Effects of Maximum Size of Brick Coarse Aggregate on Fresh and Hardened Properties of Concrete

by

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Recommendation of the Board of Examiners

The thesis titled "**Effects of Maximum Size of Brick Coarse Aggregate on Fresh and Hardened Properties of Concrete**" submitted by Aziz Hasan Mahmood, Student ID 125608 of Academic Year 2012-2013 has been found as satisfactory and accepted as partial fulfillment of the requirement for the degree of Master of Science in Civil Engineering.

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Dedication

I would like to dedicate this thesis to my parents, my grandparents, my wife, and all my teachers who brought me up to this moment.

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Abstract

Investigation was carried out to study the effects of maximum aggregate size (MAS) of brick coarse aggregate (12.5 mm, 19.0 mm, 25.0 mm, 37.5 mm, and 50.0 mm) on fresh and hardened properties of concrete. For investigation, first class bricks were collected and broken into pieces to make coarse aggregate according to the gradation requirements of ASTM C 33. The aggregates were tested for specific gravity, absorption capacity, unit weight, and abrasion resistance. Cylindrical concrete specimens of diameter 100 mm and length 200 mm were made for MAS of 12.5 mm, 19.0 mm, 25.0 mm, and 37.5 mm with varying sand to aggregate volume ratio (s/a) (0.40 and 0.45), W/C ratio (0.45, 0.50, and 0.55), and cement content (375 kg/m^3 and 400 kg/m^3). For MAS of 50.0 mm, cylindrical concrete specimens of diameter 150 mm and length 300 mm were made with varying s/a ratio (0.40 and 0.45), cement content (375 kg/m^3 and 400 kg/m^3), and W/C ratio of 0.45. A total of 52 different cases were considered and a total of 552 concrete specimens were made for testing. The specimens were tested for splitting tensile strength at the age of 28 days, and compressive strength, stress-strain curve, and Young's modulus at the age of 7 days, 28 days, and 90 days. Ultrasonic Pulse Velocity (UPV) through the specimens was measured using Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT).The rebound number on the specimen surface was also measured using a Schmidt hammer.

Results have revealed that for a higher cement content, smaller sized brick coarse aggregate (12.5 mm) gives higher compressive strength, splitting tensile strength, and Young’s modulus of concrete. But for a lower cement content, and lower W/C ratio, these properties tend to increase with an increase in maximum size of aggregate up to 37.5 mm. The compressive strength of concrete increases with an increase in s/a ratio from 0.40 to 0.45. Moreover, the UPV is higher for concrete made with larger MAS. Based on the experimental results, relationships between compressive strength and Young's modulus, compressive strength and tensile strength, compressive strength and UPV, Young’s modulus and UPV, compressive strength and rebound number are proposed for different MAS of brick aggregate.

CHAPTER 1: INTRODUCTION

1.1 General

Coarse aggregate plays an important role in concrete as it typically occupies over half of the volume of concrete (Meddah, 2010), and it is likely that changes in coarse aggregate properties can affect the fresh and hardened properties of concrete. The mechanical properties of coarse aggregate are often considered to impart strength to concrete. Moreover, physical properties of coarse aggregate like the maximum aggregate size (MAS), surface texture, shape, gradation etc. also influence concrete properties. To predict the behavior of concrete under general loading requires an understanding of the effects of these physical properties of aggregate as well. The understanding of the effects of maximum aggregate size (MAS) on concrete properties can lead to important findings in the research field of Concrete Technology. This understanding can only be gained through extensive testing and observation.

In Bangladesh, the most commonly used coarse aggregate is brick aggregate which is made by crushing bricks into brick chips. Bricks are often broken into pieces without considering the MAS that may influence the properties of concrete. Though coarse aggregate is used to occupy volume in concrete, use of larger size aggregate can reduce the cement content in concrete, which is largely responsible for shrinkage and creep (Ioannides and Jeff, 2006). On the other hand, larger size coarse aggregates lower the water demand resulting a decrease in the water/cement ratio (W/C), which gives strength to concrete (Neville, 2011). This is because as aggregate size increases, the surface area to be wetted decreases. Though several studies with contradictory conclusions have been conducted to find the optimum MAS of coarse aggregate to make concrete, no such study has been done on brick chips as coarse aggregate.

In light of the above discussion, it is expected that a study that investigates the effects of maximum aggregate size (MAS) of brick coarse aggregate on fresh and hardened properties of concrete is necessary. Thus, this study has been planned to investigate the effects of MAS of brick coarse aggregate on fresh and hardened properties of concrete. Another proposal of this study is to study the effects of sand to aggregate volume ratio and cement content on properties of concrete. With this view, a research project was undertaken in the Department of Civil and Environmental Engineering (CEE) of Islamic University of Technology (IUT), under the supervision of Prof. Dr. Md. Tarek Uddin, to study the variation of the fresh properties (e.g. workability), as well as hardened properties (e.g. compressive strength, tensile strength, and Young's Modulus) of concrete with different MAS of brick aggregate. This investigation also adopted means to study some non-destructive test (NDT) methods, such as, determining Ultrasonic Pulse Velocity (UPV) through concrete specimen and determining rebound number using Schmidt hammer and tried to correlate the results from NDT with concrete strength. This investigation also focused on understanding the failure pattern of concrete made with different MAS, sand to aggregate volume ratio (s/a), cement content, and W/C ratio.

1.2 Background

Thorough investigation on the effect of MAS of coarse aggregate on fresh and hardened properties of low-strength, high strength and traditional concrete were done by researchers; and their findings indicate that it is important that we know how MAS influences the structural and durability performances of concrete. These researches mostly used stone, granite, and basalt aggregates (Aitcin and Mehta, 1990; Bloem and Gaynor, 1963; Cetin and Carrasquillo, 1998; Ezeldin and Aitcin, 1991; Giaccio et al, 1992). However, in Bangladesh, brick chips aggregate is the most widely used coarse aggregate in construction (Mohammed, 2014). But proper investigation on the effects of MAS of brick aggregate on properties of concrete is still limited. Construction sites are often found to use coarse aggregates without proper gradation, and thus the concrete strength often can't be predicted, which drives design engineers to go for over-design.

Moreover, in Bangladesh, the most widely used maximum size of coarse aggregate in construction is often termed as 20 mm down, i.e., the MAS of aggregate is 20.0 mm. But, literature review suggests, use of smaller or larger maximum sizes can give better strength to structural concrete (Cetin and Carrasquillo, 1998). Therefore, this study has been planned to find the effect of maximum size of brick coarse aggregate on properties of concrete.

1.3 Objectives of the Study

The objectives of this study are as follows:

1. To understand the variation of fresh and hardened properties of concrete with the variation of maximum size of coarse aggregate.
2. To understand the effects of variation of s/a ratio and cement content on properties of concrete.
3. To study the effects of maximum aggregate size on ultrasonic pulse velocity through concrete.
4. To understand the relationships between non-destructive and destructive tests to evaluate concrete properties.

1.4 Methodology

This study investigated the effects of MAS of brick aggregate on fresh and hardened properties of concrete. For investigation, first class bricks were collected from local market and broken manually into maximum sizes of 50.0 mm, 37.5 mm, 25.0 mm, 19.0 mm, and 12.5 mm. To comply with the grading requirements specified by ASTM C 33, brick aggregate of sizes 9.5 mm and 4.75 mm were also sieved. The aggregates were tested for specific gravity, absorption capacity, abrasion resistance, and unit weight. The mixture proportion was prepared with varying W/C ratios of 0.45, 0.50, and 0.55; s/a ratio of 0.40 and 0.45; and cement contents of 375 kg/m^3 and 400 kg/m^3.

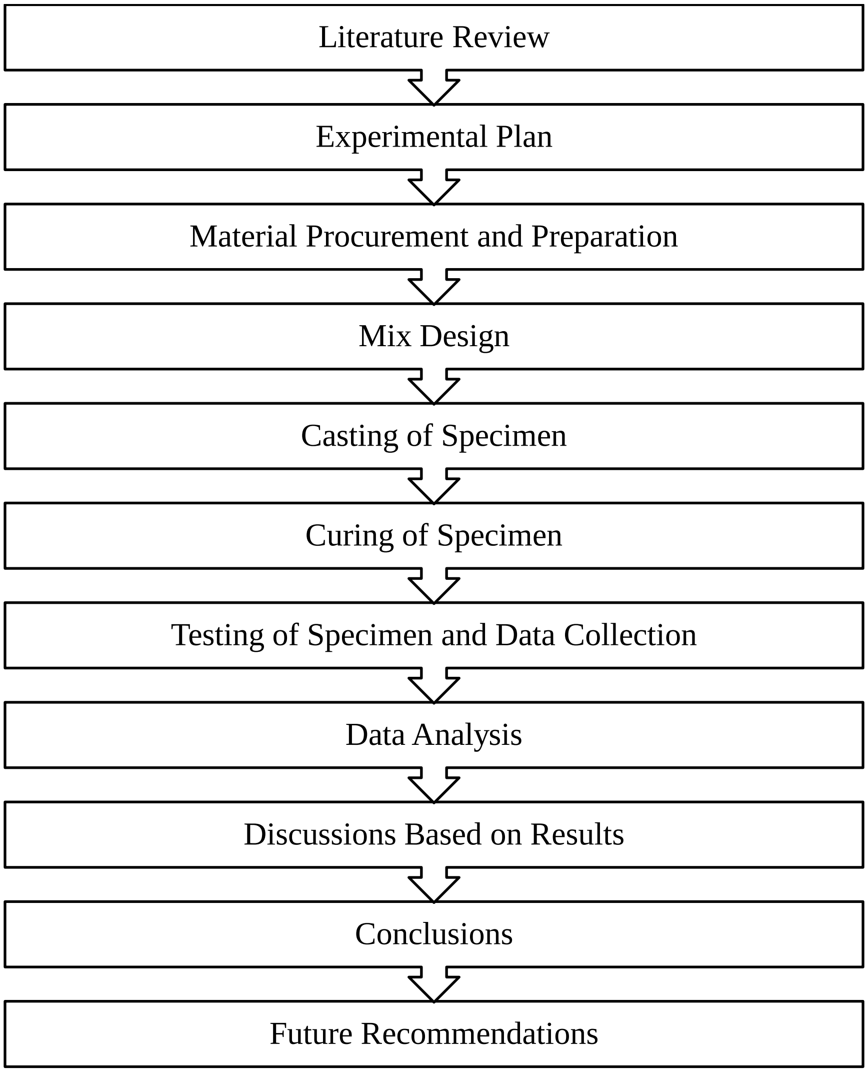
528 cylindrical concrete specimens of 100 mm diameter and 200 mm height were made for MAS of 12.5 mm, 19.0 mm, 25.0 mm, and 37.5 mm. For 50.0 mm MAS, 24

cylindrical specimens of diameter 150 mm and height 300 mm were made according to ASTM C31.

Prior to compressive strength test, UPV was measured on unloaded wet specimens by using Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT) according to ASTM C 597 (2003). UPV was obtained by measuring the time, in microseconds (μs), that an ultrasonic pulse took to travel between the transmitter and the receiver across the length of each concrete specimen, using the PUNDIT. The specimen length was divided by the time recorded to calculate the pulse velocity. The transducers used were 75 kHz (the range specified by ASTM C 597 is 20 to 100 kHz). A thin couplant (solid vaseline) was used in between the transducers and concrete to ensure good contact between the specimen surface and the receiver.

The rebound number on specimen surfaces was also measured according to ASTM C 805 (2003) using a Schmidt hammer. Careful selection and preparation of the concrete surface to be tested was ensured for the test and a fixed amount of energy was applied by pushing the hammer against the test surface. The plunger was allowed to strike perpendicularly to the surface, as the angle of inclination of the hammer affects the results. After impact, the rebound number was recorded by taking at least 10 readings from each tested area.

1.5 Research Flow Diagram



1.6 Layout of the Thesis

Chapter 1 thoroughly discusses the background and objectives of this study. **Chapter 2** discusses aggregate as a constituent of concrete and the influence of maximum size of coarse aggregate on concrete properties based on literature review. It also discusses non-destructive tests of concrete based on findings of recent researches. **Chapter 3** presents information on the development of methods used to design a concrete mixture, as well as the cases investigated in this study. In addition, it outlines the actual mix designs studied. It also includes background information on the key components of concrete and their respective properties. The chapter concludes with information pertaining to the test methods and procedures followed in this study. **Chapter 4** presents the results of the tests performed on specimens in both fresh and hardened state. The test results from the experimentation program in the fresh state and hardened state are discussed separately. The workability, compressive strength, splitting tensile strength, and Young's modulus of specimens are analyzed and image analysis of split specimens is also discussed. In addition, several relationships between concrete properties are also presented in this chapter. **Chapter 5** presents a summary of the conclusions drawn from the results of this research and also suggests recommendations for future works.

CHAPTER 2: LITERATURE REVIEW

2.1 General

This chapter discusses concrete in general as well as the constituents of concrete. It emphasizes on coarse aggregate as a major constituent of concrete, and it’s importance in ensuring concrete strength and durability. This chapter also discusses the effects of different maximum sizes of coarse aggregate on properties of concrete based on literature review. Literature review on some non-destructive tests of concrete are also presented in this chapter.

2.2 Aggregate in Concrete as a Constituent

Concrete is a composite material which is composed of coarse and fine granular materials called aggregates or filler embedded together in the form of a matrix with the help of the cement or binding material that fills the space between the aggregates particles and glues them together. Other materials like fly ash or ground granulated blast furnace slag may also be used as binding material. Coarse aggregates are usually obtained from natural rocks, either crushed stones or natural gravels, and fine aggregates are usually river sand. Water is added in the mix to initiate the binding process, as cement is a hydraulic material which gives strength once it starts reacting with this mixing water.

As at least 75% of the volume of concrete is occupied by aggregate, it’s quality and different physical and mechanical properties are of paramount importance. Not only may the aggregate limit the strength of concrete, but the properties of aggregate greatly affect the durability and structural performance of concrete. Aggregate was originally viewed as an inert material to fill up the voids in concrete, and for economic reasons. However, it is possible for aggregates to influence the performance of concrete as a whole (Neville, 2011).

2.3 General Classification of Aggregate

Aggregates can be classified based on their origin. Aggregates can come from natural sources, or may be derived from industrial by-products. Natural aggregates may be basalt, granite, limestone, gabbros, quartzite, schist, shingles etc.; whereas, industrial aggregates can be made from bricks, iron slag, plastic, or recycled concrete as aggregate.

But, aggregates are usually classified based on their particle size. Aggregates passing through ASTM #4 sieve (4.75 mm) are termed as fine aggregate, while those retained on the sieve are termed as coarse aggregate.

2.4 Strength of Aggregate

The compressive strength of concrete clearly depends on the strength of it's major constituent – aggregate. Since it is difficult to test the crushing strength of individual aggregate particle, the required information has to be obtained from indirect test like crushing value of bulk aggregate, or resistance to abrasion. Inadequate strength of aggregate represents a limiting case because the physical and mechanical properties of aggregate have some influence on the strength of concrete. Walker and Bloem (1956) compared concretes made with different aggregates and observed that the influence of aggregate on the strength of concrete is qualitatively the same whatever the mix proportion, and is the same regardless of whether the concrete is tested in compression or tension.

In general, the strength and Young's modulus of aggregate depend on it's composition, texture, and structure. Though, the Young's modulus of aggregate isn't often determined, it is, however, not unimportant, because the Young's modulus of concrete is generally higher for aggregates with higher Young's modulus. It affects the magnitude of creep and shrinkage of concrete as well (Neville, 2011). On the other hand, aggregate of moderate or low strength and Young's modulus can be valuable in preserving the integrity of concrete.

2.5 Types of Aggregate

Giaccio et al. (1992) studied the effects of coarse aggregate type (basalt, granite and limestone) on the mechanical properties of high-strength concrete. Compressive and flexural strength, modulus of elasticity, and stress-strain behavior were analyzed for concrete, mortar, and rock. They found that weaker aggregates, such as limestone, reduce compressive strengths significantly, since the concrete strength is limited by the aggregate strength. However, aggregate type did not affect flexural strength. Comparing fractured surfaces for the concretes show that nearly all of the exposed coarse aggregate particles are fractured in the limestone mixes. However, cracks form primarily at the matrix-aggregate interface, and only a few aggregate particles are fractured in the basalt mix. The highest modulus of elasticity was achieved in the basalt mix, followed by limestone and granite. The basalt mix also showed the highest compressive strength, followed by granite and limestone. The granite mix had the best elastic compatibility between the matrix and aggregate, but the granite had significantly lower tensile strength than the basalt.

Giaccio et al. (1993) compared fracture energies for concretes with a wide range of compressive strengths. Strength levels from 22 MPa to 100 MPa, aggregate type (basalt, limestone and gravel), aggregate size (8 mm, 16 mm and 32 mm), and aggregate surface roughness were included as variables in the study. Conclusions were drawn that concretes with weaker aggregates, such as limestone, yield lower compressive strengths than concrete with stronger coarse aggregate.

In Bangladesh, brick chips, crushed stone, shingles, jhama bricks are commonly used as coarse aggregate in construction. Brick chips is the most widely used coarse aggregate (Mohammed, 2014) and thus extensive study on the use of brick chips as coarse aggregate in concrete is necessary. Mohammed et al (2011) conducted extensive research on brick aggregate concrete, and concluded that, with similar abrasion value, brick aggregate concrete gives higher strength compared to the same with stone aggregate concrete. Moreover, concrete strength from 21 MPa to 25 MPa can be obtained using recycled coarse aggregate. Mohammed et al (2014) investigated recycled brick aggregate concrete and found that it is possible to make concrete of compressive strength 24.7 MPa. However, in order to have a better understanding of the influence of physical and mechanical properties of brick coarse aggregate on properties of concrete, further investigations are necessary.

2.6 Maximum Aggregate Size

The effect of maximum aggregate size (MAS) on the fresh and hardened properties of concrete has been a major concern for researcher for quite a long time. The grading or size distribution of aggregate is an important characteristic because it determines the paste requirement for workable concrete (Tumidajski and Gong, 2006). The required amount of the concrete paste is dependent upon the amount of void space that must be filled and the total surface area that must be covered. When the particles are of uniform size the spacing is the greatest but when a range of sizes is used the void spaces are filled, the less workable the concrete becomes, and therefore a compromise between workability and economy is necessary.

The size of aggregate used in concrete ranges from tens of millimeters down to particles less than one-tenth of a millimeter in cross-section. The maximum size used may actually vary, but in any mix, particles of different sizes are incorporated as specified by ASTM C 33.

Oliveira et al. (2006), Tumidajski and Gong (2006) concluded that aggregates strongly influence concrete's fresh and hardened properties, mix proportions, and economy. Grading limits and MAS are specified since they affect the amount of aggregate used, cement and water requirements, workability, pumpability, and durability of concrete. Moreover, MAS has a significant influence on the fracture properties of the concrete matrix as well. An optimum size of aggregate gives a workable and dense concrete mix as well as improves the performance of concrete. The increase in fracture toughness with increasing aggregate size is the result of the increased resistance to propagating crack.

There is much controversy concerning the effects of coarse aggregate size on concrete. Some research (Strange and Bryant 1979, Nallathambi et al. 1984) has shown that there is an increase in strength and fracture toughness with an increase in aggregate size. However, Gettu and Shah (1994) have stated that, in some high-strength concretes where the coarse aggregates rupture during fracture, size is not expected to influence the strength and fracture parameters. Tests by Zhou, Barr, and Lydon (1995) show that compressive strength increases with an increase in coarse aggregate size. However, most other studies disagree.

Walker and Bloem (1960) studied the effects of coarse aggregate size on the properties of normal-strength concrete. Their work demonstrates that an increase in aggregate size from 10 mm to 64 mm results in a decrease in the compressive strength of concrete, by as much as 10 percent; however, aggregate size seems to have negligible effects on flexural strength. The study also shows that the flexural-to-compressive strength ratio remains at approximately 12 percent for concrete with compressive strengths between 35 MPa and 46 MPa.

Bloem and Gaynor (1963) studied the effects of size and other coarse aggregate properties on the water requirements and strength of concrete. Their results confirm that increasing the maximum aggregate size reduces the total surface area of the aggregate, thus reducing the mixing water requirements; however, even with the reduction in water, a larger size aggregate still produces lower compressive strengths in concrete compared to concretes containing smaller aggregate. Generally, in lower strength concretes, the reduction in mixing water is sufficient to offset the detrimental effects of aggregate size. However, in high-strength concretes, the effect of size dominates, and the smaller sizes produce higher strengths.

Cordon and Gillespie (1963) also reported changes in concrete strength for mixes made with various W/C ratios and aggregate sizes. They found that, at W/C ratios from 0.40 to 0.70, an increase in MAS from 19 mm to 38 mm decreases the compressive strength by about 30 percent as shown in **Fig. 2.1**. They also concluded that, in normal-strength concrete, failure typically occurs at the matrix-aggregate interface and that the stresses at the interface which cause failure can be reduced by increasing the surface area of the aggregate (decreasing the aggregate size). If the strength of the concrete is sufficiently high, such as with high-strength concrete, failure of the specimen is usually accompanied by the fracture of aggregate particles; therefore, in high-strength concrete, compressive strength depends on aggregate strength, not necessarily aggregate size.

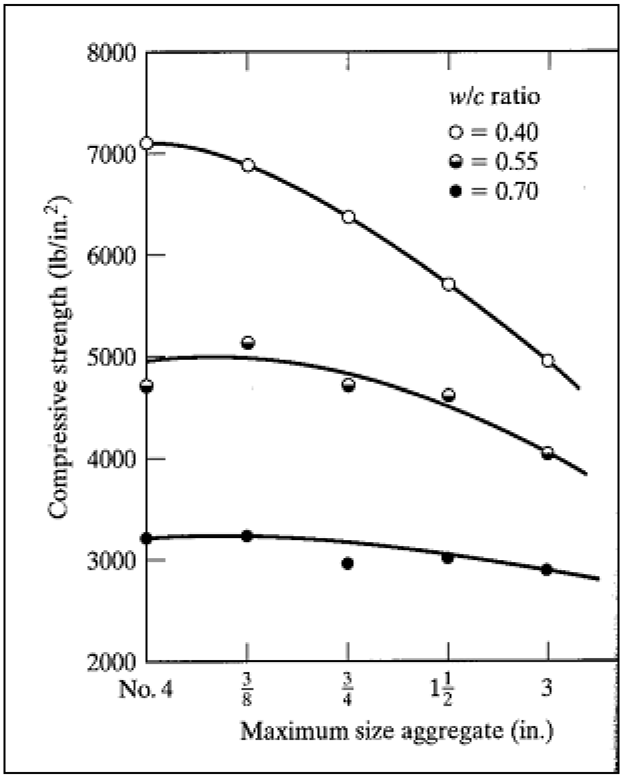


Fig. 2.1. Effect of Maximum Size of Aggregate on Compressive Strength (Cordon and Gillespie, 1963)

The effects of admixture dosage, mix proportions, and coarse aggregate size on concretes with strengths in excess of 69 MPa were discussed by Cook (1989). The two maximum size aggregates studied were a 10 mm and 25 mm limestone. The smaller sized coarse aggregate produced higher compressive strengths than the larger sized coarse aggregate. Cook (1989) observed that the difference in compressive strengths due to aggregate size is increasingly larger with a decreasing water-to-cement ratio and increasing test age. The smaller sized coarse aggregate also increases the flexural strength of the concrete. The flexural-to-compressive strength ratio remains constant at approximately 12 percent. The test specimens exhibited increases in the modulus of elasticity of approximately 20 percent between 7 to 90 days for the 10 mm limestone, and 13 percent for the 25 mm limestone.

In fact, it is generally agreed that, although larger coarse aggregates can be used to make high-strength concrete, it is easier to do so with coarse aggregates below 12.5 mm (ACI 363-95). In a study of the effects of coarse aggregate type and size on the compressive strength of normal and high-strength concrete, Ezeldin and Aitcin (1991) concluded that normal-strength concretes are not greatly affected by the type or size of coarse aggregates. However, for high-strength concretes, coarse aggregate type and size affect the strength and failure mode of concrete in compression. For high-strength concretes with weaker coarse aggregates, cracks pass through the aggregates, since the matrix-aggregate bond is stronger than the aggregate itself, resulting in a transgranular type of failure. For high-strength concrete with stronger aggregates, both matrix-aggregate debonding and transgranular failure occur. They found that cracks pass through the weaker portions of aggregate particles and then propagate into the cement paste. They also observed that the coarse aggregate types and sizes used in the study did not significantly affect the flexural strength of high-strength concrete.

Vu et al. (2011) conducted experimental investigation that concerned the effect of coarse aggregate size and cement paste volume on concrete behavior under high triaxial compression loading. Findings of the study suggested that the concrete strength slightly increases as the coarse aggregate size increases as observed under unconfined compression. Moreover, the coarse aggregate size has a significant influence on concrete strain limit-state at high confinement, the higher the coarse aggregate size, the lower is the mean stress level corresponding to concrete strain limit-state. At very high confinement levels and at very high deviatoric stress levels, the concrete axial tangent stiffness increases as the coarse aggregate size is reduced.

In light of the controversy, this study is aimed at improving the understanding of the role that brick coarse aggregate plays in the fresh and hardened properties of concrete. Furthermore, research focusing on the effect maximum size of brick coarse aggregate, is still limited and its effect is not yet well established. The present study investigates the influence of maximum size of brick coarse aggregate, which is the most commonly used aggregate in Bangladesh, on the fresh and hardened properties of concrete.

2.7 Cement Content

Cement, the binder of concrete components, has been a major focus of researchers for quite long, as cement content is perceived to control concrete strength. The term "cement content" refers to the mass of cement per m^3 of concrete. Literature suggests that with an increase in cement content, the strength of concrete increases. But use of excess cement can cause shrinkage of concrete and result in subsequent decrease in the strength of concrete (Neville, 2011). Based on this perception, a minimum cement content is often specified that may exceed the amount needed to achieve the desired strength and durability. This excessive amount should be minimized to prevent its negative impact on costs and environment because:

- cement is the most expensive component in concrete
- cement contributes about 90% of the CO_2 burden of a concrete mixture
- cement production emits approximately 5% of global carbon dioxide (CO_2) and 5% of global energy consumption (Yurdakul, 2010)

Previous studies (Wasserman et al., 2009; Popovics, 1990) suggest that high cement content in a mixture does not contribute to greater strength than the required design strength. On the contrary, high cement content causes the concrete to become sticky as well as have shrinkage and cracking problems. Therefore, cement content should be balanced to achieve performance while minimizing risk of these problems. Despite the published studies and documentation, there continues to be a misconception that more cement in a mix design means a better performing mix.

Literature suggests that cement content affects both fresh and hardened properties of concrete. For a given water content, decreasing the cement content increases stiffness of concrete with having poor workability (Lamond and Pielert, 2006; Mehta and

Monteiro, 1993). Concrete with high cement content shows high cohesiveness and becomes sticky (Lamond and Pielert 2006; Kosmatka et al. 2002; Mehta and Monteiro 1993). Thus appropriate cement content should be used to achieve the desired workability.

As far as the effect of cement content on hardened properties of concrete is considered, strength is considered to be a function of W/C ratio and independent of cement content for a given W/C ratio, therefore increasing cement content does not affect strength (Wassermann et al., 2009; Dhir et al., 2004; Schulze, 1999). Furthermore, according to Abrams rule, paste content does not affect strength although it is affected by the paste quality (Wassermann et al., 2009). On the other hand, more cement needs to be added to meet the strength specification when the minimum cement content is not sufficient (American Society of Concrete Contractors, 2005). Furthermore, achieving high strength by increasing the cement content is reportedly difficult when cement content is below 350 kg /m^3 (Rixom and Mailvaganam, 1999). These findings show a direct relationship between strength and cement content as opposed to the Abrams rule.

2.8 Sand to Aggregate Volume Ratio

The technical literature gives quite contradictory data on the effect of sand to aggregate volume ratio (s/a) on strength of concrete. Su et al. (2002) stated that, the s/a ratio is an important parameter and the rheological properties such as, the compressive and tensile strength of concrete increase with an increase in the s/a ratio. Moreover, Su et al. (2002) and Yang and Huang (1998) both concluded that the Young's modulus of concrete is not significantly affected by the change in s/a ratio.

However, Sizov (1997) stated that, an excessive amount of sand compared with the optimal causes a high consumption of cement, and its too low content leads to segregation and bleeding of concrete. Thus, it is important to study the strength of concrete for various s/a ratios and find the optimum s/a ratio for brick aggregate concrete.

2.9 Water to Cement Ratio

In usual engineering practice, the strength of concrete is assumed to depend primarily on two factors – the W/C ratio and the degree of compaction. The influence of W/C ratio on the strength of concrete has been a topic of study for researchers for quite long. In 1919, Duff Abrams proposed that when concrete is full compacted, it’s strength can be taken to be inversely proportional to the W/C ratio.

$$f_c = \frac{K_1}{K_2^{w/c}} \tag{2.1}$$

Where, *w*/*c* represents the W/C ratio of the concrete mix, and K_1 and K_2 are empirical constants.

From time to time, the W/C ratio rule of equation 2.1 has been criticized for not being sufficiently fundamental. Nevertheless, in practice, the W/C ratio is the largest single factor in the strength of concrete (Neville, 2011). Researchers have agreed that, with increase in the W/C ratio, the workability of fresh concrete increases, but the strength of hardened concrete is reduced. The nature of the curve representing W/C ratio as the abscissa and strength as the ordinate is still not beyond controversy. Neville (1959) suggested that the relationship between the strength and W/C ratio is approximately linear in the range of W/C ratio between 0.20 and 0.43. This linear relationship has also been confirmed by later research by Alexander and Ivanusec (1982) and by Kakizaki et al. (1992). But the relations discussed here may not be exactly precise. Hummel (1959) suggested that, as an approximation, the relation between logarithm of strength and the natural value of the W/C ratio can be assumed to be linear.

Mindess et al. (2003) proposed that the strength of concrete decreases with an increase in W/C ratio and proposed a relationship between compressive strength and W/C ratio as shown in **Fig. 2.2**. Similar conclusion was also drawn by Wassermann et al. (2009), Dhir et al. (2004), Kosmatka et al. (2002), Schulze (1999), Mehta and Monteiro

(1993). Popovics (1990) suggested that to increase the concrete strength, it is more efficient and economic to reduce the water content than to use more cement.

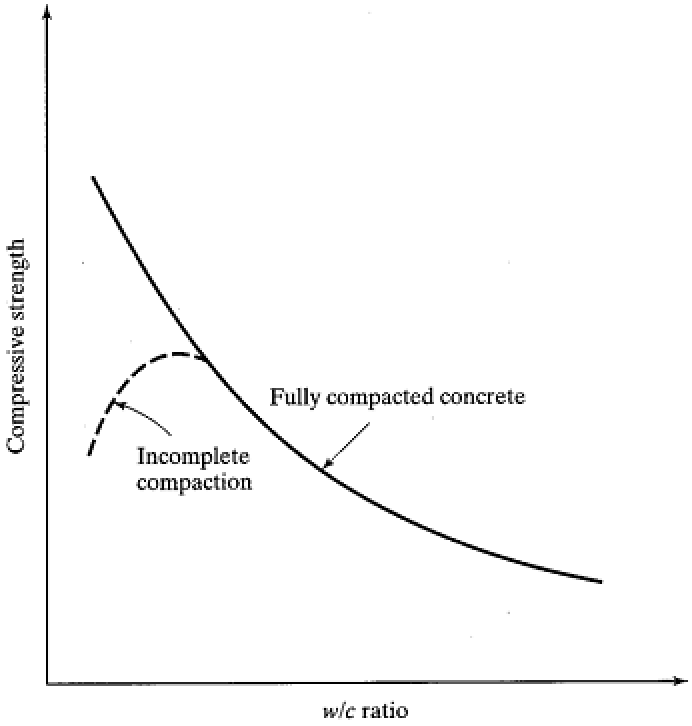


Fig. 2.2. Relationship between compressive strength and W/C ratio (Mindess et al., 2003)

2.10 Ultrasonic Pulse Velocity

Assessments of concrete structures using non-destructive techniques have interested engineers all over the world; thus many non-destructive techniques have been adopted to evaluate concrete performance (Bungey, 1989). Several non-destructive techniques are available for concrete evaluation. Some of these techniques include radar, pulse velocity, acoustic emission, radiography, infrared thermography, and many others (Limaye, 1990). One of the earliest non-destructive techniques used to evaluate concrete strength is the ultrasonic pulse velocity (UPV) technique. In recent years, ultrasonic techniques have become popular within the civil engineering industry for a wide range of applications including the evaluation of concrete structures and pavements. A reviewing of the literature indicates that ultrasonic waves are used mainly to predict concrete strength. However, this method can also be used to detect the internal defects of concrete such as cracks, delamination, and/or honeycombs (Malhotra and Carino, 1991).

Ultrasonic waves are mechanical waves with frequencies in excess of 20 kHz (ASTM C 597). These waves behave essentially the same as audible sound waves. Since ultrasonic waves do not travel through air or vacuum, couplants such as grease are needed to fill the voids between transducers and concrete surface in order to transmit or receive the waves (Galan 1990).

Scattering of ultrasonic waves into concrete is due to the heterogeneity of the concrete structure. The transition zones between aggregate and hydraulic cement paste tend to reflect part of ultrasonic waves. In addition, the mode of conversion at aggregate boundaries tends to occur because of slight differences in acoustic velocities between the aggregate and hydraulic cement paste. Gaydeck et al. (1992) studied the attenuation and propagation of ultrasonic waves in concrete using frequencies in the range of 25–250 kHz. The results of the study indicated that attenuation characteristics of ultrasonic waves could give an idea about aggregate size distribution if careful analysis is performed.

Wave velocity and energy were used in another study to evaluate concrete. The results indicated that wave velocity has better capability to detect differences between Portland Cement (PC) concretes than that of wave energy (Al-Akhras, 1995). Facaoaru (1969) reported that UPV through concrete is directly proportion to concrete strength and age.

Abo-Qudais (2005) studied UPV through concrete made with limestone aggregate of MAS 4.75 mm, 12.5 mm, 19.3 mm, and 25.0 mm. Abo-Qudais (2005) concluded that, with an increase in MAS, the UPV decreases. However, the magnitude of the UPV depends on the W/C ratio and as the W/C ratio increases, the influence of aggregate became more significant. He also concluded that, larger the aggregate size the higher will be the local water–cement ratio in the transition zone, consequently, the higher capillary voids in the transition zone, leading to reduce the ultrasound velocity into the concrete. On the contrary, Solís-Carcaño and Monero (2008) also conducted non-destructive evaluation of limestone aggregate concrete and concluded that with an increase in the transition zone, the path for ultrasonic wave becomes more tortuous and leads to lower UPV through concrete made with smaller sized aggregates. However, these findings are yet to be justified for brick coarse aggregates.

Mathematical models having the capability to predict UPV in concrete were also developed based on experimental studies (Lin et al., 2003). These models indicated that the changes in the ratio of fine aggregate volume to the total aggregate have little influence on pulse velocity. Also, pulse velocity of concrete decreased by increasing the volume of cement paste, especially for concrete with high water–cement ratio. Relationships between UPV and strength of brick aggregate concrete are yet to be established.

Moreover, the relationship between ultrasonic wave velocities measured using direct and indirect methods was evaluated by Yaman et al. (2001). The results indicated that the direct and indirect methods can be used interchangeably in evaluating the properties of the concrete.

From literature review, it is understood that the velocity of ultrasonic pulses traveling in a solid material depends on the density and elastic properties of that material. Thus MAS, aggregate gradation, W/C ratio, s/a ratio, cement content, and curing time are expected to have significant effects on the ultrasonic measurements. Many studies which evaluate concrete properties using ultrasonic techniques have been performed. Most of these studies either did not consider or failed in evaluating the effect of concrete mix parameters like MAS, s/a ratio, cement content, W/C ratio on the propagation of ultrasonic waves in the concrete. More importantly, no study on the non-destructive evaluation of MAS of brick coarse aggregate was found.

2.11 Schmidt Hammer

The Schmidt hammer (also known as the rebound or impact hammer) test is considered as a non-destructive method used for evaluation of concrete quality in terms of surface rebound hardness that is related to the uniaxial compressive strength. Being quick, cheap and non-destructive, the Schmidt hammer test is an important index test for concrete material characterization. Therefore, the methodology of the Schmidt hammer test is expected to ensure reliable data acquisition and analysis on site or in the laboratory.

The Schmidt hammer test is classified as a hardness test and is based on the principle that the rebound of an elastic mass depends on the hardness of the surface against which the mass impinges. The energy absorbed by the concrete is related to its strength (ACI, 1994). Despite its apparent simplicity, the rebound hammer test involves complex problems of impact and the associated stress-wave propagation (Akashi and Amasaki, 1984). Although there is a unique relation between hardness and strength of concrete, experimental data relationships can be obtained from given specimens.

However, this relationship is dependent on the concrete surface effecting factors, such as degree of saturation, carbonation, temperature, surface preparation, and type of surface finish. The result is also affected by type of aggregate, mix proportions, hammer type and inclination. Areas exhibiting honey-combing, scaling, rough texture or high porosity must be avoided. Amasaki (1991) presented the effect of carbonation on rebound number. Grieb (1958) showed the effect of type of aggregates on rebound number and hence estimated strength. Moreover, MAS of concrete may influence the rebound number, and this study has been planned to evaluate the effect of MAS on rebound number as well.

It should also be noted that, Schmidt hammer rebound values obtained in non-horizontal impact directions are influenced by gravitational forces to varying degrees. In order to account for this effect, the non-horizontal rebound values must be normalized with reference to the horizontal direction. ASTM C 805 stipulates that the rebound values should be normalized using the correction curves provided by the manufacturer. The rebound number recorded in laboratory can be used to evaluate the concrete strength by using the correction curves.

CHAPTER 3: EXPERIMENTAL METHOD

3.1 Introduction

In this chapter, the experimental method of the study is summarized. It includes the mix proportion of concrete, cases investigated in the study, collection and preparation of materials, material properties, experimental setup, sample preparation, curing, and testing.

3.2 Concrete Mixture Proportion and Cases Studied

100 mm by 200 mm cylindrical concrete specimens were made with varying s/a ratio (0.40 and 0.45); W/C ratio (0.45, 0.50, and 0.55), and cement content (375 kg/m^3 and 400 kg/m^3) for MAS of 12.5 mm, 19.0 mm, 25 mm, and 37.5 mm. For MAS of 50.0 mm, 150 mm by 300 mm cylindrical concrete specimens were made with varying s/a ratio (0.40 and 0.45), cement content (375 kg/m^3 and 400 kg/m^3), and W/C ratio of 0.45. A total of 52 independent cases and 552 cylindrical specimens were investigated; the mixture proportions of all 52 cases are summarized in **Table 3.1**. The notations used for the cases are explained at the bottom of **Table 3.1**.

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Table 3.1. Mixture proportion of concrete

Maximum Aggregate Size (mm)	s/a	Cement content (kg/ m^3)	W/C	Case ID	Unit content (kg/m^3)			
					Cement	Sand	Aggregate	Water
12.5	0.40	375	0.45	A12.5SA0.40C375WC0.45	375	677	953	169
			0.50	A12.5SA0.40C375WC0.50	375	658	927	188
			0.55	A12.5SA0.40C375WC0.55	375	639	901	206
		400	0.45	A12.5SA0.40C400WC0.45	400	657	926	180
			0.50	A12.5SA0.40C400WC0.50	400	638	898	200
			0.55	A12.5SA0.40C400WC0.55	400	618	871	220
	0.45	375	0.45	A12.5SA0.45C375WC0.45	375	761	873	169
			0.50	A12.5SA0.45C375WC0.50	375	740	850	188
			0.55	A12.5SA0.45C375WC0.55	375	720	826	206
		400	0.45	A12.5SA0.45C400WC0.45	400	740	849	180
			0.50	A12.5SA0.45C400WC0.50	400	718	823	200
			0.55	A12.5SA0.45C400WC0.55	400	696	798	220
20	0.40	375	0.45	A19.0SA0.40C375WC0.45	375	677	953	169
			0.50	A19.0SA0.40C375WC0.50	375	658	927	188
			0.55	A19.0SA0.40C375WC0.55	375	639	901	206
		400	0.45	A19.0SA0.40C400WC0.45	400	657	926	180
			0.50	A19.0SA0.40C400WC0.50	400	638	898	200
			0.55	A19.0SA0.40C400WC0.55	400	618	871	220
	0.45	375	0.45	A19.0SA0.45C375WC0.45	375	761	873	169
			0.50	A19.0SA0.45C375WC0.50	375	740	850	188
			0.55	A19.0SA0.45C375WC0.55	375	720	826	206
		400	0.45	A19.0SA0.45C400WC0.45	400	740	849	180
			0.50	A19.0SA0.45C400WC0.50	400	718	823	200
			0.55	A19.0SA0.45C400WC0.55	400	696	798	220
25	0.40	375	0.45	A25.0SA0.40C375WC0.45	375	677	953	169
			0.50	A25.0SA0.40C375WC0.50	375	658	927	188
			0.55	A25.0SA0.40C375WC0.55	375	639	901	206
		400	0.45	A25.0SA0.40C400WC0.45	400	657	926	180
			0.50	A25.0SA0.40C400WC0.50	400	638	898	200
			0.55	A25.0SA0.40C400WC0.55	400	618	871	220
	0.45	375	0.45	A25.0SA0.45C375WC0.45	375	761	873	169
			0.50	A25.0SA0.45C375WC0.50	375	740	850	188
			0.55	A25.0SA0.45C375WC0.55	375	720	826	206
		400	0.45	A25.0SA0.45C400WC0.45	400	740	849	180
			0.50	A25.0SA0.45C400WC0.50	400	718	823	200
			0.55	A25.0SA0.45C400WC0.55	400	696	798	220
37.5	0.40	375	0.45	A37.5SA0.40C375WC0.45	375	677	953	169
			0.50	A37.5SA0.40C375WC0.50	375	658	927	188
			0.55	A37.5SA0.40C375WC0.55	375	639	901	206
		400	0.45	A37.5SA0.40C400WC0.45	400	657	926	180
			0.50	A37.5SA0.40C400WC0.50	400	638	898	200
			0.55	A37.5SA0.40C400WC0.55	400	618	871	220
	0.45	375	0.45	A37.5SA0.45C375WC0.45	375	761	873	169
			0.50	A37.5SA0.45C375WC0.50	375	740	850	188
			0.55	A37.5SA0.45C375WC0.55	375	720	826	206
		400	0.45	A37.5SA0.45C400WC0.45	400	740	849	180
			0.50	A37.5SA0.45C400WC0.50	400	718	823	200
			0.55	A37.5SA0.45C400WC0.45	400	696	798	220
50.0	0.40	375	0.45	A50.0SA0.40C375WC0.45	375	677	953	169
			0.45	A50.0SA0.40C400WC0.45	400	657	926	180
	0.45	400	0.45	A50.0SA0.45C375WC0.45	375	761	873	169
			0.45	A50.0SA0.45C400WC0.45	400	740	849	180
Total no of cases = 52								
Cylinder per case = 3 × 3 (compressive strength at 7 days , 28 days, and 90 days for 12.5 mm MAs, 19.0 mm MAS, 25.0 mm MAS, and 37.5 mm MAS) +2(tensile strength at 28 days) = 11 nos. 2 × 3 (compressive strength at 7 days and 28 days for 50.0 mm MAS) = 6 nos.								

Total no of cylinders = 11 × 48 (for 12.5 mm MAS, 19.0 mm MAS, 25.0 mm MAs, and 37.5 mm MAS) + 4 × 6 (for 50.0 mm MAS) = 552
A12.5SA0.40C375WC0.45 denotes maximum aggregate size of 12.5 mm, s/a ratio of 0.40, cement content of 375 kg/m^3, and W/C ratio of 0.45.

The mix proportion used in this study was done in weight basis and the unit contents of the ingredients of concrete were assumed to sum up to 1 m^3 of concrete and can be correlated by the following equation:

$$\frac{C}{G_c\gamma_w}+\frac{S}{G_s\gamma_w}+\frac{A}{G_A\gamma_w}+\frac{Air\ (\%)}{100}=1 \tag{3.1}$$

Where,

C = Unit content of cement (kg/m^3 of concrete)

S = Unit content of fine aggregate (kg/m^3 of concrete)

A = Unit content of coarse aggregate (kg/m^3 of concrete)

W = Unit content of water (kg/m^3 of concrete)

γ_w = Unit weight of water ((kg/m^3)

G_c= Specific gravity of cement

G_s = Specific gravity of fine aggregate (SSD)

G_A = Specific gravity of coarse aggregate (SSD)

G_w = Specific gravity of water

Air (%)= Percentage of air in concrete (assumed at 2% without air entraining agent)

3.3 Preparation of Materials

Before casting, the materials were prepared to satisfy the specifications of ASTM C 39 (2003). For each day of casting, the total number of cylinders to be made was calculated. Then on the basis of the mixture proportion shown in **Table 3.1**, and the material properties shown in **Table 3.4** and **Table 3.5**, the total amount of material required for each day of casting was calculated on a weight basis. Prior to casting, both coarse and fine aggregates were brought to saturated surface dry (SSD) condition to ensure that the W/C ratio of the mix remained as specified by the mixture proportion. The W/C ratio of the mix was monitored carefully.

3.3.1 Coarse Aggregate

First class bricks were collected from local market and broken manually to give brick chips having MAS of 12.5 mm, 19.0 mm, 25.0 mm, 37.5 mm, and 50.0 mm. Prior to casting, these coarse aggregates were sieved separately to satisfy ASTM C 33 (2003) and were batched separately for different MAS. Once the batch was prepared, the aggregates were kept in submerged condition for 24 hours and before casting, were rubbed with a clean cloth to eliminate excess water from the aggregate surface and ensure SSD condition of the aggregates.

3.3.2 Fine Aggregate

The fine aggregate used in this study was Sylhet sand and was procured from local market. Prior to casting, the sand was sieved through No. 4 (4.75 mm) sieve to separate any coarse aggregate from the mix and then washed to avoid mud and other organic materials. Sufficient water was mixed with sand several hours before casting and lump of sand was made in the palm of the hand. If the lump broke when the palm was stretched, the sand was considered to be in SSD condition. Once SSD sand was prepared, it was stored in air tight bags to avoid moisture loss.

3.4 Material Properties

The properties of materials used were evaluated before casting by testing them in the laboratory according to specifications. The aggregates used in this study were tested for specific gravity, absorption capacity, abrasion resistance, gradation, and unit weight. The specifications followed are summarized in **Table 3.2**.

Table 3.2. Specifications followed to test material properties

Name of the property evaluated	Specification/guideline followed
Specific gravity	ASTM C 127 (for coarse aggregate) ASTM C 128 (for fine aggregate)
Absorption capacity	ASTM C 127 (for coarse aggregate) ASTM C 128 (for fine aggregate)
Abrasion resistance	ASTM C 131
Unit weight	ASTM C 29
Gradation	ASTM C 33
Fineness Modulus	ASTM C 136

3.4.1 Coarse Aggregate

To study the effects of maximum aggregate size (MAS) of brick coarse aggregate, five MAS were used in this study – 12.5 mm, 19.0 mm, 25.0 mm, 37.5 mm, and 50.0 mm. First class bricks were procured from local market, and manually broken into pieces of desired size. The gradation of brick chips for different MAS was controlled as per ASTM C 33 (2003). The gradation followed in this study is shown in **Table3.3**, and the gradation curves are shown in **Fig..1**.

The coarse aggregates were tested for specific gravity, absorption capacity, abrasion resistance, unit weight, and fineness modulus (FM). The material properties of the coarse aggregates are summarized in **Table 3.4**. From the gradation shown in **Table 3.3**, it is evident that, with an increase in MAS, the amount of smaller sized aggregates is reduced. Thus the voids formed by larger aggregates are often left void due to the absence of small aggregates, which results in a reduction of unit weight of aggregate with an increase in MAS as shown in **Table 3.4**.

3.4.2 Fine Aggregate

For this study, locally available Sylhet sand was used as fine aggregate. Prior to casting, the fine aggregate was tested for specific gravity, absorption capacity, unit weight, and fineness modulus (FM). The material properties of fine aggregate are summarized in **Table 3.5**.The FM of 2.52 is the natural FM of the sand, and the natural gradation satisfies ASTM C 33 – 03 specifications, as shown in **Figure 3.2**.

3.4.3 Cement

CEM Type II A–M cement was used in this study that conforms to BDS EN 197 – 1: 2000, and ASTM C595. The composition of the mineral components is given in **Table 3.6** (as specified by the manufacturer). It is manufactured by inter-grinding three major mineral components – Pulverized Fuel Ash (PFA), Blast Furnace Slag, and Limestone with common raw materials, clinker, and gypsum.

3.4.4 Water

Water used in this study for concrete mixing and curing was potable tap water whose unit weight was 1000 kg/m^3.

Table 3.3. Gradation of coarse aggregate (according to ASTM C 33)

Nominal size	Amounts finer than each laboratory sieve, Mass percent					
	37.5 mm	25.0 mm	19.0 mm	12.5 mm	9.5 mm	4.75 mm
37.5 to 12.5 mm	90	40	10	-	0	-
25.0 to 9.5 mm	100	90	50	15	0	0
19.0 to 4.75 mm	-	100	90	-	40	0
12.5 to 4.75 mm	-	-	100	90	50	0

Table 3.4. Properties of coarse aggregate

Aggregate Type	Specific Gravity	Absorption Capacity (%)	Abrasion (%)	SSD Unit Weight (kg/m^3)					Fineness Modulus
				50.0 mm	37.5 mm	25.0 mm	19.0 mm	12.5 mm	
Brick Coarse Aggregate	2.30	15.1	38.3	1230	1232	1235	1236	1238	Controlled as per ASTM C 33 – 03

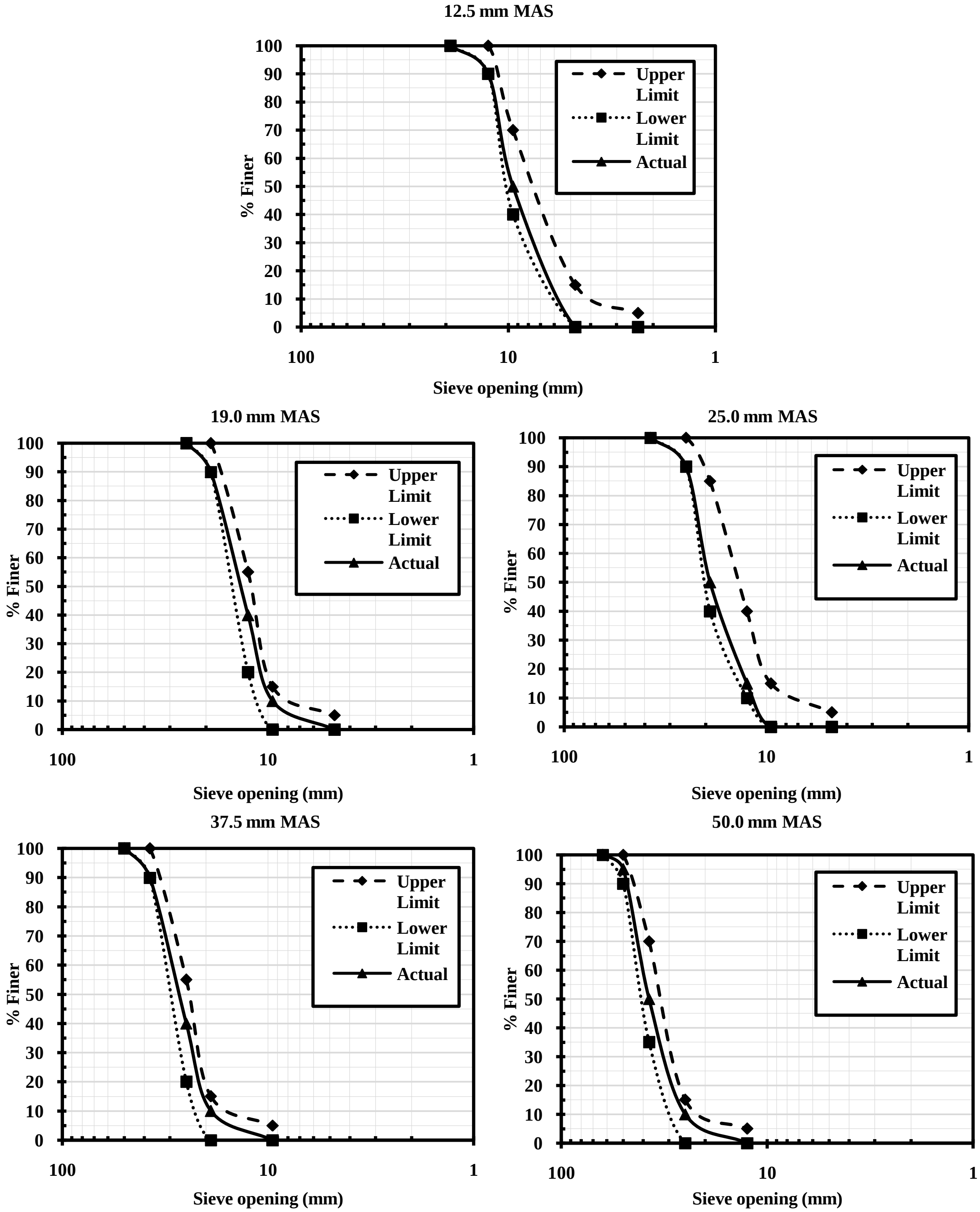


Fig. 3.1. Gradation of coarse aggregate

Table 3.5. Properties of fine aggregate

Aggregate Type	Specific Gravity	Absorption Capacity (%)	Abrasion (%)	SSD Unit Weight (kg/m3)	Fineness Modulus
Sylhet Sand	2.45	3.30	-	1520	2.52

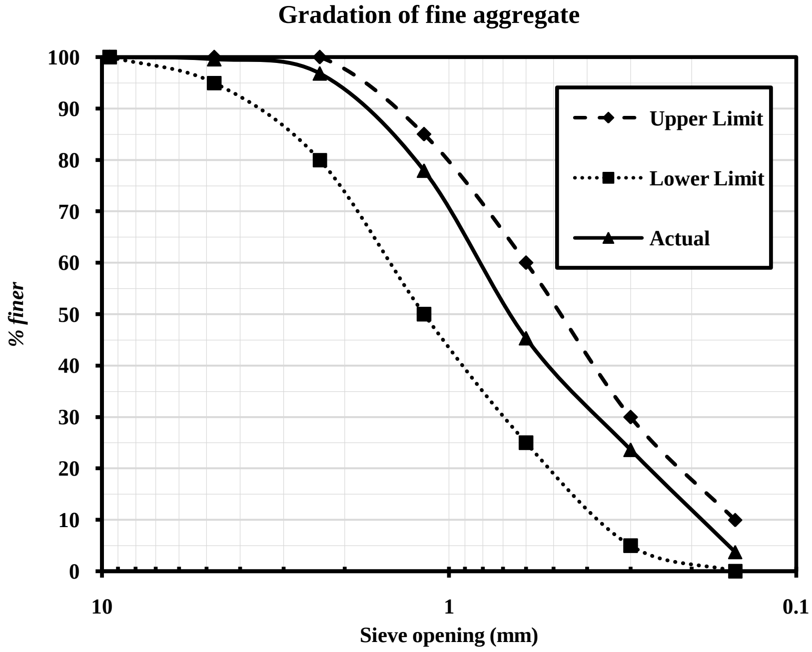


Fig. 3.2. Gradation of fine aggregate

Table 3.6. Composition of cement

Component	Percentage
Clinker	80–94%
Slag, Fly Ash, and Limestone	6–20%
Gypsum	0–5%

3.5 Experimental Setup

After casting of concrete specimens, they were cured initially for 24 hours by covering the cylindrical molds with wet clothes and polythene to prevent moisture loss.

The specimens were demolded after 24 hours of casting, followed by curing under water till the age of testing according to ASTM C 31.

The strain of concrete specimens was measured by a strain measurement setup of gauge length 100 mm with two dial gauges. The stress of concrete at strain level 0.0005 was used to determine the Young’s modulus of concrete. The splitting tensile strength of concrete was tested at 28 days. The failure surfaces of broken concrete specimens were also checked carefully after crushing of the concrete cylinders to corroborate the findings of this investigation.

Prior to compressive strength test, UPV was measured on unloaded wet specimens by using Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT) according to ASTM C 597 (2003). The rebound number on concrete specimen was measured using Schmidt Hammer according to ASTM C 805 (2003).

3.6 Sample Preparation

3.6.1 Mold Preparation

For studying the effects of MAS of brick coarse aggregate, cylindrical molds of diameter 100 mm and height 200 mm were used for 12.5 mm, 19.0 mm, 25.0 mm, and 37.5 mm MAS. Cylindrical molds of diameter 150 mm and height 300 mm were used for 50.0 mm MAS. Prior to casting, the cylinders were made air-tight by adjusting the screws, and the inner surface was lubricated by using grease according to ASTM C 31 (2003).

3.6.2 Casting and Mixing of Fresh Concrete

For casting of fresh concrete, mixture machine available in the Concrete Lab of Islamic University of Technology (IUT) was used. Trial mix was done for every case before the final mix. The mixing procedure followed in this study was quite different than the conventional mixing technique followed in construction sites in Bangladesh. The conventional technique is to put all the ingredients (cement, sand, coarse aggregate, water) simultaneously in the mixture. But in fact, it is not the best way to attain the desired strength of concrete. To ensure the quality of concrete, the following steps were followed to mix concrete:

Step 1: The inner surface of the mixing machine was wiped with a moist piece of cloth, so that the surface wouldn't absorb the mixing water.

Step 2: Half of the sand was poured into the machine and spread to give a notable bed like surface for the cement to put upon it.

Step 3: Cement was then placed on the sand bed.

Step 4: Rest of the sand was then poured on top of the cement.

Step 5: The sand and cement was then mixed for 30 seconds.

Step 6: Water was then poured into the sand-cement mixture carefully to avoid accidental spillage from the mixture machine. The machine was let to rotate and mix the cement-sand paste for one and a half minute more.

Step 7: The coarse aggregate was then introduced inside the mixing machine and the mixing was continued for further 3 minutes.

The total mixing time was 5 minutes. After five minutes, the concrete mix was poured on a non-absorbent sheet to continue with the slump test and casting procedure simultaneously.

3.6.3 Slump Test

Slump is a term used to describe how consistent a concrete sample is. The test also determines the workability of concrete, i.e. how easy it is to handle, compact, and mold concrete. The slump test of concrete in this study was done according to ASTM C 143 (2003).

A sample of freshly mixed concrete was placed and compacted by rodding with a tamping rod, in a mold shaped as the frustum of a cone. The tamping rod was a round, straight steel rod, 16mm in diameter and approximately 600 mm in length, having the tamping end rounded to a hemispherical tip, the diameter of which was 16 mm. The mold was made of non-absorbent metal that wasn't readily attacked by the cement paste. The metal was not thinner than 1.5 mm. The mold was in the form of a frustum of a cone with a base of 200 mm in diameter, a top of 100 mm in diameter, and a height of 300 mm. After placing and compacting the concrete, the mold was raised, and the concrete was allowed to subside. The vertical distance between the original and displaced position of the center of the top surface of the concrete was measured and reported as the slump of the concrete.

Concrete was poured into the mold in three layers of approximately equal volume, and each layer was tamped 25 times with the tamping rod.

3.6.4 Casting of Concrete Samples

In this study, concrete cylindrical specimens of 100 mm and 150 mm diameter, and height 200 mm and 300 mm respectively, were made. The specifications followed are briefly stated below. The cylindrical samples were made according to ASTM C 31 (2003).

The main differences in casting 100 mm diameter and 200 mm height concrete cylinders with that of 150 mm diameter and 300 mm height concrete cylinders are the number of layers in which they are being tamped, the specification of the tamping rod, and the number of times the layer is tamped/rodded. The differences are summarized in **Table 3.7**.

Table 3.7. Differences between 100 mm diameter and 150 mm diameter concrete cylinder specimens

	100 mm diameter and 200 mm height	**150 mm diameter and 300 mm height**
Tamping rod diameter	10 mm	16 mm
Length of tamping rod	300 mm	500 mm
No. of concrete layers in the mold to be tamped	2	3
No. of tamping	25 times	25 times

Tamping rod of diameter 10 mm and length 300 mm was used to compact concrete cylinders of diameter 100 mm and height 200 mm in two layers. On the other hand, tamping rod of diameter 16 mm and length 500 mm was used to compact concrete cylinders of diameter 150 mm and height 300 mm in three layers. First of all, the concrete sample was placed in the cylinder mold by moving the sampling tool used to pour concrete around the perimeter of the mold, to ensure even distribution and minimize segregation. Each layer of concrete was rodded 25 times with the hemispherical end of the tamping rod. The bottom layer was rodded throughout its depth. The rodding was distributed uniformly over the cross section of the mold. For each upper layer, the tamping rod was allowed to penetrate through the layer being rodded, and into the layer below by approximately 25 mm.

After rodding each layer, the outside of each mold was tapped lightly 10 – 15 times with a hammer, to close any holes left by rodding and to release any large air bubbles that may have been trapped. After tapping, each layer of the concrete along the side of each mold was scaled with a steel scale. Under filled molds were adjusted with representative concrete during consolidation of the top layer. After consolidation, excess concrete from the surface was stroked off with a trowel.

3.6.5 Curing of Specimen

The curing of specimens was done according to ASTM C 192 (2003). To prevent the evaporation of water from the unhardened concrete, each specimen was immediately covered with a wet burlap and a non-absorptive polythene sheet on top of the wet burlap. This initial curing of the specimens continued until the samples were demolded.

Each specimen was demolded after 24 hours of casting and taken immediately for moist curing. All specimens were moist cured at 23.0 ± 2^0 C from the time of the molding until the moment of test. Each specimen was placed in a curing bath so as to allow free water on entire surface area of the specimen. This final curing of each specimen continued until the day of testing.

3.7 Testing

The properties of hardened concrete were evaluated by means of both destructive and non-destructive testing. In destructive tests (DT), a specimen is completely destroyed by applying pressure to evaluate the concrete strength, e.g. compressive strength, tensile strength, Young’s modulus, and stress-strain curve. In non-destructive tests (NDT), the specimen strength is determined without damaging the specimen. In this study, concrete properties were evaluated by means of NDTs like Ultrasonic Pulse Velocity (UPV) test and Schmidt hammer.

3.7.1 Destructive Test

3.7.1.1 Compressive Strength

The compressive strength of concrete in this study was determined according to ASTM C 39 (2003). In this method, compressive axial load was applied to molded cylinders at a rate which is within a prescribed range of 0.15 to 0.35 MPa/s, until failure occurred. The compressive strength of the specimen was then calculated by dividing the maximum load attained during the test by the cross-sectional area of the specimen. The diameter and length of each cylinder specimen were measured using a Vernier calipers, and the cross-section was calculated. To determine the compressive strength of a particular batch of concrete on a particular age, the average compressive strength of three specimens was taken. Since the specimen length to diameter ratio for cylinder samples was not less than 1.75, the compressive strength measured was not multiplied by any correction factors as specified by ASTM C 39 (2003).

The compressive strength of concrete was measured at 7 days, 28 days, and 90 days using compressive strength testing machine according to ASTM C 39 (2003). A strength conversion factor (k_s) was determined to correlate the compressive strength of 100 mm by 200 mm cylindrical specimens to 150 mm by 300 mm cylindrical specimens. The strength conversion factor (k_s) is defined by the following equation:

$$k_s = f'_{c,100mm} / f'_{c,150mm} \tag{3.2}$$

Where, $f'_{c,100mm}$ and $f'_{c,150mm}$ are the compressive strength of concrete calculated from 100 mm by 200 mm cylindrical specimens and 150 mm by 300 mm cylindrical specimens respectively. The mixture proportions for both were kept the same. The strength conversion factor was found to be 1.02.

3.7.1.2 Splitting Tensile Strength

The splitting tensile strength of concrete was determined according to ASTM C 496 (2003), by applying a diametral compressive force along the length of cylindrical concrete specimens, until failure. The rate of loading was 0.7 to 1.4 MPa/min. This loading induces tensile stresses on the plane containing the applied load and relatively high compressive stresses in the area immediately around the applied load. Tensile failure occurs rather than compressive failure because the areas of load application are in a state of triaxial compression, thereby allowing them to withstand much higher compressive stresses than would be indicated by a uniaxial compressive strength test result. The maximum load sustained by a specimen is divided by appropriate geometrical factors to obtain the splitting tensile strength as shown in equation (3.3).

$$T = \frac{2P}{\pi l d} \tag{3.3}$$

Where,

T = splitting tensile strength (MPa)

P = maximum applied load indicated by the testing machine (N)

l = length (mm)

d = diameter (mm)

Before placing the specimen in the testing machine (Universal Testing Machine, UTM), diameter of each specimen was determined by averaging three diameters measured near the ends and the middle of the specimen. Diametral lines were drawn on each end of the specimen using a marker to ensure that they are in the same axial plane. The specimen was placed in between the UTM bearing plates and aligned so that the lines marked on the ends of the specimen are vertical and centered.

3.7.1.3 Young's Modulus

The Young’s modulus of each specimen was measured according to ASTM C 469 (2003), during compressive strength test of the specimen. The specimen was placed with the strain-measuring setup attached, on the bearing block of the compressive strength testing machine. The axis of the specimen was carefully aligned with the center of thrust of the spherically-seated upper bearing block. The load was applied at a constant rate within the range 35 ± 5 psi (241 ± 34 kPa/s). Without interruption, the applied load and corresponding longitudinal strain were measured until failure of the specimen. The stress at a strain level of 0.0005 was calculated directly, or through linear interpolation. The Young's modulus was calculated using the following equation:

$$\text{Young's Modulus} = f_{0.0005}/0.0005 \tag{3.4}$$

Where, $f_{0.0005}$ is the stress at a strain level of 0.0005 in MPa.

3.7.2 Non-destructive Test

3.7.2.1 Ultrasonic Pulse Velocity

The ultrasonic pulse velocity (UPV) through wet concrete specimen was measured using a PUNDIT apparatus, prior to compressive strength test. The specimen dimensions were measured using Vernier calipers. The equipment was verified to operate properly by performing a zero-time adjustment. For this adjustment, coupling agent was applied to the ends of the reference bar provided by the manufacturer, and the transducers were pressed firmly against the ends of the bar until a stable transit time was displayed. The zero reference was adjusted until the displayed transit time agreed with the value marked on the bar.

Once the reference was adjusted, appropriate coupling agent (grease) was applied to the transducer faces and then the transducers were placed on opposite sides of the cylinder. The faces of the transducers were pressed firmly against the concrete surfaces until a suitable transit time was displayed. The transit time was recorded for further calculation using the flowing equation:

$$UPV = L/T \tag{3.5}$$

Where, UPV is the pulse velocity in m/s, L is the specimen length through which the pulse travelled in m, and T is the transit time in s.

3.7.2.2 Schmidt Hammer

The rebound number on hardened concrete specimen was determined by using a spring-driven steel hammer called the Schmidt hammer as per ASTM C805. The Schmidt hammer is a spring-loaded steel hammer, that when released, strikes a steel plunger in contact with the concrete surface. The rebound distance of the steel hammer from the steel plunger is measured on a linear scale attached to the frame of the instrument.

The hammer was held firmly on the specimen so that the plunger is perpendicular (α = -90^0) to the test surface. The hammer was then gradually pushed towards the test surface until the hammer impacted. After impact, pressure on the hammer was maintained and, the button on the side of the hammer was depressed to lock the plunger in it’s retracted position. The rebound number on the scale was then recorded to the nearest whole number. Ten readings were taken from each specimen. Readings differing from the average of 10readings by more than 6 units were discarded and the average of the remaining readings was calculated to record the rebound number.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 General

In this chapter, the results obtained throughout the investigation are summarized and discussed. The effects of MAS of brick aggregate concrete on compressive strength, splitting tensile strength, Young's modulus, and UPV are discussed. The effects of s/a ratio and cement content on compressive strength, Young’s modulus, and splitting tensile strength of concrete are also discussed. Moreover, for different MAS, the stress-strain relationship of concrete, relationships between compressive strength and Young's modulus, compressive strength and tensile strength, UPV and compressive strength, UPV and Young’s modulus, compressive strength and rebound number are also proposed.

4.2 Effect of Maximum Aggregate Size

4.2.1 Workability of Concrete

The effect of MAS of brick aggregate on workability of concrete for different s/a ratio, cement content (cc) and W/C ratio is shown in **Fig. 4.1**. The workability of concrete increases with an increase in the MAS. It is well established that, besides aggregate shape and surface texture, the gradation of aggregate is an important parameter that influences workability of concrete, as gradation of aggregate determines how efficiently the particles pack together. As shown in **Table 2.4**, with an increase in MAS, the amount of smaller sized aggregates reduce in the mix. This contributes to higher workability of concrete made with larger aggregates due to less internal friction caused by the aggregate.

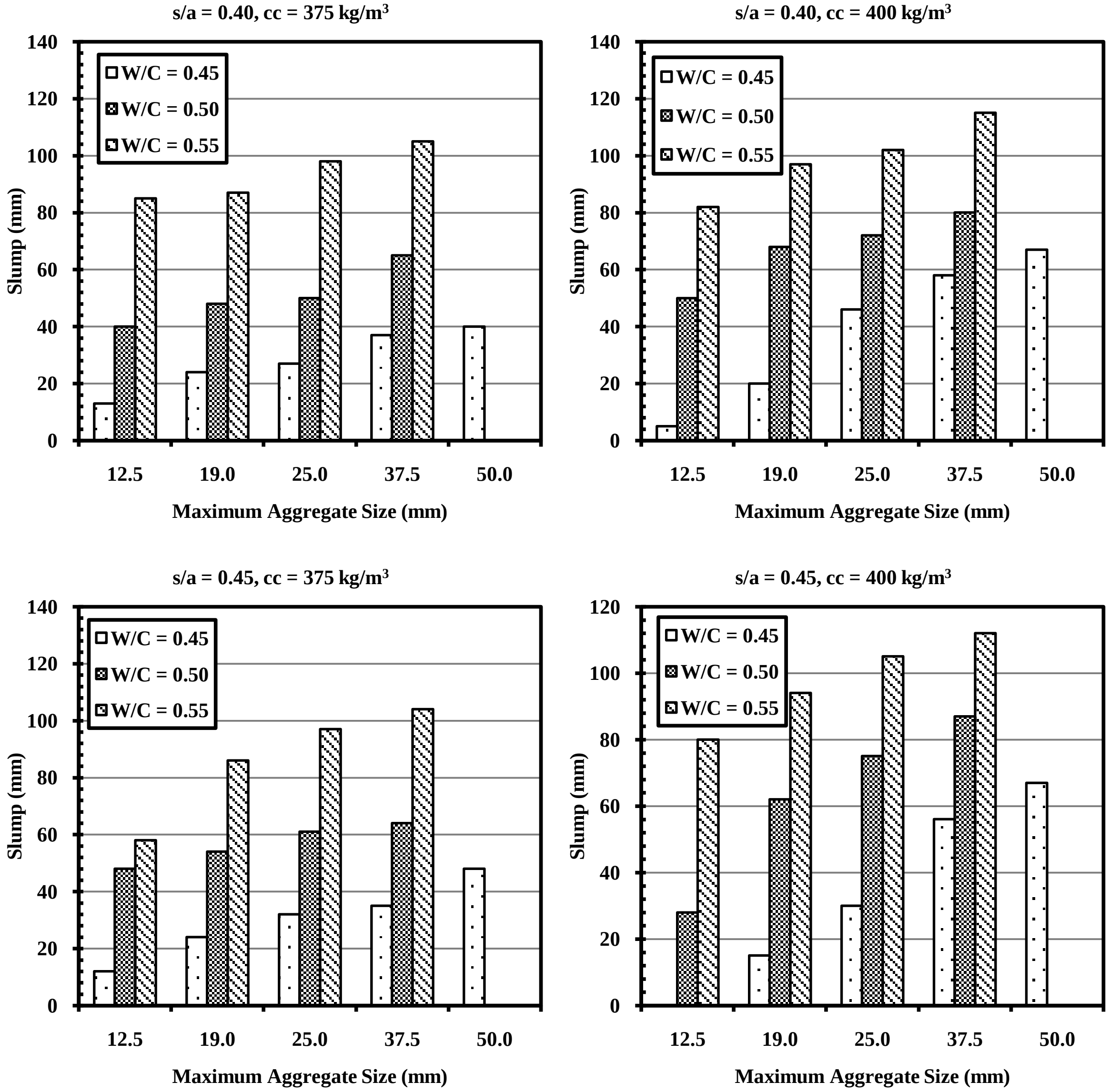


Fig. 4.1. Effect of maximum size of aggregate on workability of concrete

4.2.2 Compressive Strength of Concrete

The effect of MAS of brick aggregate on 28 days compressive strength of concrete is shown in **Fig.4.2**. At lower cement content of 375 kg/m^3, and W/C ratio of 0.45 and 0.50, the compressive strength increases with the increase in MAS up to 37.5 mm, and then decreases irrespective of the variation in s/a ratio from 0.40 to 0.45. But at a higher cement content of 400 kg/m^3, the compressive strength reduces with the increase in MAS, irrespective of the change in s/a ratio and W/C ratio. At lower cement content, the failure in concrete specimen is initiated in the aggregate-mortar interface, and visual inspection of broken samples suggests mortar failure. In such cases, with the increase in aggregate size, the amount of aggregate-mortar interface is reduced (as explained in **Section 4.3**), and this results in a higher compressive strength for larger sized aggregates. On the other hand, at high cement content, the failure initiates in the interface as well as within the aggregate, and visual inspection suggests combined failure. In such cases, lower sized aggregates give more compressive strength than larger sized aggregates. Moreover, the strength reduces with an increase in W/C ratio for all cases.

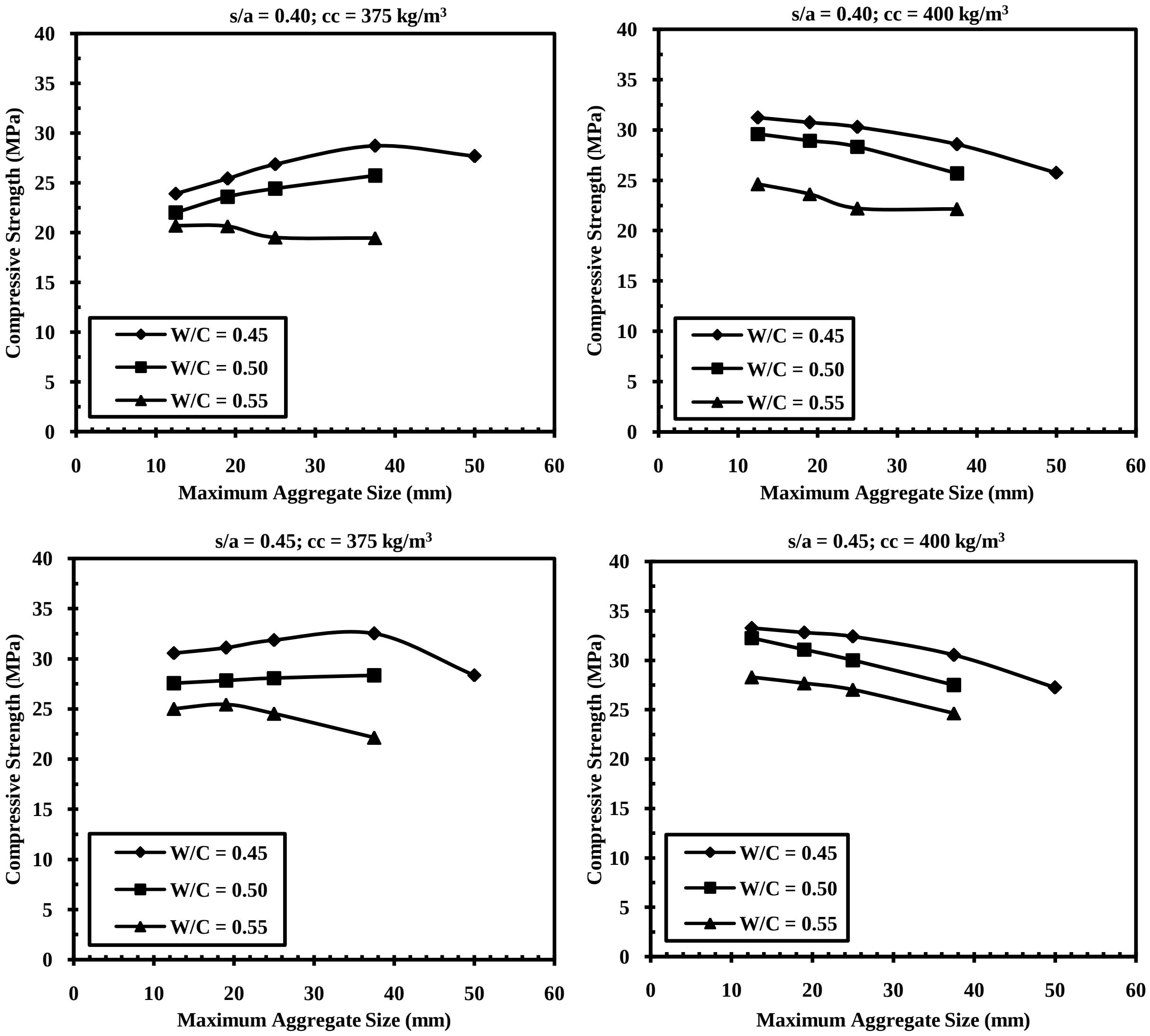


Fig. 4.2. Effect of maximum size of aggregate on compressive strength of concrete

4.2.3 Splitting Tensile Strength of Concrete

The effect of MAS on 28 days splitting tensile strength of brick aggregate concrete is shown in **Fig. 4.3**. With an increase in MAS, the splitting tensile strength decreases irrespective of variation of cement content and s/a ratio. The trend of the results related to tensile strength is different from the results of compressive strength of concrete as explained in **Section 4.2.2**. It is understood that separate relationships between compressive strength and splitting tensile strength of concrete for different MAS are to be developed instead of a general relationship as proposed in codes (ACI 318-14).

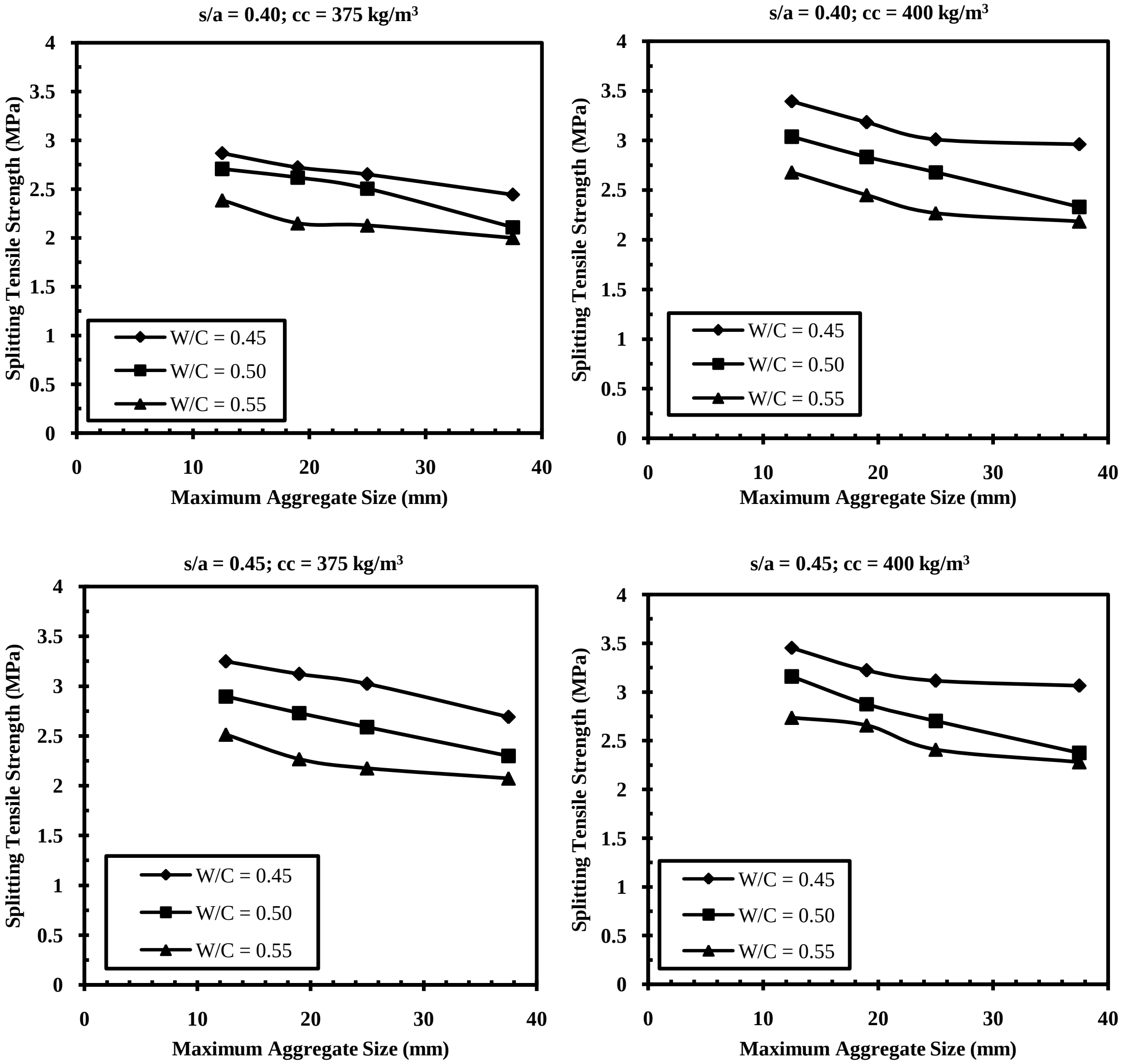


Fig. 4.3. Effect of maximum size of aggregate on splitting tensile strength of concrete

4.2.4 Young’s Modulus of Concrete

The effect of MAS of brick aggregate on 28 days Young's modulus of concrete for different s/a ratio, cement content and W/C ratios is shown in **Fig. 4.4**. At low cement content of 375 kg/m^3, and low W/C ratio of 0.45, the Young’s modulus increases with the increase in maximum size of aggregate. But at a higher cement content of 400 kg/m^3, the Young’s modulus of concrete decreases with the increase in maximum size of aggregate. Similar trends of results are also observed for compressive strength of concrete as explained in **Section 4.2.2**. Literature reveals that concrete with higher compressive strength gives higher Young’s modulus (Neville 1997, Yıldırım 1995), and findings of this study are analogous to those suggested by early researchers.

4.2.5 Ultrasonic Pulse Velocity

The effect of MAS of brick aggregate concrete on UPV through concrete is shown in **Fig. 4.5**. For all the cases, irrespective of change in the s/a ratio and cement content, the UPV through concrete increases with the increase in MAS. From **Fig. 4.10** (as discussed in **Section 4.3**), it is evident that in concrete samples made with 12.5 mm MAS, the mortar-aggregate interface, i.e. the Interfacial Transition Zone (ITZ) is higher compared to other MAS, which leads to a tortuous path for the ultrasonic pulse to move towards the receiver. This results in an increase in pulse travel time, and consequent lower velocity. In concrete made with larger aggregates, the mortar-aggregate interface reduces and the pulse can cover the path in shorter times, resulting an increase in the UPV with the increase in MAS. Based on the experimental data, it is found that the UPV through brick aggregate concrete may vary in between 3.60 km/s to 3.75 km/s

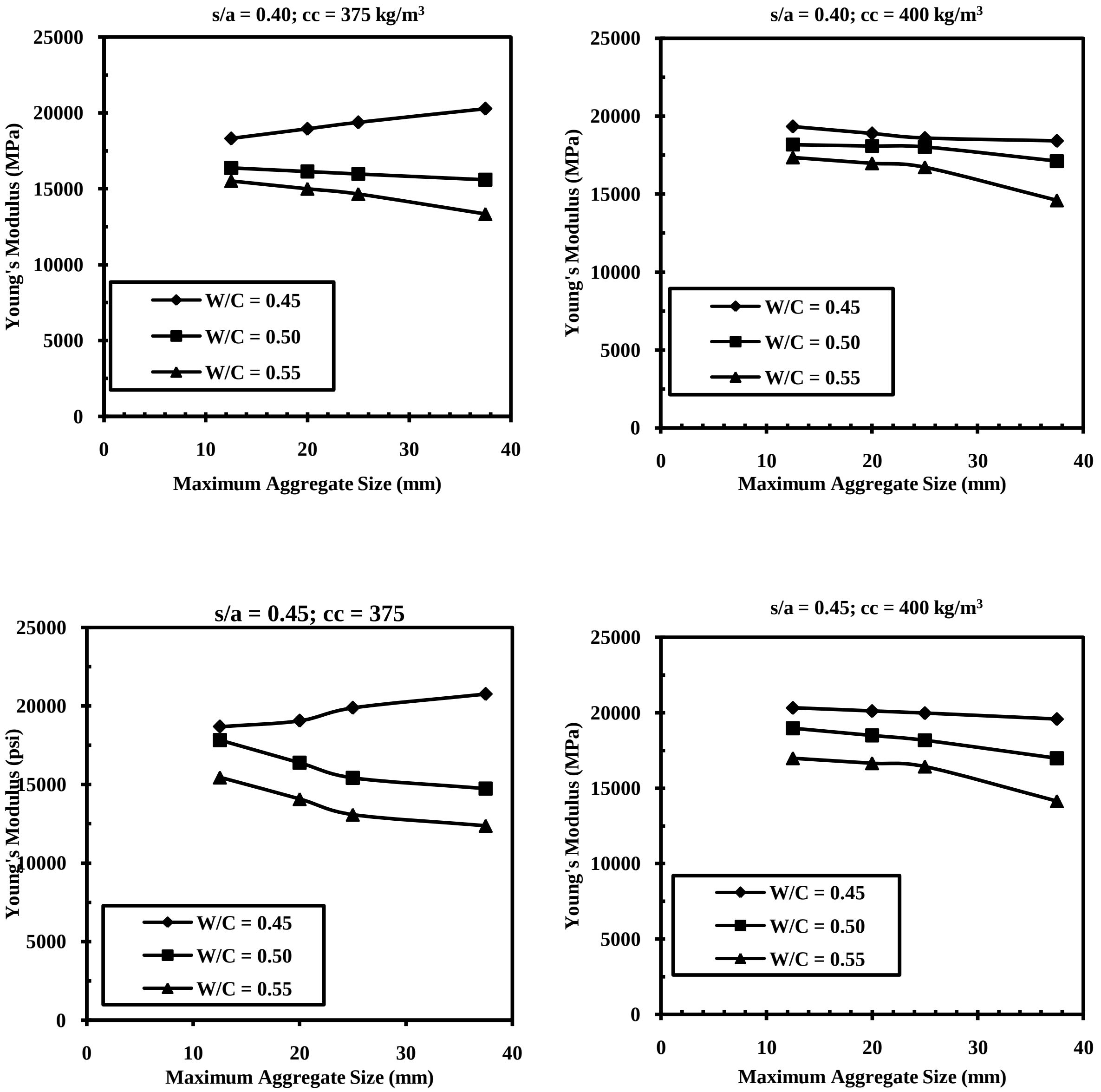


Fig. 4.4. Effect of maximum size of aggregate on Young's modulus of concrete

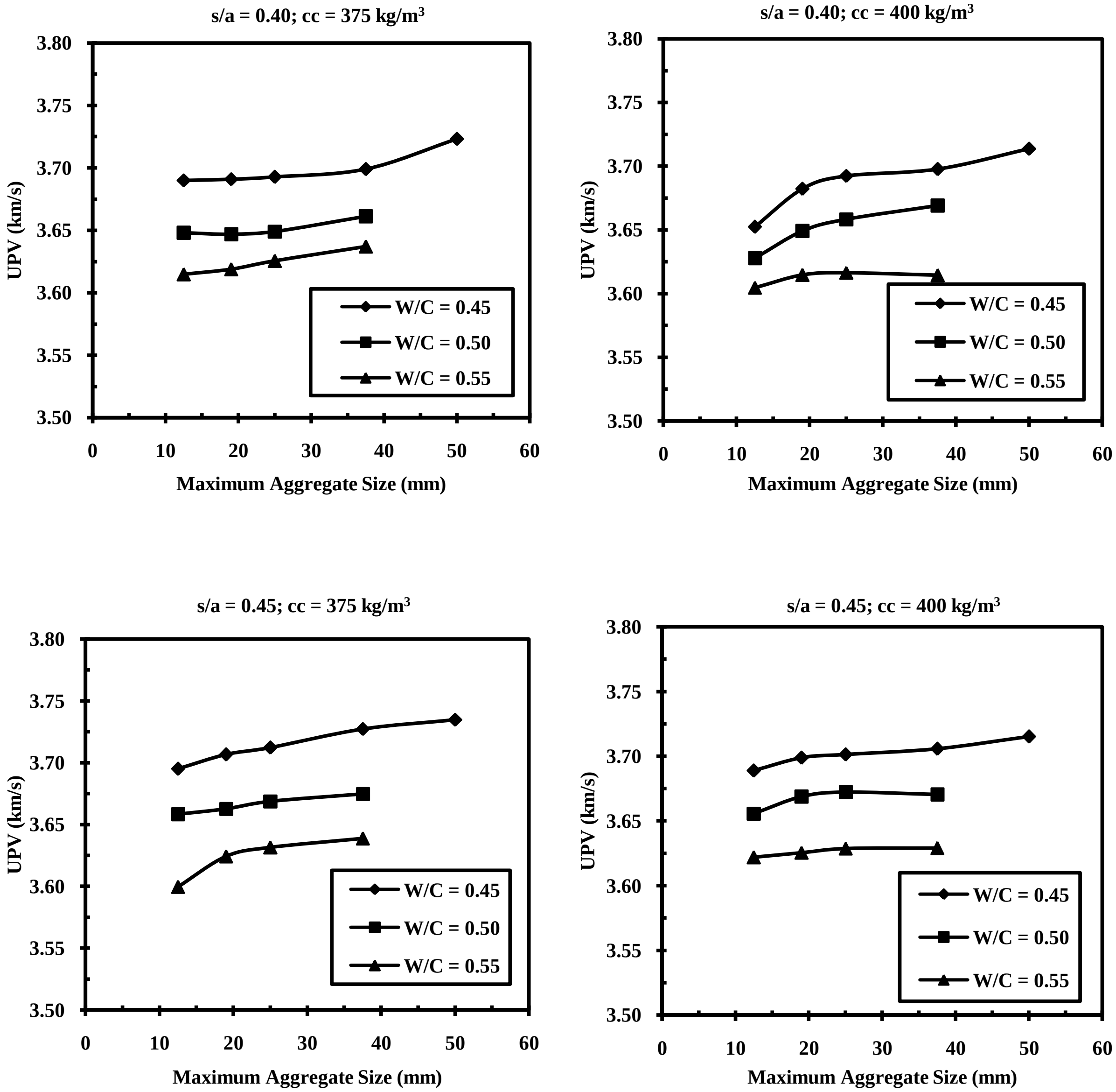


Fig. 4.5. Effect of maximum size of aggregate on UPV through concrete

4.2.6 Stress-strain Curve

Variation of normalized stress (ratio of stress to compressive strength) with strain for concrete made with aggregates having different MAS is shown in **Fig. 4.6**. In this study, an attempt has been made to formulate a relationship between stress and strain of concrete made with brick aggregate of maximum sizes 12.5 mm, 19.0 mm, 25.0 mm, and

37.5 mm based on large number of experimental data. The stress-strain data of concrete made with 50.0 mm MAS couldn’t be determined for some limitations. Based on these data, the following stress-strain relationships are proposed for brick aggregate concrete made with different MAS:

MAS 12.5 mm: $\frac{f_c}{f_c^{'}} = \frac{1.9712 \times \varepsilon}{0.00193 + \varepsilon}$ $R^2 = 0.89$; $0 \leq \varepsilon \leq 0.0025$ (4.1)

MAS 19.0 mm: $\frac{f_c}{f_c^{'}} = \frac{1.5916 \times \varepsilon}{0.00153 + \varepsilon}$ $R^2 = 0.92$; $0 \leq \varepsilon \leq 0.0025$ (4.2)

MAS 25.0 mm: $\frac{f_c}{f_c^{'}} = \frac{1.7558 \times \varepsilon}{0.00188 + \varepsilon}$ $R^2 = 0.85$; $0 \leq \varepsilon \leq 0.0025$ (4.3)

MAS 37.5 mm: $\frac{f_c}{f_c^{'}} = \frac{1.7862 \times \varepsilon}{0.00208 + \varepsilon}$ $R^2 = 0.95$; $0 \leq \varepsilon \leq 0.0025$ (4.4)

Where, f_c is stress at strain ε and f_c' is compressive strength of concrete. This equation is valid till strain level of 0.0025. It is due to the limitation of recording strain data after maximum stress level.

Fig. 4.7 shows the stress-strain curve of concrete (for strain up to 0.0005) according to the relationships proposed in equations (4.1) – (4.4). From **Fig. 4.7**, it is evident that the stress-strain curve becomes flatter with the increase of MAS, i.e., Young’s modulus of concrete decreases with an increase in MAS.

4.2.7 Unit Weight of Concrete

The change of unit weight of concrete with MAS is shown in **Fig. 4.8** for different s/a ratio, cement content, and W/C ratio. From **Fig. 4.8**, it is evident that there is a tendency of a very small amount of reduction in unit weight (less than 1%) with the increase of MAS. Moreover, the unit weight of concrete also decreases with an increase in the W/C ratio. **Fig. 4.8** shows that the unit weight of concrete made with brick aggregate ranges from 2000 – 2200 kg/m^3, whereas stone aggregate concrete has an unit weight of 2300 – 2400 kg/m^3 (Neville 2011). So, it is understood that by using brick aggregate instead of stone aggregate, it will be possible to reduce self-weight of concrete by as much as 15%.

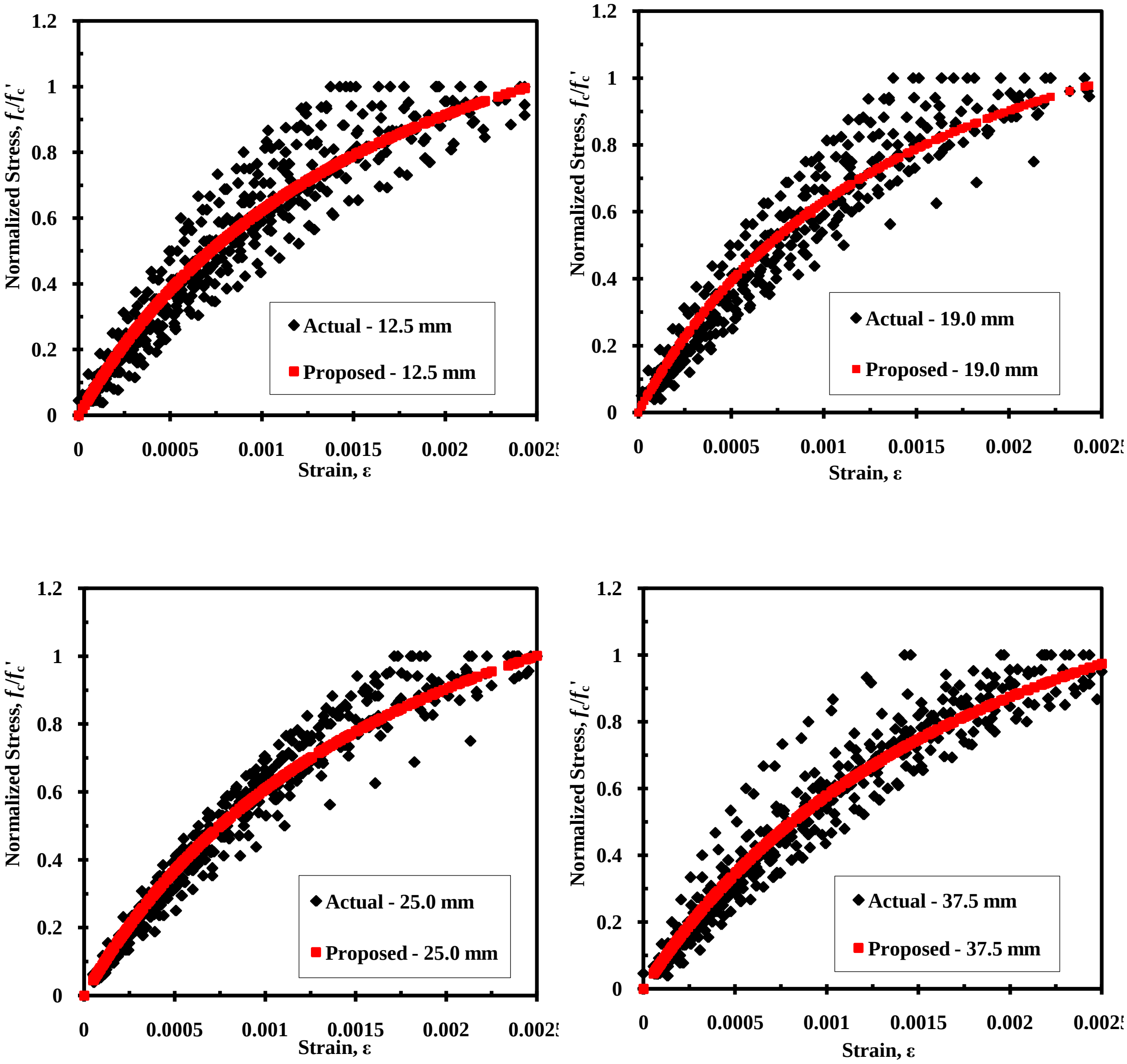


Fig. 4.6. Stress-strain curve of concrete

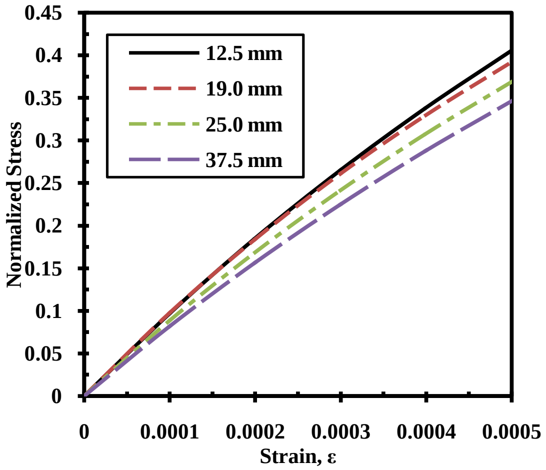


Fig. 4.7. Stress-strain curve of concrete for proposed equations (4.1) - (4.4)

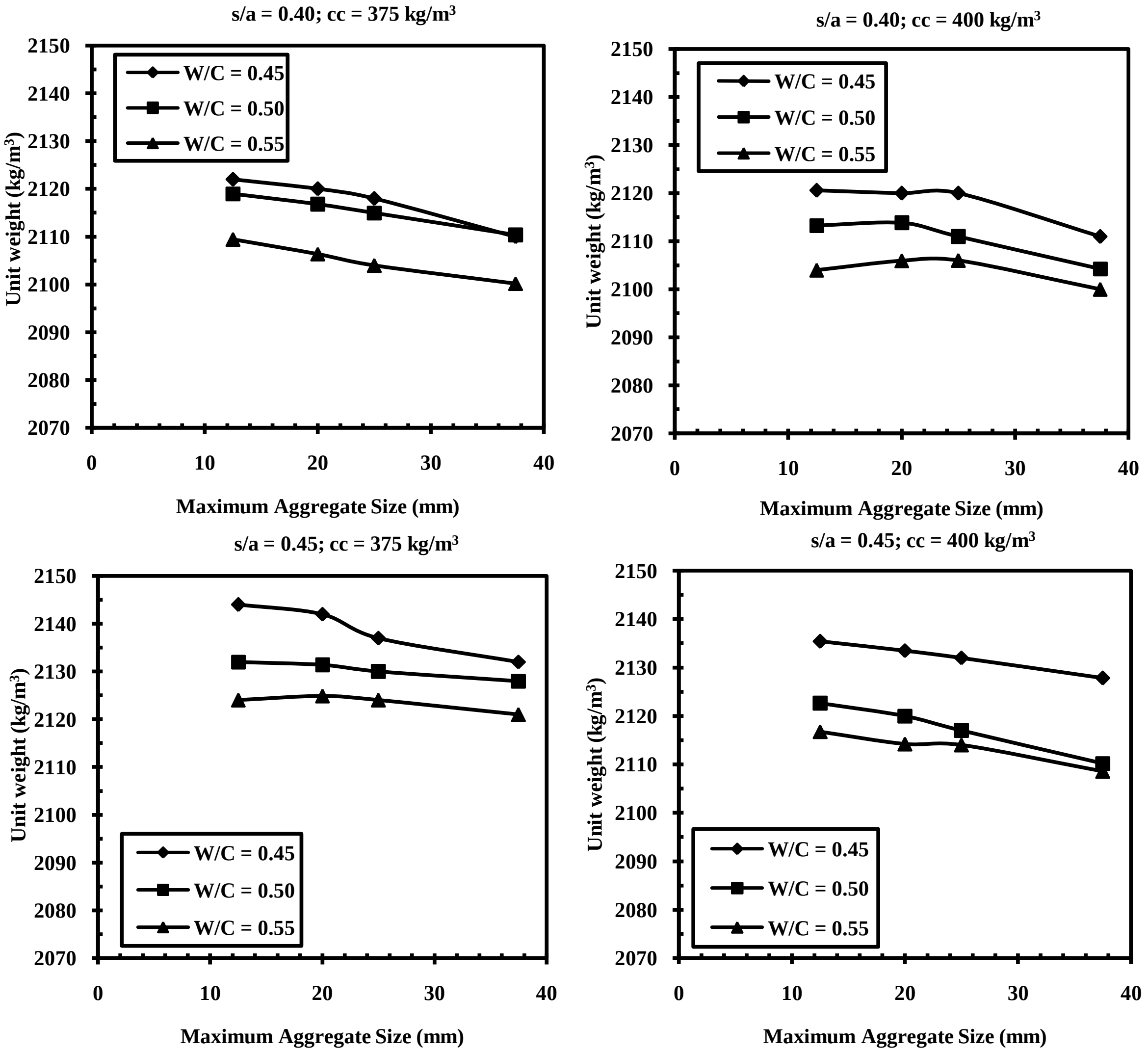


Fig. 4.8. Effect of maximum size of aggregate on unit weight of concrete

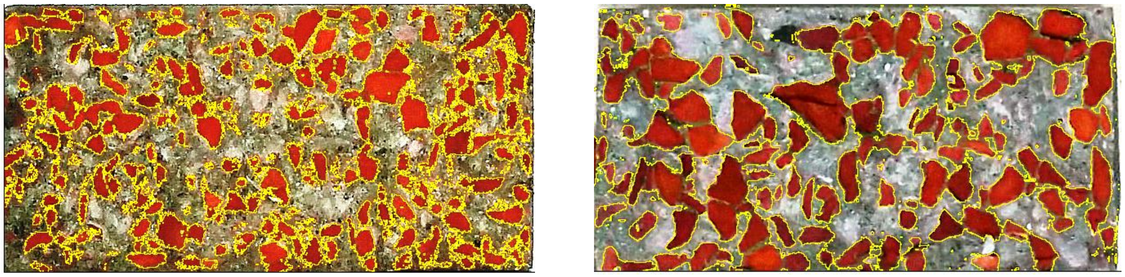
4.3 Image Analysis

The image analysis of the specimens was done to find the perimeter of Interfacial Transition Zone (ITZ) around the coarse aggregate in the specimens. The images (as shown in **Fig. 4.9**) were collected from 100 mm by 200 mm split specimens after splitting tensile strength test, which breaks specimens along the mid-section of the original cylindrical specimens. Later, the images were analyzed using ImageJ software to calculate the perimeter of ITZ around coarse aggregates on the splitted surface. The photographs of split samples and perimeter of ITZ around coarse aggregate of different MAS is shown in **Fig. 4.9**. From the image analysis, the perimeter of ITZ was calculated and was plotted against different MAS as shown in **Fig. 4.10**. It is evident that the perimeter of ITZ around coarse aggregate in the concrete mix reduces significantly with the increase of MAS.

Thus, for larger MAS, relatively lower content of cement will be needed to improve the ITZ around coarse aggregate. As a result, for a lower content of cement, relatively higher compressive strength and Young's modulus is found in case of larger MAS. On the other hand, for a smaller MAS the ITZ will be relatively improved with a larger cement content resulting in an increase in compressive strength and Young's modulus for smaller MAS. Moreover, for larger MAS, there is a possibility of formation of weaker ITZ due to blockage of bleed water under aggregate.

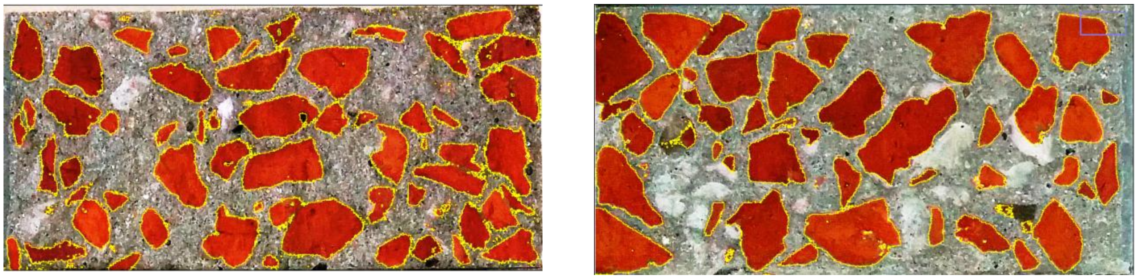
4.4 Effect of Age of Concrete on Compressive Strength

Fig. 4.11 shows the gain of strength of concrete made with different MAS over time for s/a ratio of 0.40, cement content of 375 kg/m^3, and W/C ratio of 0.45. From **Fig. 4.11**, it is evident that the rate of gain of strength at early age up to 28 days is significant for all MAS due to early hydration of cement. But, the rate of gain of strength beyond 28 days is not that significant. The effect of MAS on compressive strength is found to be more significant at 28 days and 90 days compared to 7 days.



(a) 12.5 mm MAS

(b) 19.0 mm MAS



(c) 25.0 mm MAS

(d) 37.5 mm MAS

Fig. 4.9. Image analysis of split samples using ImageJ software

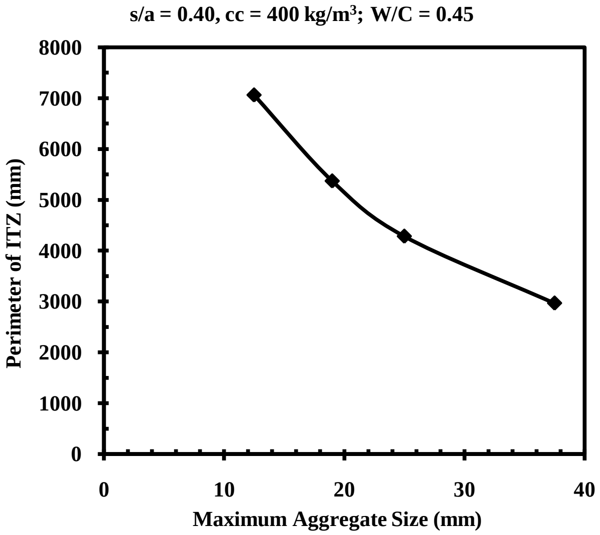


Fig. 4.10. Effect of maximum aggregate size on perimeter of ITZ (in a plane passing through the geometric axis of the cylinder)

4.5 Effect of Cement Content

4.5.1 Compressive Strength of Concrete

Fig. 4.12 illustrates the effect of cement content on compressive strength of concrete for different s/a ratio and W/C ratio. Two cement contents of 375 kg/m^3 and 400 kg/m^3 were used in this study. Based on **Fig. 4.12**, it can be summarized that, for W/C ratio of 0.45 and 0.50, the compressive strength increases with an increase of cement content for MAS of 12.5 mm, 19.0 mm, and 25.0 mm irrespective of variation in s/a ratio.

However, for MAS of 37.5 mm and 50.0 mm, the compressive strength decreases with an increase in cement content. Furthermore, the variation in strength in compressive strength due to variation in cement content is relatively more for concrete made with smaller MAS. Tumidajski and Gong (2006) drew a conclusion that, at higher cement contents, there is a monotonic decrease in compressive strength with increasing proportion of the 37.5 mm aggregate in the coarse aggregate fraction, resulting a decrease in the compressive strength of larger aggregates with an increase in the cement content. For a W/C ratio of 0.55, the compressive strength of concrete increases with an increase in MAS irrespective of change in s/a ratio.

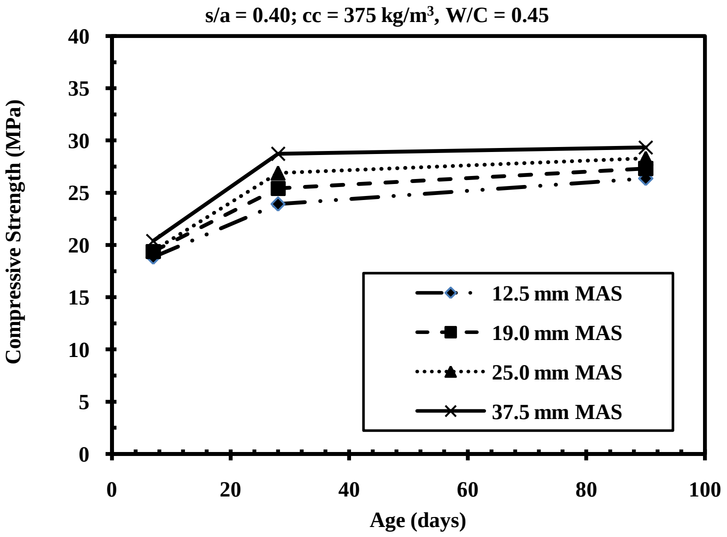


Fig. 4.11. Effect of age of concrete on compressive strength of concrete

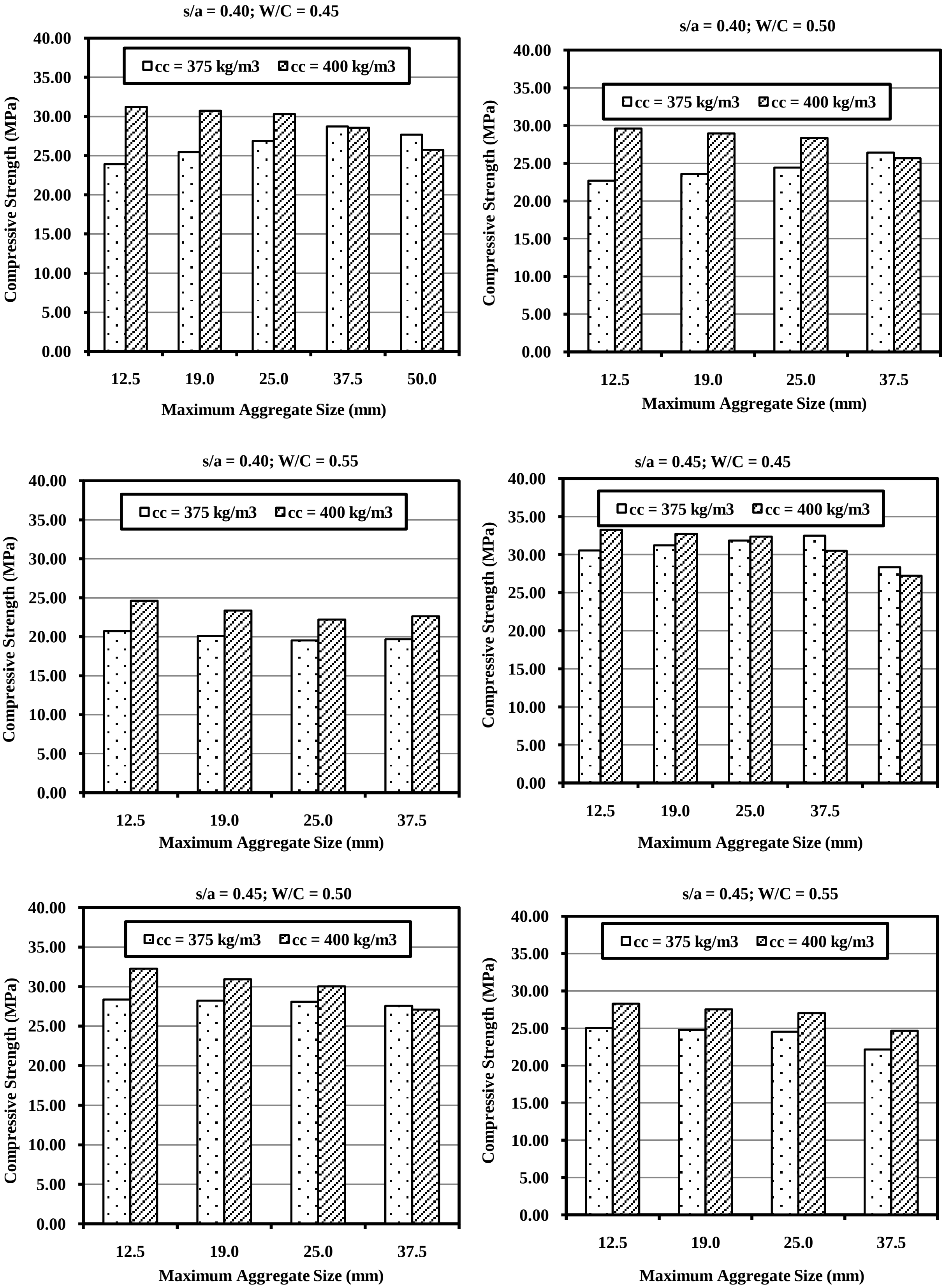


Fig. 4.12. Effect of cement content on compressive strength of concrete

4.5.2 Splitting Tensile Strength of Concrete

The effect of cement content on splitting tensile strength of concrete is shown in **Fig.4.13**. From **Fig. 4.13**, it is evident that the splitting tensile strength of concrete increases with an increase in the cement content from 375 kg/m^3 to 400 kg/m^3, irrespective of the variation in s/a ratio and W/C ratio.

4.5.3 Young's Modulus of Concrete

The effect of variation of cement content from 375 kg/m^3 to 400 kg/m^3 on Young's modulus of concrete is shown in **Fig. 4.14**. For W/C ratio of 0.50 and 0.55, the Young's modulus of concrete significantly increases with an increase in the cement content, irrespective of the variation in s/a ratio. However, at lower W/C ratio of 0.45, the Young's modulus increases with an increase in cement content for smaller sized 12.5 mm MAS. As the MAS increases, the Young's modulus starts to decrease with an increase in cement content, and for 37.5 mm MAS, the Young's modulus decreases with an increase in the cement content. It should be mentioned here that, at a lower cement content of 375 kg/m^3 and W/C ratio of 0.45, the Young's modulus of concrete increases with an increase in MAS. On the other hand, at a higher cement content of 400 kg/m^3 and W/C ratio of 0.45, the Young's modulus of concrete decreases with an increase in MAS. This is explained in Section 4.2.4.

4.6 Effect of Sand to Aggregate Volume Ratio

4.6.1 Compressive Strength of Concrete

The effect of sand to aggregate volume ratio (s/a) (0.40 and 0.45) on the compressive strength of concrete is shown in **Fig. 4.15**. It can be observed that an increase in s/a ratio results in an increase in compressive strength irrespective of the variation in cement content and W/C ratio. However, the variation is more significant for concrete made with lower cement content of 375 kg/m^3. Yang et al (1997) and Yang et al (2010) also found that the compressive strength of concrete increases with an increase in s/a ratio.

4.6.2 Splitting Tensile Strength of Concrete

The effect of variation of sand to aggregate volume ratio (s/a) on splitting tensile strength of concrete is shown in **Fig. 4.16**. It is evident from **Fig. 4.16** that the splitting tensile strength of concrete increases with an increase in the s/a ratio irrespective of the variation of cement content and W/C ratio. Similar conclusion is also drawn in Section 4.6.1, which discusses the effect of s/a ratio on compressive strength of concrete.

4.6.3 Young's Modulus of Concrete

The effect of variation of s/a ratio on Young's modulus of concrete is shown in **Fig. 4.17**. For W/C ratio of 0.45 and 0.50, the Young's modulus of concrete increases with an increase in the s/a ratio, irrespective of the change in cement content. However, for a higher W/C ratio of 0.55, the Young's modulus of concrete decreases with an increase in the s/a ratio.

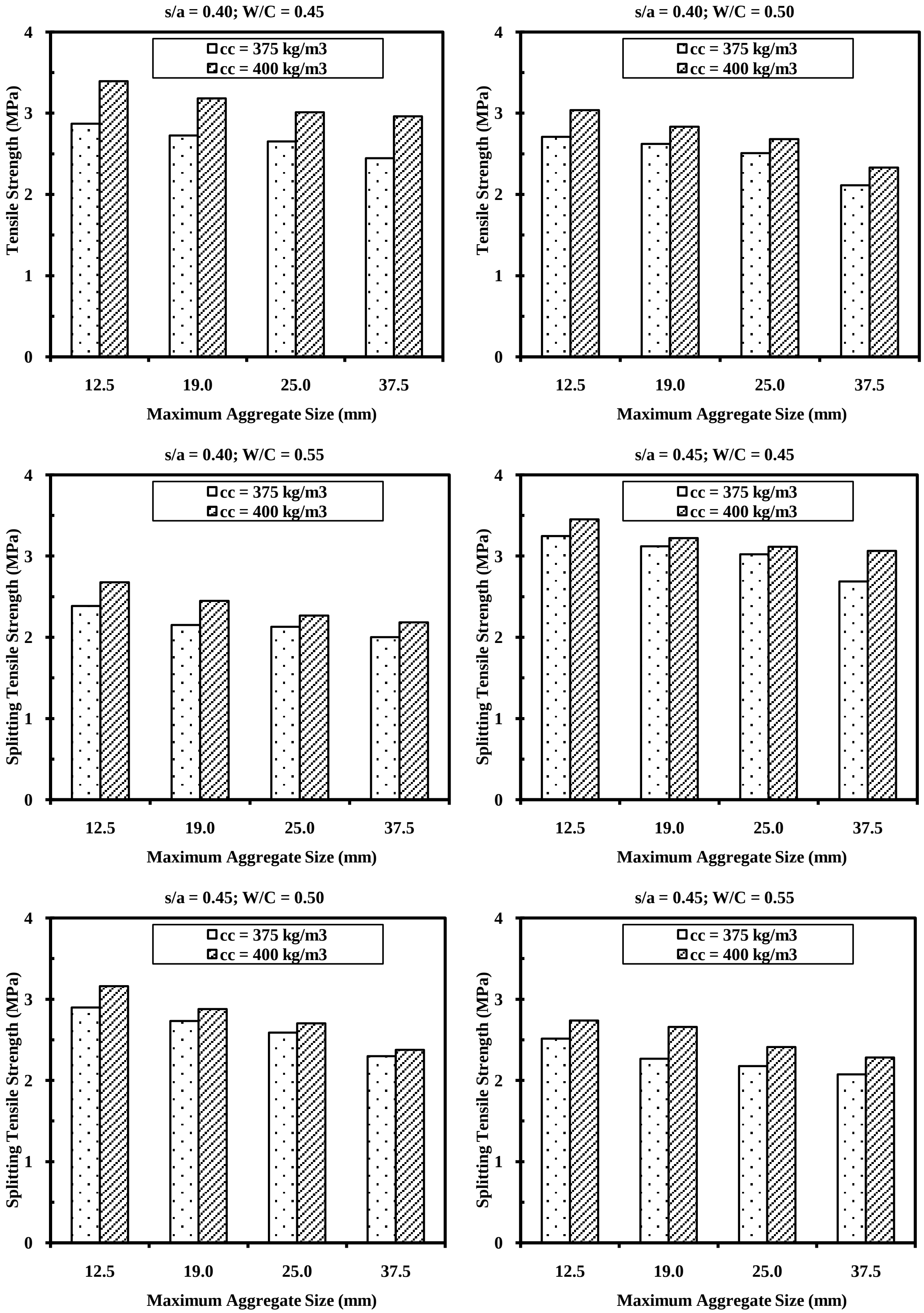


Fig. 4.13. Effect of cement content on splitting tensile strength of concrete

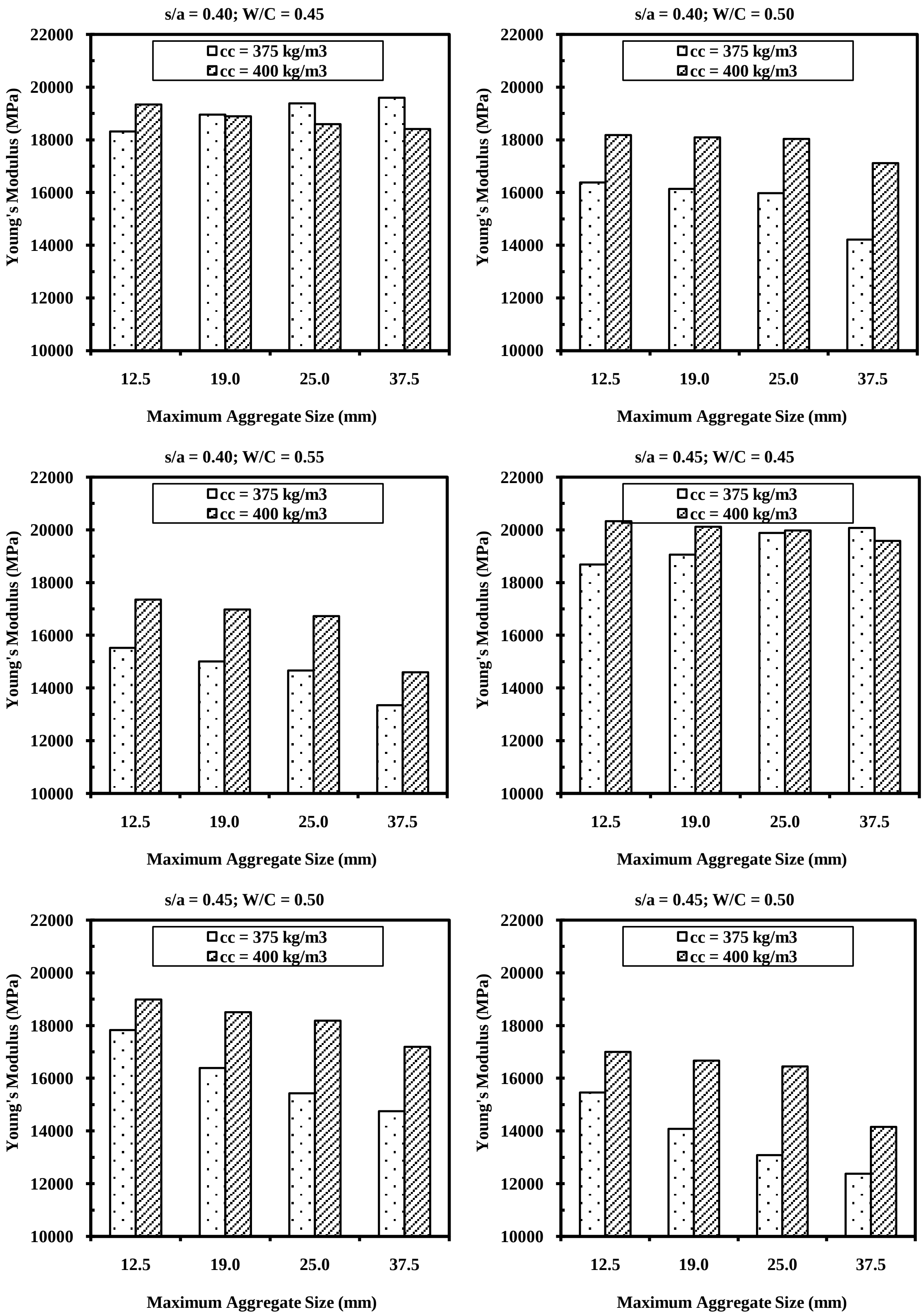


Fig. 4.14. Effect of cement content on Young’s modulus of concrete

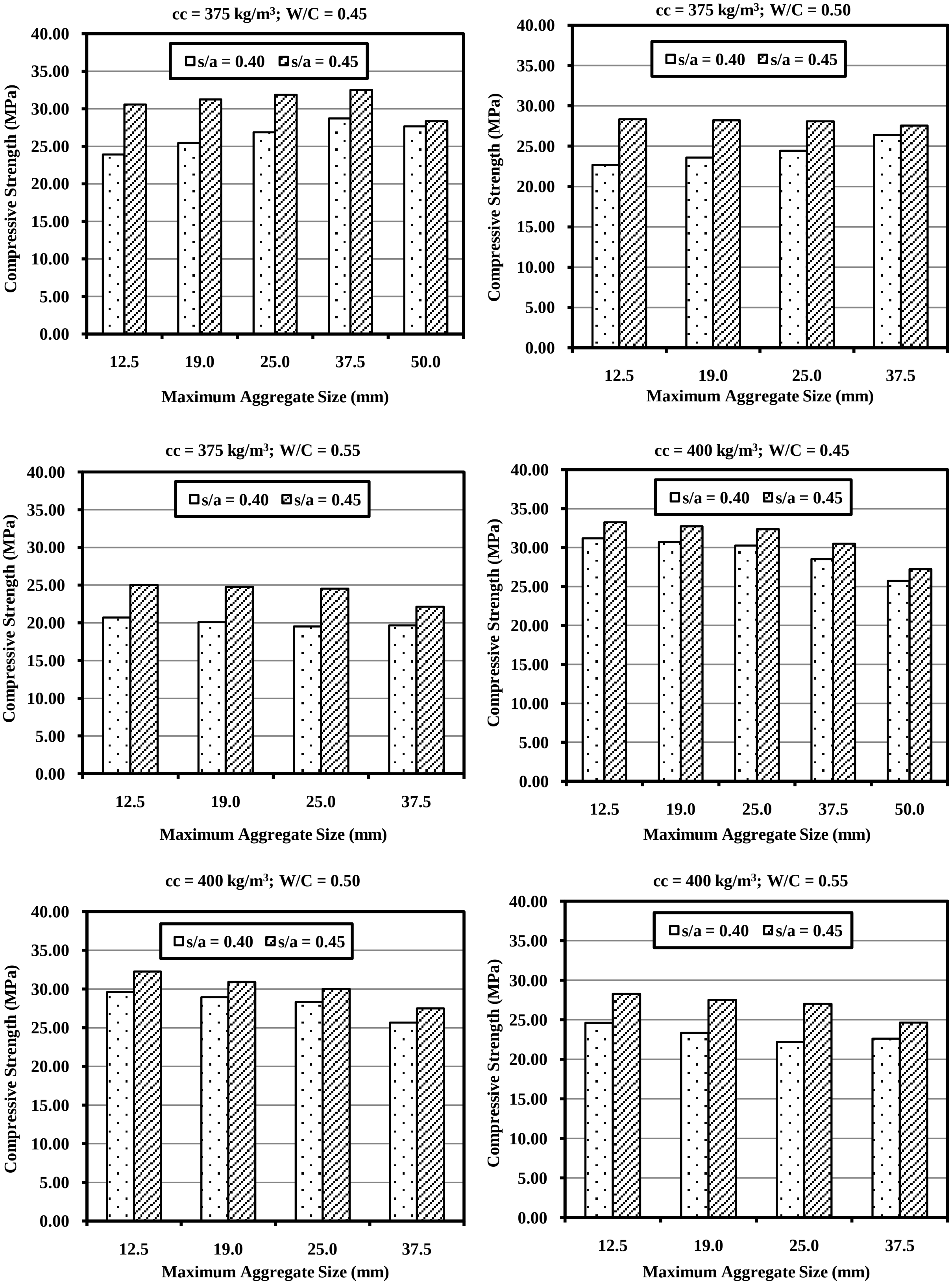


Fig. 4.15. Effect of s/a ratio on compressive strength of concrete

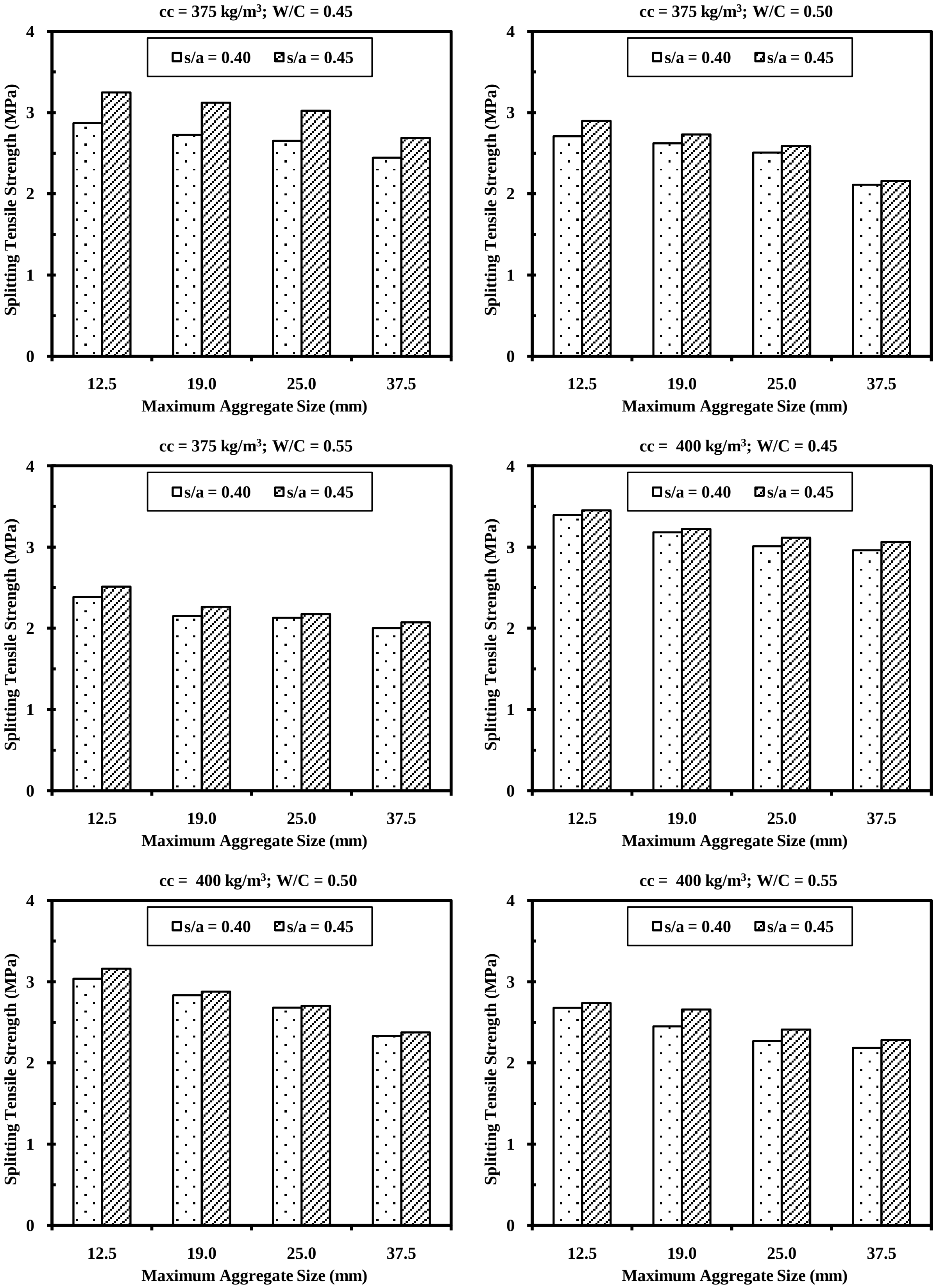


Fig. 4.16. Effect of s/a ratio on splitting tensile strength of concrete

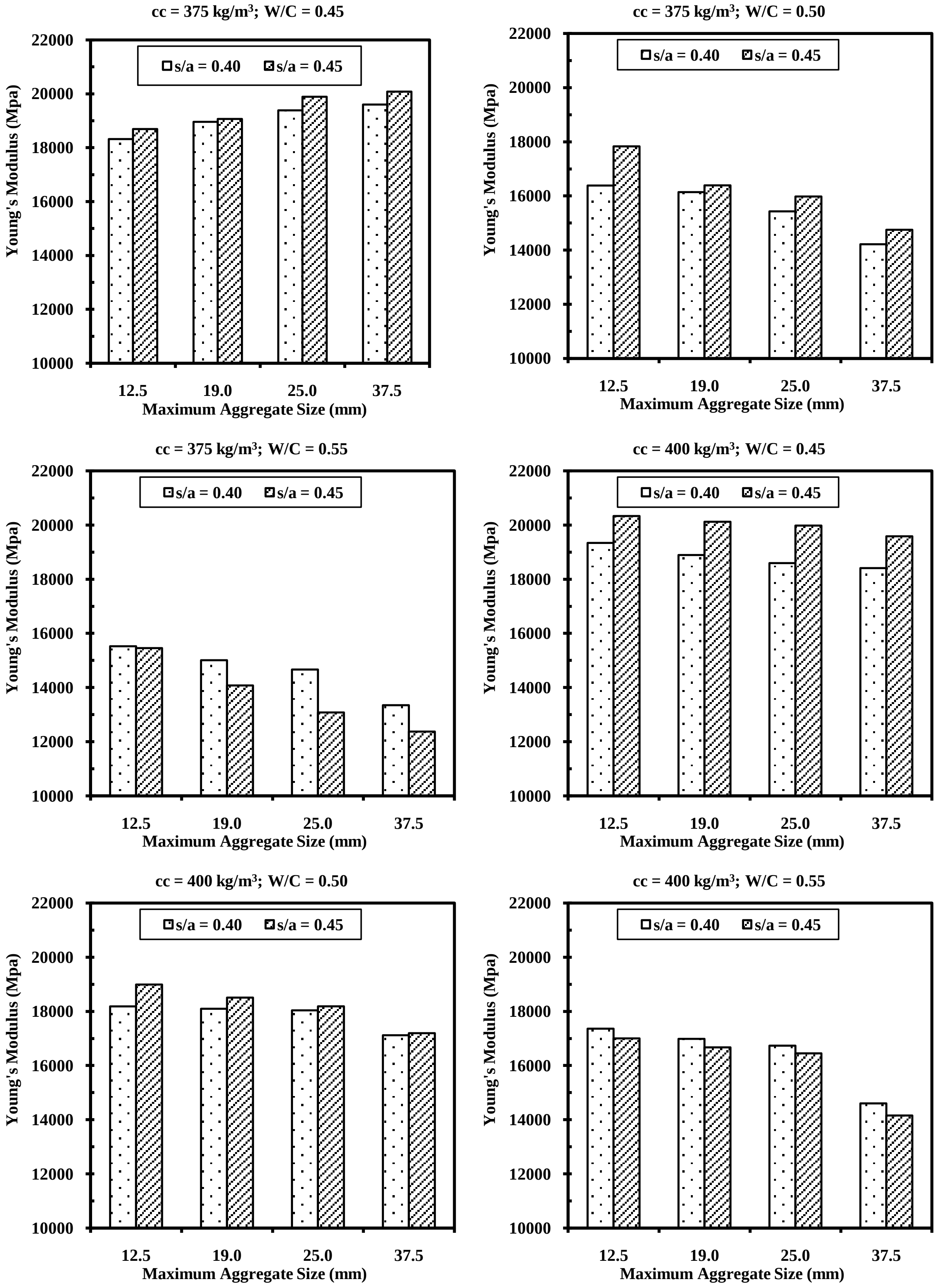


Fig. 4.17. Effect of s/a ratio on Young’s modulus of concrete

4.7 Relationship between Compressive Strength and Young’s Modulus

Fig. 4.18 shows the relationship between the Young's modulus and square root of compressive strength of concrete for different MAS. Based on **Fig. 4.18**, the relationships between Young's modulus and compressive strength of brick aggregate concrete for different MAS are proposed as following:

$$E_c\,(12.5\ mm) = 3170\ \sqrt{f'_c} \quad ; \quad R^2 = 0.93 \tag{4.5}$$

$$E_c\,(19.0\ mm) = 3132\ \sqrt{f'_c} \quad ; \quad R^2 = 0.91 \tag{4.6}$$

$$E_c\,(25.0\ mm) = 3063\ \sqrt{f'_c} \quad ; \quad R^2 = 0.90 \tag{4.7}$$

$$E_c\,(37.5\ mm) = 2816\ \sqrt{f'_c} \quad ; \quad R^2 = 0.91 \tag{4.8}$$

Where, E_c is the Young's modulus and f_c' is the compressive strength of concrete in MPa. Using these relationships, the strength of brick aggregate concrete for a particular maximum aggregate size with known compressive strength can be judged.

It is understood that for the same strength of concrete, the Young’s modulus is reduced with the increase of MAS.

It is important to note that, ACI 318-14 suggests the following equation for Young’s modulus of concrete:

$$E_c\,(37.5\ mm) = 4732\ \sqrt{f'_c} \tag{4.9}$$

Where, E_c is the Young's modulus and f_c' is the compressive strength of concrete in MPa.

It is evident that coefficients of **equations (4.5) – (4.8)** for different MAS of brick aggregate are lower than the coefficient suggested by ACI 318-14 and other researchers who studied stone aggregate concrete (Kesegić, 2008). This may be due to the fact that, the Young's modulus of brick is less than that of stone and it is well established that the

Young's modulus of concrete is a function of the Young's modulus of the aggregate itself (ACI 318-14, Kesegić, 2008). The results presented here may be justified by studying the Young’s modulus of different brick aggregate and stone aggregate.

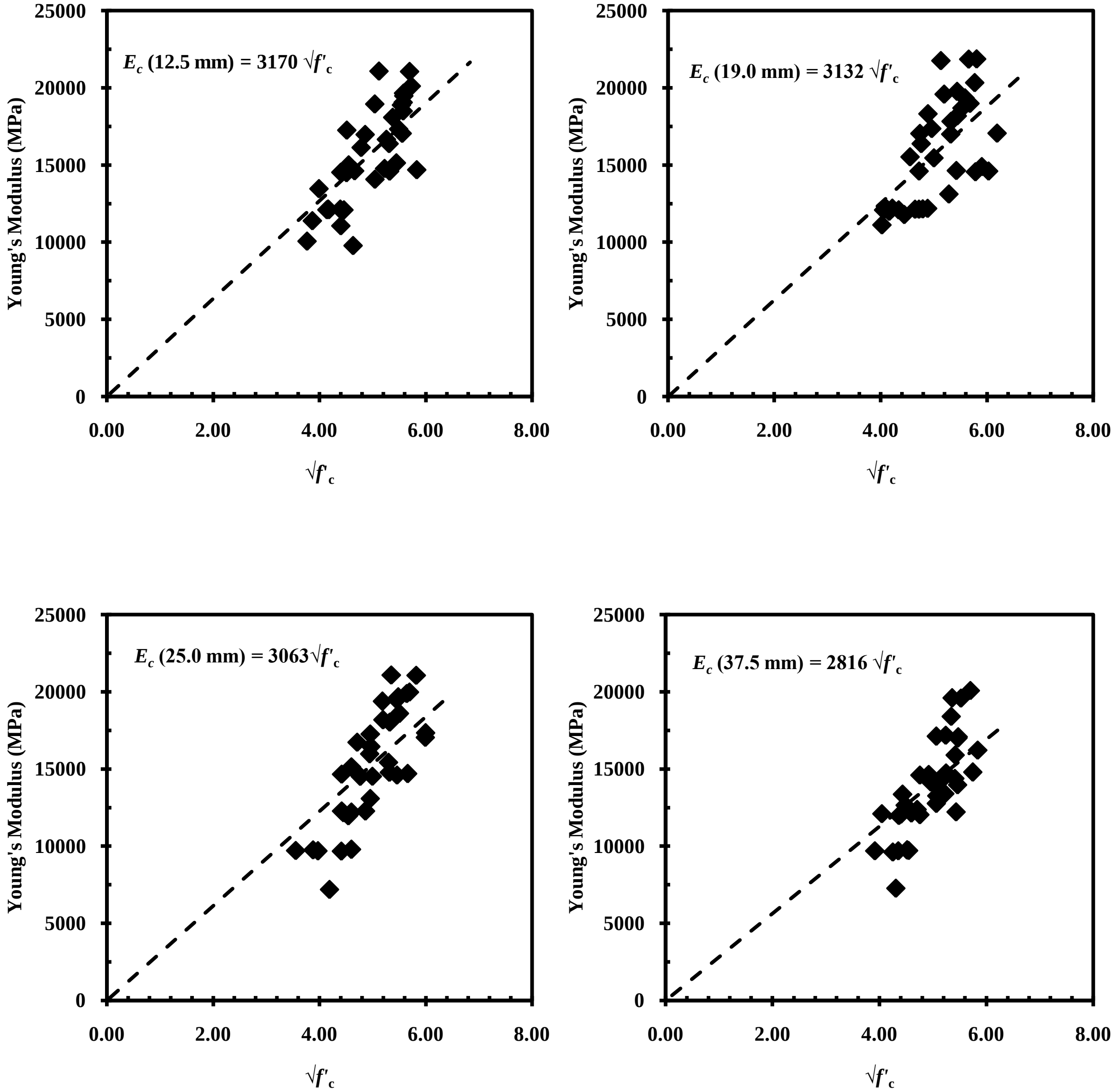


Fig. 4.18. Relationship between compressive strength and Young's modulus

4.8 Relationship between Compressive Strength and Splitting Tensile Strength

The variation of splitting tensile strength of concrete made with different MAS of brick aggregate with compressive strength is shown in **Fig. 4.19**. Based on the experimental data in **Fig. 4.19**, the tensile strength of concrete can be correlated with compressive strength by the following equations:

$$f_t\,(12.5\ mm) = 0.509\sqrt{f'_c} \quad ; \quad R^2 = 0.90 \tag{4.10}$$

$$f_t\,(19.0\ mm) = 0.485\sqrt{f'_c} \quad ; \quad R^2 = 0.89 \tag{4.11}$$

$$f_t\,(25.0\ mm) = 0.471\sqrt{f'_c} \quad ; \quad R^2 = 0.88 \tag{4.12}$$

$$f_t\,(37.5\ mm) = 0.462\sqrt{f'_c} \quad ; \quad R^2 = 0.88 \tag{4.13}$$

Where, f_t is the splitting tensile strength in MPa and f_c' is the compressive strength of concrete in MPa.

Concrete made with MAS of 12.5 mm exhibits the maximum splitting tensile strength for a given compressive strength. This could be attributed to improved bond between aggregate and cement paste due to smaller size of aggregate at a given aggregate content, similar to the findings by Cetin et al. (1998).

The relationship between splitting tensile strength and compressive strength of concrete proposed by ACI 318-14, Ivey and Buth (1967), and Hanson (1961) is as follows:

$$f_t(37.5\ mm) = 0.556\sqrt{f'_c} \tag{4.14}$$

Where, f_t is the splitting tensile strength in MPa and f_c' is the compressive strength of concrete in MPa.

It is evident that the coefficients proposed in equations (4.10) – (4.13) are slightly lower than that proposed in equation (4.14). This can be attributed to the use of brick aggregate, which may result in a lower splitting tensile strength compared to stone aggregate concrete.

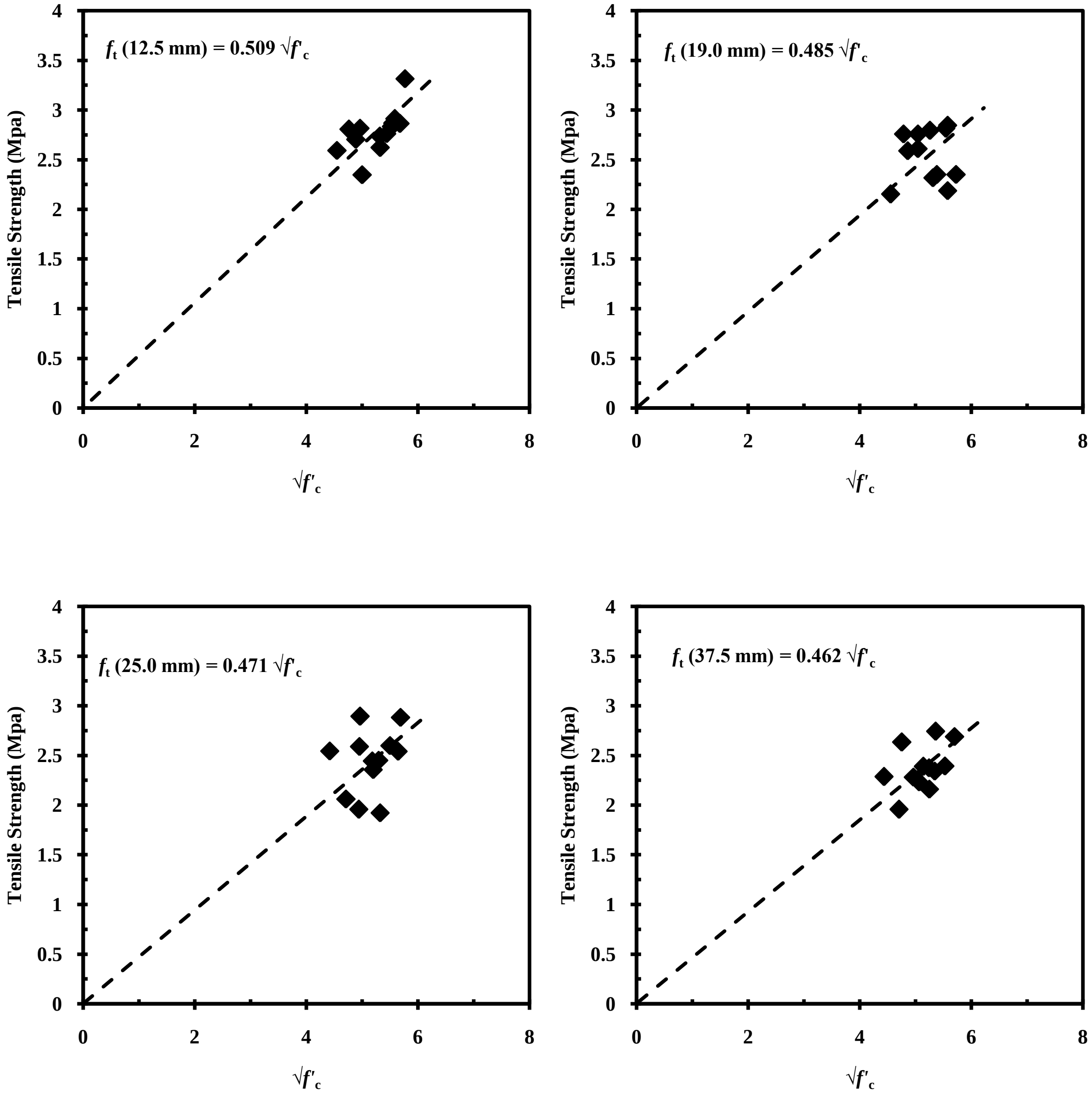


Fig. 4.19. Relationship between tensile strength and compressive strength

4.9 Relationship between Compressive Strength and UPV

Fig. 4.20 shows the relationship between Ultrasonic Pulse Velocity (UPV) and compressive strength of concrete made with different MAS. An exponential relationship is found between the compressive strength and UPV of concrete made with brick aggregate of different MAS. Based on the experimental data, the following relationships are proposed:

12.5 mm MAS: $f_c' = 0.088\, e^{1.58(UPV)}$; $R^2 = 0.86$ (4.15)

19.0 mm MAS: $f_c' = 0.421e^{1.16(UPV)}$; $R^2 = 0.82$ (4.16)

25.0 mm MAS: $f_c' = 0.226e^{1.32(UPV)}$; $R^2 = 0.87$ (4.17)

37.5 mm MAS: $f_c' = 0.876e^{0.92(UPV)}$; $R^2 = 0.85$ (4.18)

Where, f_c' is the compressive strength of concrete in MPa and *UPV* is the Ultrasonic Pulse Velocity in km/s.

Over decades, several relationships between UPV and compressive strength have been proposed, specially for normal density concrete (Yang et al., 2010, Ben-Zeitun, 1986, Ravindrarajah, 1997, Price, 1996). Sturrup et al. (1984) proposed a logarithmic relationship, while Ben-Zeitun (1986) suggested linear relationships. However, exponential relationships are the most common ones suggested by researchers (Ravindrarajah, 1997, Bogas et al., 2013, Solís-Carcaño et al., 2008, Lin et al., 2007, Trtnik et al., 2009). Solís-Carcaño et al. (2008) used limestone aggregate for making concrete and proposed the following relationship between compressive strength and pulse velocity:

$$f_c' = 0.5697e^{0.001(UPV)} \qquad (4.19)$$

Where, f_c' is the compressive strength of concrete in MPa and UPV is the pulse velocity in m/s.

Bogas et al. (2013) used Iberian expanded clay lightweight aggregate for making lightweight concrete and proposed the following relationship between compressive strength and pulse velocity:

$$f_c' = 3.38e^{0.62(UPV)} \qquad (4.20)$$

Where, f_c' is the compressive strength of concrete in MPa and *UPV* is the pulse velocity in km/s. For a better description, the expressions recommend by Solís-Carcaño et al. (2008) and Bogas et al. (2013) are also shown in **Fig. 4.20**.

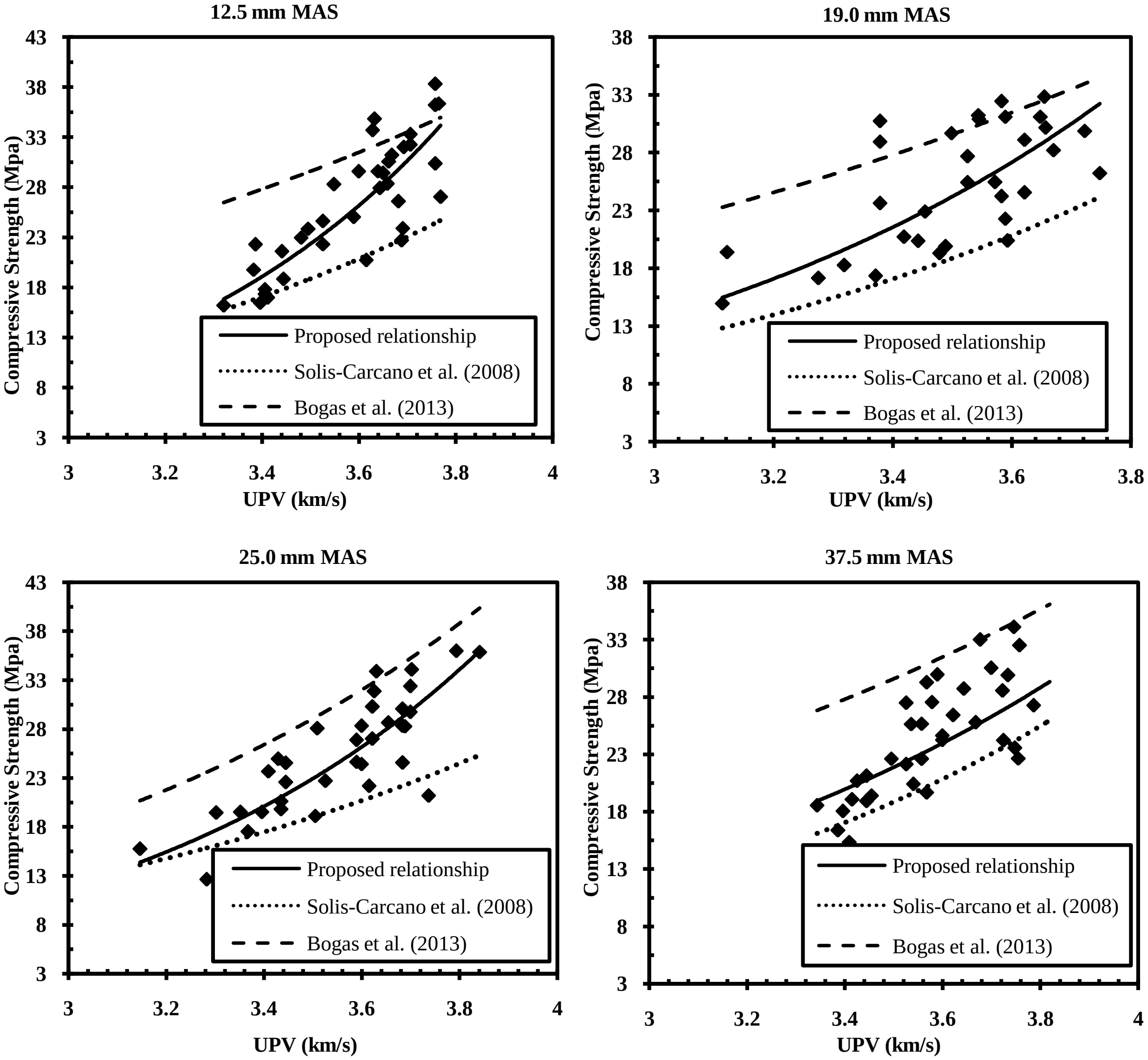


Fig. 4.20. Relationship between compressive strength and UPV

4.10 Relationship between Young's Modulus and UPV

The relationships between Ultrasonic Pulse Velocity (UPV) and Young's Modulus of concrete made with aggregates of different MAS are shown in **Fig. 4.21**. An exponential relationship is found between UPV and Young's Modulus of concrete made with brick aggregate of different MAS. Based on the experimental data, the following relationships are proposed:

12.5 mm MAS: $E_c = 1485\, e^{0.181\,(UPV\text{^}2)}$; $R^2 = 0.86$ (4.21)

19.0 mm MAS: $E_c = 1397e^{0.143\,(UPV\text{^}2)}$; $R^2 = 0.80$ (4.22)

25.0 mm MAS: $E_c = 1335e^{0.186\,(UPV\text{^}2)}$; $R^2 = 0.84$ (4.23)

37.5 mm MAS: $E_c = 1273e^{0.181\,(UPV\text{^}2)}$; $R^2 = 0.82$ (4.24)

Where, E_c is the Young's modulus of concrete in MPa and UPV is the ultrasonic pulse velocity through concrete in km/s.

The relationship between Ultrasonic Pulse Velocity (UPV) and Young's Modulus of concrete has been a focus for researchers for quite sometimes, and an exponential relationship has recently been proposed by Yıldırım, et al. (2011) for limestone aggregate concrete as follows:

$$E_c = 6000\, e^{0.076(UPV\text{^}2)} \tag{4.25}$$

Where, E_c is the Young's modulus of concrete in MPa and UPV is the ultrasonic pulse velocity through concrete in km/s.

A similar approach has been adopted in this study to find a relationship between UPV and Young's modulus for brick aggregate concrete. For a better description, the relationship between pulse velocity and Young's Modulus proposed by Yıldırım, et al. (2011) is also shown in **Fig. 4.21**. Young's moduli presented in this figure were obtained from the stress–strain curves of the cylindrical specimens. The relationship obtained confirm that this method may be used for estimating the Young's Modulus of concrete (made with brick aggregates of different MAS) in existing structures where taking out cores is not preferred due to dimensional constrains of structural members.

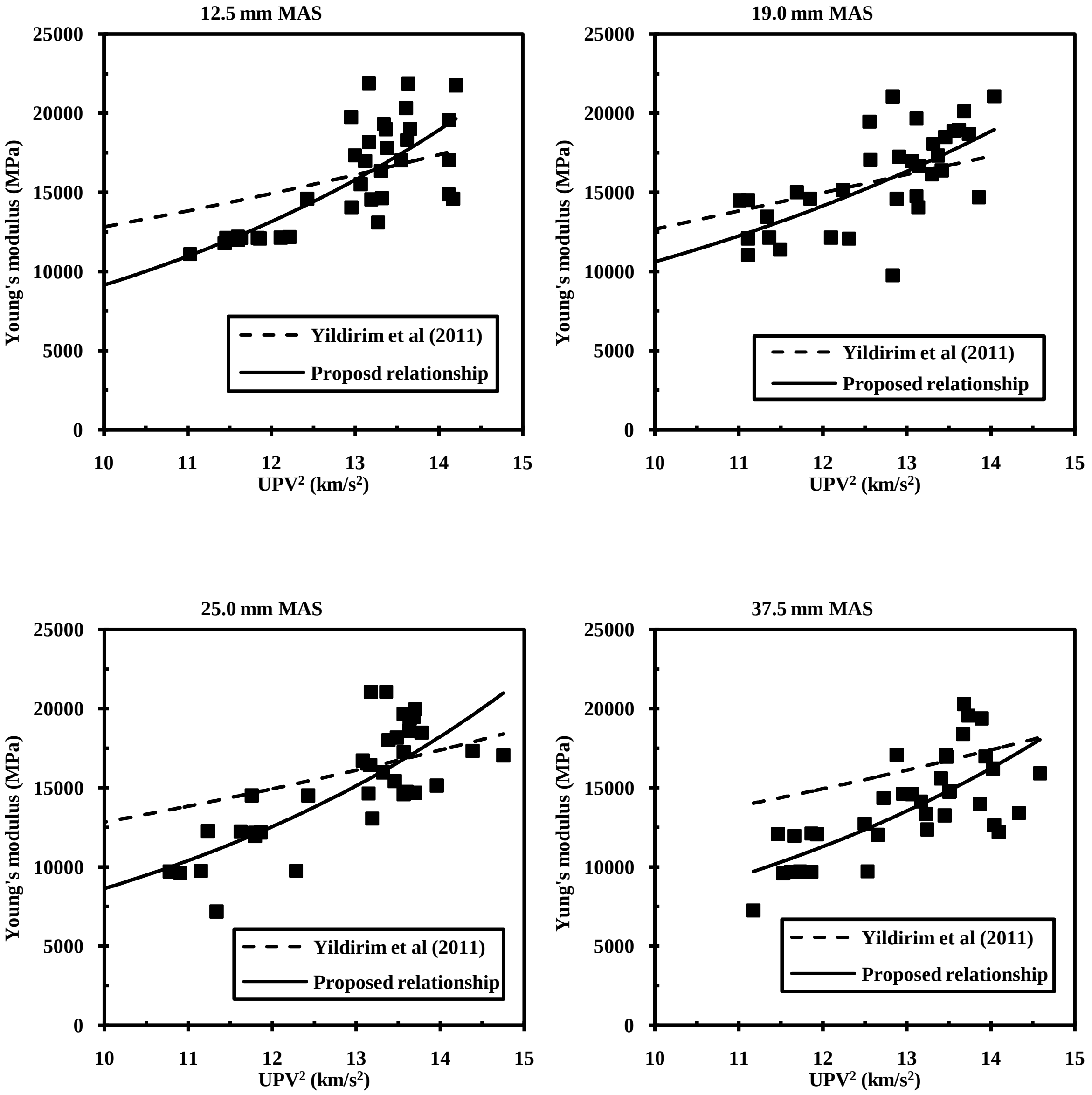


Fig. 4.21. Relationship between Young’s modulus and UPV

4.11 Relationship between Compressive Strength and Rebound Number

The relationships between compressive strength and rebound number of concrete made with aggregates of different MAS are shown in **Fig. 4.22**. A linear relationship is found between the compressive strength and rebound number of concrete made with brick aggregate of different MAS. Based on the experimental data, the following relationships are proposed:

12.5 mm MAS: $f'_c = 1.151N - 3.47$; $R^2 = 0.93$ (4.26)

19.0 mm MAS: $f'_c = 1.155N - 4.50$; $R^2 = 0.92$ (4.27)

25.0 mm MAS: $f'_c = 1.088N - 3.39$; $R^2 = 0.92$ (4.28)

37.5 mm MAS: $f'_c = 1.049N - 0.98$; $R^2 = 0.93$ (4.29)

Where, f'_c is the compressive strength of concrete and N is the rebound number recorded from Schmidt hammer test.

The relationship between compressive strength of concrete and rebound number is useful when non-destructive evaluation of concrete is necessary. Al-Mufti and Fried (2012) used gravel aggregate for making concrete and conducted Schmidt hammer test on hardened specimens. They proposed a linear relationship for normal strength gravel aggregate concrete as follows:

$$f'_c = 1.630N - 24.44 \tag{4.30}$$

Where, f'_c is the compressive strength of concrete and N is the rebound number recorded from Schmidt hammer test.

A similar approach has been adopted in this investigation to find a relationship between compressive strength of concrete and rebound number for brick aggregate concrete for different MAS. For a better description, the relationship between compressive strength of concrete and rebound number proposed by Al-Mufti and Fried (2012) is also shown in **Fig. 4.22**. The relationships proposed here can be used for estimating the compressive strength of concrete (made with brick aggregates of different MAS) in existing structures where taking out cores is not preferred due to dimensional constrains of structural members.

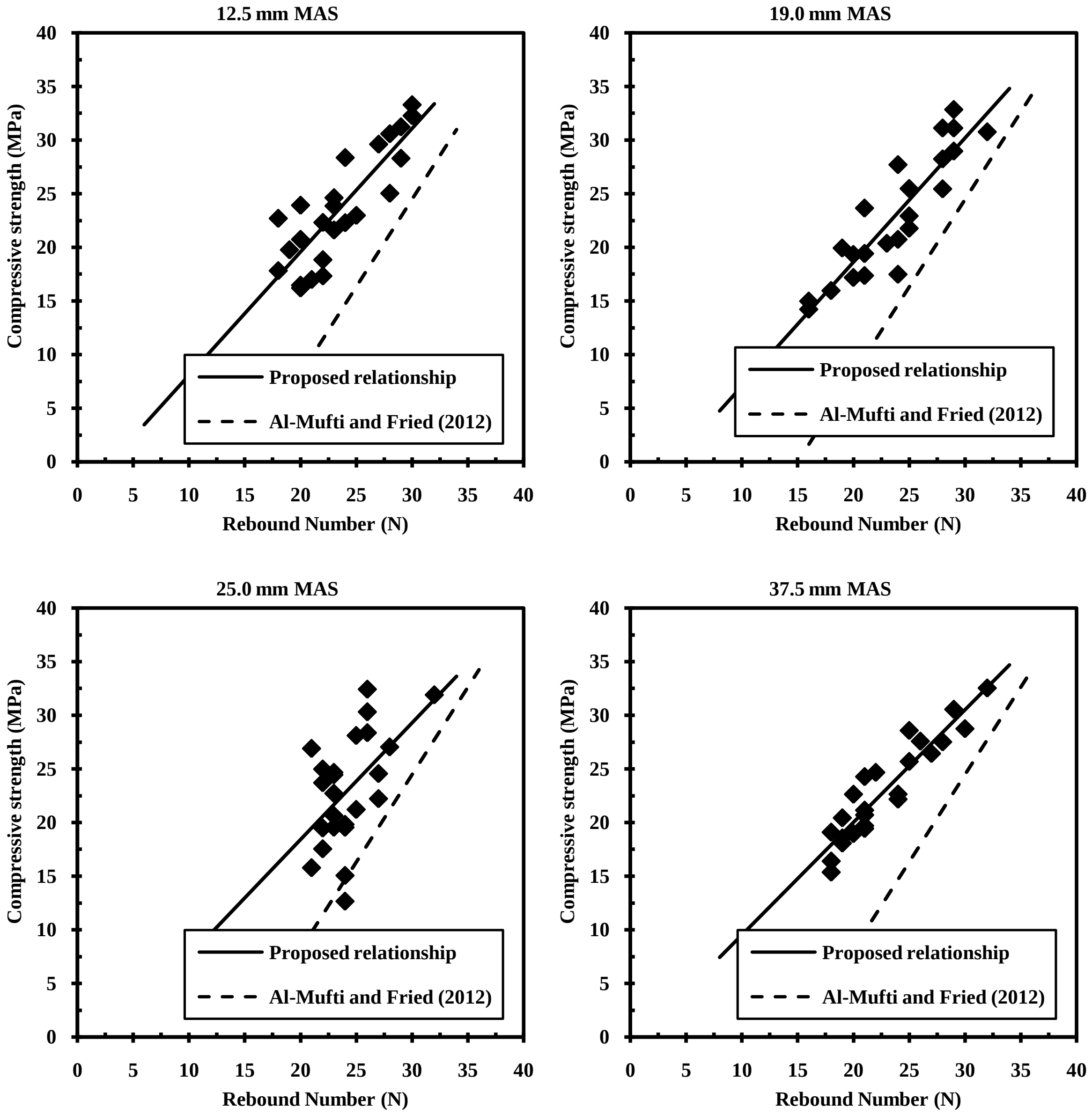


Fig. 4.22. Relationship between compressive strength and rebound number

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 General

This chapter includes the summary of the research findings based on discussions in Chapter 4. Moreover, recommendations and future works related to this investigation are also proposed in this chapter.

5.2 Conclusions

Based on the experimental results of this study, the following conclusions are drawn:

1. The workability of concrete increases with an increase of MAS irrespective of the variation in s/a ratio, cement content, and W/C ratio.
2. The compressive strength and Young's modulus of concrete made with W/C ratio of 0.45 and 0.50, and cement content of 375 kg/m^3 increase with an increase in the MAS up to MAS of 37.5 mm, beyond which, they decrease with an increase in MAS. On the other hand, when the cement content is increased to 400 kg/m^3, the compressive strength and Young's modulus decrease with an increase in MAS.
3. The compressive strength and Young's modulus of concrete made with higher W/C ratio (W/C = 0.55) decrease with an increase in the MAS, irrespective of variation of cement content and s/a ratio.
4. The splitting tensile strength of concrete decreases with an increase in MAS, irrespective of the variation of s/a ratio and cement content.
5. The compressive strength of concrete increases with an increase in s/a ratio from 0.40 to 0.45.

6. The effect of cement content on compressive strength is more significant for smaller MAS of coarse aggregate.
7. UPV through concrete increases with an increase in MAS due to reduction in interfacial transition zone (ITZ) in concrete made with larger sized aggregates.
8. Relationships between stress and strain of concrete made with brick aggregates of MAS of 12.5 mm, 19.0 mm, 25.0 mm, and 37.5 mm are proposed.
9. Relationships between compressive strength and Young's modulus of concrete; and splitting tensile strength and compressive strength of concrete made with brick aggregates of MAS of 12.5 mm, 19.0 mm, 25.0 mm, and 37.5 mm are proposed.
10. Relationships between UPV and compressive strength, and rebound number and compressive strength of concrete made with brick aggregates of 12.5 mm, 19.0 mm, 25.0 mm, and 37.5 mm MAS are proposed.

5.3 Recommendations

From this study, this is evident that at a lower cement content of 375 kg/m^3, construction engineers can go for larger sized aggregates to make concrete, if strength of concrete is to be improved. But if larger sized aggregate is discouraged considering the reinforcement cover, then smaller sized coarse aggregates can be used for better strength at a relatively higher cement content of 400 kg/m^3. Smaller sized aggregates can also be useful for better tensile strength of concrete.

Moreover, non-destructive tests on structural members made with brick aggregate concrete can be conducted and results can be used to evaluate the concrete strength using the proposed relationships in this study for different MAS.

5.4 Limitations and Future Work

Though this study has been primarily planned to study the effect of MAS on fresh and hardened properties of concrete, the scope was not limited to the effect of MAS only. This study also investigates the effect of variation of s/a ratio (0.40 and 0.45) and cement content (375 kg/m^3 and 400 kg/m^3) on compressive strength of concrete. A total of five different MAS were studied, but the variation of s/a ratio and cement content were limited to two. Future works can be planned to study the effects of s/a ratio and cement content variations to find an optimum s/a ratio and cement content for brick aggregate concrete.

Though this study discusses the effect of MAS on major concrete properties like compressive strength, splitting tensile strength, stress-strain curve, and Young's modulus; the scope of the research can be expanded to study the effect of MAS on modulus of rupture of concrete, flexural and shear behavior of concrete under load as well.

Moreover, chloride ingress and other durability aspects of brick aggregate concrete are recommended to be addressed. Performance of brick aggregate concrete in marine environment should also be addressed.

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