Bee’ah sourced recycled aggregate concrete.
- RA2: Jabal Ali sourced recycled aggregate concrete.
- Ready mix 1-1: C45 grade ready mix concrete casted at Phase 2.
- Ready mix 1-2: C75 grade ready mix concrete casted at Phase 2.
- Ready mix 2-1: C45 grade ready mix concrete casted at Phase 3.
- Ready mix 2-2: C60 grade ready mix concrete casted at Phase 3.
- Ready mix 2-3: C80 grade ready mix concrete casted at Phase 3.
- Cy: Cylinder specimen.
- Cu: Cube specimen.
- Cy1: 4x8 in. cylinder specimen.
- Cy2: 6x12 in. cylinder specimen.
- Cu1: 4x4x4 in. cube specimen.
- Cu2: 6x6x6 in. cube specimen.
- TS: Target Strength.
- t: Pooled test random variable.
- Sp: Pooled test standard deviation.
- x_1, x_2: Variable’s average.
- s_1, s_2: Variable’s standard deviation.
- Avg.: Average value.

- St. dev.: Standard deviation value.
- *n*: Number of variables.
- D_F: Degree of freedom.
- t-table: Pooled test t-table value.
- ITZ: Interfacial transition zone.

5.1 Evaluation of Compressive Strength Analysis

In this section, compressive strength results for all samples from six concrete mixes prepared in the laboratory with different aggregate types and samples from two ready mix concrete producers with various strength levels are compared to their target strength at both 28th and 90th day. Moreover, the effect of concrete age on their compressive strength is investigated.

5.1.1 Target strength. The ratio between the compressive strength of Cu2 specimen and the 70 MPa target compressive strength (TS) for the six concrete mixes at 7th, 28th, and 90th day is calculated. In addition, for the five ready mixes concrete, the ratio between the Cu2 specimen compressive strength and their target strength is calculated. Results presented in Table 5.1 show that all the natural and ready mixes concrete exceeded 75% of their target strength on the 7th day, and they gave more than 90% on the 28th day. On the other hand, strength for 90th day was higher than their target strength as all of the Cu2/TS ratios came higher than 1. All lightweight concrete mixes and Bee’ah recycled aggregate concrete resulted in a lower compressive strength on the 7th, 28th, and 90th day due to their lower aggregate strength. On the other hand, Jabal Ali recycled aggregate concrete showed corresponding compressive strength to that of the natural as it exhibited higher strength than that of lightweight aggregates and other recycled aggregate types.

5.1.2 Age of concrete effect on compressive strength. The ratio between the compressive strength of the same specimen shape and size for different concrete mixes at 7th to 28th day and at 90th to 28th day was calculated. Results show that concrete age has affected its compressive strength as most of compressive strength ratios for Cy1, Cy2, Cu1, and Cu2 specimens for different mixes have been found less than 1 for 7th to 28th day and ranging between 0.73-0.97 for the natural concrete, as shown in Table 5.2. Contrariwise, most of ratios have been found more than 1 for 90th to 28th day in Table 5.3. These results indicate that compressive strength had increased with the concrete getting older. Some scattered results in Table 5.3 show lower compressive strength for the 90th day than the 28th day especially on the Cy2 specimen; nonetheless, the majority of the results indicate higher strength. Similar results were reported in the literature. Studies conducted by Lo et al. [18], Beshr et al. [27], and Beushausen et al. [28] conclude that the natural concrete mixes typically achieve 0.7-0.8 of the 28th day strength in the first 7 days.

Table 5.1: Summary of Cu2/TS ratios at 7th, 28th, and 90th day

Test date Mixes	7th day	28th day	90th day
	Cu2/TS	Cu2/TS	Cu2/TS
10 mm Natural	0.75	0.97	1.13
20 mm Natural	0.83	1.04	1.10
LWT1	0.70	0.87	0.88
LWT2	0.64	0.87	0.85
RA1	0.69	0.87	0.95
RA2	0.79	0.95	0.99
Ready mix 1-1	1.00	1.16	1.25
Ready mix 1-2	0.79	0.91	1.02
Ready mix 2-1	1.06	1.31	1.35
Ready mix 2-2	0.90	1.11	1.04
Ready mix 2-3	0.81	1.04	1.08

Table 5.2: Summary of 7th /28th day ratios for Cy1, Cy2, Cu1, and Cu2

Test date Mixes	Ratio between 7th /28th day for compressive strength			
	Cy1	Cy2	Cu1	Cu2
10 mm Natural	0.73	0.73	0.88	0.78
20 mm Natural	0.92	0.74	0.92	0.80
LWT1	0.84	1.02	0.82	0.81
LWT2	0.81	0.89	0.72	0.74
RA1	0.86	0.80	0.97	0.80
RA2	0.84	0.72	0.76	0.83
Ready mix 1-1	0.96	0.88	0.98	0.86
Ready mix 1-2	0.82	0.92	0.97	0.87
Ready mix 2-1	0.86	0.85	0.85	0.81
Ready mix 2-2	0.91	0.84	0.84	0.81
Ready mix 2-3	0.95	0.79	0.83	0.78

A presentation for the statistical analyses conducted in this study is shown in Figure 5.1.

Two specimen shapes, cylinder, and cube, with 4x8 in. (100x200 mm) and 6x12 in. (150x300 mm) sizes were used to study the effect of specimen size on the concrete

Table 5.3: Summary of 90th /28th day ratio for Cy1, Cy2, Cu1, and Cu2

Test date / Mixes	Ratio between 90th /28th day for compressive strength			
	Cy1	Cy2	Cu1	Cu2
10 mm Natural	1.00	1.04	1.08	1.16
20 mm Natural	1.11	0.82	1.13	1.06
LWT1	1.02	1.19	1.08	1.01
LWT2	1.08	0.94	1.01	0.98
RA1	1.09	1.18	1.09	1.09
RA2	1.10	0.92	1.10	1.04
Ready mix 1-1	1.03	1.04	1.25	1.08
Ready mix 1-2	0.98	1.00	1.08	1.13
Ready mix 2-1	1.08	1.01	1.09	1.03
Ready mix 2-2	1.04	0.96	0.95	0.94
Ready mix 2-3	1.16	0.98	1.07	1.04

compressive strength using t-pooled analysis method. If results showed an effect of the specimen size, statistical analyses would run using separate results of the two specimen sizes to investigate the effect of aggregate type on the specimen shape factor, the effect of aggregate type on compressive strength and the correlation between aggregate strength and concrete strength. If results showed no effect, results of two specimen sizes will be combined to run the analyses.

5.2 Specimen Size Effect Analysis

The t-pooled hypothesis testing method is used to compare the compressive strength of the 6 inch and the 4 inch standard specimen sizes for the same specimen shape and concrete mix. Testing was conducted for available "$n_1=n_2=4$" samples of results (2 samples from each of Phases 2 and 3) and was carried out for the compressive strength at 7th, 28th and 90th day.

In this testing method, a random variable "t" was calculated and compared to a 95% confidence level t-table value for two tailed test, and "n_1+n_2-2" degrees of freedom. If the calculated "t" value ranges in the ±ve t-table value, the hypothesis is accepted, and the averages are equal. If it did not, it indicates that the averages are not equal to each other.

The null and alternative hypotheses for this case are:

$H_o : \mu_1 = \mu_2$ and $H_a : \mu_1 \neq \mu_2$

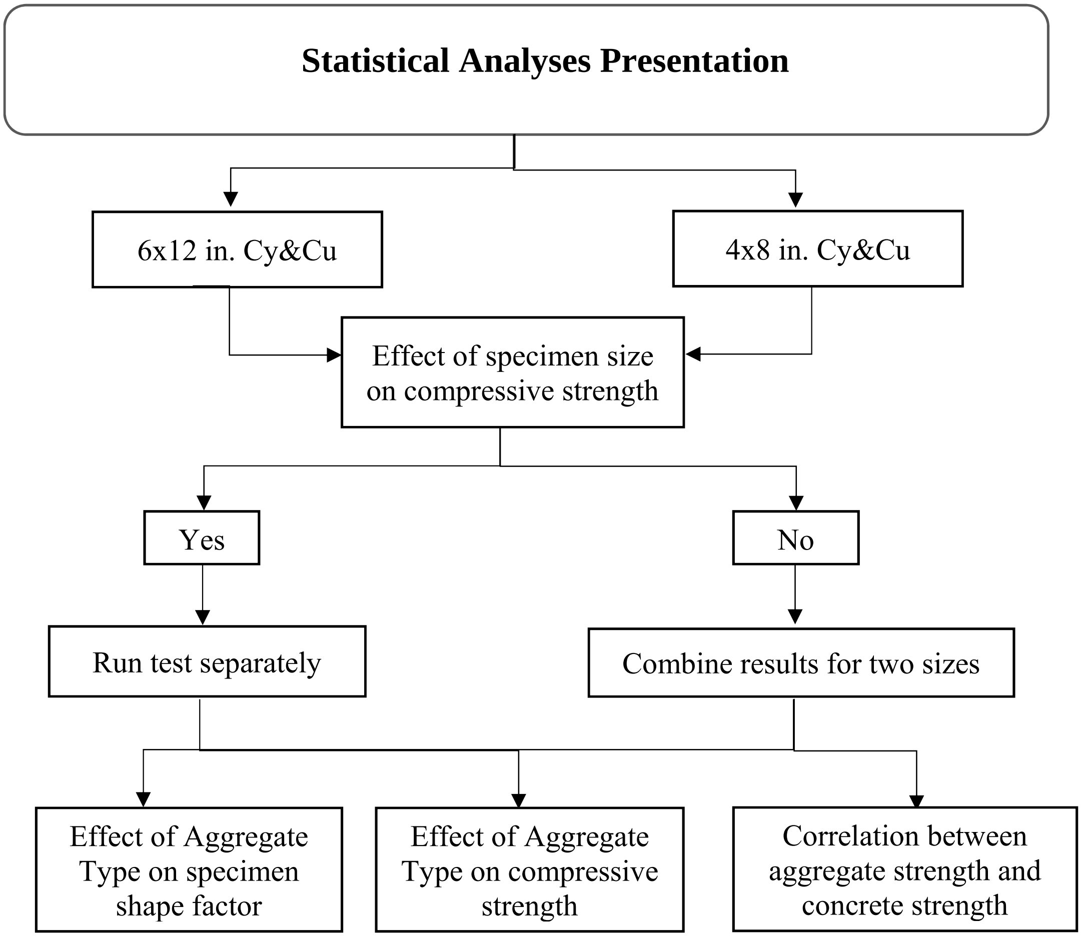


Figure 5.1: Presentation of the Statistical analyses conducted in this study.

The random value "t" is calculated by equation (5.1):

$$t = \frac{(\bar{x}_1 - \bar{x}_2) - (\mu_1 - \mu_2)}{s_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \tag{5.1}$$

Where,

$\bar{x}_1, \bar{x}_2$ are the compared averages.

n_1, n_2 are the variables number.

Sp is the pooled standard deviation

The estimate of the pooled standard deviation "*Sp*" is calculated by equation (5.2):

$$s_p = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}} \tag{5.2}$$

Where,

s_1, s_2 are the variables standard deviation.

n_1, n_2 are the sample sizes.

$D_F = n_1 + n_2 - 2 = 6$

95% confidence from the t-table = 2.447

A sample of the calculations is shown in Table 5.4 for 20 mm natural mix at 7th day. In this table, a light grey highlighted cell for the random value "t" means that its value is within the range of ±ve T-table value, and the averages are equal. On the other hand, a dark grey highlighted cell for "t" means that its value is out of the acceptance range, and the averages are not equal.

Table 5.4: Calculations for comparing between Cy1 and Cy2, Cu1 and Cu2 specimen for 20 mm Natural mix at 7th day

	20 mm Natural			
	7th day			
	Cy1	Cy2	Cu1	Cu2
	62.90	50.40	62.03	59.44
	63.02	57.00	65.60	59.33
	56.26	47.20	52.34	57.28
	56.44	45.30	61.91	56.48
Avg.	59.66	49.98	60.47	58.13
St. dev.	3.817	5.134	5.683	1.483
n	4	4	4	4
Sp	4.524		4.153	
t	3.026		0.795	
t-table	±2.447		±2.447	

Table 5.5 presents a summary of the results of the t-pooled analysis done for average compressive strength of Cy1/Cy2, and Cu1/Cu2 for six concrete mixes on 90th day. This is the main concern of the current study as it will be the workable strength for the concrete after it is matured and ready to be loaded. A summary of analysis results on 7th, and 28th day is presented in Appendix C.

Table 5.5: Summary of t pooled analysis results for Cy1/Cy2 and Cu1/Cu2 at 90th day

Test date	90th day					
Mixes	10 mm Nat.	20 mm Nat.	LWT1	LWT2	RA1	RA2
Cy1/Cy2	1.654	2.412	0.940	1.387	-0.739	1.710
Cu1/Cu2	-2.776	0.198	-1.113	-1.294	-2.295	-0.711

Results in Table 5.5 show 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. Only the 10 mm natural concrete mix showed a slightly lower compressive strength for the 4 inch cube specimen than the 6 inch one.

Based on this conclusion, in all the following analyses, the group of testing results of both 4 and 6 inch standard specimen sizes were combined to study the aggregate type effect and specimen shape effect on the concrete compressive strength.

5.3 Specimen Shape Effect Analysis

In this section, the specimen shape factor (ratio between the compressive strength of cylinder and cube) for six concrete mixes is calculated. Furthermore, the effect of aggregate type on their specimen shape factor is investigated. Finally, the specimen shape factor for five concrete mixes with different target strength levels is studied to clarify the effect of target strength level on it.

5.3.1 Specimen shape effect. The effect of specimen shape on concrete compressive strength is investigated by calculating the average Cy/Cu compressive strength ratio using the trimmed average value (i.e., the average of 6 data samples after excluding the highest and lowest values out of the available 8 samples of results, 4 samples from each of phases 2 and 3 for the same concrete mix). Calculations were done for the six mixes at 7th, 28th and 90th day. A sample of calculations done for 10mm natural concrete mix is shown in Table 5.6.

A summary of the calculations of the average Cy/Cu for all six mixes at 7th, 28th, and 90th day is shown in Table 5.7.

Results in Table 5.7 show that generally the cylinder specimens gave lower compressive strength than that of the cube specimens, which is compatible with the data from the literature [9,-12]. The cylinder/cube ratio for all concrete mixes is less than 1 on all 7th, 28th and 90th day, and it ranges between 0.781-0.929 on the 90th testing day. This is believed to be a result of the lateral expansion that happens due to the Poisson's ratio in the cylinder.

When the height of the specimen increases with respect to its width, it results in some additional lateral strain and stresses and leads to an earlier failure to the central part by lateral splitting and thereby exhibiting the lower compressive strength. However, in the cube case, the cracks tend to happen in its sides which disintegrate leaving a relatively undamaged central core.

Table 5.6: calculation of average ratio of Cy/Cu for 10 mm natural concrete mix at 7th, 28th and 90th day

	10 mm Natural mix		
	7th day	28th day	90th day
	Cy/Cu	Cy/Cu	Cy/Cu
	0.710	0.931	0.965
	0.837	0.954	0.857
	0.867	0.902	0.795
	0.863	0.885	0.788
	0.876	0.887	0.810
	0.881	0.975	0.819
Avg.	0.839	0.922	0.839

Table 5.7: Summary of average Cy/Cu ratio for six concrete mixes at 7th, 28th, and 90th day

Test date Mixes	7th day	28th day	90th day
	Cy/Cu	Cy/Cu	Cy/Cu
10 mm Natural	0.839	0.922	0.839
20 mm Natural	0.925	0.925	0.866
LWT1	0.946	0.806	0.878
LWT2	0.957	0.829	0.818
RA1	0.872	0.934	0.929
RA2	0.855	0.836	0.781

5.3.2 Aggregate type effect on specimen shape factor. The specimen shape factors "Cy/Cu" for six concrete mixes were compared using the t-pooled hypothesis testing method in order to investigate the aggregate type effect on them. Calculations were done for the calculated trimmed averages of available 8 samples, 4 samples from each of phases 2 and 3 for the same concrete mix on the 7th, 28th and 90th day.

D_F =10

95% confidence from the t-table = 2.228

Table 5.8 shows an example of calculations done for comparing between Cy/Cu ratios of 10 mm and 20 mm natural concrete mixes at the 7th day where a light grey highlighted "t" value indicates an equivalent averages while a dark grey highlighted one indicates un equivalent ones.

A summary of the results of these calculations on the 90th day is shown in Table 5.9. In addition, a summary of analysis results on 7th, and 28th day is presented in Appendix C.

Table 5.8: Calculations for comparing between Cy/Cu ratios of 10 mm and 20 mm natural concrete mixes at 7th day

	7th day	
	20 mm Natural	10 mm Natural
	Cy/Cu	Cy/Cu
	0.836	0.710
	0.880	0.837
	0.948	0.867
	0.950	0.863
	0.921	0.876
	1.014	0.881
Avg.	0.92	0.84
St. dev.	0.061	0.065
n	6	6
Sp	0.063	
t	2.335	
t-table	±2.228	

Table 5.9: Summary of t pooled analysis results for Cy/Cu for the six concrete mixes at 90th day

	90th day					
Mixes	10 mm Nat.	20 mm Nat.	LWT1	LWT2	RA1	RA2
10 mm Nat.		0.860	1.301	-0.652	3.104	-1.808
20 mm Nat.			0.534	-2.087	3.130	-3.531
LWT1				-2.971	3.108	-4.525
LWT2					5.989	-1.640
RA1						-7.393
RA2						

Results of the analysis of studying the aggregate type effect on the specimen shape factor at 90th day in Table 5.9 indicated that the aggregate type has a significant effect it and the following observations were concluded:

1. Both 10 mm and 20 mm natural aggregate concrete mixes resulted in an equivalent Cy/Cu factors which indicate that both of them were affected in the same way to the specimen shape effect. Changing the aggregate size did not affect the specimen shape effect on the compressive strength of the concrete mix.
2. Both lightweight concrete mixes showed equivalent specimen shape factors with those of the 10 mm and 20 mm natural aggregate concrete mixes, which indicate that reducing the aggregate unit weight, did not

affect the specimen shape effect on the compressive strength of the concrete mix.

3. For lightweight aggregate concrete, the specimen shape effect was influenced by the aggregate type.
4. Recycled aggregate concrete mixes show different specimen shape factors than those of the natural and lightweight aggregate concrete mixes due to their different aggregate properties. Recycled aggregate properties cannot be controlled due to the variability of their sources even in the same patch, which may have different quality and strength.

5.3.3 Concrete target strength level effect on the specimen shape factor. Summary of calculated specimen shape factors Cy1/Cu1 and Cy2/Cu2 of the five ready mix concrete with different target strengths at 7th, 28th, and 90th day are shown in table 5.10. Results for samples collected from the same ready mix producer show that increasing the target strength level of the concrete mix had increased the specimen shape factor of it which indicates that they were less affected by the specimen shape, and that normal strength concrete was affected more by the specimen shape factor than the high strength concrete. Similar results were reported by Elwell et al. [58] and Abd et al. [12].

Table 5.10: Summary of Cy1/Cu1 & Cy2/Cu2 ratios at 7th, 28th, and 90th day

Test date / Mixes	7th day		28th day		90th day	
	Cy1/Cu1	Cy2/Cu2	Cy1/Cu1	Cy2/Cu2	Cy1/Cu1	Cy2/Cu2
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

5.4 Aggregate Type Effect on Concrete Compressive Strength Analysis

Compressive strengths of six concrete mixes were compared using the pooled t-testing method to investigate the effect of the aggregate type on it (refer to testing procedure in Section 5.2). Testing was conducted using the calculated trimmed averages of available 8 samples, 4 samples from each of Phases 2 and 3 for the same specimen shape and concrete mix. The analysis was done for each specimen shape “Cy & Cu” at 7th, 28th and 90th day.

$D_F = 10$

95% confidence from the t-table = 2.228

A sample of analysis calculation for comparing between cylinder specimen's compressive strength of 10 mm and 20 mm natural concrete is presented in Table 5.11. A light grey highlighted "t" value indicates an equivalent averages while a dark grey highlighted one indicates un equivalent ones.

Table 5.11: Calculations for comparing between compressive strength of Cy for 10 mm and 20 mm natural concrete mixes at 7th day.

	Compressive strength at 7th day	
	20 mm Natural	10 mm Natural
	Cy	Cy
	47.20	36.00
	50.40	42.80
	56.26	45.31
	56.44	45.80
	57.00	46.80
	62.90	47.40
Avg.	55.03	44.02
St. dev.	5.514	4.238
n	6	6
Sp	4.918	
t	3.879	
t-table	±2.228	

A summary of the results of the t-pooled analysis done for comparing compressive strength of cylinder and cube specimen for six concrete mixes at 90th day is shown in Tables 5.12 and 5.13, respectively. Moreover, a summary of the analysis results conducted on the 7th, 28th day is presented in Appendix C.

The analysis results for the cylinder specimen in Table 5.12 were affected by both the aggregate type and specimen shape effect. In order to investigate the aggregate type effect separately, the 90th day specimen shape factors were applied to the compressive strength of the cylinders and then re-compared using the t-pooled testing method. A summary of the analysis results for the adjusted cylinder compressive strength is shown in Table 5.14.

Table 5.12: Summary of t pooled analysis results for Cy of six concrete mixes at 90th day

	90th day- cylinder					
Mixes	10 mm Nat.	20 mm Nat.	LWT1	LWT2	RA1	RA2
10 mm Nat.		0.880	-4.079	-4.263	-3.837	-0.616
20 mm Nat.			-3.247	-3.510	-2.899	-1.188
LWT1				-0.581	0.865	2.534
LWT2					1.412	2.866
RA1						2.072
RA2						

Table 5.13: Summary of t pooled analysis results for Cu of six concrete mixes at 90th day

	90th day-cube					
Mixes	10 mm Nat.	20 mm Nat.	LWT1	LWT2	RA1	RA2
10 mm Nat.		0.736	-3.390	-4.060	-2.677	-0.705
20 mm Nat.			-3.663	-4.217	-3.067	-1.404
LWT1				-0.800	0.894	3.199
LWT2					1.711	4.018
RA1						2.340
RA2						

Table 5.14: Summary of t pooled analysis results for adjusted Cy of six concrete mixes at 90th day

	90th day- adjusted cylinder					
Mixes	10 mm Nat.	20 mm Nat.	LWT1	LWT2	RA1	RA2
10 mm Nat.		1.346	-3.065	-4.773	-1.138	-2.040
20 mm Nat.			-3.075	-4.175	-1.941	-2.511
LWT1				-1.717	2.056	0.623
LWT2					3.814	2.175
RA1						-1.153
RA2						

Results in Tables 5.13 and 5.14 show that generally the concrete compressive strength was highly affected by the aggregate type, refer to different failure modes in Appendix B. The following observations were concluded:

1. Both 10 mm and 20 mm natural aggregate concrete mixes produced corresponding compressive strength for both cylinder and cube specimens. For the aggregate sizes used in the study, changing the aggregate size had no effect on the concrete compressive strength.
2. Both lightweight concrete mixes show less compressive strength than the two natural concrete mixes with different aggregate sizes for both cylinder

and cube specimens. This is attributed to their lower aggregate strength compared to the natural aggregate.

3. Both the LAYTAG and the Pumice lightweight aggregate concrete mixes produced an equivalent compressive strength for both cylinder and cube specimen, which matches their corresponding aggregate strengths.
4. Regardless of the specimen shape, the Bee’ah recycled aggregate concrete mix resulted in lower compressive strengths than those of the natural concrete mixes affected by its weaker aggregate, while it gave an equivalent strengths to those of the lightweight aggregate concrete mixes which exhibited a corresponding aggregate strength to Bee’ah aggregate. This conclusion is compatible with the results reported by McNeil et al. [26] who conclude that compressive strength has decreased with replacing the natural aggregate with recycled aggregate.
5. The Jabal Ali recycled aggregate concrete mix resulted in an equivalent compressive strength to those of the natural concrete mixes for both cylinder and cube specimens which again matches their corresponding aggregate strength, and similarly gives higher compressive strength than those of the lightweight aggregate mixes.
6. In accordance with the higher strength shown by the Jabal Ali recycled aggregate than the Bee’ah recycled aggregate, its concrete mix exhibited a slightly higher compressive strength than that of Bee’ah recycled aggregate 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 in the same patch which may have different properties and strength.

5.5 Correlation between Aggregate Strength and Concrete Compressive Strength

Regression analysis was conducted to investigate the relation between the strength of the six types of aggregate considered in this study represented with their weight loss percentage that resulted from the LA Abrasion test, and their concrete mixes’ trimmed equivalent compressive strength. Analysis was done for both cylinder and cube specimens’ compressive strength at 28th day.

Results illustrated in Figure 5.2 indicate a good correlation between the aggregate strength and their concrete mix compressive strength. The squared R value reached 0.929 with the cylinder compressive strength and 0.815 with the cube strength. These results refer to the great role played by the aggregate type in affecting the concrete compressive strength.

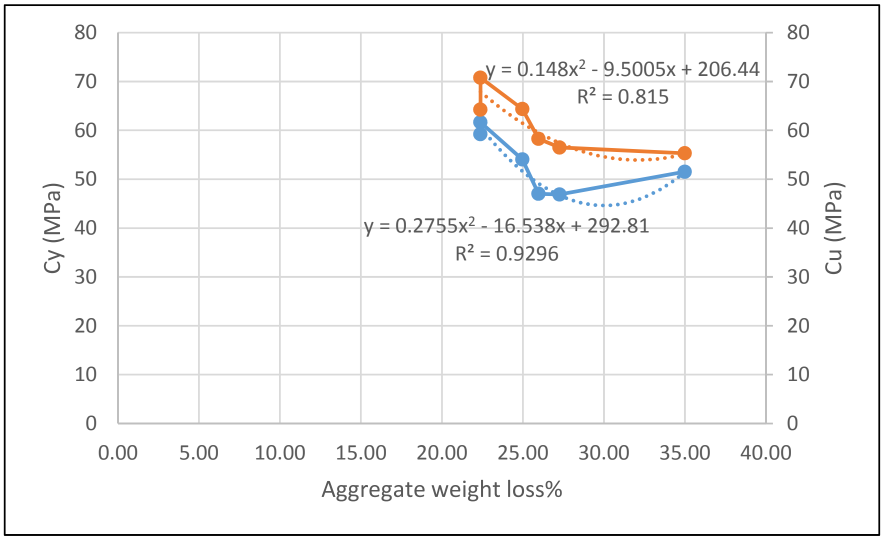


Figure 5.2: Relation between aggregate strength and Cy and Cu trimmed average compressive strength for different concrete mixes at 28th day.

5.6 Modulus of Elasticity

Results of modulus of elasticity test shown in Figure 4.5 indicate that it was significantly affected by the aggregate type. Looking in deep in the results of the 90th day testing, the 10 mm natural concrete mix gave the highest elastic modulus followed by the 20 mm natural concrete mix. Both lightweight and recycled aggregate concrete mixes showed lower elastic modulus than the natural concrete affected by their weaker aggregate compared to the natural aggregate. Jabal Ali recycled aggregate concrete mix gave slightly lower modulus than the natural concrete mix matching with corresponding strength shown by this type of aggregate to natural aggregate strength. Both Pumice lightweight and Bee'ah recycled aggregate concrete mixes show an equivalent elastic modulus which is again correlated to their aggregate corresponding strength.

In view of the ready-mix concrete results, modulus of elasticity was increasing with the increase in the target compressive strength level of the concrete mix. For each ready mix producer, higher strength concrete exhibited higher elastic modulus.

Elastic modulus "E" for natural concrete mixes was calculated using equation (5.3) from ACI363R-10 standard [79]. For lightweight aggregate and recycled aggregate concrete mixes, equation (5.4) from ACI318-14 standard [80] was used. Calculated modulus of all concrete mixes were compared to their tested results at 28th day to investigate their correlation to the standard equation.

$$E = 3.2\sqrt{f_c'} + 6.9 \qquad (5.3)$$

Where,

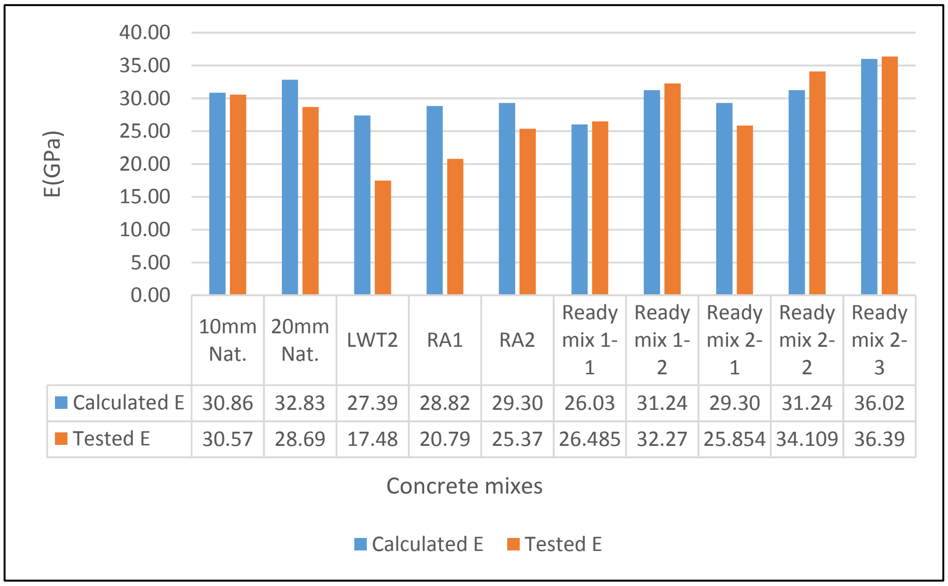
f_c' is the cylinder Cy2 compressive strength at 28th day from Table 4.3.

$$E = 4.73 \times 0.85 \times \sqrt{f_c'} \qquad (5.4)$$

Where,

f_c' is the cylinder Cy2 compressive strength at 28th day from Table 4.3.

As shown in Figure 5.3, the tested modulus of elasticity for most of the concrete mixes were lower than their standard predicted values, especially for the lightweight and recycled aggregate concrete mixes as on 28th day; concrete mixes might not be fully cured and dried and may still contain some moisture.



	10mm Nat.	20mm Nat.	LWT2	RA1	RA2	Ready mix 1-1	Ready mix 1-2	Ready mix 2-1	Ready mix 2-2	Ready mix 2-3
🟦 Calculated E	30.86	32.83	27.39	28.82	29.30	26.03	31.24	29.30	31.24	36.02
🟧 Tested E	30.57	28.69	17.48	20.79	25.37	26.485	32.27	25.854	34.109	36.39

Figure 5.3: Comparison between calculated and tested elastic modulus for different concrete mixes at 28th day.

Table 5.15 summarizes some of the modulus elasticity results from the literature. The results of the current study for the natural and lightweight aggregate concrete mixes are similar results for those found in the literature.

Table 5.15: Results of modulus of elasticity from literature and the thesis tested results

Reference	Modulus of Elasticity (GPa)	Remarks
Topcu et al. [19]	33-39 17-18	Natural aggregate concrete. Lightweight aggregate concrete.
Katz [25]	11.3	Recycled aggregate concrete.
Beshr et al. [27]	21-28	High strength concrete.
Beushausen et al. [28]	27.03-44.81	High strength concrete.
Wu et al. [30]	31-39.5	w/c = 0.44.
Zhou et al. [31]	18.6-51.3	High performance concrete.
Aitcin PC et al. [35]	31.7-37.9	High strength concrete.
Sengul et al. [38]	25.3-38 36.3-51.1	Normal strength concrete. High strength concrete.
Meddah et al. [48]	28.5-37	Normal & high strength concrete.
Wardeh et al. [81]	39.5 30-36	Natural aggregate concrete. 15%, 30%, and 50% RCA.
Thesis Results	28-36 17.5 21-25	Normal & high strength concrete. Lightweight aggregate concrete. Recycled aggregate concrete.

5.7 Splitting Tensile Strength

Results of split tensile strength shown in Figure 4.6 indicate that it was less affected by the aggregate type than the compressive strength. Considering the results of the 90th day, recycled aggregate concrete mixes exhibited slightly higher split tensile strength than the natural concrete; whereas, Pumice lightweight aggregate concrete mix show a significant higher split tensile strength than the natural concrete. This could be attributed to the special procedure of presoaking followed for those types of aggregates which strengthen the bond between the aggregate and the cement paste. In addition, the small size and rough surface of the Pumice lightweight aggregate may have resulted in advanced results.

Ready-mix concrete results show that for each ready mix producer, higher strength concrete resulted in a higher split tensile strength.

Split tensile strength for natural concrete mixes was calculated as per equation (5.5) from ACI363R-10 standard [79] while for lightweight and recycled aggregate concrete mixes, calculations are done using equation (5.6) from ACI318-14 standard [80], and all compared to the tested values.

$$f_{spt} = 0.59\sqrt{f_c'} \tag{5.5}$$

Where,

f_c' is the cylinder Cy2 compressive strength at 28th day from Table 4.3.

$$f_{spt} = 0.56 \times 0.85 \times \sqrt{f_c'} \tag{5.6}$$

Where,

f_c' is the cylinder Cy2 compressive strength at 28th day from Table 4.3.

The tested split tensile strength for all the concrete mixes were found lower than the standard predicted value especially for the 10 mm and 20 mm concrete mixes. This indicates weak bond strength, resulting in an early failure in the lateral direction, as shown in Figure 5.4.

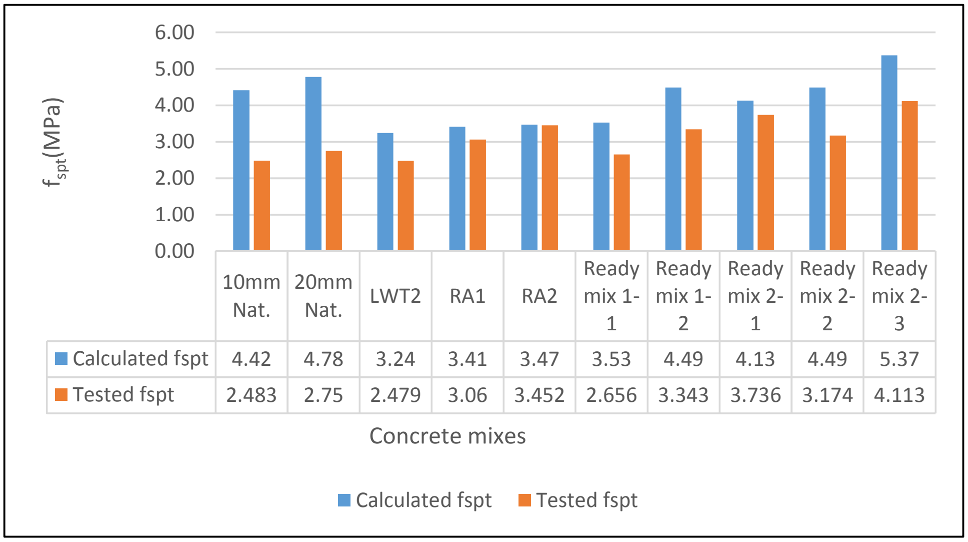


Figure 5.4: Comparison between calculated and tested split tensile strength for different concrete mixes at 28th day.

Table 5.16 summarizes some of the results of split tensile strength from the literature and the tested results of the thesis. Results varied based on different aggregate types used and the target concrete mixes strengths. Results of the current study are compatible with the data from literature.

5.8 Flexural Strength

Results of flexural strength test shown in Figure 4.7 indicate that the flexural strength of concrete had slightly been affected by the aggregate type. Considering the results of the 90th day testing, both recycled aggregate concrete mixes resulted in a lower

Table 5.16: Results of split tensile strength from literature and the thesis tested results

Reference	Split tensile strength (MPa)	Remarks
Topcu et al. [19]	3.7-3.9 1.6-1.7	Natural aggregate concrete. Lightweight aggregate concrete.
Tabsh et al. [20]	4 2.9-4	Natural aggregate concrete. Recycled aggregate concrete.
Choi et al. [82]	1.8-2.5	Recycled aggregate concrete.
Poon et al. [21]	3-4.2	Normal & high strength concrete.
Katz [25]	3.1	Recycled aggregate concrete.
McNeil et al. [26]	3.3 2.7-3	Natural aggregate concrete. 15%, 30%, and 50% RCA.
Beshr et al. [27]	2.4-4	High strength concrete.
Beushausen et al. [28]	3.74-4.35	High strength concrete.
Wu et al. [30]	5-5.3	w/c = 0.44.
Ozturan et al. [32]	3.9-5.2	Normal & high strength concrete.
Sengul et al. [38]	2.59-3.88 4.44-8.14	Normal strength concrete. High strength concrete.
Wardeh et al. [81]	3.6 3-3.3	Natural aggregate concrete. 30%, 65%, and 100% RCA.
Thesis Results	2.5-4.11 2.5 3-3.5	Normal & high strength concrete. Lightweight aggregate concrete. Recycled aggregate concrete.

flexural strength than the natural concrete mixes because of their lower aggregate strength. In spite of the lower strength of the Pumice aggregate compared to the natural aggregate, its concrete mix exhibited higher strength than natural concrete mixes. This could be a result of the presoaking procedure followed during mixing and its small rough particles which enhanced the interlocking between the aggregate and the cement paste leading to higher bond strength.

Equation (5.7) from ACI363R-10 standard and equation (5.8) from ACI318-14 standard [79] were used to predict the flexural strength for natural concrete mixes and lightweight and recycled aggregate concrete mixes, respectively.

$$f_r = 0.94\sqrt{f_c'} \qquad (5.7)$$

Where,

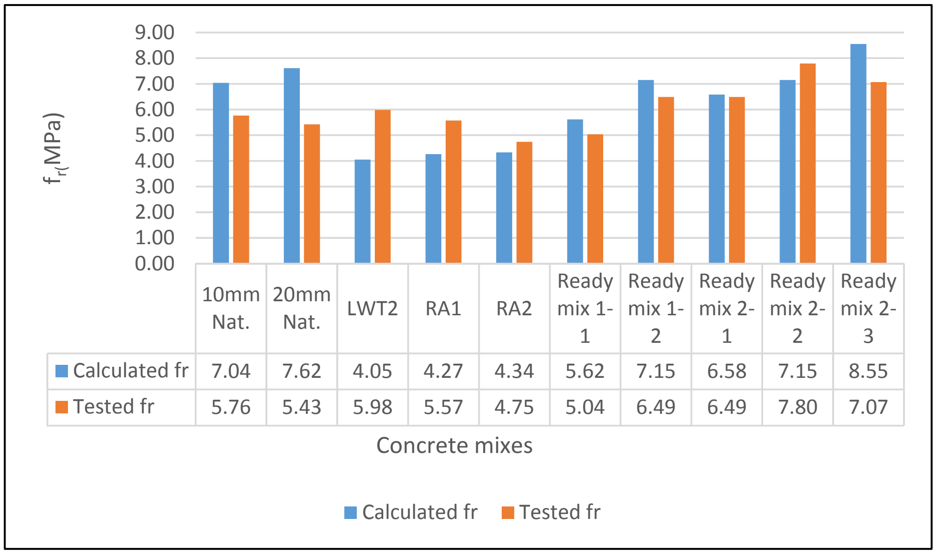
f_c' is the cylinder Cy2 compressive strength at 28th day from Table 4.3.

$$f_r = 0.7 \times 0.85 \times \sqrt{f_c'} \qquad (5.8)$$

Where,

f_c' is the cylinder Cy2 compressive strength at 28th day from Table 4.3.

Most of the concrete mixes have resulted in a lower tested flexural strength than the calculated values, as shown in Figure 5.5; whereas, Pumice lightweight aggregate and recycled aggregate concrete mixes exhibited a higher flexural strength than those predicted, especially for the Pumice lightweight aggregate concrete mix. This could be a result of its 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.



	10mm Nat.	20mm Nat.	LWT2	RA1	RA2	Ready mix 1-1	Ready mix 1-2	Ready mix 2-1	Ready mix 2-2	Ready mix 2-3
🟦 Calculated fr	7.04	7.62	4.05	4.27	4.34	5.62	7.15	6.58	7.15	8.55
🟧 Tested fr	5.76	5.43	5.98	5.57	4.75	5.04	6.49	6.49	7.80	7.07

Figure 5.5: Comparison between calculated and tested flexural strength for different concrete mixes at 28th day.

Table 5.17 summarizes some of the results of the flexural strength from the literature and the thesis tested results which came compatible to each other. Variation in values is attributed to the different types of aggregate used and the strength level targeted in those studies.

A summary of all statistical analyses conducted in this study is concluded in Figure 5.6.

Table 5.17: Results of flexural strength from literature and the thesis tested results

Reference	Flexural strength (MPa)	Remarks
Katz [25]	5.4	Recycled aggregate concrete.
McNeil et al. [26]	10.2 8.9-9.7	Natural aggregate concrete. 15%, 30%, and 50% RCA.
Beushausen et al. [28]	2.66-2.93	High strength concrete.
Kilic et al. [29]	5.2-17.3	High strength concrete.
Ozturan et al. [32]	4.7-5.3	Normal & high strength concrete.
Ezeldin et al. [37]	7.4-9.2	High strength concrete.
Ajamu et al. [47]	4.4-4.93	Normal concrete with different aggregate sizes.
Wardeh et al. [81]	4.9 3.95-4.75	Natural aggregate concrete. 15%, 30%, and 50% RCA.
Thesis Results	5.5-7.8 6 4.75-5.57	Normal & high strength concrete. Lightweight aggregate concrete. Recycled aggregate concrete.

Statistical Analyses

Statistical analysis used	No. of samples used	Used for what	Outcomes
t-pooled test method	4 samples of results	Effect of specimen size on compressive strength	Specimen size effect is negligible on compressive strength
t-pooled test method	6 samples of results	Effect of Aggregate type on Specimen shape factor	Aggregate type has a significant effect on Specimen shape factor
t-pooled test method	6 samples of results	Effect of Aggregate type on Compressive strength	Aggregate type has a significant effect on compressive strength
Regression analysis	Average of group of samples of results	Correlation between aggregate strength and concrete compressive strength	Concrete compressive strength is highly correlated to its aggregate strength

Figure 5.6: Summary of the Statistical analyses conducted in this study.

Chapter 6: Conclusions

An experimental study was carried out to investigate the effect of the specimen configuration and aggregate type on the concrete compressive strength. Six concrete mixes with different aggregate types, 10 mm and 20 mm natural, LAYTAG and Pumice lightweight, and two types of recycled aggregate from two sources "Bee'ah and Jabal Ali" were cast and tested for compressive strength, elastic modulus, splitting tensile strength, and flexural strength. In addition, samples from five ready-mix concrete with four grades "C45, C75, C60, and C80" were collected from two producers and were evaluated for the same mechanical properties. Two specimen shapes, cylinder and cube, were used with 100 x 200 mm (4 x 8 in.) and 150 x 300 mm (6 x 12 in.) sizes. Compressive strength was evaluated on the 7th, 28th and 90th day while the elastic modulus, split tensile strength and flexural strength were evaluated on the 28th, 90th day.

The following could be concluded from this study:

- Most of the natural and ready-mix concrete achieved more than 75% of their target strength in the first 7 days, and more than 97% on the 28th day and exceeded those on the 90th day. However, both the lightweight and recycled aggregates concrete mixes achieved between 64-79% of their target strength on the 7th day, 87-95% on the 28th day, and between 85-99% on the 90th day due to their lower aggregate strength.
- As long as typical standard specimen sizes are used, 4 in. x 8 in. (100 mm x 200 mm) and 6 in. x 12 in. (150 mm x 300 mm) with aspect ratio of 2, the specimen size effect on compressive strength is negligible regardless of the specimen shape and the aggregate type. Both sizes resulted in an equivalent strength.
- The cylinder specimens generally resulted in less compressive strength than that of the cubes on all of the 7th, 28th and 90th day. The cylinder/cube ratio ranged between 0.781-0.929 for the 90th day. This is attributed to the Poisson's ratio effect which causes some additional lateral strain and stresses that cause an earlier failure to the central part of the cylinder by lateral splitting, and thereby exhibits the lower compressive strength.
- The specimen shape effect on compressive strength was found affected by the aggregate type used in the concrete mix. 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.

- Neither the aggregate size nor the aggregate unit weight had influenced the effect of specimen shape on the concrete compressive strength.
- Increasing the concrete target strength had decreased the effect of specimen shape on compressive strength. Normal strength concrete was found affected more by the specimen shape than the high strength concrete.
- Aggregate type has a significant effect on the concrete compressive strength which was affected by the aggregate strength. Both lightweight and recycled aggregate concrete mixes exhibited lower strength than natural concrete due to their weaker aggregate. On the contrary, Aggregate size and unit weight were found with a negligible effect on the concrete compressive strength.
- For all the concrete mixes in the study, the concrete compressive strength highly correlates to the aggregate strength.
- The modulus of elasticity was highly affected by the aggregate type and similarly to compressive strength; elastic modulus highly correlates with the aggregate strength.
- Higher strength concrete exhibited higher modulus of elasticity than normal strength concrete.
- Both flexural and split tensile strengths were less affected by the aggregate type than the compressive strength and elastic modulus.
- Modulus of elasticity, flexural strength, and split tensile strength testing results for most of the concrete mixes were found lower than those predicted by the ACI standard [79, 80].
- Pumice lightweight aggregate and recycled aggregate concrete mixes exhibited a higher flexural strength than those predicted by the ACI standard [79, 80]. This could be a result of an enhanced bond strength that resulted due to its small size and rough surface, leading to better interlocking with the cement paste, and the special presoaking procedure followed during mixing.

Additional work is needed to continue investigating and better understand the effect of the aggregate type on different mechanical properties of the concrete. Future research could:

- Evaluate concrete mixes utilizing other types of aggregate in order to collect additional data for comparative study.

- Study concrete mixes with different target strength to help create other strength curves for an aggregate strength/concrete strength relation chart.
- Try to compute transforming factors between compressive strength of mixes with different aggregate types.

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Appendices

The appendix consists of Appendix A which provides the concrete mix proportions of the six concrete mixes considered in this study, Appendix B which shows figures of the compressive strength failure modes of the different concrete mixes, and Appendix C which presents a summary of statistical analysis conducted at 7th, and 28th day.

Appendix A: Mixes Design and Experimental Figures

Table A.1 presents the concrete mix proportions and the typical volumetric fraction for the six concrete mixes with different aggregate types.

Table A.1: Typical volumetric fraction and concrete mix proportions for six different concrete mixes.

Constituent	Mix						
	Typical Volumetric Fraction	10 mm Natural (Kg/ft^3)	20 mm Natural (Kg/ft^3)	LWT1 (Kg/ft^3)	LWT2 (Kg/ft^3)	RA1 (Kg/ft^3)	RA2 (Kg/ft^3)
Cement	0.08	7.132	7.132	7.132	7.132	7.132	7.132
GGBS	0.06	4.840	4.840	4.840	4.840	4.840	4.840
SILICA	0.02	1.245	1.245	1.245	1.245	1.245	1.245
water	0.18	5.094	5.094	5.094	5.094	5.094	5.094
Coarse aggregate	0.33	24.285	24.285	11.862	12.609	22.137	23.070
Dune sand	0.165	12.142	12.142	12.142	12.142	12.142	12.142
Crushed sand	0.165	12.142	12.142	12.142	12.142	12.142	12.142

Appendix B: Failure Modes

This appendix presents figures for the compressive strength failure for the different concrete mixes and ready concrete mixes considered in this study. Figure B.1 shows the 10 mm natural concrete mix failure, Figure B.2 for 20 mm natural concrete mix, Figure B.3 for “LWT1” LAYTAG lightweight aggregate concrete mix, Figure B.4 for “LWT2” Pumice lightweight aggregate concrete mix, Figure B.5 for Bee’ah recycled aggregate concrete mix, and B.6 for Jabal Ali recycled aggregate concrete mix.

Followed by, Figure B.7 for C45 ready mix concrete, Figure B.8 for C60 ready mix concrete, and Figure B.9 for C80 ready mix concrete.

Figure B.1: Compressive strength failure for 10 mm Natural concrete mix

Figure B.2: Compressive strength failure for 20 mm Natural concrete mix

Figure B.3: Compressive strength failure for LWT1 concrete mix

Figure B.4: Compressive strength failure for LWT2 concrete mix

Figure B.5: Compressive strength failure for RA1 concrete mix

Figure B.6: Compressive strength failure for RA2 concrete mix

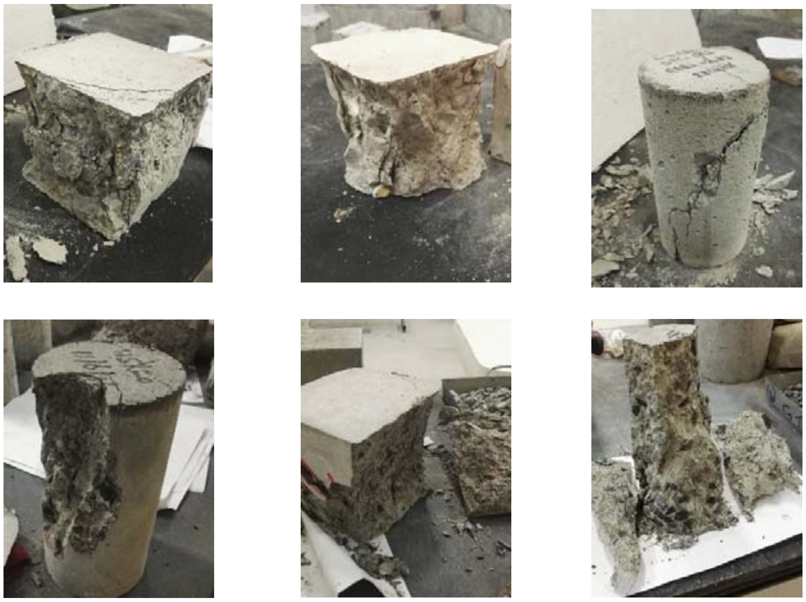

Figure B.7: Compressive strength failure for C45 ready-mix concrete

Figure B.8: Compressive strength failure for C60 ready-mix concrete

Figure B.9: Compressive strength failure for C80 ready-mix concrete

Appendix C: Statistical Analyses Calculations

This appendix presents a summary of statistical analyses results at 7th, and 28th day for specimen size effect on compressive strength, aggregate type effect on specimen shape factor, and aggregate type effect on concrete compressive strength detailed for the statistical analyses done in this study. Tables C.1-C.2 shows the results of specimen size effect statistical analysis at 7th, and 28th day, respectively. Tables C.3-C.4 shows the results of aggregate type effect on specimen shape factor statistical analysis at 7th, and 28th day, respectively.

Finally, Tables C.5-C.6 shows the results of aggregate type effect on cylinder specimen compressive strength statistical analysis at 7th, and 28th day, respectively. Tables C.7-C.8 shows the results of aggregate type effect on cube specimen compressive strength statistical analysis at 7th, and 28th day, respectively.

Table C.1: Summary of t pooled analysis results for Cy1/Cy2 and Cu1/Cu2 on 7th day

Test date	7th day					
Mixes	10 mm Nat.	20 mm Nat.	LWT1	LWT2	RA1	RA2
Cy1/Cy2	1.402	3.026	0.976	-2.422	0.862	0.556
Cu1/Cu2	-1.014	0.795	-1.082	-2.931	1.155	-1.252

Table C.2: Summary of t pooled analysis results for Cy1/Cy2 and Cu1/Cu2 at 28th day

Test date	28th day					
Mixes	10 mm Nat.	20 mm Nat.	LWT1	LWT2	RA1	RA2
Cy1/Cy2	2.443	0.740	3.718	0.486	0.445	0.168
Cu1/Cu2	-2.454	-0.416	-1.175	-3.472	-1.533	-1.423

Table C.3: Summary of t pooled analysis results for Cy/Cu for the six concrete mixes at 7th day.

	7th day					
Mixes	10 mm Nat.	20 mm Nat.	LWT1	LWT2	RA1	RA2
10 mm Nat.		2.335	3.305	3.599	1.153	0.431
20 mm Nat.			0.692	1.025	-1.977	-2.020
LWT1				0.403	-3.596	-3.033
LWT2					-4.012	-3.349
RA1						-0.665
RA2						

Table C.4: Summary of t pooled analysis results for Cy/Cu for the six concrete mixes at 28th day.

	28th day					
Mixes	10 mm Nat.	20 mm Nat.	LWT1	LWT2	RA1	RA2
10 mm Nat.		0.162	-6.828	-4.844	0.583	-2.276
20 mm Nat.			-8.938	-5.995	0.506	-2.455
LWT1				1.673	8.033	0.856
LWT2					5.752	0.192
RA1						-2.628
RA2						

Table C.5: Summary of t pooled analysis results for Cy of six different concrete mixes at 7th day.

	7th day					
Mixes	10 mm Nat.	20 mm Nat.	LWT1	LWT2	RA1	RA2
10mm Nat.		3.879	-0.431	-2.366	-0.440	-0.452
20mm Nat.			-4.915	-6.581	-4.701	-3.250
LWT1				-3.316	-0.059	-0.244
LWT2					2.586	0.836
RA1						-0.211
RA2						

Table C.6: Summary of t pooled analysis results for Cy of six different concrete mixes at 28th day.

	28th day					
Mixes	10 mm Nat.	20 mm Nat.	LWT1	LWT2	RA1	RA2
10 mm Nat.		0.964	-4.391	-5.134	-3.549	-1.326
20 mm Nat.			-5.264	-6.144	-4.670	-1.944
LWT1				-0.052	1.824	1.716
LWT2					2.276	1.862
RA1						0.676
RA2						

Table C.7: Summary of t pooled analysis results for Cu of six different concrete mixes at 7th day.

	7th day					
Mixes	10 mm Nat.	20 mm Nat.	LWT1	LWT2	RA1	RA2
10 mm Nat.		6.577	-3.904	-7.162	-2.637	-1.055
20 mm Nat.			-7.301	-10.487	-7.282	-3.378
LWT1				-1.944	1.919	1.106
LWT2					4.509	2.463
RA1						-0.018
RA2						

Table C.8: Summary of t pooled analysis results for Cu of six different concrete mixes at 28th day.

	28th day					
Mixes	10 mm Nat.	20 mm Nat.	LWT1	LWT2	RA1	RA2
10 mm Nat.		2.554	-2.092	-3.375	-3.360	0.047
20 mm Nat.			-4.104	-5.635	-5.397	-2.295
LWT1				-0.629	-0.945	1.986
LWT2					-0.447	3.077
RA1						3.136
RA2						

Vita

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